Innovative and Sustainable Approaches in Civil Engineering: Materials, Structures And Digital Technology

Editor
ONUR SARAN

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Innovative and Sustainable Approaches in Civil Engineering: Materials, Structures And Digital Technology

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PREFACE

Civil engineering is increasingly shaped by the need for sustainable solutions, advanced materials, and digital technologies that enhance the performance and resilience of infrastructure systems. Recent advances in materials science, structural engineering, and computational methods have enabled more efficient design, accurate analysis, and performance-based evaluation of civil engineering applications.

This book, "Innovative and Sustainable Approaches in Civil Engineering: Materials, Structures, and Digital Technology," presents selected studies addressing current challenges in civil engineering. Chapters cover advanced and sustainable construction materials, structural behavior under environmental and dynamic influences, and the applications of digital technologies such as image processing and computational analysis in engineering practice.

The book aims to provide an integrated perspective that connects material performance, structural response, and digital methodologies. It is designed for researchers, graduate students, and engineers seeking a concise overview of current innovations and sustainable approaches in civil engineering.

Assistant Professor ONUR SARAN

VAN YUZUNCU YIL UNIVERSITY

CONTENTS

CONTENTS

CHAPTER 1

PRODUCTION OF DIFFERENT PLASTICS IN THE WAY OF ENDING POTENTIALLY IN CONCRETE PRODUCTION

FİDAN GÜZEL[1]

Introduction

Petrochemicals and fossil fuels are vital in plastic production. 99% of the raw materials used in plastic production are petroleum-based. This accounts for approximately 8.5% of global oil production, 4.5% of gasoline consumption, and 3.5% of energy consumption (Jambeck et al., 2015). Large-scale operations such as mining, drilling, and cracking are the primary methods for extracting natural resources. 99% of the primary materials used in this phase of the cycle come from fossil fuels, while only 1% come from plant sources (Williams and Rangel-Buitrago, 2022). Petroleum-based plastic pellets are produced through the polymerization of petroleum monomers. This process produces different types of plastic pellets, which are then transferred to other processes that manufacture plastic products. As shown in Figure 1, the plastic production process begins with the extraction and refining of crude oil, which produces

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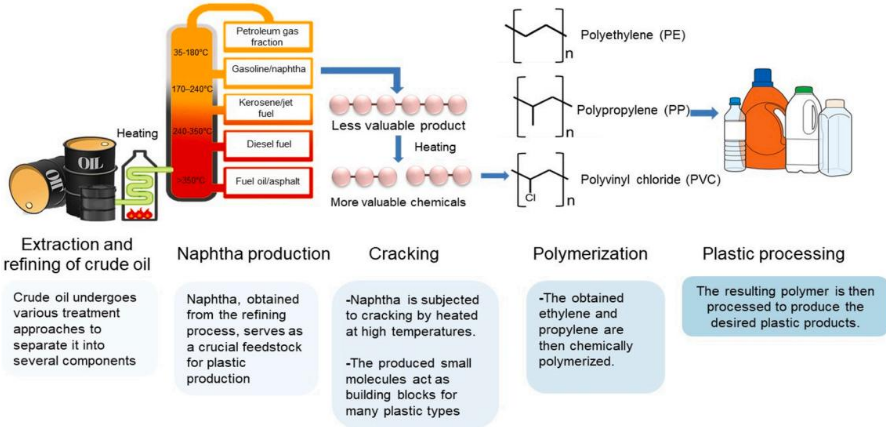
a raw material called naphtha. The resulting naphtha is then subjected to a process called cracking, which breaks it down into smaller molecules like ethylene and propylene. These molecules are then polymerized into polymers, which are used in the production of plastic products such as PE (polyethylene), PP (polypropylene), and PVC (polyvinyl chloride). This process requires significant energy consumption and produces significant environmental impacts, such as greenhouse gas (GHG) emissions and pollution (Rodríguez et al., 2019).

Synthetic polymers are obtained by linking hundreds or even thousands of organic subunits ("monomers") together with strong covalent chemical bonds (Chamas et al., 2020). Bakelite, the first fully synthetic polymer, was synthesized by the polycondensation reaction of phenol and formaldehyde and began to be produced in the early 20th century. However, true mass production of polymers dates back to the 1950s. From the 1950s to the present, global plastic production has increased parabolically, reaching 380 million tons annually in 2015 (Geyer et al., 2017). Today, thousands of different types of polymers are produced commercially (Rosato, 2013). Low-cost, standard thermoplastic polymers hold the largest market share, and these are the products we call plastics, used in many areas of our daily lives. These materials, usually gaseous or liquid at the beginning of the plastic production process, are converted from liquid to solid end-products by the application of heat, pressure, or both.

Polymer production processes have made it possible to develop plastics with specialized properties for specific applications. Thousands of different types of plastics have been obtained by adding elements such as carbon, hydrogen, nitrogen, oxygen, fluorine, silicon, sulfur, and chlorine. Polymers are produced using polymerization techniques such as anionic, cationic, and step-growth, which allow the formation of large molecules from monomers (Subramanian, 2019).

Figure 1 The process of obtaining plastic products from crude oil



Kaynak: Jialo et al., 2024

Using a single type of monomer results in the formation of homopolymers, while using two or more different monomers results in the formation of copolymers. The polymerization process is usually controlled by a catalyst or initiator, and the polymers produced in this process are generally thermoplastic. Plastics are synthetic polymers that are divided into two main groups: thermosets and thermoplastics (Ali et al., 2023). Thermoset polymers are petrochemical-derived materials that undergo irreversible chemical changes during the curing (hardening) process and cannot be reshaped (Aizudin et al., 2022). In contrast, thermoplastics are still derived from petrochemicals, but they soften and can be shaped without losing their chemical structure when heated, and they can resolidify when cooled. Thanks to these properties, thermoplastics can be recycled and reused in the production of value-added products in a variety of applications. This section will discuss thermoplastic and thermoset plastics. Unless otherwise stated, the plastics in question are taken from Subramanian (2019).

Thermoplastics

Thermoplastics are produced from monomers and, in the presence of a catalyst, a polymer is formed by the application of heat and pressure. In this process, monomers combine with each other, increasing chain length; chain growth is halted by the joining of reactive ends. During the polymerization reaction, polymer chains simultaneously lengthen. By adding predetermined inhibitors (chain growth inhibitors), polymers with a constant average chain length can be produced; this property is a key factor in determining many of the plastic's physical properties and processability. Increasing chain length increases strength, creep resistance, stress-crack resistance, melting temperature (Tm), and melt viscosity. Due to the polymer's non-degradable nature, it also makes it more difficult to process.

The average molecular weight (MW) distribution of polymer molecules can be generated; the MW difference between large and small molecules can be narrow or wide. A narrow MW distribution provides more uniform properties, while a broad distribution improves processability (TS706).

Thermoplastics soften or melt when heated and harden when cooled. Various processing techniques have been developed to exploit these properties and mold them into specific shapes. No chemical changes or cross-linking occur between molecules during processing. Because thermoplastics soften again when heated again, the polymerized chains can be reshaped by heat, making them "thermoformable."

1. Polyolefins

The general properties of polyolefins (POs) can be tailored by the catalyst design used. Derived from relatively inexpensive raw materials, POs generally exhibit hydrophobic properties. Surface modification is required to improve certain properties such as adhesion, wettability, printability, and biocompatibility. When exposed to light or heat, POs generally exhibit an induction period during which oxygen uptake or changes in physical properties are minimal. POs are prone to degradation by heat and oxidation, making them unsuitable for practical applications such as automotive parts unless protected with effective antioxidants.

2. Polyethylene

Polyethylene (PE) is one of the most resistant plastics to degradation when discarded in the environment. It is known to show no visible change during long-term use in soil or marine environments (e.g., cable sheathing and sonar devices). It is the most important plastic type in terms of production volume. The low-density polyethylene (LDPE) market accounts for approximately 75% of packaging film production, followed by extrusion coating and injection molding products. LDPE, which accounts for approximately 64% of global plastic production, is typically used in packaging and bottle forms and is discarded after short-term use. Some physical properties of polyethylene plastic are shown in Table 1.

Theoretically, PE protects its structure against photo-oxidation. However, if it contains branching, impurities, or residual catalytic species, it may lose its mechanical properties in the external environment. Due to their low degradability, plastic bags accumulate in the environment and cause pollution. Furthermore, due to their low mass and frequent contamination, recycling them is not economically viable. They do not fully decompose in composting facilities; therefore, bag fragments contaminate the compost and require additional processing.

Table 1. General physical properties of polyethylene plastic type

Physical Parameter	Value	Unit
Specific gravity	0.91–0.94	–
Tensile modulus	10-60	MPa
Flexural modulus	550-1000	KPa
Hardness	78–108	Shore D
Melting transition temperature	110-135	°C

The development of commercially viable biodegradable plastics represents a significant step toward protecting and revitalizing the global environment, as it addresses the need to transform a significant portion of municipal solid waste. Biodegradable polymers with controllable lifespans are becoming increasingly important in waste management. Biodegradation is defined as a form of degradation by microorganisms, and its main advantage is that it enables the assimilation of already large amounts of waste into the natural environment.

Fully biodegradable polymers are converted by microorganisms into small molecules (such as carbon dioxide, water, minerals, and biomass) and do not cause any adverse environmental impact or toxicity. The time it takes for degradation to occur is measured by the life cycle time. Many polymers claimed to be biodegradable are actually bioerodable, hydrobiodegradable, photodegradable, slowly degradable, or only partially biodegradable.

PE constitutes the largest fraction of plastic in the municipal waste stream, consisting primarily of high-density polyethylene (HDPE) packaging materials. Recycling of this type of waste produces recycled plastic with highly homogeneous and consistent properties. HDPE is derived from products such as milk and juice bottles (homopolymers) and shampoo bottles (copolymers), and the recovered resin exhibits rheological properties similar to the original raw material because it does not undergo significant thermal degradation during processing.

3.Polypropylene

Polypropylene (PP) is a thermoplastic widely used in many different applications thanks to its unique properties. It is commercially available in three main forms: atactic, syndiotactic, and isotactic. Isotactic polypropylene (IPP) is the most common form on an industrial scale. In this form, the methyl groups are regularly aligned in the same direction, allowing for the formation of a crystalline structure and giving the material a high melting point and superior mechanical properties. PP is widely used in automotive, packaging, textile, and consumer goods due to its light weight, chemical resistance, and heat processability. Its high melting point (approximately 160–170°C) gives it an advantage over polyethylene in applications involving hot liquids. It also exhibits low moisture absorption and good electrical insulation properties. Melting point and other key properties (such as specific gravity and flexural modulus) are listed in Table 2.

PP does not undergo any cross-linking during processing, so the material can be melted and reformed. This facilitates recycling. However, like other polyolefins, PP is resistant to environmental degradation. Auto-oxidative degradation, initiated by the combination of light, heat, and oxygen, can lead to chain breaks and deterioration in physical properties. However, PP is known to be less resistant to oxidative degradation compared to PE. Therefore, antioxidants and UV stabilizers are often added to PP products, especially those used outdoors. Additionally, additives are commonly used to ensure process stability in applications such as injection molding and fiber production.

Table 2. Some physical properties of polypropylene plastic type

Physical Parameter	Value	Unit
Specific gravity	0.905	–
Tensile modulus	23.46 ±0.23	MPa
Flexural modulus	1140-1550	KPa
Hardness	73	Shore D
Melting transition temperature	178.1	°C

Recycled PP is commonly used in automotive parts, trash cans, transport crates, and various construction products. However, the mechanical properties of recycled PP may be lower than those of virgin PP because PP undergoes thermal degradation during recycling. Therefore, in some cases, it may be necessary to add additives to recycled PP to improve its properties.

4.Polystyrene

Polystyrene (PS) is a tough, transparent thermoplastic obtained by free-radical polymerization of styrene monomer. The amorphous structure of PS is characterized by high optical transparency and brittleness. Due to its low density, easy processability, and low cost, polystyrene is widely used in packaging, disposable products (e.g., plates, forks, spoons), insulation materials, and electronic components.

There are three main types of PS commercially available: general-purpose polystyrene (GPPS), impact polystyrene (HIPS), and expanded polystyrene (EPS). GPPS offers high gloss and transparency, while HIPS is modified with an elastomer (usually polybutadiene) to increase impact resistance. EPS, on the other hand, is a closed-cell foam containing blowing agents and is primarily used in thermal insulation applications.

PS has a low glass transition temperature (~100°C), which makes it resistant to heat. Furthermore, its susceptibility to environmental stress cracking and poor resistance to organic solvents are limiting factors in some applications. However, its light weight and processability make it an ideal material for many single-use products.

From a recycling perspective, PS is among the most difficult thermoplastics to recycle. Foam forms like EPS, being large in volume but light in mass, create logistical challenges during transportation and reprocessing. Furthermore, PS's susceptibility to degradation during remelting can lead to a loss of material properties.

Despite these challenges, PS is recyclable, and recycled PS (rPS) is often used in low-grade applications. In recent years, solvent-based recovery techniques and chemical recycling methods have been explored to increase PS recycling efficiency.

5.Polyethylene terephthalate (PET)

Polyethylene terephthalate (PET) is an aromatic polyester obtained through the condensation reaction of terephthalic acid and ethylene glycol. Highly crystalline, PET is known for its excellent mechanical properties, chemical resistance, and gas barrier properties. Table 3 shows the basic physical properties of PET plastic (Olam, 2011). PET is most commonly used in beverage bottles, food packaging, and synthetic fibers (e.g., polyester textile fiber). Its properties, such as high transparency, low permeability, and good processability, have made it a preferred material, particularly in the packaging industry.

PET's melting point is approximately 250°C, and its glass transition temperature is between 70–80°C. The degree of crystallinity can be adjusted depending on processing conditions, allowing PET to be produced in either a semi-crystalline or amorphous form. Crystalline PET is generally preferred for engineering applications, while amorphous PET is used in packaging applications requiring high transparency.

Table 3. Basic physical properties of PET plastic

Physical Parameter	Value	Unit
Specific gravity	1.38-1.56	–
Tensile modulus	40-60	MPa
Flexural modulus	1000-3500	KPa
Hardness	96	Shore D
Melting transition temperature	250	°C

Kaynak: Olam, 2011

PET recycling has a well-developed infrastructure, particularly for bottle-based waste. Mechanical recycling is widely used, and washed and shredded waste PET can be remelted and used in various products. Recycled PET (PET), suitable for food contact, can be obtained through appropriate treatment and cleaning processes.

6.Polycarbonate (PC)

Polycarbonate (PC) is a transparent, amorphous thermoplastic produced by the condensation reaction of bisphenol A (BPA) and phosgene. Its high impact strength, optical clarity, and heat resistance make it a significant component of engineering plastics.

PC's glass transition temperature is approximately 145°C, enabling it to maintain its structural integrity at relatively high temperatures. Completely transparent due to its lack of a crystalline structure, PC is used in a wide variety of applications, including optical discs (CDs/DVDs), safety glasses, lighting elements, and automotive components.

Despite its high heat and impact resistance, polycarbonate is susceptible to scratching, and prolonged exposure to UV rays can cause yellowing or changes in its mechanical properties. Therefore, in outdoor applications, it is often combined with UV stabilizers to improve this aspect of PC.

PC can be easily shaped using processing methods such as injection molding, extrusion, and thermoforming. It can also be combined with other plastics (e.g., PC/ABS) to achieve enhanced properties. From a recycling perspective, PC can be mechanically recycled, but its susceptibility to thermal degradation requires careful temperature control during reprocessing. Research into chemical recycling methods is ongoing, with a particular focus on the safe recovery of BPA.

7.Polymethyl methacrylate (PMMA)

Polymethyl methacrylate (PMMA) is a transparent, amorphous thermoplastic obtained by radical polymerization of methyl methacrylate (MMA) monomer. It is often referred to as "acrylic glass" or "plexiglass" due to its high optical transparency, hardness, and resistance to atmospheric conditions.

PMMA has a glass transition temperature of approximately 105°C, and it offers high mechanical strength and resistance to UV rays. These properties make it widely used in lighting fixtures, automotive lamps, optical lenses, billboards, and structural elements that replace glass.

While polymethyl methacrylate is harder and more scratch-resistant than polycarbonate, it has lower impact resistance. Therefore, in some applications, PMMA is reinforced with rubber modifications to enhance impact resistance.

In terms of processing, PMMA can be easily shaped by injection molding, extrusion, and thermoforming. Its excellent surface quality and coloration properties also make it a preferred material for aesthetic applications.

Recycling: PMMA is mechanically recyclable due to its thermoplastic structure. In addition, chemical recycling methods have been developed in recent years, and recycling studies into MMA monomer have attracted attention.

8.Polyamide

Polyamides (PAs) were the first engineering thermoplastics and were initially developed into high-strength textile fibers that were essentially hygroscopic (moisture-absorbing) and required drying before processing. Their highly crystalline structure—which can be controlled to a certain extent during processing—has a significant impact on all properties, resulting in higher strength, stiffness, and higher heat deflection temperatures. PAs are sensitive to ultraviolet (UV) radiation and have higher creep and cold flow resistance compared to many less rigid thermoplastics. Table 4 below shows some of the physical properties of PAs.

Table 4. Physical properties of polyamide plastic type

Physical Parameter	Value	Unit
Specific gravity	1.03–1.05	–
Tensile modulus	161,000	psi
Flexural modulus	41,800–200,000	psi
Hardness	78–108	Rockwell R
Melting transition temperature	94	°C

Thermosets

The production of thermoset plastics differs significantly from that of thermoplastics; thermoset polymerization occurs through a two-stage curing process using a single material and molding technique. This process involves the reaction of two chemicals in the presence of a peroxide and an accelerator, with or without heat. The resulting pressure depends on the molecules involved. In the first stage, mostly linear molecules are formed, and even these linear chains contain unreacted portions that can flow under heat and pressure.

The final stage of thermoset polymerization occurs in the molding press. Under pressure, the partially reacted compound undergoes cross-linking reactions between the molecular chains. Thermoset monomers with three or more reactive ends cause the molecular chains to combine into three-dimensional cross-links. Flexible thermosets have longer chains with fewer cross-links.

A thermoset plastic has strong, irreversible, permanent bonds. It does not melt when reheated after curing, so thermoset materials cannot be reshaped. Continued heating can cause the cross-links to break, leading to degradation. Many thermosets polymerize via a condensation reaction, which produces a byproduct such as water during the reaction in the mold. If these volatile byproducts are not removed during molding, they can lead to problems such as dimensional instability and reduced part strength. However, some thermoset materials react via an addition reaction without the formation of byproducts; in this case, permanent cross-links can form even at room temperature. Thermosets, thanks to their cross-linked structure, can withstand higher temperatures and provide better dimensional stability than most thermoplastics.

1.Phenol-formaldehyde

Phenol-formaldehyde resins, the workhorses of thermosets, are compounds containing fillers and are molded using compression, transfer, and injection molding methods. These materials are high-performance engineering plastics used as bonding and impregnation materials, exhibiting high electrical and flame resistance, as well as good heat resistance and heat deflection temperature. They are a low-cost material with excellent moldability and dimensional stability, as well as good water and chemical resistance.

2. Unsaturated Polyester

Unsaturated polyester resins are dissolved in styrene to induce free-radical chain-growth copolymerization between the resin and styrene monomers. Styrene acts as a linking agent between the polyester chains, resulting in the formation of a cross-linked network. Approximately 7% volumetric shrinkage occurs during the curing and cross-linking stages. Shrinkage is one of the main disadvantages of this process, as it negatively impacts the dimensional stability of the final product and leads to poor surface quality.

The inclusion of a thermoplastic additive in the formulation reduces shrinkage. Products containing unsaturated polyester resins are not widely recycled due to their poor material properties, long processing times, and irregular shapes and compositions.

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CHAPTER 2

SUSTAİNABİLİTY İN CONCRETE PAVEMENTS

1. Şeyma SÜNBÜL[1]
2. Ahmet TORTUM[2]

Introduction

The economic development of modern societies and the effectiveness of their logistics networks is contingent on the quality and durability of their road infrastructure. Concrete roads, a cornerstone of this infrastructure, are of strategic importance worldwide due to their superior performance under heavy traffic loads, long service lives, rigid structures, and low maintenance costs. However, this engineering accomplishment is accompanied by a substantial environmental cost, which endangers sustainability. This is primarily attributable to the prevailing linear economic model, characterised by the conventional 'take-make-dispose' paradigm. The predominant component of this cost is Portland cement (PC), which functions as the primary binding agent in concrete. The environmental impact of cement production is significant, with a

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contribution of 7-8% to global CO_2 emissions (International Energy Agency, 2023; Shi, Jiménez, & Palomo, 2011). Additionally, the process generates pollutants such as SO_x, NO_x gases, and cement kiln dust, which contribute to air quality concerns (Shi, Jiménez, & Palomo, 2011). The most fundamental strategy to mitigate this impact is to substitute PC with additional cementing materials (ACMs). These ACMs have been shown to enhance the performance of concrete through a pozzolanic reaction, while concomitantly reducing the use of PCs, thus leading to a decrease in carbon emissions and resource consumption (Yang, Jung, Cho, & Tae, 2015). This reaction consumes calcium hydroxide ($Ca(OH)_2$), a weak phase remaining from the PC hydration, and forms additional calcium-silica-hydrate (CSH) gel, which provides durability in the concrete matrix (Abdel-Gawwad et al., 2019). Consequently, this mechanism enhances both the concrete's mechanical properties and its resistance to aggressive external influences. Moreover, the extraction of aggregates, such as natural sand and gravel, which are indispensable for paving, results in the rapid depletion of natural resources and the occurrence of permanent damage to ecosystems (Grădinaru, Muntean, Șerbănoiu, Ciocan, & Burlacu, 2020). This situation, in combination with the landfill burden imposed on the environment by construction and demolition waste originating from urban transformation and infrastructure renewal projects, has brought the concrete road industry to a critical turning point. The primary objective is currently to develop innovative material solutions that will enhance the sustainability of these structures, while preserving established engineering advantages, constituting a conventional industry practice. The concrete road industry is currently facing an environmental impasse, which necessitates a strategic shift from a linear production model based on the 'take-make-dispose' principle to a circular economy model that views waste as a resource (Heisel, Schlesier, & Hebel, 2019). This paradigm shift provides a vision for a future that is both environmentally and economically sustainable for the concrete pavement industry. The primary objective of this chapter is to synthesize and critically evaluate academic studies on the primary waste and industrial byproducts that form the technical basis of this vision. In this context, the utilisation of industrial by-products, such as blast furnace slag and fly ash, as cement substitutes, and recycled concrete aggregates, waste tires and various industrial wastes as natural aggregate substitutes, was discussed. A comprehensive examination was conducted of the impact of these alternative materials on the properties of fresh and hardened concrete, the environmental benefits they provide, and the technical difficulties encountered in their application. This examination was undertaken in light of the extant literature on the subject. To address the issue in question, a holistic approach was adopted, with the use of sustainable materials being examined along two main axes. Firstly, the substitution of cement – the component of concrete with the greatest environmental impact – with industrial byproducts was addressed. Secondly, the utilisation of recycled and waste materials as aggregates to reduce natural resource consumption was discussed. In addition to these fundamental strategies, alternative binding systems such as geopolymer concrete, which offer a vision of a cement-free future, were also addressed. Finally, the synthesis of these disparate approaches, the common challenges encountered, and the research gaps in the literature are presented in a discussion section, and the main findings of the section are summarised in a conclusion.

Cement Substitutes

A pivotal aspect of strategies devised to mitigate the environmental impact of concrete pertains to the optimisation of Portland cement utilisation, the constituent with the most substantial carbon footprint. This enhancement in performance has been facilitated by the incorporation of SCMs, which have been demonstrated to enhance or preserve the engineering performance of concrete while concurrently reducing the amount of cement utilised (Abdel-Gawwad et al., 2021). These materials, which are typically by-products of industrial processes, contribute to the circular economy by enabling the valorisation of waste. In addition, they exhibit pozzolanic or latent hydraulic properties that significantly improve the mechanical properties of concrete and its long-term durability (Bajpai, Soni, Shrivastava, & Ghosh, 2023). In the context of industrial applications and academic literature, materials such as ground blast furnace slag, fly ash, silica fume and rice husk ash are commonly used as substitutes due to their high pozzolanic activity.

Ground Blast Furnace Slag

Ground blast furnace slag, a by-product of iron and steel production, is one of the most widely used and most researched additional cementing materials in concrete technology. The physical appearance of this material, which is typically obtained as a fine off-white powder, is presented in Figure 1.

Figure 1 Ground blast furnace slag

Hadi et al., 2018

It has been demonstrated that, due to its latent hydraulic properties, slag consumes calcium hydroxide ($Ca(OH)_2$), a weak phase resulting from cement hydration, and forms additional calcium-silica-hydrate (CSH) gel. The result of this process is an improvement in the strength and durability of concrete (Aghaeipour & Madhkhan, 2017). The most extensively studied effect of this mechanism on concrete performance is on compressive strength. A substantial body of research has repeatedly demonstrated that the substitution of slag results in a reduction in the early-age strength of concrete, attributable to the sluggish nature of the pozzolanic reaction. However, as the reaction progresses, it leads to a substantial augmentation in the late-age strength of concrete after 28 days when compared to the reference concrete (Nath & Sarker, 2014). The extent of strength development is contingent upon the replacement rate of the slag utilised. A study by Siddique et al. (2012) reported that 40-50% GGBFS replacement yielded optimum results in terms of mechanical properties, while replacements above this rate led to more significant decreases, especially in early-age strength (Siddique & Kaur, 2012). Nevertheless, the true strategic value of GGBFS for concrete road pavements lies in its profound impact on durability, which determines long-term engineering performance. It has been demonstrated that resistance to chloride ion permeation, a critical parameter for roads where anti-icing salts are utilised, particularly during the winter period, is significantly enhanced by the incorporation of slag (Nicula et al., 2021). The protective effect of GGBFS is attributable to two primary mechanisms: firstly, the creation of a barrier within the concrete's pore structure that hinders the physical passage of chloride ions; and secondly, the chemical binding of chloride ions to slag hydration products, thereby preventing their free movement within the matrix. The basis of this dual effect is the denser, less connected, and more impermeable microstructure created by the slag (Khan, Kayali, & Troitzsch, 2016; Wang, Tae, Lin, & Wang, 2022). In addition to the hardened concrete properties, the positive effect of GGBFS on the rheological properties of fresh concrete should not be overlooked. Karimpour (2010) conducted a study which indicated that mixtures containing GGBFS exhibited superior workability in comparison to reference concrete (Karimpour, 2010). This facilitated the placement and compaction of concrete during road construction, with the potential to result in savings of both labour and time. Consequently, the utilisation of GGBFS not only contributes to the effective management of industrial waste, thereby generating an environmental benefit, but also distinguishes itself as an indispensable material in the construction of concrete roads that are characterised by enhanced durability and longevity. These roads have been empirically demonstrated to exhibit superior mechanical and durability properties.

Fly Ash

In terms of significant contributions to the circular economy from the energy sector, alongside the iron and steel industry, the fly ash obtained by burning coal in thermal power plants is of note. A visual representation of fly ash, typically collected as a fine residue from flue gases, is provided in Figure 2.

Figure 2 Fly ash

Toklu et al., 2017

The spherical and fine particle structure of fly ash has been shown to create a ball bearing effect in fresh concrete, thereby reducing friction between particles (Wang, Shen, Lyu, He, & Nguyen, 2021). This effect significantly improves the workability of the mixture and reduces the amount of water required for the same strength class. Fly ash, a pozzolanic material, analogous to slag, converts calcium hydroxide ($Ca(OH)_2$), a phase that emerges because of cement hydration and is characterised by its fragility in terms of durability, into a functional CSH gel over time. The sluggish progression of this reaction resulted in fly ash concretes demonstrating diminished early age strength, yet these concretes exhibited elevated strength and exceptional durability performance over time. In large surface applications such as concrete road pavements, fly ash has been shown to reduce the heat of hydration and significantly contribute to preserving structural integrity by reducing the risk of thermal cracking (Kumar, Rao, & Kumar, 2024). The utilisation of fly ash in road concrete extends beyond conventional concrete, with its growing importance in specialised technologies, such as roller-compacted concrete (RCC), being a salient example. A study undertaken by Bayqra et al. (2022) demonstrated that the substitution of cement with fly ash in RCC mixtures at rates of up to 60% is particularly efficacious for the utilisation as road base layers. While these elevated substitution rates diminish the strength of the material at an early age, they enhance the resistance of RCC to abrasion and improve its durability properties, including its capacity for water absorption. This, in turn, results in a substructure that is more durable in the long term (Bayqra, Mardani-Aghabaglou, & Ramyar, 2022). In a more radical approach to sustainability, fly ash is no longer considered a substitute for cement; rather, it assumes the role of the primary binder in cement-free systems, such as geopolymer concrete. In a comprehensive study by Badkul et al. (2022), it was proven that alkali-activated fly ash with GGBFS has the potential to produce a road pavement that is completely cementless and which exhibits mechanical and durability performance equivalent to that of conventional concrete (Badkul, Paswan, Singh, & Tegar, 2022). The primary weakness of concrete with elevated fly ash content is their considerably diminished early-age strength. This impracticality hinders the use of replacement rates exceeding 50%, which is critical for the sustainability goals of projects requiring rapid road opening. To surmount this challenge, innovative solutions are being developed that extend the limits of conventional materials. The issue of early-age strength loss associated with the use of high fly ash is being addressed through the investigation of advanced approaches, including nanotechnology. Indeed, Abdel-Gawwad's study demonstrated that the addition of negligible quantities of nano-sized magnesia to mortars containing elevated levels of fly ash significantly compensates for the resultant loss of strength by accelerating the hydration process and tightening the microstructure (Abdel-Gawwad et al., 2021).

As is evident, fly ash is not merely a substitute for cement; rather, it occupies a pivotal role within the domain of concrete pavement technology as a multifunctional material. The utilisation of fly ash has been shown to enhance the performance of specialised applications, such as RCC, and to serve as the primary binder in emerging technologies, including geopolymers. Moreover, advancements in advanced materials have led to the enhancement of fly ash's inherent weaknesses. Such hybrid approaches have the potential to enable the production of ultra-low-carbon concretes in the future while maintaining their engineering performance.

Silica Fume and Metakaolin

A variety of mineral admixtures are utilised to enhance the properties of concrete for specific applications. Silica fume, being a key constituent, plays a pivotal role in the production of high-performance concrete. Silica fume, a by-product of the production of silicon and ferrosilicon alloys, is a material that is finer than cement grains, has an amorphous structure and has extremely high pozzolanic activity. The extremely fine particulate nature of silica fume, which is typically dark grey in colour, is depicted in Figure 3.

Figure 3 Silica fume

www. hsamaterial.com (AD:15.11.2025)

The utilisation of silica fume in concrete has been demonstrated to enhance the mechanical properties and service life of structural applications (Khan, Rehman, & Ali, 2020). Even at low rates, silica fumes have been shown to refine the pore structure of concrete, thereby significantly increasing its impermeability (Panjehpour, Ali, & Demirboga, 2011). This, in turn, makes it possible to produce ultra-high strength concretes. Therefore, silica fumes are critical for improving the abrasion resistance and longevity of road pavements, especially those exposed to heavy traffic loads and environmental influences. In addition to industrial byproducts, processed pozzolans such as metakaolin, which is produced by calcining kaolinite clay at specific temperatures, are also available. Metakaolin, a highly purified and reactive material, has been shown to exhibit increased early-age strength, particularly when compared to materials such as slag and fly ash, which are known to be weaker. The visual appearance of metakaolin, distinguished by its fine particle size and typical off-white colour, is illustrated in Figure 4.

Figure 4 Metakaolin

Olawale., 2013

Research has demonstrated that the substitution of up to 15% of metakaolin for cement enhances the early and late-age strengths of concrete in comparison to the reference concrete (Ding & Li, 2002). In addition to enhancing strength, metakaolin has been demonstrated to substantially improve concrete durability. The mechanism by which this occurs is the enhancement of pores, thereby reducing the rate of diffusion of sodium and chloride ions (Sharbatdar, Abbasi, & Fakharian, 2020). Indeed, the use of 8% metakaolin has been reported to reduce the chloride diffusion coefficient by approximately 50% (Ding & Li, 2002). In terms of fresh concrete properties, it has also been stated that concretes containing metakaolin exhibit superior workability in comparison to concretes containing silica fume at analogous replacement rates (Liang, Zhu, Li, Liu, & Guo, 2021). The combination of metakaolin and silica fume has been shown to yield hybrid designs that exhibit effective outcomes in high-performance applications, characterised by optimised mechanical and rheological performance (Sharbatdar, Abbasi, & Fakharian, 2020).

Rice Husk Ash

In the context of sustainability, agricultural by-products such as rice husk ash (RHA) also warrant consideration. The production of this ash involves the controlled burning of rice husk, resulting in a high proportion of amorphous silica. The physical form of RHA, typically obtained as a greyish powder following this incineration process, is depicted in Figure 5.

Figure 5 Rice husk ash

www.arstradingcompany.com (AD: 15.11.2025)

This characteristic renders it an effective pozzolan. The utilisation of RHA not only contributed to the circular economy by means of the use of an agricultural by-product but also enhanced the mechanical properties and durability of concrete (Alhazmi, Shah, & Basheer, 2021). In a study conducted by Liang et al. (2021) on a metakaolin-based geopolymer system, it was proven that the addition of RHA significantly refined the void structure, thus improving the resistance of the material to freeze-thaw cycles. In fresh concrete, the porous structure and high surface area of RHA increase the water requirement of the mixture, which necessitates the use of a higher percentage of superplasticizer to achieve the targeted workability (Liang, Zhu, Li, Liu, & Guo, 2021). The pozzolanic activity of RHA is prominent in hardened concrete properties. A study by Joshaghani (2017) observed that the early-age strengths of concretes containing RHA were lower than those of reference concrete, but that their late-age strengths surpassed those of reference concrete as the pozzolanic reaction progressed. The study observed that the highest 90-day compressive strength was attained in a mixture containing 20% RHA as cement, and that substitutions above this level resulted in a decrease in strength (Joshaghani, 2017). Moreover, statistical optimisation methods have been demonstrated to facilitate the identification of optimal substitution rates for RHA in road concrete mixtures, thereby ensuring the attainment of both workability and flexural strength objectives (Camargo-Perez, Abellan-Garcia, & Fuentes, 2023). As is evident, RHA has the potential to become a valuable solution for an environmental imperative from an engineering perspective; however, the success of this transformation depends on optimising the opposing effects on fresh and hardened concrete with a holistic approach.

Other Sustainable Materials

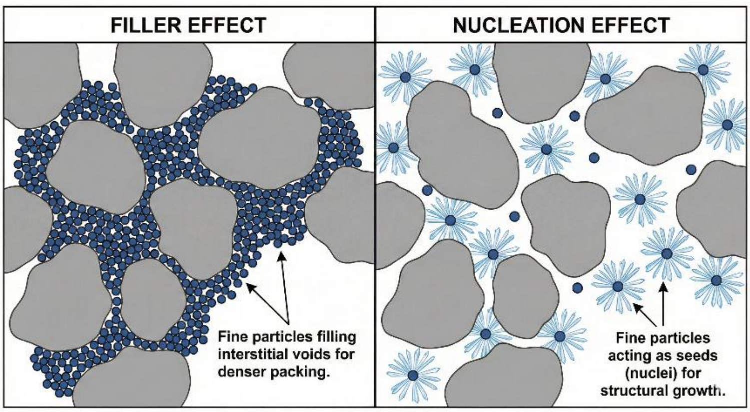
In addition to the primary supplementary cementing materials, other regionally available wastes and natural minerals are also gaining importance in the pursuit of reducing the environmental impact of concrete. For instance, it has been demonstrated through empirical field applications that sustainable concretes that meet standard road pavement requirements can be produced by utilising red mud, a large-volume and difficult-to-dispose by-product of the aluminium industry, as a cement substitute (Zhou, Chen, Peng, Chen, & Chen, 2025). The distinctive physical appearance of red mud, characterized by its vibrant colour resulting from the bauxite refining process, is shown in Figure 6.

Figure 6 Red mud

www.indiamart.com (AD: 25.11.2025)

Another example of a similar approach to the valorization of agricultural waste is olive biomass bottom ash obtained from the olive industry. Rosales et al. (2025) conducted a study that reported the successful application of the ash in question to a concrete road section. This was achieved by utilising an eco-hybrid cement additive, thereby attaining the desired mechanical performance (Rosales, Rosales, Agrela, López-Alonso, & Cuenca-Moyano, 2025). This finding underscores the considerable potential of regionally abundant agricultural and industrial byproducts to produce local and sustainable building materials. In recent years, ground limestone has also become a prevalent component in Portland Limestone Cements (PLCs), owing to its environmental benefits and cost-effectiveness. The two most evident physical effects of PLC are filler and nucleation. The filler effect is a process in which limestone particles, which are finer than cement grains, fill the voids between them, thereby increasing the packing density of the particles. This results in a denser cement paste with fewer voids, thus increasing the impermeability and durability of the concrete. The nucleation effect, as observed in this study, has been demonstrated to facilitate the formation and growth of C-S-H gels, the principal hydration product of cement, through the provision of additional surfaces provided by fine limestone grains. This process has been shown to accelerate cement hydration, particularly during the early stages of hardening, thereby promoting the acquisition of strength (Li & Cao, 2024). The underlying mechanisms of these improvements are visualized in Figure 7, which schematically illustrates how fine particles fill interstitial voids and act as seeds for hydration product growth.

Figure 7 Schematic representation of filler (left) and nucleation effects (right)



Illustrated by the author based on Cuesta 2023

In terms of chemical composition, the calcium carbonate ($CaCO_3$) content of limestone reacts with the tricalcium aluminate (C_3A)

phase of cement to form additional carboaluminate phases, including monocarboaluminate. The formation of these new phases has been shown to further refine the microstructure of the cement paste, thereby contributing to its durability (Wang, Tae, Lin, & Wang, 2022). However, at elevated replacement rates, a decline in advanced age strengths may be observed, attributable to the dilution effect resulting from limestone's comparatively lower reactivity compared to cement. Moreover, the extant literature posits that the formation of carbonates can, in certain instances, exert a deleterious effect on the sulfate resistance of concrete (Neithalath & Cam, 2012). Consequently, ground limestone, when utilised in the correct proportions, has been demonstrated to be an effective material for producing concrete that is both more economical and have a lower carbon footprint, with good early-age performance. In lieu of a solitary solution for mitigating the carbon footprint of concrete, a plethora of mineral admixtures are available for selection, contingent on the requirements of the project. The utilisation of these materials frequently entails a trade-off. The enhanced long-term durability achieved through the utilisation of materials such as GGBFS and fly ash is frequently counterbalanced by diminished early-age strength. Conversely, the utilisation of metakaolin or low-content limestone has been demonstrated to enhance early-age performance. This has prompted a shift in contemporary concrete design towards ternary and quaternary mix designs, which leverage the synergistic effects of various admixtures rather than the properties of a single material. For instance, designs that combine the advanced age strength of slag with the early age strength advantages of metakaolin, or hybrid approaches that address the weaknesses of high-grade fly ash with nanoparticles, are promising strategies that can achieve sustainability goals without compromising engineering performance (Ding & Li, 2002). The pursuit of optimisation, in conjunction with aggregate substitutions, serves to further enhance the sustainability potential of concrete.

Comparative Assessment of Cement Substitutes

Research has demonstrated that, rather than a single solution for reducing concrete's carbon footprint, there is a wide range of mineral admixtures that can be selected based on the specific requirements of the project. The utilisation of these materials frequently necessitates a trade-off. It is important to note that superior long-term durability is often accompanied by diminished strength at an early age. In this context, mineral admixtures can be categorised according to their primary effects. GGBFS and fly ash, due to the slow nature of their pozzolanic reactions, have been observed to reduce the early-age strength of concrete. However, this slow reaction produces a denser and more impermeable microstructure, thereby significantly increasing the resistance of concrete to chemical agents such as chlorides and sulfates. These agents directly affect the service life of road pavements and increase their long-age strength (Loudon, 2003). While the spherical particle structure of fly ash is known to contribute positively to workability, GGBFS has been found to exhibit particularly effective chloride resistance. Conversely, there exist additives that have been demonstrated to enhance early-age strength. Metakaolin has been demonstrated to exhibit high reactivity, which has been shown to result in a significant increase in early-age strength (Dan, Ma, Li, Ma, & Tan, 2023). This property enables the road to be opened to traffic more quickly. In a similar manner, silica fume, with its ultra-fine structure and high pozzolanic activity, creates a much denser matrix, contributing to both early-age strength and maximising surface durability properties such as abrasion resistance (Khan, Rehman, & Ali, 2020). Despite the absence of a pozzolanic reaction, ground limestone has been demonstrated to promote early age strength through the acceleration of cement hydration, thereby exerting a nucleation effect (Poernomo, Winarto, Mahardana, Karisma, & Ajiono, 2021). The utilisation of agricultural by-products, such as rice husk ash (RHA), represents a significant advancement in the realm of sustainability, offering the prospect of enhancing the long-term performance of concrete when employed in optimal proportions (Kannur & Chore, 2023).

These differences are driving modern concrete design towards ternary and even quaternary blended binder systems that utilise the synergistic effects of different admixtures, rather than single materials. This approach is critical for concrete pavements subjected to heavy traffic loads and challenging environmental conditions. For instance, a design that combines the advanced age strength and durability advantages of slag with the early age strength-enhancing effect of metakaolin, which allows the road to be opened to traffic quickly, can compensate for the weaknesses of both materials. In a similar manner, strategies that address the early-age strength weakness caused by using high fly ash content with innovative materials, such as nanoparticles, are promising approaches that can achieve sustainability goals while maintaining the engineering performance required for long-lasting pavements. This demonstrates that sustainable concrete pavement mix design is no longer a static recipe, but rather a dynamic optimization process based on addressing the weaknesses of materials and combining their advantages.

Aggregate Substitutes

A comprehensive strategy for concrete sustainability has been shown to reduce the carbon footprint of the binder system, whilst simultaneously raising questions regarding the origins of aggregates, which comprise approximately 60 – 75% of the concrete volume (McNeil & Kang, 2013). The annual extraction of billions of tons of sand and gravel worldwide exerts significant pressure on natural ecosystems, endanger water resources and engenders a grave problem of resource depletion. Consequently, in accordance with the tenets of circular economy, research into alternative materials that can substitute for natural aggregates has emerged as a pivotal and rapidly evolving domain within the field of concrete road technology (Rahman, Imteaz, Arulrajah, Piratheepan, & Disfani, 2014; Shuaicheng, Jiong, & Qingli, 2018). These alternatives encompass a broad spectrum of materials, including construction and demolition waste (e.g. RCA), recycled asphalt pavements (RAP), and industrial by-products such as steel slag, foundry sand, waste glass, plastic, and rubber (Ramírez-Vargas et al., 2024). The recycling of construction waste in the field of road engineering is regarded as a technology that is highly energy-efficient and environmentally friendly. This is because it reduces the need for natural aggregates and provides a solution to the problem of waste disposal (Arisha, Gabr, El-Badawy, & Shwally, 2018; Cardoso, Silva, De Brito, & Dhir, 2016). The utilisation of these materials has the potential to reduce landfill loads and, in certain instances, to enhance the technical properties of concrete. Among these alternatives, construction and demolition waste, end-of-life tires, and various other industrial wastes are of particular significance, all of which differ in their origins and behaviour within the concrete.

Recycled Concrete Aggregates

One of the most common approaches to aggregate substitution is the evaluation of the significant volumes of construction and demolition waste resulting from urban transformation and infrastructure renewal projects. Recycled concrete aggregates (RCA), which are derived from these wastes, are a prime example of the circular economy. A representative sample of RCA, produced through the crushing and processing of such demolition waste, is shown in Figure 8.

Figure 8 Recycled Concrete Aggregates

Kim et al., 2023

Nevertheless, the primary challenge associated with RCA is the presence of a residual mortar layer that adheres to its surface, thereby augmenting its water absorption capacity. This layer has been shown to increase the water absorption rate of the aggregate and generally reduce its mechanical properties. Another important waste generated from highway infrastructure is recycled asphalt pavement (RAP). Whilst the utilisation of RAP aggregates in concrete is a promising method of conserving natural resources, it has been demonstrated that this practice can have a detrimental effect on the mechanical properties of concrete. This is because the bitumen film which covers the RAP particles forms a weak bond with the cement paste. In a study conducted by Ghazy et al. (2022), it was observed that the increasing substitution of natural aggregate with RAP systematically reduced the compressive, splitting tensile, and flexural strengths of concrete. In order to compensate for the loss of strength, the study under review also investigated the effects of adding materials such as fly ash and polypropylene fibre to the mixture (Ghazy, Abd Elaty, & Abo-Elenain, 2022). In a study conducted by Shah et al. (2023), sustainable concrete mixes were optimised using both RCA and RAP (Shah et al., 2023). The integration of these hybrid designs within a circular economy framework facilitates the concurrent management of diverse waste streams, thereby offering a comprehensive contribution to the overarching principles of the circular economy. Another significant resource for the valorisation of construction and demolition waste is Mixed Recycled Aggregates (MRA), comprising materials from diverse origins (concrete, brick, ceramics, etc.) that are crushed and processed together. Rosales et al. (2025) conducted a study in which these materials were tested on a real-scale road project. The study demonstrated that concrete pavement produced using MRA successfully achieved the target compressive strength and was a viable alternative to conventional concrete (Rosales, Rosales, Agrela, López-Alonso, & Cuenca-Moyano, 2025). This study is of great importance as it goes beyond the laboratory scale and demonstrates that MRA can be effectively used as a sustainable resource in large-scale infrastructure projects. One of the most critical concerns in the utilisation of recycled concrete aggregates (RCA) pertains to freeze-thaw resistance, a vital consideration for road pavements, particularly in cold climate regions. The increased porosity of RCA has the capacity to diminish concrete's resistance to freeze-thaw damage. However, this issue can be circumvented through the implementation of appropriate engineering methodologies. A study by Tarhan & Şahin (2023) investigated the freeze-thaw performance of concrete containing RCA. The findings of the study demonstrated that the incorporation of an air-entraining admixture (AEA) into the mixture led to a substantial enhancement in freeze-thaw resistance, achieved by the formation of minute air voids within the concrete matrix and a concomitant reduction in capillary permeability (Tarhan & Şahin, 2023). This finding is significant because it demonstrates that, with standard practices such as air-entraining admixture, RCA-containing concrete can be safely used in road and field concretes exposed to harsh climatic conditions. When evaluated collectively, these findings prove that mineral-based aggregates obtained from construction and demolition waste, when optimized with the right engineering approaches and additive technologies, are both technically viable and an essential resource for sustainable road pavements in terms of circular economy.

Waste Tires and Rubber Aggregates

End-of-life tyres, which are among the most problematic items of urban waste, have been found to be utilised as aggregate substitutes in the production of concrete. Rubber particles obtained from waste tires significantly alter the properties of concrete when added to it. The conversion of these end-of-life tires into usable concrete aggregates, ranging from coarse chips to fine crumb rubber, is visualised in Figure 9.

Figure 9 Waste tires and rubber aggregates

Zhang et al., 2023

A study by Barišić et al. (2021) investigated the substitution of natural aggregate with waste tire particles in cement-stabilized soil layers (Barišić, Zvonarić, Grubeša, & Šurdonja, 2021). The findings of the study demonstrated that an augmentation in the rubber content led to a reduction in the compressive strength of the mixture.

However, this was accompanied by an enhancement in the material's ductility and energy absorption capacity. This suggests that concrete containing waste tyres could potentially find applications in road bases or barriers, which do not require high load-bearing capacity but do require properties such as impact absorption or flexibility. This approach offers a solution to the problem of tyre waste, which occupies a significant volume in landfills, and has the potential to impart new functional properties to concrete. The primary technical challenge in utilising waste tyres pertains to the surface characteristics of these tyres. The hydrophobic and smooth nature of the tyre surfaces results in the formation of a weak interfacial transition zone (ITZ) when in contact with cement paste. This ITZ has been observed to reduce the mechanical properties of the concrete, particularly its compressive strength. To overcome this problem, significant research is being conducted on the surface modification of rubber particles prior to their incorporation into concrete. In a study by He et al. (2021), rubber powder surfaces were modified by roughening them with chemicals such as sodium hydroxide (NaOH) and coating them with silane coupling agents (He et al., 2021). The findings of the study demonstrated that the modified rubber particles exhibited a more robust bond with the cement paste, consequently leading to a substantial reduction in compressive strength loss when compared to concrete incorporating unmodified rubber. These findings suggest that advanced techniques, such as surface modification, may pave the way for higher and safer use of waste tires in structural applications. The performance of waste tyres in specialised road technologies such as roller-compacted concrete pavement (RCCP) is also being studied in detail. In the study undertaken by Keleş et al. (2024), waste tyres were utilised in varying proportions as a replacement for both fine and coarse aggregate (Keleş, Bayrak, & Bayata, 2024). The study confirmed that the utilisation of waste tyres results in a reduction of the mechanical properties of concrete, including compressive and tensile splitting strength. However, it was also found that this material can exhibit greater ductile behaviour. A salient finding of this study is that the reduction in strength is significantly more pronounced when waste tyres are utilised as a coarse aggregate substitute as opposed to a fine aggregate substitute. This finding indicates that waste tires can be utilised in rigid pavements such as RCCP, particularly as a fine aggregate substitute, with minimal compromise to mechanical performance.

Other Waste Materials

The quest for sustainable resources that can substitute for natural aggregates is an ongoing endeavour that extends beyond construction and demolition waste, encompassing a diverse array of industrial, agricultural, and urban waste streams. This approach has the potential to provide local solutions to regional waste problems and impart distinct functional properties to concrete. This optimisation process serves to further enhance the sustainability potential of concrete through the incorporation of aggregate substitutes. A wide range of alternative materials have been investigated in many studies in literature for use in concrete road pavements. These include agricultural by-products, such as rice husk ash (RHA), which is also known as a cement substitute but also considered as aggregate, and local industrial wastes, such as coal bottom ash obtained from tea factories and plastic waste, which is an important component of urban waste. Each of these materials exerts a distinct effect on the fresh and hardened properties of concrete; however, when utilised in optimal proportions and with suitable engineering methodologies, they possess the capacity to evolve into valuable resources for sustainable road construction. The function of industrial by-products in the context of sustainable concrete production extends beyond the replacement of binders. It is evident that steel slag, a by-product of the steelmaking process, has the potential to serve as a highly effective substitute for natural aggregate. Its elevated hardness, exceptional abrasion resistance and superior mechanical interlocking properties render it a compelling option for the abrasion course of concrete road pavements, particularly those exposed to substantial traffic loads. The granular morphology of steel slag aggregates, typically utilized for their high abrasion resistance, is depicted in Figure 10.

Figure 10 Steel slag aggregates

Taha et al., 2014

Nevertheless, the primary impediment to the extensive utilisation of steel slag is the potential for volumetric expansion arising from the hydration of the free lime (CaO) and magnesium oxide (MgO) present within its structure over time. In the absence of effective regulation, the process may result in substantial internal stress and the formation of cracks within the concrete structure. To address the issue of stability, it is necessary to store the slag for a specified period and to allow it to age prior to use. Alternatively, special treatments such as steam curing may be applied (Li, Shen, Yang, Guo, & Liu, 2022). The implementation of these measures has the potential to provide a durable road surface and to transform industrial waste into a more valuable product. Moreover, the utilisation of slag aggregate has been demonstrated to markedly enhance the durability of road pavements, particularly in cold climates where deicing salts are employed, by diminishing the chloride ion diffusion coefficient of concrete (Ahn, Lee, & Park, 2021). Another example of industrial waste being utilised as aggregate is that of waste metallic dust from the metalworking industry. A study undertaken by Sarı et al. (2025) investigated the potential of this material to function as a fine aggregate replacement in the context of roller-compacted concrete (RCC), yielding encouraging results (Sarı, Öztürk, Gönen, & Emiroğlu, 2025). The visual appearance of waste metallic dust, investigated for its filler effect in RCC mixtures, is shown in Figure 11.

Figure 11 Waste metallic dust

www.nanokar.com.tr (AD: 25.11.2025)

The study demonstrated that substituting up to 10% of the waste metallic powder increased the compressive strength of the concrete in comparison to the reference concrete. This increase was attributed to the higher density of the metallic powder and the filler effect that creates a tighter microstructure. A decline in strength was evident at elevated substitution rates; nevertheless, it has been demonstrated that the unit weight of the concrete increases and the water absorption rate decreases when this waste is employed, consequently yielding a less permeable and potentially more durable structure. The findings of this study suggest that waste metallic powder can be a valuable alternative, capable of both solving an environmental problem and improving some properties of concrete, especially in applications such as road base layers. In the context of sustainability, agricultural by-products such as rice husk ash (RHA) emerge as promising aggregate substitutes. In addition to its pozzolanic properties, RHA can also be utilised as a fine aggregate to substitute for natural sand. This approach is notable for its utilisation of agricultural waste, thereby reducing pressure on natural sand resources. In a study conducted by Alhazmi et al. (2021), the substitution of sand with rice husk ash at different rates in sustainable concretes developed for rigid road pavements was investigated (Alhazmi, Shah, & Basheer, 2021). Concrete test specimens produced with varying substitution rates of rice husk ash, as investigated in such studies, are illustrated in Figure 11.

Figure 11 Rice husk ash

González-Fonteboa et al., 2021

The findings of the study demonstrated that the utilisation of RHA exhibited effective performance in terms of concrete's mechanical properties and was a viable alternative to produce environmentally sustainable road concrete. This finding demonstrates the potential of RHA not only as a binder additive but also as a valuable fine aggregate replacement. The utilisation of regionally abundant industrial byproducts offers significant opportunities for sustainable concrete production. An illustrative example is that of tea factory coal bottom ash, which is obtained in abundance from factories in regions where tea production is concentrated. In a study conducted by Hacımustafaoğlu et al. (2023), the usability of coal ash as a fine aggregate (sand) replacement in concrete roads was investigated. The study revealed that the replacement of coal ash with alternative materials resulted in enhanced compressive and flexural strengths of the concrete, in comparison to the reference concrete. A decline in strength has been documented at substitution levels exceeding a specific ratio; however, when utilised at an optimal rate, this regional waste has been demonstrated to reduce pressure on natural sand resources and enhance the mechanical performance of concrete (Hacımustafaoğlu, Kütük, & Kara, 2023). This is a significant finding that demonstrates how local waste can be transformed into a valuable resource for local infrastructure projects. Plastic waste, which occupies a significant proportion of urban solid waste, is also being investigated as an aggregate source, particularly for low-density concrete applications. In a study conducted by Mulyono et al. (2021), the utilisation of polyethylene terephthalate type plastic bottle waste at varying rates as a replacement for coarse aggregate in road concrete mixtures was investigated (Mulyono, Saefudin, Purnomo, & Widiasanti, 2021). The processed form of PET plastic waste, prepared for utilisation as coarse aggregate substitution, is illustrated in Figure 12.

Figure 12 Plastic waste aggregates

Lee et al., 2019

The findings of the study demonstrated that an augmentation in the proportion of plastic waste resulted in a reduction in both the compressive strength and the tensile splitting strength of concrete. This decline in strength was attributed to inadequate adhesion (bond) between the plastic surface and the cement paste, as well as the plastic's low rigidity. The findings of this study indicate that the utilisation of plastic waste as aggregate can be regarded as a beneficial measure for the environment, particularly in applications that do not necessitate high strength, such as low-traffic roads or non-load-bearing elements. However, it is imperative to exercise caution in managing the adverse effects on structural performance. In summary, the utilisation of alternative aggregates in concrete roads presents a multifaceted potential, as opposed to a single-type solution, with each waste material exhibiting its own advantages and disadvantages. While the mechanical performance of such materials as steel slag can be enhanced, the environmental benefits of materials such as waste tyres and plastics are frequently counterbalanced by a certain degree of loss of strength. Consequently, the future of sustainable road design necessitates a holistic approach that assesses these materials not solely for their deficiencies, but for their inherent capabilities that can be actualised through the implementation of appropriate engineering interventions.

Alternative Binding Systems

In the context of sustainability, the search for alternatives to PC has evolved beyond partial substitution, with the focus now shifting towards the development of entirely alternative binder systems that do not necessitate the use of PC. The objective of this approach is to eliminate the high carbon emissions resulting from PC production, with industrial waste serving as the primary resource. These systems encompass a wide range of applications, including geopolymer concretes obtained through alkaline activation of aluminosilicate-based industrial waste; polymer concretes using resins such as polyester or epoxy as binders; and special hydraulic cements produced with a lower carbon footprint than traditional PC. The objective of this approach is to eliminate the high carbon emissions resulting from PC production, with industrial waste serving as the primary resource. These systems encompass a wide range of applications, including geopolymer concretes obtained through alkaline activation of aluminosilicate-based industrial waste; polymer concretes using resins such as polyester or epoxy as binders; and special hydraulic cements produced with a lower carbon footprint than traditional PC. The binder phase of geopolymer concrete is formed by the chemical activation of aluminosilicate-rich industrial wastes or minerals, such as fly ash, blast furnace slag, and metakaolin, with a highly alkaline solution comprising sodium hydroxide and sodium silicate (Amran, Alyousef, Alabduljabbar, & El-Zeadani, 2020). This process, termed geopolymerization, yields an amorphous, three-dimensional network structure analogous to the

C-S-H gel formed by PC hydration, yet with a wholly distinct chemical structure (Dave, Sahu, & Misra, 2020). This approach eliminates the use of cement clinkers, a process which is known to generate high levels of carbon emissions during its production. A considerable amount of research is currently underway to demonstrate the viability of this technology not only at the laboratory scale but also in sophisticated engineering applications, such as road pavements. A study was conducted to examine the road pavement performance of geopolymer concrete mixtures containing varying proportions of fly ash and slag. The study concluded that these concretes, which were designed without cement, exhibited sufficient mechanical strength and high durability properties when compared to traditional concrete. This suggests that they are an extremely promising alternative for green and environmentally friendly road pavements (Badkul, Paswan, Singh, & Tegar, 2022). It has been demonstrated that fly ash and GGBFS-based geopolymer concrete constitutes a valid alternative to conventional concrete, particularly in the context of sustainable rural road network development (Bellum, Muniraj, & Madduru, 2020). A significant challenge encountered in the implementation of geopolymer concrete is the necessity of elevated temperatures for the initiation of the reaction process (Girish, Shetty, & Nayak, 2024). This presents a significant obstacle for road construction requiring cast-in-place applications. Nevertheless, considerable progress has been made in addressing this issue. It has been established that geopolymer systems comprising solely of fly ash experience sluggish hardening at ambient temperature; however, the incorporation of GGBFS into the mixture has been shown to expedite the reaction by augmenting the calcium content of the system, thereby enabling curing at ambient temperature (Nath & Sarker, 2014). This finding significantly enhances the practicality of geopolymer concrete for construction site applications. The versatility of geopolymer systems is evidenced by their capacity to utilise diverse waste materials. Indeed, in a geopolymer system utilising metakaolin as a binder, the incorporation of rice husk ash (RHA) has been demonstrated to enhance the freeze-thaw resistance of the material (Liang, Zhu, Li, Liu, & Guo, 2021). In addition, it has been demonstrated that the mechanical properties and durability of fly ash-based geopolymers can be enhanced by incorporating a high-reactivity pozzolan such as silica fume into the mixture, rendering them suitable for applications including interlocking paving stones (Bajpai, Soni, Shrivastava, & Ghosh, 2023). This finding indicates that a diverse range of industrial and agricultural by-products can be utilised in a synergistic manner within geopolymer binders, thereby enabling the attainment of specific performance objectives. It is important to note that cementless binder systems are not limited to geopolymers. Furthermore, advanced composites utilising polymers as binders also occupy a significant position within this domain. One such material, polymer concretes (UPC), which use unsaturated polyester resin as a binding agent, offer superior properties, particularly high compressive strength, corrosion resistance, and very rapid setting (Zhang, Zhang, Lv, & Yang, 2022). An examination of the performance of UPC as a road pavement material revealed that it exhibited excellent road performance, especially at medium-high temperatures, and a significantly superior water resistance compared to asphalt mixtures (Zhang et al., 2020). Such polymeric composites are regarded as promising alternatives for industrial floors, bridge decks, and special road repair projects, especially in cases where chemical resistance or very fast repair is required (Zhang, Zhang, Liu, & Lv, 2021). Another innovative approach in polymer concrete is the direct use of melted waste thermoplastics as binders. In this method, plastics such as waste low-density polyethylene (LDPE) act as a binding agent, replacing cement and uniting the aggregate particles. This technology offers significant potential for increasing the recycling rate of waste polyethylene. It has been determined that plastic concretes utilising low-density polyethylene as a binder have the capacity to meet the performance criteria required for road pavements, with the proviso that appropriate aggregate grading and additives are employed (Du et al., 2023). To mitigate the environmental impact of cement production, there is an ongoing development of specialized cements that have a reduced carbon footprint when compared to Portland cement. One such material is Green Calcium Sulfoaluminate Cement (GCSA), which is produced at lower temperatures using industrial waste and offers a significant environmental advantage over traditional cement. It has been demonstrated that the utilisation of GCSA in the production of foam concrete is a successful endeavour, particularly in applications such as road fill. The performance of GCSA has been shown to meet commercial standards (Ge et al., 2020).

In summary, these innovative approaches, which challenge the dominance of Portland cement (PC) and rely entirely on cement-free binder systems, are poised to play a critical role in helping the construction industry achieve its sustainability goals. Geopolymer concretes, polymer composites, and specialty cements such as GCSA offer technically and environmentally viable alternatives that go beyond partial replacement of PC. The utilisation of industrial and agricultural waste as resources, the overcoming of practical obstacles such as ambient curing, and the recycling of waste plastics are accelerating the transition of these materials from the laboratory to construction site applications. These technologies have been demonstrated to reduce carbon emissions to a considerable extent, whilst also offering superior mechanical performance and durability. It is therefore reasonable to hypothesise that they will provide a solid foundation for green infrastructure projects in the future.

Discussion

Research into cement substitutes, aggregate substitutes and alternative binder systems has demonstrated that, taken individually, they offer significant potential for enhancing the sustainability of concrete pavements. Nevertheless, the real-world effectiveness and future of these technologies lie in combining these individual approaches to create synergistic effects, understanding common challenges, and developing strategies to overcome them. At this juncture, it is imperative to address the primary trade-offs encountered in the realm of sustainable concrete pavement design, the potential for integrated solutions, and the directions for future research.

The future of sustainable concrete design is predicated on the development of synergistic solutions that combine diverse waste streams into a single product. This approach is exemplified by systems that utilise recycled materials in both the aggregate and binder phases. For instance, research has demonstrated that geopolymer concrete (GPC) – derived from fly ash and slag – functions as the binding agent, with the coarse aggregate substituted with RAP at levels of up to 100%. Recent studies have demonstrated that geopolymer concrete mixtures containing up to 50% coarse RAP replacement can effectively meet the strength criteria stipulated by standards. These mixtures have been found to be particularly well-suited for pavement quality concrete (PQC) applications (Ghosh, Ransinchung, & Kumar, 2024). This approach is significant, as it demonstrates the capacity to produce a bi-directional sustainable composite material through the integration of two distinct waste types, thereby eliminating the necessity for cement and significantly reducing natural aggregate consumption. Another important synergistic approach is to compensate for the performance degradation caused by using one sustainable material with another high-tech material. The utilisation of recycled aggregates, encompassing both concrete and asphalt-based materials, frequently culminates in a decline in the mechanical performance of concrete. However, rather than perceiving this as a disadvantage, it can be regarded as an engineering problem that can be addressed through the utilisation of advanced materials. Indeed, a study has demonstrated that the loss in concrete containing RCA and RAP can be compensated for by adding nanosilica to the mixture. The effects of nanosilica, namely its microstructure-tightening and pozzolanic reaction-accelerating properties, have been shown to offset the negative effects of recycled aggregates. This offers the potential to produce a composite that is both sustainable and performs at a certain level (Shah et al., 2023). One of the most significant problems that endangers the long-term performance of concrete pavements is shrinkage and the subsequent cracking that ensues because of drying and thermal effects. One of the most innovative approaches developed to address this problem is the use of expansion agents, which compensate for shrinkage in situ by providing controlled expansion to the concrete. Magnesium oxide (MgO)-based expansion agents (MEA) are among the most significant materials in this field. As demonstrated in a comprehensive review by Zhang (2022), the gradual hydration of MgO within the cement paste creates a controlled expansion during and after the concrete hardening process, thereby cancelling or reducing shrinkage stresses (Zhang, Zhang, Lv, & Yang, 2022). This technology has the potential to significantly increase the service life and durability of structures, particularly by preventing the formation of shrinkage cracks in jointed concrete roads and bridge decks. These strategies demonstrate that achieving sustainability is not at odds with optimised performance. Indeed, integrated solutions in materials science have the potential to minimise environmental impact while simultaneously increasing structural durability.

The utilisation of sustainable materials frequently necessitates a compromise, as it modifies the performance characteristics of concrete. A salient challenge pervasive across the materials examined pertains to the attainment of equilibrium between early-age and late-age strength. Materials with low pozzolanic activity, such as GGBFS and fly ash have been observed to reduce early-age strength, which poses a significant practical obstacle for projects requiring rapid road opening. The creation of hybrid systems incorporating more reactive materials, such as metakaolin or nanoparticles, has been identified as a potential solution to address this weakness. Another significant challenge is the volumetric stability and standardisation of the material. The risk of volumetric expansion for certain industrial waste materials, such as steel slag, necessitates additional processing, including ageing, prior to utilisation, resulting in increased cost and complexity. The chemical and physical properties of waste materials are subject to variation depending on the source, which poses a significant challenge to the production of concrete of consistent quality. The establishment of standards for widespread use is therefore essential. Finally, workability and increased water demand must be considered. Porous or high-surface-area materials, including but not limited to rice husk ash, recycled concrete aggregates, and certain fine wastes, have been observed to exert a dual effect on the mixture's water demand and workability. This frequently necessitates the incorporation of superplasticizer admixtures with higher percentages and greater financial expenses.

Extensive research on sustainable concrete pavement materials has generated a significant body of knowledge and presented many promising alternatives. However, further research is required to address outstanding questions and fill existing gaps before progress in this field can be sustained and these innovative materials can be widely implemented in industrial settings. It is imperative to meticulously assess the performance of positive results obtained in laboratory environments under long-term traffic loads on real road sections. The determination of parameters such as fatigue behaviour, resistance to environmental influences and abrasion performance over time through controlled field trials and long-term monitoring programs is essential to demonstrate the reliability and applicability of these materials. Nevertheless, further work on the characterisation, quality control and standardisation of wastes that may vary regionally and seasonally, such as tea factory ash or olive biomass ash, will encourage more consistent and safe use of these local resources. The development of processing and treatment methods to ensure that waste from different sources meets similar performance criteria will also constitute an important part of these standardisation efforts. The potential of these material-focused sustainability approaches is anticipated to be further enhanced when combined with advanced engineering concepts such as functional concrete technologies that transmit light, self-heal, generate energy, or reduce air pollution. This integration signifies a substantial advancement towards the development of multifunctional and sustainable road infrastructures in the future.

Conclusion

A plethora of alternative materials have been identified as potential substitutes for conventional components, with the objective of enhancing the environmental sustainability of concrete pavements. The utilisation of resources such as industrial byproducts, recycled materials, and agricultural waste offers the potential to reduce both natural resource consumption and landfill problems. The extant literature suggests that these materials can enhance the mechanical properties of concrete, particularly its long-term durability. Moreover, the emergence of cementless systems, such as geopolymer and polymer concrete, offers a more radical environmental advantage by eliminating the reliance on Portland cement. Notwithstanding the positive findings, it has also been recognised that the utilisation of alternative materials frequently entails a trade-off. The primary technical challenges hindering the widespread adoption of these materials include early-age strength reduction, volumetric stability concerns, workability issues, and material property variability. Nevertheless, these challenges must not be considered insurmountable. It is evident that, when utilising appropriate engineering methodologies and implementing context-specific optimisations, sustainable materials can provide solutions that are both technically viable and potentially economically competitive. It is therefore possible to achieve a simultaneous optimisation of both sustainability and performance objectives, as opposed to being required to choose between them. The future of the concrete pavement industry is contingent on the adoption of these innovative and sustainable materials. To achieve this potential, it is imperative to standardise their properties, develop quality control mechanisms, and validate laboratory-scale successes with long-term field performance data. Following the implementation of the steps, it is inevitable that these materials, which are currently regarded as alternatives, will become the foundation of future standard concrete pavement applications.

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CHAPTER 3

SUPERİOR PERFORMANCE İN CONCRETE ROAD PAVEMENTS

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Introduction

Road infrastructure is widely regarded as a cornerstone of the economic and social vitality of modern societies. Concrete roads represent a vital component of this infrastructure due to their high load-bearing capacity, extended service life, and robust construction, which enables them to function remarkably well under substantial traffic loads (Fang et al. 2023). The Portland Cement Concrete (PCC) employed in these pavements has heretofore exhibited satisfactory performance for conventional applications. However, it is evident that this traditional approach is encountering challenges in effectively addressing the mounting and increasingly substantial traffic loads, as well as the progressively adverse environmental conditions. The performance limits of conventional concrete,

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particularly in the context of contemporary challenging conditions, can be categorised into two primary headings: mechanical limits and durability deficiencies. Regarding mechanical limits, while standard concrete applications generally target a specific compressive strength, the truly critical parameter for concrete roads is flexural strength, which resists the bending stresses caused by cyclic traffic loads. Conventional concrete is inherently brittle and exhibits relatively low flexural strength, which predisposes it to fatigue cracks under heavy and cyclical loads (Ramírez-Vargas et al. 2024, Vidyashree et al. 2025). This phenomenon is known to cause the degradation of the pavement's structural integrity over time. In addition to mechanical deficiencies, a more critical limitation is that of durability deficiencies resulting from the material's microstructure. Conventional concrete is characterised by the presence of microvoids and a capillary pore network, which are inherent to the hydration process. The most significant consequence of this structure is high permeability (Cai et al. 2021, Akkaya and Çağatay 2021). The porous nature of the concrete allows water and other aggressive ions, such as chlorides from winter deicing salts or sulfates from groundwater, to penetrate the concrete. The water, which permeates the concrete, undergoes a process of freezing and expansion, thereby inducing internal stresses and precipitating surface deterioration, including scaling, particularly in areas subjected to repeated freeze-thaw cycles. Moreover, the porous nature of the surface renders it susceptible to abrasion and tear, resulting in the deterioration of its texture and the diminution of its slip resistance over time (Ahn, Lee and Park 2021). These limitations result in pavements not reaching their expected service life and frequent and costly maintenance and repair activities that increase lifecycle costs (Kumari, Gupta and Deshwal 2022). The High-Performance Concrete (HPC) paradigm has been developed as a solution to the limitations of traditional materials. It is important to note that high performance does not entail the maximisation of a single property. HPC is a concrete type that has been specifically designed for a challenging application area and has the capacity to meet expectations for material improvement in a holistic sense. In this context, high performance for a concrete pavement primarily encompasses high mechanical flexural strength and fatigue resistance (Singaravel et al. 2024, Kravanja, Mumtaz and Kravanja 2024). Nevertheless, the most distinctive feature of HPC is its superior durability. This is primarily achieved through the optimisation of the water-to-binder ratio and the tight microstructure achieved using mineral additives, resulting in low permeability (Ding et al. 2023). This configuration has been shown to enhance the concrete's resistance to chloride ion permeation, sulfate attack, and freeze-thaw cycles (Tran and Phan 2024). To be considered high-performance, a pavement must demonstrate not only high levels of abrasion resistance but also ensure that surface integrity is maintained under the pressures of traffic. To overcome these limitations of conventional concrete and achieve the mentioned high-performance profile, the use of micro-sized pozzolans such as silica fumes is a well-described strategy in the literature in HPC applications (Vaitkus et al. 2021). To achieve these high-performance objectives, a range of strategies have been proposed by materials science that enhance the conventional concrete matrix and address various challenges. Fiber-reinforced concrete (FRC) is a material that has been developed for the primary purpose of altering the brittle nature of concrete. The objective is to enhance its flexural strength and impact toughness. As posited by Paul et al. (2020), the utilisation of diverse fibre types, including steel, polymeric, and basalt, has been demonstrated to impede crack formation and propagation at the microscopic level (Paul, van Zijl and Šavija 2020). This development has been shown to result in a substantial enhancement of the fatigue life and structural integrity of the coating. Another significant approach is polymer-modified concrete (PMC), which modifies the cement matrix itself with organic compounds.

Polymer emulsions, such as latex, have been shown to form a film within the concrete's internal structure. This process has been found to increase adhesion, slightly improve flexibility, and significantly reduce impermeability to harmful chemicals, particularly chloride ions (Huang et al. 2010). Fiber reinforcement, polymer modification, and the use of micro-sized pozzolans such as silica fume are strategies whose effects are well described in the literature and have been proven in practice (Li et al. 2022). Nanoengineering, representing the latest step in materials science, offers the potential to fundamentally alter these improvements at the atomic and molecular level (Mohanty et al. 2025). However, the potential of nanomaterials, representing the latest advances in materials science, opens a new horizon in this field that has not yet been fully synthesised. A substantial number of valuable laboratory studies have been published in the literature examining the effects of these nanoparticles on the microstructure or individual mechanical properties of cement paste (Abdel-Gawwad et al. 2021). There is a significant gap in studies that address the effects of fibre reinforcement, polymer modification and nanomaterial integration on the performance of concrete road pavements from a holistic perspective. The objective of this study is to analyse the functions of these advanced material technologies, which have been utilised to surmount the constraints of conventional concrete in enhancing the performance of roads. The study will also disclose the present solutions and capabilities proffered by these methodologies for optimising both the mechanical performance and durability of roads.

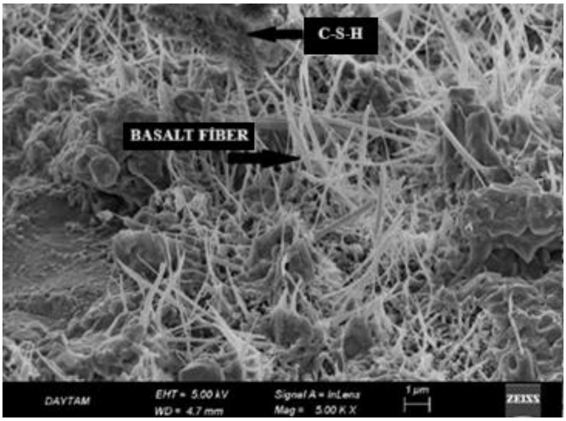
Improving Mechanical Performance of Concrete Pavements

Despite its high compressive strength, the relatively low flexural strength and brittle fracture behaviour of conventional concrete is one of the most critical design limitations, especially for road pavements subjected to cyclic traffic loads (Yu et al. 2024). This phenomenon is known to cause microscopic cracks to coalesce rapidly into macrocracks, thereby reducing the pavement's fatigue life before the onset of failure. To address this fundamental weakness, materials scientists have developed various solutions using composite material theory to strengthen the matrix itself. These approaches encompass the creation of crack-bridging mechanisms through fibre reinforcement (FRC) (Hasani et al. 2021), the enhancement of the flexibility and adherence of the matrix through PMC (Liang et al. 2021), and, at the most fundamental level, the strengthening of the microstructure of the cement paste through nano-engineering (Heikal, Zaki and Ibrahim 2021).

Enhancing Flexural Strength and Toughness with Fiber Reinforced Concrete

FRC is a composite material that is obtained by randomly distributing short, discontinuous fibres made of various materials, such as steel, polypropylene, polyvinyl alcohol (PVA), basalt or glass, into the brittle matrix of concrete (Anas et al. 2022). The addition of these fibres has been shown to affect the mechanical properties and fractured behaviour of concrete in different ways. Research has demonstrated that the incorporation of basalt and glass fibres, particularly in high-strength concrete, results in a substantial enhancement of tensile and flexural strengths upon splitting. This augmentation does not result in a significant alteration of the compressive strength and modulus of elasticity of the material (Kizilkanat et al. 2015). As illustrated in Figure 1, the integration of basalt fibres within the concrete matrix contributes to the enhancement of tensile capacity, a phenomenon that has been documented in the extant literatüre (Sünbül and Tortum 2025).

Figure 1 Crack bridging mechanism in fiber reinforced concrete



Sünbül and Tortum., 2025

The primary function of fibres is to induce a radical alteration in the post-cracking behaviour of concrete, as opposed to enhancing its ultimate compressive strength. Conventional concrete typically fractures abruptly and brittlely following the formation of the initial crack. In contrast, in FRC, the fibres act to bridge the crack, a phenomenon referred to as the crack-bridging effect (Kumar, Sharma and Ray 2024). The bridging mechanism functions by utilising energy to impede the propagation of the crack, thereby enhancing the material's toughness, defined as its capacity to absorb energy prior to fracturing. In the context of concrete road pavements, this approach signifies that fatigue cracks, occurring under the influence of cyclical traffic loads, are effectively mitigated. Consequently, the progression of such cracks is retarded, and the pavement demonstrates a ductile response rather than undergoing a sudden structural collapse.

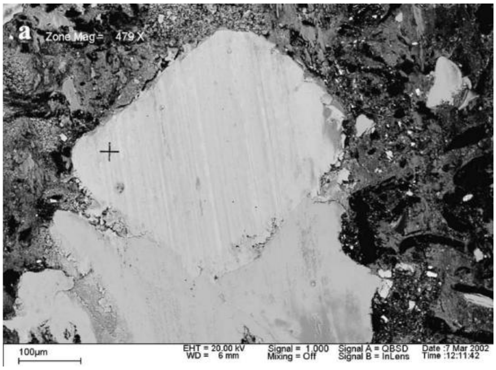
As demonstrated in the relevant literature, steel fibres contribute significantly to bending strength and fatigue resistance thanks to their high elasticity modules. In contrast, synthetic fibres such as polypropylene are especially effective in controlling early-age plastic shrinkage cracks and increasing impact resistance (Du et al. 2024, Fode, Jande and Kivevele 2024). The positive effect of fibre reinforcement on fatigue life is evident in studies focusing on the fatigue life prediction of fibre-reinforced roller-compacted concrete pavements. The present studies examined the performance of macrosynthetic and steel fibres, confirming that the primary contribution of the fibres is to delay fatigue damage by creating a bridging mechanism at crack sites. The extraction of fibres from the matrix necessitates energy, thereby impeding crack growth and augmenting the fatigue life of the concrete (Rooholamini, Karimi and Safari 2023). Regarding the mechanical properties of the materials under consideration, the findings of the studies indicated that the addition of fibres had no significant effect on compressive strength. However, it was observed that there was an increase in indirect tensile and flexural strengths. Nevertheless, in fracture energy tests, steel fibres exhibited higher values. Statistical regression models developed to predict fatigue life have determined that the most significant factors affecting fatigue life are stress level, fracture energy, and fibre content, respectively. A study revealed that the optimal volumetric ratio for steel and macro-synthetic fibres in terms of fatigue performance was 0.5%. It was reported that increasing the steel fibre ratio to higher levels, such as 0.7% or 1%, negatively affected fatigue performance by making the compression of concrete more difficult (Rooholamini, Karimi and Safari 2023). The effect of the fibre-matrix interface on performance can become more complex depending on the type of matrix, whether it contains aggregates or not, and the stiffness of the fibre. For instance, studies that have reinforced cemented sand with synthetic fibres have demonstrated that these fibres transform the material's brittle behaviour into semi-brittle or ductile behaviour, thereby enabling it to bear loads more than its peak strength. However, contradictory studies have also been conducted which demonstrate that the effect of fibre type on performance varies significantly depending on the type of stress. In contrast to concrete containing coarse aggregate, the failure mechanism of which develops along the shear planes, the steel and polyolefin fibres, which are rigid fibres, increased the strength by acting as shear wedges. Conversely, the flexible polypropylene fibres had a negative effect on compressive strength because they could not prevent shear (Chindaprasirt et al. 2021). The determining factor in tensile and flexural strength was the fibres' bridging ability. The formation of a strong (hydrophilic) interfacial bond between steel fibres and the cement matrix was observed, resulting in a "rigid bridging" effect. This phenomenon led to an enhancement in tensile and flexural strength, though concurrently increased brittleness. In contrast, synthetic fibres such as polypropylene and polyolefin have been shown to provide a weaker (hydrophobic) interfacial bond, resulting in a flexible bridging effect, thereby increasing ductility and significantly reducing brittleness (Bentur and Mindess 2006). These findings emphasise that fibre length is also a critical parameter for the bridging effect. In conclusion, case studies on FRC confirm the critical role of this technology in transforming concrete's brittle fracture behaviour into ductile performance. The primary function of fibres, whether they are steel, synthetic, or natural, is to increase flexural strength, impact resistance, and, most importantly, energy absorption capacity through crack-bridging mechanisms. However, the examined examples demonstrate that this performance is critically dependent on the optimal fibre dosage, and excessive fibre use can be counterproductive by impeding concrete consolidation. Furthermore, the fibre's rigidity and the hydrophilic or hydrophobic bond it forms with the matrix have a direct impact on the final product. While fiber reinforcement controls cracks at the macro level, another way to enhance mechanical performance is to improve the matrix itself at the micro level, which is where polymer modification comes into play.

Mechanical Contributions of Polymer Modified Concretes

PMC is a distinct category of concrete that is produced by incorporating various polymer additives into the cement matrix. The incorporation of these polymers has been demonstrated to engender a substantial enhancement in the mechanical properties of the concrete, a phenomenon attributable to the modification of its microstructure. During the process of hydration, the polymers form a film around the cement particles, thereby enhancing the adhesion between the aggregate and the cement paste. Furthermore, they have been shown to fill the voids within the concrete, resulting in a more homogeneous and less permeable structure (Naseem et al. 2023). Styrene-Butadiene (SBR), Latex Modified Concrete has been shown to enhance the aggregate-cement interface, augment crack and chemical resistance, and prolong durability, while concomitantly reducing water absorption and corrosion. However, while the incorporation of latex does enhance workability, it concomitantly results in a reduction of compressive strength. This balance can be optimised, particularly at elevated temperatures, by the addition of specific nonionic emulsifiers, such as high-Ethylene Oxide, Alkyl Ethylene Oxide, to the latex formulation, along with suitable superplasticisers to the mixture (Han, Han and Cheong 2024).

The presence of polymers has been demonstrated to enhance the Interface Transition Zone (ITZ), which is considered the weak link in concrete, thereby creating a stronger and more homogeneous structure that positively impacts the overall mechanical performance (Liu et al. 2025). Research has demonstrated that PMC exhibits a substantially higher level of compressive strength in comparison to conventional concrete. The utilisation of diverse polymer types, notably epoxy resins, SBR, acrylic polymers, and ethylene-vinyl acetate, has been demonstrated to result in substantial enhancements in compressive and flexural strength. The morphological features and surface characteristics associated with such modifications are illustrated in Figure 2 (Österle and Urban 2004).

Figure 2. SEM view of the modified surface



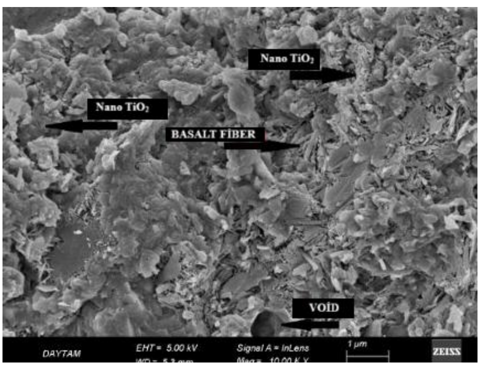
Österle and Urban., 2004

As posited by Bhrani et al. (2025), the incorporation of 3% Ethylene-Vinyl Acetate (EVA) polymer has been demonstrated to enhance the 28-day compressive strength by 33%, and the flexural strength by 63% (Bharani, Kumar and Suryavarman 2025). The addition of polymers has been demonstrated to enhance the impact resistance, abrasion resistance, and overall durability of concrete. When utilised in conjunction with steel fibres, the polymer addition was observed to further increase the flexural strength of concrete (Li, Liang and Li 2023). Polymer modification has been demonstrated to exert a favourable influence on the deformation properties of concrete. PMC has been shown to exhibit superior flexibility and reduced modulus of elasticity when compared to conventional concrete. This property renders it particularly well-suited for repair applications and scenarios necessitating impact damping. In addition, tensile strength and ductility have been shown to increase due to the crack-bridging effect of the polymer film (Bharani, Kumar and Suryavarman 2025). The incorporation of polymers, including water-based epoxy resin emulsions, into cementitious concrete has been demonstrated to enhance the mechanical properties that are paramount for the integrity of road pavements. Upon hydration, these polymers form a cross-linked network that fills voids and microcracks. The mechanical effects of these polymers demonstrate that their incorporation into bituminous mixtures results in a slight reduction in compressive strength, accompanied by a significant increase in flexural strength. The latter property is of relevance to road pavements. It has been demonstrated that as the polymer content increases, there is a concomitant improvement in impact strength, flexural fatigue life, and abrasion resistance. In addition, the polymer modification demonstrated a reduced degree of drying shrinkage in comparison with conventional concrete. This is attributed to the polymer film filling the voids, resulting in enhanced durability properties, including water impermeability and freeze-thaw resistance (Hammodat 2021). The mechanical and functional effects of polymer modification on a specific application, namely Polymer Modified Pervious Concrete, were also investigated. A study testing polymer such as SBR, PVA, and EVA found that the polymers increased the material's mechanical strength and resistance to raveling. It was found that PVAC and EVA polymers provided significant increases in flexural strength, ranging from 25% to 50%, and indirect tensile strength (ITS) of up to 55%, rather than compressive strength. In addition to mechanical gains, one of the most significant advantages of polymer modification is the substantial enhancement in freeze-thaw resistance; polymerized samples exhibited significantly reduced strength loss after cycling. It was also found that the polymers delayed hydration, reducing 7-day strength but increasing 28-day ultimate stiffness. It is important to note that the utilisation of polymers did not result in substantial alterations to porosity and drainage, which are the fundamental functions of permeable concrete (Giustozzi 2016). Polymer modification has been demonstrated to enhance the mechanical behaviour of concrete, thereby surpassing the performance of conventional concrete. The polymer film has been shown to enhance critical parameters such as flexural strength, tensile strength, and fatigue life, which are of paramount importance for the durability and resilience of concrete pavements. Polymer films facilitate crack bridging and enhance ductility, contributing to the overall improvement in these crucial properties. This has been demonstrated to enhance the pavement's crack resistance under heavy traffic loads and environmental stresses. In addition to the mechanical benefits of polymers, their capacity to strengthen the aggregate-matrix bond and improve pore structure maximises durability performance, which directly impacts pavement life. This includes such factors as abrasion resistance, freeze-thaw durability, and chemical resistance. PMC has been identified as a strategic solution for the construction of durable, flexible, and long-lasting highway infrastructures. This includes conventional pavements with optimised workability, such as LMC, and sustainable drainage systems, such as Polymer-Modified Permeable Concrete.

Enhancing Mechanical Properties with Nanomaterials

While fibres bridge cracks at the macro level and polymers organically modify the matrix, the most fundamental approach to improving mechanical performance is to fundamentally improve and strengthen the microstructure of concrete through nanoengineering. The present study explores the reactivity of materials beyond traditional micron-sized pozzolans, including nano-silica, nano-titanium dioxide (nano-TiO_2), nano-clays and nano-iron oxides (nano-Fe_3O and nano-Fe_2O_3). The unique reactivity of these materials is attributed to their exceptionally small particle sizes and huge surface areas (Ghoddousi et al. 2020, Verma, Shukla and Pal 2025, Heikal, Zaki and Ibrahim 2021). The enhancement of mechanical performance exhibited by these diverse nanomaterials is attributable to a multitude of mechanisms that are fundamentally analogous and collectively reinforcing. Firstly, these particles exhibit accelerated pozzolanic reactivity. For instance, nano-silica has been observed to react rapidly with CH crystals (Verma, Shukla and Pal 2025, Heikal, Zaki and Ibrahim 2021), while mixtures of nano-MT and nano-TiO_2 have also been confirmed to exhibit pozzolanic activity and reduce CH peaks (Sadeghi-Nik et al. 2017). It has been reported that nano-Fe_3O_4 can similarly react with $Ca(OH)_2$ to promote C-S-H gel nucleation (Seifan, Mendoza and Berenjian 2022). Similarly, colloidal nanosilica has been reported to exhibit pozzolanic reactivity when used with micromaterials such as alccofine; XRD, FTIR, and TG analyses all confirmed the depletion of $Ca(OH)_2$, CH and the formation of additional C-S-H gels (Bhat and Naqash 2022). In all cases, the result is the production of denser and stronger secondary binder gels. Furthermore, these particles function as seeds or nucleation sites for the growth of the C-S-H gel. This process has been shown to accelerate the hydration process, resulting in a more homogeneous microstructure (Jagadisha et al. 2021, Bhat and Naqash 2022). In addition to these chemical and catalytic roles, the presence of these nanoparticles results in the physical filling of the smallest voids due to their nanometric size. Visual evidence of this filling mechanism and the resulting dense microstructure is presented in Figure 3 (Sünbül and Tortum 2025).

Figure 3 SEM image of the Nano-TiO_2 pore-filling effect



Sünbül and Tortum., 2025

This filling effect has been reported to be the primary mechanism for nano-Fe_3O_4 (NF) (Seifan, Mendoza and Berenjian 2022). This phenomenon has been observed in the context of nano-Fe_2O_3 (Heikal, Zaki and Ibrahim 2021). Furthermore, colloidal nanosilica has been demonstrated to enhance pore structure and reduce total porosity through its nano-sized filling effect (Bhat and Naqash 2022). The combined result of these pozzolanic, nucleation, and filling mechanisms, perhaps most critically, is the strengthening of the ITZ. The ITZ is recognised as the weak link in conventional concrete due to its chemical and physical compaction and densification (Jagadisha et al. 2021). In mixtures containing colloidal nanosilica and alccofine, field emission scanning electron microscopy images have also revealed a denser and more compact ITZ structure, thus strengthening the aggregate-cement bond (Bhat and Naqash 2022). The enhanced bond between the aggregate and the cement paste is the principal mechanism that directly augments the tensile strength, flexural strength, and fatigue resistance of concrete in compression, flexure, and splitting (Mohanty et al. 2025). However, to maximise the microstructural benefit, the form and dosage of the nanomaterial are critical, and the dosage required for optimal performance varies significantly depending on the specific type of material used.

The fundamental mechanical limitations of conventional concrete, such as brittle fracture behaviour and low flexural strength, can be overcome with the HPC concept. Advanced material strategies that have been explored include fibre reinforcement for macro-level toughness, polymer modification for matrix flexibility, and nanoengineering for microstructural integrity. These form the cornerstones of the mechanical performance of HPC composites. These approaches, whether used individually or synergistically, transform concrete pavements into composites that are more resistant to fatigue under cyclic traffic loading, more ductile, and have higher energy absorption capacity. Nevertheless, it should be noted that the long-term service life of a pavement cannot be assured exclusively through the implementation of these mechanical improvements. A true High-Performance Concrete must combine these mechanical advantages with superior durability against aggressive environmental influences such as freeze-thaw cycles, chemical attacks such as chloride and sulfate attacks, and surface abrasion.

Durability Gains and Microstructural Densification

The durability of concrete pavements is a critical factor in determining their long-term service life and lifecycle cost, as it is directly related to their resistance to environmental attack. While high mechanical performance, such as flexural strength and fatigue life, is a requirement for a pavement to carry traffic loads, the ability to maintain this performance over time is dependent on the material's inherent resistance to environmental degradation (Scheving 2011, Jung et al. 2022). The material's high durability is defined by its ability to maintain the material's physical and chemical integrity. This, in turn, minimises the necessity for costly maintenance and repairs. The issue of environmental threats to road pavements is a multifaceted one. The penetration of chloride ions from deicing salts ($NaCl$, $CaCl_2$) utilised during the winter months has been observed to induce corrosion or expedite surface degradation, particularly in the presence of reinforcement. Repetitive freeze-thaw cycles result in surface flaking/scaling and internal cracking due to the formation of ice within the pore water of the matrix, thereby creating internal hydraulic and osmotic pressures. Sulfate attacks, originating from groundwater or environmental sources, result in expansion and cracking of the formation through the process of ettringite or gypsum formation. Finally, traffic-induced surface abrasion has been shown to cause loss of surface texture and reduced skid resistance (Skrzypczak, Radwański and Pytlowany 2018, Aghaeipour and

Madhkhan 2020). The root cause and accelerator of nearly all these deterioration mechanisms is the inherent porous microstructure of conventional concrete and its resulting permeability. The infiltration of water and aggressive chemicals into the matrix is known to initiate such destructive reactions (Zhuge 2020). Consequently, the primary approach to achieving enhanced durability is to disrupt the concrete's permeability network. The achievement of this objective necessitates the implementation of a multifaceted strategy within the context of HPC applications. This strategy involves the refinement and compaction of the pore structure within the binding matrix. This approach encompasses a range of techniques, from traditional mineral admixtures that compact the matrix at the micron level, to advanced nanoparticles that refine the pore structure at the nanoscale, thereby enhancing abrasion and frost resistance. Finally, there are specialized technologies that impart functional properties to the surface.

Achieving Dense Microstructure with Mineral Additives

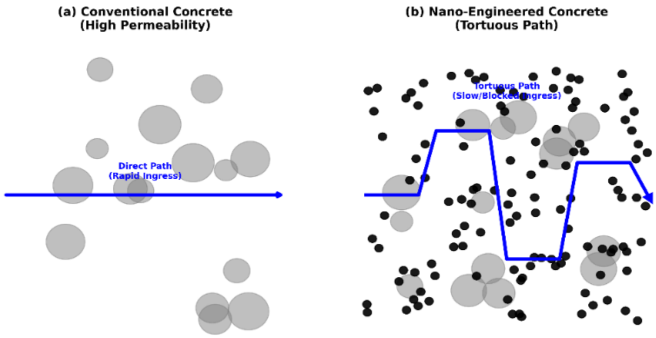
The foundation of strategies that enhance durability is formed by pozzolanic materials measuring less than one micron in size. These have been utilised in applications for a considerable number of years. Silica fume, regarded as a vital constituent of high-performance concrete, is the most notable of these materials. The pozzolanic reactivity of silica fumes are attributable to its submicron particle size, which is considerably smaller than the cement grains. This dual effect is a consequence of the fume's submicron particles (Singh and Singh 2024). First, it creates a microfiller effect, physically filling the voids between cement grains and increasing packing density (Khan, Rehman and Ali 2020). Secondly, and more crucially, it reacts rapidly with weak CH to form a secondary, strong, and dense C-S-H gel (Khan and Siddique 2011). The combination of these two effects has been shown to disrupt the concrete's capillary network, thereby effectively locking the matrix (Chen, Wu and Liang 2024). Consequently, the use of silica fume has been shown to dramatically reduce the chloride ion permeability of concrete, as measured by the Rapid Chloride Permeability Test (RCPT), and to increase its resistance to chemical attack (Khan and Siddique 2011). This renders it a critical component in protecting road pavements against deicing salts. Another industrial byproduct that has been used as extensively as silica fume is fly ash (FA), which is obtained from thermal power plants. As posited by Yener and Hinislioğlu (2011), the pozzolanic reaction rate of FA is comparatively diminished in relation to that of silica fume. Nevertheless, the former has been demonstrated to engender notable durability advantages over time (Yener and Hinislioğlu 2011). The workability of fresh concrete is increased due to the spherical particle morphology of the aggregate, whilst at the same time, the pozzolanic reaction results in the depletion of CH. This has been shown to increase the concrete's resistance, particularly to sulfate attack, by diluting the C_3A phase, which is susceptible to such attack, and reducing reactive CH. Furthermore, it has been demonstrated to significantly reduce chloride permeability by refining the pore structure in the long term (Dungca and Jao 2017, Kumar, Sharma and Ray 2024). Ground blast furnace slag (GGBFS), a byproduct of the iron and steel industry, has been found to exhibit latent hydraulic properties in addition to pozzolanic properties. That is it has the capacity to form a binding C-S-H gel on its own when activated by CH from cement (Al-Hindawi, Al-Dahawi and Al-Zuheriy 2024). The utilisation of GGBFS confers remarkable resistance, particularly to chloride ion penetration; at elevated replacement rates, this resistance is comparable to, and in some cases exceeds, that of silica fume. Furthermore, it exhibits an exceptional resistance profile to sulfates and other chemical assaults (Ogawa et al. 2009). In addition to these common industrial byproducts, other strength-enhancing pozzolans are available. For instance, metakaolin (MK), a by-product of the calcination of kaolin clay, is a manufactured pozzolan with high reactivity, comparable to that of silica fume. It has been demonstrated to facilitate rapid strength and toughness development (Cheng et al. 2024). In addition, natural pozzolans such as volcanic ash, tuff, or pumice, which have been utilised since Roman concrete, have been found to function effectively as cement alternatives and to enhance durability, contingent on their geographical location (Ahmed and Ibraheem 2024). In conclusion, despite their divergent reaction kinetics, all these micro-sized mineral additives refine the matrix microstructure and disrupt capillary pore continuity, the primary pathway for mass transfer. This renders concrete pavements significantly more resistant and durable, particularly to the destructive effects of deicing salts and harsh environmental cycles.

Effect of Nanomaterials on Durability Properties

Nanomaterials improve the durability of road pavement concrete beyond that of micro-pozzolans. The durability of road pavement concrete is enhanced by nanomaterials to a greater extent than that of micro-pozzolans. These enhancements are evident in critical parameters such as permeability, chemical resistance, abrasion resistance, fatigue performance, and crack control by refining the concrete's internal pore structure and strengthening the matrix. The pozzolanic reactivity and superior filler properties of these materials are the key factors contributing to their effectiveness. The ability of these materials to penetrate even the smallest voids that micro-sized additives cannot reach has been demonstrated in numerous studies (Puthiyapurayil and Sirin 2025). The nanoparticle-rich microstructure of cement paste is characterised by the presence of nanopores within the C-S-H gels and the ITZ, which are filled by these particles, thereby leading to a substantial densification of the microstructure, with a resultant void ratio that approaches zero.

This unique microstructure refinement exerts a direct and cumulative effect on durability parameters. It is evident that the most significant effect is the substantial decrease in permeability. In the field of durability, the concept of permeability serves as a foundational principle. The incorporation of nanomaterials into the concrete matrix, specifically into its micropores, results in the formation of a denser structure that exhibits a reduced capacity for the penetration of harmful substances, such as water and chlorides. Nano-SiO_2, nano-$CaCO_3$, and nano-TiO_2 have been found to significantly reduce water sorption, chloride migration, and overall water/chloride permeability. In a similar manner, carbon-based nanomaterials such as graphene oxide, carbon nanotubes and carbon nanofibres have been demonstrated to substantially diminish water sorption and chloride penetration depth (Mohanty et al. 2025). Research conducted on graphene-based nanomaterials has demonstrated that these materials can reduce total porosity, refine the pore size distribution, and consequently significantly reduce water sorption (Jayasooriya, Rajeev and Sanjayan 2022). These improvements in microstructure have been shown to increase not only water and chloride resistance, but also resistance to chemical deterioration, including sulfate attacks, acid attacks and carbonation depth (Mohanty et al. 2025, Jayasooriya, Rajeev and Sanjayan 2022). The nanofilling effect has been shown to disrupt the continuity of the void network, with the result that it is almost completely occluded. This ultra-tight microstructure creates a highly tortuous and discontinuous pathway for water, and especially chlorides from deicing salts, or even blocks it completely (Afzal and Rasool 2024, Shan and Yu 2022). This mechanism, which forces aggressive ions to follow a longer and more difficult path, is illustrated in Figure 4.

Figure 4 Schematic of direct (a) vs. tortuous (b) ingress paths



Illustrated by the author Based on Afzal and Rasool, 2024

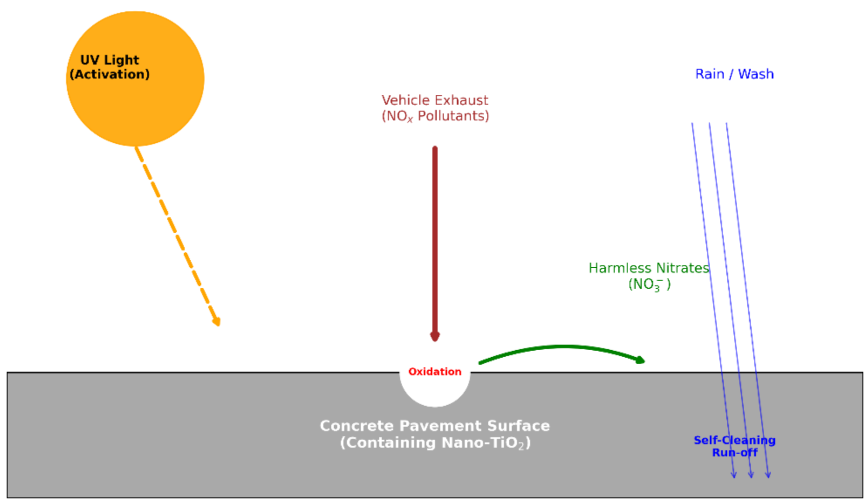
RCPT tests, concretes containing nanomaterials exhibit very low or negligible permeability values, significantly extending the life of the coating against chemical attack and reinforcement corrosion (Liu et al. 2024). This decrease in permeability is directly related to improved abrasion and freeze-thaw resistance. The surface of concrete road pavements is subjected to constant friction from wheels. Abrasion resistance, a critical component in the lifespan of the road surface, is notably enhanced by nanomaterials. Regarding freeze-thaw reactions, nanomaterials offer two essential protective mechanisms. Primarily, they function to prevent the increase of water. This is due to the material's ultra-low permeability, which prevents water from penetrating the matrix at critical levels (Salemi and Behfarnia 2013). Secondly, even in the event of water ingress, the pore structure is so refined that the ice crystals formed cannot generate enough internal pressure to damage the already internally strengthened matrix. This provides material-based protection that has been demonstrated to complement and even surpass the protection provided by traditional air-entraining additives (Ebrahimi et al. 2018).

Indeed, studies have demonstrated that various nanomaterials provide specific and robust improvements in this area. A plethora of studies in the extant literature have reported that nano-TiO_2 and nano-SiO_2 provide very significant increases in surface abrasion indices; nano-Al_2O_3 significantly reduces weight loss and abrasion depth; and graphene oxide significantly increases abrasion resistance. The fatigue life of concrete, which represents its performance under cyclic traffic loads, can also be significantly increased with nanomaterials. It has been reported that the addition of nano-TiO_2 can dramatically increase theoretical fatigue life and is one of the most effective nanomaterials in this field. Carbon nanofibres and graphene oxide have also been reported to extend the service life of concrete slabs and allow for reduced coating thickness (Mohanty et al. 2025). The existing literature on Graphene Oxide contains certain nuances worthy of attention. It has been stated that Graphene Oxide alone may not create a significant change in fatigue life, but when used synergistically with other additives such as silica fume, it significantly increases fatigue life (Li, Zhang and Ou 2007, Jayasooriya, Rajeev and Sanjayan 2022). Nanomaterials also increase durability through crack control and freeze-thaw resistance. Recent observations have indicated that the presence of nano-SiO_2 has a positive effect on the self-healing process of minor cracks. In contrast, carbon nanotubes and graphene-based materials have been shown to impede nanoscale degradation, particularly the formation of shrinkage cracks, through the formation of bridges across the cracks. Moreover, the addition of Graphene Oxide has been documented to enhance concrete's resistance to freeze-thaw cycles and mitigate weight loss, attributable to its refined pore structure and augmented matrix density (Mohanty et al. 2025, Jayasooriya, Rajeev and Sanjayan 2022). The field of nanoengineering has the potential to significantly extend the durability profile of concrete beyond the scope of micro-porous materials, extending to the nanopore level. The incorporation of nanosilica, graphene-based materials, carbon nanotubes, and other metal oxide nanoparticles into the matrix results in an ultra-dense structure, attributable to superior physical packing, pozzolanic, and nucleation effects. The ultra-dense structure of the material has been shown to directly improve chemical resistance by preventing the penetration of aggressive chemicals such as chlorides, sulfates, and acids. Furthermore, the material has been demonstrated to enhance freeze-thaw resistance by reducing water absorption. Concurrently, this dense matrix increases surface hardness, enhances abrasion resistance, and enables functional durability mechanisms such as crack bridging and self-healing. Among the nanomaterials under investigation, nano-TiO_2 is distinguished by its capacity to extend beyond passive protective mechanisms, thereby endowing surfaces with functional properties that offer active and environmental benefits (Han, Zhang and Ou 2017).

Surface Improvement and Functionality

The contribution of nanomaterials to concrete pavements is not limited to enhancing intrinsic mechanical performance or improving passive durability. Furthermore, these materials have the capacity to impart smart or functional properties to concrete, thereby enabling active interaction with its environment. In this area, nano-TiO_2 has been found to be particularly effective due to its photocatalytic properties (Han, Zhang and Ou 2017). This functionality contributes to the surface's durability and environmental performance in two fundamental ways: Firstly, it is effective in the removal of air pollutants. When activated under UV light, nano-TiO_2 photocatalytically oxidises harmful nitrogen oxides (NOx) from vehicle exhausts into nitrates (NO3−) (Beeldens 2006). Secondly, it has been demonstrated to possess self-cleaning properties. The photocatalytic reaction instigated by the TiO_2 catalyst has been shown to break down organic pollutants on the surface (Shen et al. 2012), while also rendering the surface hydrophilic. This hydrophilic property enables rainwater to spread as a film on the surface, penetrating between the dirt and the surface, thereby facilitating the easy removal of dirt particles (Beeldens 2006). This complete cycle, encompassing photocatalytic oxidation and the subsequent self-cleaning mechanism, is schematised in Figure 5.

Figure 5 Working principle of smart pavement



Illustrated by the author based on Beeldens, 2006

Nevertheless, the assurance of the durability and sustainability of this photocatalytic effect poses significant practical challenges. Primarily, nitrates (NO_2) formed because of the air-purification reaction must be regularly removed from the surface by rainwater or artificial washing to prevent their accumulation and subsequent suffocation of photocatalytic activity (Chouhan and Chandrappa 2023). Moreover, the durability of this effect is a matter of concern. It is imperative that TiO_2 is not lost from the surface due to abrasion or weathering; therefore, its addition to the top layer of concrete keystones is recommended. As a preliminary investigation into the pilot project in Antwerp demonstrated, a 20% reduction in air purification efficiency was observed following approximately one year of operation. This decline is hypothesised to be attributable to factors such as surface fouling, degradation, and abrasion (Beeldens 2006). An alternative approach to these fouling and cleaning problems has been studied, in which the surface is rendered hydrophobic rather than hydrophilic. Concomitantly, methodologies that modify the surface chemistry of nano-TiO_2 are also being developed. While the surface of pure nano-TiO_2 is inherently hydrophilic, some studies have investigated coating the surface with materials such as polytetrafluoroethylene to render it hydrophobic. This modification has been shown to result in a substantial increase in the surface's contact angle with water. The high contact angle and the pavement's micro-roughness facilitate the adhesion of rainwater and its subsequent ease of movement across the surface. This process of adhesion and subsequent removal is responsible for the entrapment and elimination of solid particles such as dust and dirt, as well as products like nitrates formed by the photocatalytic reaction. This approach not only maintains the cleanliness of the road surface but also ensures the sustained photocatalytic activity, which is susceptible to diminution over time due to pollution. Consequently, photocatalytic air purification and hydrophobic surface cleaning properties are synergistically combined (Lu et al. 2023). This functionality, in addition to its durability, provides a novel perspective on the future of environmentally sustainable road pavements. To extend the service life of concrete pavements in accordance with the HPC goals, a multi-layered approach to the durability challenge is required. It is widely accepted that traditional mineral admixtures provide a fundamental line of defence against permeability at the micro-level by disrupting the capillary pore network. The nanomaterials under investigation have been found to extend this protection to the nanopore level, thereby maximising resistance to abrasion, freeze-thaw, and chemical attack. In conclusion, the incorporation of materials such as nano-TiO_2 has resulted in the evolution of the concept of durability. This evolution transcends the conventional passive protection, thereby encompassing active functional properties that yield environmental benefits, including air purification and self-cleaning. However, practical challenges, such as the decline in this functional effectiveness over the service life, highlight the need for further research to optimize these advanced technologies.

Case Studies and Application Examples

The theoretical and laboratory-scale evidence suggests that advanced material technologies have the potential to enhance the mechanical performance and environmental durability of concrete pavements. However, the successful translation of these innovative solutions into field applications is critical to demonstrating the practical validity and economic viability of the HPC paradigm. The real-world ramifications of this theoretical foundation have been comprehensively investigated in specific case studies and pilot projects at the international and national levels. These applications provide concrete evidence of the extensive range of capabilities of HPC, including the ability to overcome mechanical challenges such as extending fatigue life under heavy traffic loads, ensuring long-term durability against aggressive environmental conditions, and providing active environmental benefits such as air purification. Pavement applications developed using UHPC represent some of the most significant case studies in terms of mechanical performance. UHPC exhibits mechanical behaviour that far exceeds that of conventional concrete. This is due to the exceptional stiffness of its cement matrix and the frequent inclusion of steel fibre reinforcement. For instance, a particular case study of UHPC, developed to meet the stringent demands of airport pavements under increased axle loads and high traffic frequencies, examined the field performance of this concrete type (Li et al. 2024). The study demonstrated that the optimized UHPC, which contains both fine and coarse aggregates, addresses practical issues such as workability and reducing the risk of early-age shrinkage cracks, which are critical for in-situ casting. The mechanical performance of the developed UHPC was found to be superior compared to conventional C30 airport concrete. Conventionally, the compressive strength of concrete is expected to exceed 35 MPa; however, the ultimate compressive strength of the designed UHPC was found to exceed 155 MPa. Even more critical for road pavements is the 28-day flexural strength expected to be greater than 3.5 MPa for conventional concrete, which was measured as 25.4 MPa for the designed UHPC. This exceptional flexural performance can be attributed to the strong bonding of the steel fibres with the matrix, which effectively bridges the cracks. In addition, the dense internal structure of UHPC, in conjunction with the incorporation of steel fibres and hard basalt aggregates, resulted in a substantially diminished level of abrasion loss when compared to that exhibited by conventional concrete. This case study provides concrete evidence that the optimised UHPC can offer high flexural strength, abrasion resistance and practical workability, which are essential for the most challenging pavement sites (Li et al. 2024). In a separate case study, researchers sought to modify conventional Pavement Quality Concrete (PQC), UHPC and Ultra High-Performance Fiber Reinforced Concrete (UHP-FRC) containing coarse aggregate. These modifications were developed and compared to reduce shrinkage (Rambabu, Sharma and Akbar 2024). The study revealed that fibre-free UHPC provided a significant increase in fatigue life compared to PQC, with compressive strengths exceeding 100 MPa and flexural strengths exceeding 11 MPa. However, the material demonstrated a propensity for brittle fracture, a phenomenon that poses a risk to road pavements such as PQC. The transformative effect was found to be most significant when 2.5% steel fibre was incorporated into the UHPC matrix. The incorporation of fibres resulted in a substantial enhancement of compressive strength, with an increase exceeding 40%, and flexural strength, with an increase exceeding 58%, in comparison with the fibre-free UHPC. In addition to this increase in mechanical strength, the integration of steel fibres has addressed two crucial issues pertinent to concrete pavement applications. Firstly, a significant increase in fatigue life, a critical parameter for pavements subjected to cyclic traffic loading, was observed, with a recorded increase of 146% to 443%. Additionally, a notable enhancement in ductility was evident, attributed to the prevention of brittle fracture through a crack-bridging mechanism. Secondly, it dramatically reduced the high drying shrinkage of UHPC, one of its major drawbacks, by 96%, creating a much more stable material that minimises the risk of shrinkage cracks, a common problem in large-surface pavement applications. The present study demonstrates that UHPC -FRC with coarse aggregate not only offers superior mechanical strength but also addresses decisive service issues such as shrinkage and fatigue for the design of long-lasting and sustainable concrete pavements (Rambabu, Sharma and Akbar 2024). The enhancement of mechanical performance can be accomplished not solely through the utilisation of cement-based systems, such as UHPC, but also through the synergy of diverse materials. In particular, the focus has been on the utilisation of polyester fibre and SBR, latex-modified concrete (FPMC) to enhance the durability and impact resistance of cement-based road pavements (Xu et al. 2014). In this case study, it was determined that the addition of an optimal amount of polyester fibre significantly increased the flexural strength, flexural toughness, and impact strength, which are critical for road pavements, while insignificantly decreasing the compressive strength. In a similar manner, the incorporation of SBR latex led to a substantial enhancement in both flexural and impact toughness, reaching levels that were several times higher than those observed in the control mixture. Nevertheless, the most significant finding of the study is the composite effect created by the combined use of polyester fibre and SBR latex. The optimized FPMC mixture exhibited superior performance in flexural toughness and impact strength in comparison to samples containing solely fibre or polymer. It was determined that the underlying cause of this synergy could be attributed to the presence of specific microstructural analyses. SBR latex has been demonstrated to enhance the ITZ through the formation of a continuous polymer film within the cement matrix. In addition, it has been shown to ensure a tighter bond between the polyester fibre and the cement paste, thereby reducing defects at the fibre-matrix interface and enhancing the role of fibre in toughness and crack resistance (Xu et al. 2014). The field performance of HPC necessitates meticulous optimisation of mechanical strength and long-term durability. This balance is particularly evident in case studies examining coating applications using combined Blast Furnace Slag and steel fibres (Yahyaee and Elize 2024). A study was conducted that yielded findings indicating the positive impact of GGBFS and steel fibres on abrasion resistance. The highest abrasion resistance was measured in a mixture containing 50% GGBFS and 1.5% steel fibres, which also exhibited the highest compressive strength. This finding indicates a positive correlation between mechanical strength and abrasion resistance. However, the study yielded equivocal outcomes in water absorption tests: the lowest water absorption was observed in a mixture containing 40% GGBFS without fibres, while the highest water absorption was observed in a mixture containing 50% GGBFS and 1.5% steel fibres, which exhibited the greatest mechanical strength. This phenomenon is hypothesised to be attributable to the elevated proportion of steel fibres, which has been demonstrated to diminish the workability of fresh concrete. This, in turn, has been shown to result in an increased frequency of compressive failures and an elevated level of porosity within the matrix. This case study provides a significant practical illustration demonstrating that an intervention designed to maximise mechanical strength can have a detrimental effect on another critical durability property due to workability issues (Yahyaee and Elize 2024). Evidence of practical challenges regarding durability is also apparent in case studies of Roller Compacted Concrete (RCC) pavements. Due to its predominantly arid, air-entrained nature, RCC is prone to freeze-thaw (F-T) damage if it becomes critically water saturated (Naik et al. 2001). However, it has been demonstrated that this sensitivity can vary between laboratory tests and field performance. For instance, in a case study conducted in Wisconsin, RCC pavement samples containing 30% Class C FA failed the standard rapid freeze-thaw laboratory test in water but performed satisfactorily in a different air-freeze-thaw test procedure that better reflects field conditions (LaHucik and Roesler 2017). Indeed, field observations indicate that unentrained RCC pavements perform satisfactorily for over 10 years in cold climates, if critical saturation is not reached. This emphasises the significance of design measures, such as high-density compaction and a well-drained base course, in preventing critical saturation, rather than the material recipe itself, for F-T durability of RCC. The Wisconsin case study demonstrated that chloride ion permeability is also directly related to compaction quality, with the better compacted upper portions of casing cores exhibiting greater resistance to chloride penetration than the lower portions. Moreover, the substitution of low-calcium FA has been documented to enhance the chemical resistance of RCC, thereby improving its sulfate resistance (Naik et al. 2001). Durability problems are not only attributable to external environmental aggressions; internal volumetric changes to the material itself are also a contributing factor. The high shrinkage tendency of engineering cement composites (ECC), despite their high toughness and ductility, poses a practical challenge, leading to cracking in pavements and consequent durability issues. A case study was conducted with the objective of addressing this issue for critical applications, such as steel bridge decks. The study resulted in the development of a new low-shrinkage, high-toughness, and lightweight ECC (Xie et al. 2025). In this study, a multilayered material design strategy was employed to address the high shrinkage problem. First, volumetric expansion was achieved using a 5% calcium sulfoaluminate-calcium oxide-based expansion agent. Secondly, the pre-wetting of porous ceramic sand as an internal cure aggregate served to compensate for autogenous shrinkage by providing moisture during the later stages of cement hydration. The combination of these two strategies resulted in a 45% reduction in the 56-day shrinkage compared to the control group. This volumetric stability was achieved while mechanical performance was optimised by hybrid fibre and micro-sized calcium carbonate ($CaCO_3$) fibres. The presence of these fibres has been demonstrated to enhance tensile ductility by fortifying the fibre-matrix interface. This case study demonstrates that the synergy of multiple advanced material strategies, such as expansion agents, internally cured aggregates, and hybrid fibre systems, can produce coating material with both superior mechanical properties and critical volumetric stability, i.e. low shrinkage (Xie et al. 2025). Correct interpretation of durability case studies necessitates an understanding of the complex chemical mechanisms of environmental impacts on-site, particularly in instances of chloride-induced corrosion. While some chlorides penetrate concrete and actively trigger corrosion as free chlorides, others bind to cement hydration products, becoming bound chlorides, rendering them temporarily harmless. Nevertheless, the most critical challenge in practical applications is the reversibility of this process. The pH of the concrete's pore solution is lowered by carbonation from the atmosphere or chemical attacks from acid rain/deicing salts. This decrease in pH results in the re-dissolution of previously bound chlorides into a free state, a process referred to as chloride desorption. This phenomenon has the potential to cause current service life models to overestimate durability by exacerbating the corrosion risk through the abrupt increase in free chloride concentration (Moogooee 2024). This intricate mechanism elucidates the way the selection of mineral additives (SCMs) exerts a direct influence on durability in the field. An examination of resistance to chloride desorption at low pH conditions revealed that GGBFS and FA additives exhibited favourable behaviour. Conversely, the low chloride binding capacity of silica fume and its inefficiency in desorption at low pH necessitate a re-evaluation of its utilisation in aggressive environments where chloride-induced corrosion is a substantial concern. However, an exception to this rule has been observed in environments where carbonation and chloride coexist. In such cases, the presence of FA has been shown to result in lower post-carbonation pH levels due to its lower $Ca(OH)_2$ content. It has been established that FA additives release over 95% of bound chlorides; consequently, they are not recommended for this specific environmental context. The case studies demonstrate the necessity for sophisticated optimisation in the selection of materials, including the type of deicing salt employed. For instance, $MgCl_2/CaCl_2$ has been shown to result in lower desorption compared to NaCl (Moogooee 2024). Durability analyses should focus not only on material chemistry but also on the synergy of environmental insults and on-site mechanical loads. A case study was conducted to examine the performance of concrete pavements in cold regions and salty soils. The study revealed that the combined effects of these environments can significantly accelerate concrete deterioration (Sadeghi, Kordani and Zarei 2024). The findings of the present study indicate that fatigue damage caused by vehicle loads creates microcracks within the concrete. These fissures function as conduits for the ingress of freeze-thaw cycles and chloride-sulfate composite salts, which can penetrate the concrete's internal structure with greater rapidity and depth. Consequently, concrete that has already suffered fatigue damage exhibits much more rapid deterioration when subjected to these combined environmental insults compared to unfatigued concrete. This synergistic effect leads to a significant decrease in both the material's physical properties, such as mass loss and a decrease in dynamic modulus of elasticity, and its mechanical properties, such as compressive strength and flexural strength. This case study demonstrates the critical importance of considering the simultaneous effects of traffic fatigue and chemical/physical environmental insults in pavement service life models (Sadeghi, Kordani and Zarei 2024). Finally, case studies demonstrate that the active functional benefits offered by nanomaterials also come with their own practical durability challenges. A case study was conducted to examine the functional durability of nano-TiO_2's air purification properties, i.e. the duration for which the material maintains its functionality under traffic and environmental conditions (Yan et al. 2025). The study identified two primary factors affecting performance: clogging and abrasion. It has been established that the accumulation of dust and dirt particles within the porous coatings of photocatalysts has a detrimental effect on their performance. It has been demonstrated that clogging can impede the penetration of ultraviolet (UV) light through the catalyst, thereby hindering the photochemical reaction. Concurrently, this obstruction can also prevent the interaction between pollutants (NOx) and the catalyst's active surface, a phenomenon that has been shown to result in a substantial decline in exhaust gas separation efficiency. Furthermore, laboratory tests simulating traffic-related abrasion resulted in the physical loss and removal of nano-TiO_2 particles from the aggregate surface, leading to a significant decrease in NOx separation efficiency. This case study demonstrates that stabilising the nanomaterial against abrasion and developing design/maintenance strategies to prevent surface clogging are critical for the longevity of photocatalytic coatings (Yan et al. 2025). These case studies provide concrete illustrations of the practical application of the theoretical potential of advanced material technologies in the field. The utilisation of systems such as UHC and UHC-FRC in challenging environments, including airport pavements, exemplifies their capacity to manage exceptional mechanical loads, fatigue demands, and practical concerns such as shrinkage. Furthermore, the efficacy of synergistic systems, such as ECC and FPMC, in achieving specific objectives, including toughness and dynamic performance, has been substantiated through case studies. Nevertheless, these case studies also highlight the critical complexity and nuanced optimisation requirements of real-world applications. Several potential conflicts have been identified, including those between maximum mechanical strength and low permeability, discrepancies between standard laboratory tests and actual performance in the field, the complex effects of material chemistry on long-term durability, and most importantly, the fact that the imparted function has its own durability issues. It is therefore clear that these solutions require a careful engineering approach.

Synthesis and Critical Discussion

The transition from a conventional strength-based approach to a performance-based paradigm in the design and construction of concrete pavements, centred on lifecycle cost and environmental impact, is no longer a choice but a necessity under today's increasingly severe traffic loads and aggressive climate conditions. The fundamental synthesis presented by the advanced material technologies examined in this study is that the sustainability of concrete pavements depends not on a single increase in compressive strength, but on the pavement's holistic resistance to the dynamic and environmental loads to which it is subjected. The brittle structure and capillary porosity of conventional concrete limit its performance in flexural strength and fatigue life, which are the most critical parameters for road pavements. Multi-scale material strategies under investigation have the potential to radically alter these limits. From a mechanical perspective, it is evident that the primary threat to concrete road pavements does not stem from static loads, but rather from the cyclic stresses generated by wheel runs. In this regard, the incorporation of FRC has been demonstrated to transform the brittle fracture behaviour of concrete into a ductile one, thereby significantly increasing the pavement's fatigue life and ensuring structural integrity by bridging cracks. However, the success of a road pavement is not limited to crack control alone; the pavement's surface properties and inherent density are equally critical. The enhancement of the ITZ through the implementation of nanoengineering and polymer modification has been demonstrated to optimise resistance to traffic-induced surface abrasion by augmenting the adhesion of aggregates to the matrix. This is a vital advantage for the pavement's long-term skid resistance and driving safety. When evaluated in terms of field performance, the delicate balance between mechanical strength and durability becomes evident. It has been established that the most significant factors contributing to the deterioration of concrete roads are winter deicing salts and freeze-thaw cycles. These substances have the capacity to penetrate the porous structure of conventional concrete, thereby inflicting damage to the pavement both internally and on the surface. The utilisation of mineral additives, such as silica fumes and nanofillers, impedes the nanoscale pore network, thereby establishing an impermeable barrier for water and chloride ions. However, a review of the literature reveals that practical obstacles, such as workability and shrinkage, may be encountered when transferring these material achievements from the laboratory environment to the field. This is particularly pertinent in the context of large surface applications, such as road construction, where the excessive use of fibres can impede compaction and result in matrix defects. Moreover, high-performance mixtures may be susceptible to the risk of shrinkage cracking. It is imperative that the material design be optimised for the specific application conditions on site. The performance of concrete is evolving beyond its traditional applications in load-bearing and passive durability. Through the integration of nanotechnology, concrete is being developed to incorporate intelligent properties that interact with the environment. Specifically, the use of nano-TiO_2 has been demonstrated to transform concrete road surfaces into an active layer that improves air quality by decomposing exhaust gases through photocatalytic reactions and self-cleans by degrading organic contaminants. While this functionality has the potential to transform concrete roads in urban areas into environmentally sustainable infrastructure, the concept of sustainable functionality remains a significant research challenge. It has been demonstrated that the continuous abrasion and surface contamination caused by traffic can result in the gradual loss of effectiveness of these active nanoparticles, or indeed their detachment from the surface. Consequently, the success of smart road pavements is contingent not only on the chemical reaction efficiency in laboratory settings but also on the physical durability of this functional layer when subjected to traffic loads.

Conclusion and Future Recommendations

The integration of advanced material technologies has transformed concrete road pavements, turning them from passive casting materials into mechanically ductile, chemically impermeable, and functionally active composite systems. However, based on the findings and case studies in existing literature, there are still significant gaps to be filled before this transformation can be completed. Firstly, it has become clear that the highest mechanical strength does not necessarily equate to the greatest durability. In fact, excessive use of fibres or additives can hinder workability and result in errors during field application. Therefore, future designs should focus not only on achieving maximum strength, but also on striking the optimal balance between workability and durability. Additionally, as demonstrated by advanced applications such as roller-compacted concrete (RCC) and complex chemical processes such as chloride desorption, standard laboratory tests do not always accurately simulate real-world performance and environmental interactions. Therefore, future studies must focus on holistic performance models that consider scale effects, field curing conditions and the combined effects of traffic fatigue and chemical attack rather than relying on laboratory results. Similarly, widespread adoption of nanotechnology-enhanced smart concretes hinges on resolving physical durability issues such as abrasion and contamination under traffic conditions. Ultimately, concrete pavements should no longer be designed using standard, prescription-based approaches. The industry must transition to 'tailor-made' engineering approaches based on parameters such as the location's traffic load, the number of freeze-thaw cycles and the type of salt to which it will be exposed. This new design philosophy, which involves selecting fibres, polymers and nanomaterials to meet these specific conditions, will form the basis of sustainable and resilient transport infrastructure.

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CHAPTER 4

INTEGRATED DESIGN VISION AND ADVANCED CONCRETE TECHNOLOGIES IN FUTURE FUNCTIONAL PAVEMENTS

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Introduction

The role of road pavements in the development of civilisations has been historically significant. The primary functions of road pavements are to carry traffic loads and to provide a driving surface that is safe and comfortable. In this conventional approach, the design of pavements was primarily concerned with structural adequacy, geometric standards, and durability (Ajirotutu et al. 2024). Nevertheless, the multifaceted challenges of the 21st century have precipitated shifts in expectations of road infrastructure. Urbanisation, characterised by high population density, has been

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identified as a significant factor contributing to the rapid deterioration of infrastructure under increasing traffic loads (Ismael et al. 2024). This phenomenon is further compounded by the impact of sudden and heavy rainfall, a consequence of climate change, which places considerable strain on urban drainage systems. Additionally, rising temperatures, a consequence of global warming, have been shown to exacerbate the urban heat island effect, further exacerbating the challenges faced by urban areas (Ismael et al. 2024). Moreover, the construction sector's substantial consumption of natural resources and its considerable carbon footprint have given rise to concerns regarding resource scarcity (Al-Numan 2024). In the face of these global pressures, pavements are no longer regarded as merely passive load-bearing elements. It is evident that a fundamental shift is occurring within the domain of road engineering, precipitating by the emergence of a novel concept: that of functional pavement. The term functional pavement is defined as an engineering structure that goes beyond its traditional structural roles and actively interacts with its environment, providing additional environmental, energetic, safety, or smart benefits (Liu et al. 2007). The objective of these newly developed pavements is to transform infrastructure from a problem into part of the solution. The functional pavement application range is extensive. Permeable concretes that can reduce urban flooding and recharge groundwater resources by managing rainwater (Xie, Akin and Shi 2019); air-purifying concretes that can clean city air by decomposing harmful NOx gases released from vehicle exhausts thanks to their photocatalytic properties (Ballari and Brouwers 2013); conductive concretes or integrated heating systems that increase safety by preventing icing in winter; low-noise pavements that improve the quality of life by absorbing traffic noise (Mikhailenko et al. 2022); photovoltaic roads that can convert solar energy into electricity (Del Serrone, Peluso and Moretti 2023); and self-healing concretes that can autonomously repair microcracks within their own structure are examples of functional pavements. Research in the literature optimises pavement materials individually based on sustainability or performance (Umer et al. 2017). Similarly, studies on functional pavements, such as permeable, photocatalytic, or self-healing systems, often focus on maximizing a specific function, such as water management or air purification, leaving aside how to integrate these technologies into a holistic infrastructure design. The primary objective of this study is to analyse the practical application of the objectives of "Sustainability," "Performance," and "Functionality." In this regard, the study goes beyond a mere enumeration of specific functional concrete technologies by engaging in a detailed discussion of their intersections with sustainability and performance objectives, potential synergies, and trade-offs through the utilisation of case studies. Synthesising these diverse, innovative research areas has been shown to have the potential to reveal the feasibility of future "Sustainable, Durable, Functional" ideal pavement systems.

Sustainable and Special Concrete Coating Technologies

The conceptual framework underpinning the functional pavement vision is predicated on the integration of advanced material technologies that can incorporate these functions. Beyond the conventional poured concrete, concrete systems are available for specific applications, exhibiting variations in both construction techniques and final properties. These systems have been engineered to address specific environmental or operational challenges, including but not limited to heavy loads, the need for rapid construction, and water management. In this context, innovative pavement types such as roller compacted concrete (RCC) for extreme heavy load-bearing function, permeable concrete for urban water management, foam concrete for geotechnical mitigation solutions and polymer concrete for rapid repair or superior chemical resistance constitute the cornerstones of this functional approach (Kamal and Bas 2021, Rebeiz, Serhal and Craft 2004).

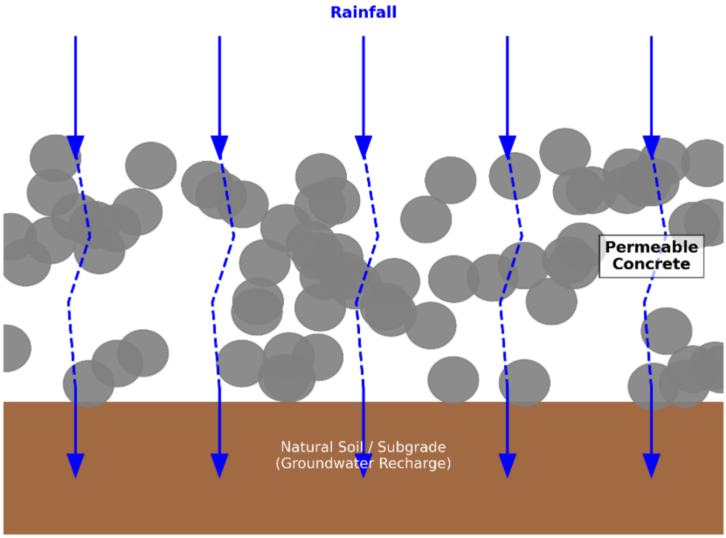
Roller Compacted Concrete Pavements

RCC represents a hybrid rigid pavement solution that combines the durability of traditional concrete pavements with the rapid construction techniques of asphalt pavements. The fundamental distinction between these categories is contingent on the consistency exhibited by the concrete and the method of its placement. RCC is a dry mix with virtually no slump, and, in contrast to traditional concrete pouring, it is laid with high-density asphalt pavers and compacted using heavy vibrating steel rollers (Aghaeipour and Madhkhan 2020). The primary reasons for the popularity of RCC in road pavements are its rapid construction, high early-age strength, and superior performance under heavy loads. As a rigid pavement system, RCC distributes loads over a wider area, thereby reducing stress on the base layers. This renders it an optimal solution for areas characterised by very heavy and slow-moving traffic loads, including port areas, intermodal terminals, military facilities, industrial storage areas, and heavy industrial roads (Sünbül and Tortum 2024). Furthermore, the RCC has been demonstrated to be intimately associated with the subjects of sustainability and functionality which are discussed in this study. From a functional perspective, the primary function of RCC is to provide extreme heavy-duty support, a function that falls short of traditional flexible or standard rigid pavements. From a sustainability perspective, RCC mixes frequently exhibit an ability to accept high concentrations of mineral admixtures. The utilisation of these admixtures has been demonstrated to reduce the pavement's embodied carbon footprint by decreasing the amount of cement utilised, while concomitantly enhancing the mix's workability and long-term durability (BAV and G 2022). Consequently, RCC is distinguished as a high-performance solution that combines the durability of rigid pavements with the construction speed of flexible pavements. Its primary function is to provide superior structural capacity to withstand extremely heavy loads in areas such as ports and industrial sites. Furthermore, the capacity of RCC to accommodate elevated levels of waste and industrial by-products without compromising performance criteria renders it a pivotal pavement technology, successfully integrating sustainability and functionality.

Permeable Concrete Pavements and Urban Water Management

The process of increasing urbanisation, whereby natural soils are replaced with impermeable surfaces, has been shown to increase the amount and velocity of rainwater runoff. This has serious hydrological consequences, including urban flooding, water contamination, and the inability of groundwater resources to recharge (Öztürk Yılmaz et al. 2024). Permeable concrete pavements represent a functional pavement technology that offers an engineered solution to this problem. A distinguishing characteristic of permeable concrete, in contrast to conventional concrete, is its minimal or absence of fine aggregate content. The aggregate particles are coated with a thin layer of cement paste, creating a deliberately porous structure between the particles (Sánchez-Mendieta, Galán-Díaz and Martinez-Lage 2024). The high porosity of permeable concrete is the defining characteristic that determines its primary function, namely water permeability. Rainwater falling on the surface rapidly percolates through the pavement, infiltrating directly into the underlying foundation layers and subsequently into the natural ground. This mechanism has been demonstrated to significantly reduce surface runoff, thereby alleviating the burden on existing drainage systems and reducing the risk of flooding. This hydrological mechanism, which facilitates groundwater recharge and reduces surface runoff, is illustrated in Figure 1.

Figure 1. Hydrological cycle in permeable pavement



Illustrated by the author based on Xie et al., 2019

Moreover, the pavement system has the capacity to enhance water quality by filtering out certain contaminants present in the initial runoff. In addition to replenishing groundwater resources by facilitating the infiltration of water into the soil, its porous nature enables the reduction of surface temperatures through water evaporation, thereby mitigating the Urban Heat Island effect (Syros et al. 2024). Notwithstanding the advantages, permeable concrete pavements encounter numerous challenges in terms of their widespread adoption. It is an established fact that a high void density invariably results in a reduction of mechanical strength. Consequently, their utilisation is predominantly confined to areas characterised by minimal traffic and low velocity, such as parking lots, pedestrian walkways, and residential roads. Furthermore, the clogging of voids over time can reduce the pavement's water permeability, necessitating regular maintenance and cleaning (Zhou et al. 2024, Barua and Islam 2024, Huang, Song and Sheng 2024). From a sustainability perspective, permeable concrete represents a pivotal component of the "Sustainable Urban Drainage Systems" philosophy (Monachese et al. 2024). Recent research has concentrated on the utilisation of geopolymer binders or recycled aggregates in lieu of cement, with a view to further enhancing the environmental benefits of permeable concrete. These innovative approaches lay the foundation for pavements that are both low-carbon and function as water management systems (Rao et al. 2024). The concept of permeable concrete pavements represents a system that offers active environmental benefits, thereby challenging traditional engineering approaches. The primary function of these green spaces is to directly impact urban hydrology by managing stormwater in urban areas. The capacity of these wetlands to mitigate flood risk, facilitate groundwater recharge, and purify pollutants renders them a vital component of sustainable urban drainage systems. Notwithstanding their inherent limitations regarding mechanical strength, they offer a critical solution in low-traffic urban applications where water management takes precedence over structural requirements.

Cellular Lightweight Concrete and Geotechnical Applications

Cellular Lightweight Concrete (CLC) is a material characterised by its very low density, which is produced by the controlled incorporation of air bubbles into a cement mortar or paste, typically using a special foaming agent. In contradistinction to conventional concrete, this system generally contains no coarse aggregate. The structure of the material is composed of millions of discrete air pores, which are entrapped within the cement matrix. This configuration enables the material's density to be meticulously calibrated across a substantial range, spanning from approximately 300 kg/m³ to 1800 kg/m³ (Lu et al. 2022). The primary function of foamed concrete in road pavements is its extreme lightness compared to traditional filling materials. This lightweight fill function provides a critical advantage, particularly in geotechnically challenging ground conditions (Wilk 2025). In the context of roads constructed on soils with inadequate bearing capacity, the utilisation of conventional heavy fills has been observed to result in substantial settlement, instability, or foundation failure (Jusi, Dhamrodji and Maizir 2024). When utilised as an infill material or base layer in such soil conditions, the implementation of concrete results in a substantial reduction in the ground load. This approach has been demonstrated to minimise total settlement and accelerate the construction process (Lu et al. 2025). Moreover, when employed in embankments adjacent to structures, such as bridge approach embankments or behind culverts, it significantly reduces lateral soil thrust on the structure, thereby enabling a more economical structural design (Prakash, Tiwari and Dash 2024). In addition to its low weight, its closed-cell structure provides foam concrete with good thermal and acoustic insulation properties. However, these properties are generally secondary benefits in road pavement applications (Jusi, Dhamrodji and Maizir 2024). From a mechanical standpoint, given that compressive strength declines markedly with decreasing density, foam concrete is typically employed as a load-distributing base layer rather than as a surface coating that directly supports traffic loads (Papánová, Prišč and Martinovičová 2024). In the view of sustainability, the employment of substantial quantities of pozzolanic materials, such as fly ash or silica fume, as substitutes for cement in foam concrete mixtures is a common practice. The utilisation of these materials has been demonstrated to engender a reduction in costs and environmental impact, whilst concomitantly enhancing the stability and long-term durability of the foam structure (Tamoor and Zhang 2025, Vinod 2024). In summary, the primary functional contribution of foam concrete in pavement systems appears to be as a geotechnical solution rather than structural durability. The material's low density, when considered in conjunction with its capacity to alleviate loads on weak soils and control settlements, renders it a strategic engineering material in situations where traditional fill materials are inadequate. This material, which is also aligned with sustainability goals, offers significant potential, particularly in the context of infrastructure projects that encounter geotechnical challenges.

Polymer Modified Concretes and Rapid Repair Potential

Polymer concrete is a high-performance composite material that utilises synthetic polymer resin as a binding agent, in lieu of Portland cement (Taha, Genedy and Ohama 2019). This group of materials differs from Polymer Modified Concrete (PMC), which is achieved by adding a polymer admixture to a cementitious mixture. In polymer concrete, no hydraulic reaction occurs; instead, the aggregates are bound entirely by a polymer matrix (Ostad-Ali-Askari et al. 2018). The functional advantages of polymer concretes in paving applications demonstrate their superiority over cement-based systems. The most notable of these properties is their rapidly curing time. In contrast to cement-based concrete, which requires days to set and attain strength, polymer concrete has been shown to reach full traffic load strength within a few hours (Ahmad et al. 2022). The rapid repair function is of particular importance in critical infrastructure applications where the cost of traffic disruption is high, such as airport runways, highway repairs, bridge expansion joints, or industrial floor repairs (Mohammed et al. 2022). In addition to speed, these materials offer superior mechanical performance and excellent chemical resistance (Bedi, Chandra and Singh 2013). Whilst traditional polymer concretes are frequently the subject of criticism regarding their cost and reliance on petroleum-derived resins, recent research has opened new avenues in this area. The utilisation of waste plastics as binders or aggregates in the production of polymer concrete fosters strong synergies with sustainability objectives (Mashaan and Ouano 2025). Plastic-based polymer concretes, in which waste plastics are utilised as binders or aggregates by thermal or chemical means, offer a solution to the landfill problem and contribute to the conservation of valuable natural resources (Jo, Park and Park 2008). Polymer concretes are high-performance materials developed for specialised engineering applications where rapid repair and superior chemical and mechanical resistance are critical. While their expense has traditionally been a disadvantage, their potential to extend infrastructure life and their integration into sustainability using waste plastics places them at the forefront of modern paving technologies.

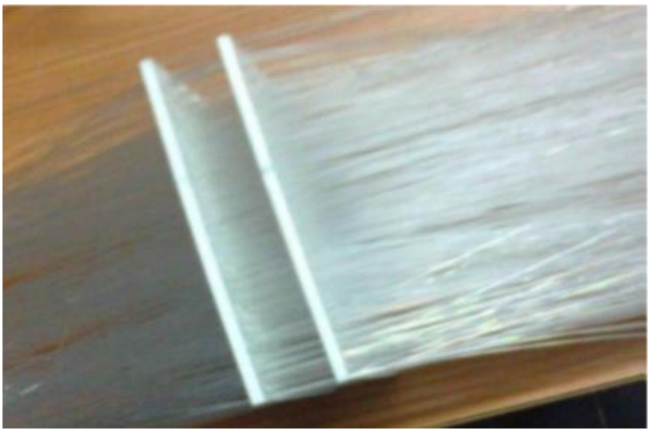
New Functions Integrated into Concrete

Beyond specific types of concrete, the integration of advanced technologies into the concrete matrix or the system itself is transforming road pavements from passive structural elements into active, intelligent systems. This transformation encompasses a wide range of applications, from the introduction of new roles for pavements, such as aesthetics and energy production, to advanced crack control mechanisms that extend the material's inherent service life, and to surfaces that actively interact with their environment to improve air quality or self-clean.

Light Transmissive Concrete and Photovoltaic Coatings

In the context of endeavours to mitigate the ecological consequences of road infrastructure, there has been a proliferation of innovative functions, including the reduction of energy consumption and the generation of energy. These approaches seek to redefine the pavement's relationship with the urban environment in a manner that is both aesthetically pleasing and functional, thereby transforming it into an active component in the urban energy landscape. The technologies emerging in this area can be categorized into two main areas: light transmission and photovoltaic generation. Light Transmitting Concrete (LTC) is produced by embedding thousands of optical fibres arranged in a regular pattern within a concrete matrix (I. Luhar et al. 2021, Bai et al. 2024). The transmission of light from one surface of the concrete to the other is facilitated by these optical fibres, thereby endowing the material with a translucent appearance. The arrangement of optical fibres facilitating this light transmission is depicted in Figure 2.

Figure 2. Optical fibres arrangement



Juan and Zhi., 2013

From a structural standpoint, this material – which remains a concrete – proffers unparalleled aesthetic possibilities by virtue of its capacity to transmit light (Alsayed et al. 2025). Although not yet extensively implemented in road pavements, it possesses the potential to be utilised in urban design, such as pedestrian walkways, sidewalks, or tunnel entrances, thereby introducing natural light into underpasses during the day and enhancing safety and aesthetics through ground lighting at night (Singh and Sinha 2024).

Photovoltaic Pavements represent the most ambitious concept in this field, with the focus being on the energy-generating function of pavements. The integration of photovoltaic (PV) panels directly onto the road surface is the key feature of this concept (Li, Ma and Wang 2023). These systems, designated as solar roads or solar pavements, aspire to repurpose the substantial surface area currently occupied by highways, parking facilities and bicycle paths into a solar power plant (Hu et al. 2021). This technology incorporates PV cells that are embedded beneath a special layer of durable, non-slip, and traffic-resistant glass. The resulting electricity can be fed into the grid, utilised for road lighting, or employed to power traffic signals. Additionally, integrated heating elements can be utilised to prevent icing during winter, thereby acquiring a secondary function (Li, Ma and Wang 2023, Chen et al. 2025). Nevertheless, it should be noted that this technology is still in its development phase. The high initial cost of these panels, in addition to their comparatively lower efficiency when subjected to tilt angles, soiling, shading, and other factors, poses a significant challenge to their long-term durability, particularly in contexts involving heavy vehicle traffic. Nevertheless, it should be noted that this technology is still in its development phase. The high initial cost of these panels, in addition to their comparatively lower efficiency when subjected to tilt angles, soiling, shading, and other factors, poses a significant challenge to their long-term durability, particularly in contexts involving heavy vehicle traffic (Palmintier et al. 2016).

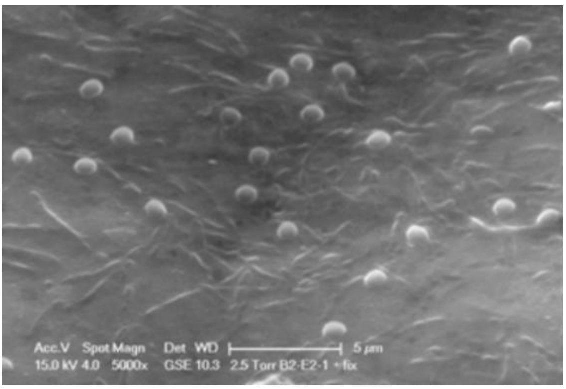
Advanced Crack Control for Longevity and Durability

Concrete's most significant weakness as a pavement material is its low tensile strength and consequent propensity to crack. These fissures represent the predominant conduit for the ingress of water, chloride ions, sulfates, and other deleterious chemicals into the concrete matrix. This phenomenon has been shown to result in several undesirable consequences, including reinforcement corrosion, freeze-thaw damage, and overall material deterioration, which collectively contribute to a significant reduction in the pavement's service life (Lu et al. 2022, Marsavina et al. 2009, Otieno, Alexander and Beushausen 2010). Conventional reinforcing steel is employed to regulate crack widths once they have formed, rather than to prevent them. In response to this inadequacy, modern materials science offers advanced approaches that address cracking at two levels. The primary strategy entails the proactive prevention of crack formation through the incorporation of shrinkage-compensating admixtures. The secondary strategy involves the reactive repair of existing cracks by employing self-healing concrete concepts. A substantial proportion of cracks in road pavements are attributable to drying shrinkage, particularly during the initial stages of pavement construction. Shrinkage-Compensating Admixtures have been developed to address this issue. The primary function of these admixtures, the most common of which are based on Magnesium Oxide (MgO) or Calcium Sulfoaluminate, is to provide controlled expansion during the hardening process of the concrete (Collepardi et al. 2005, Lyu et al. 2019, Louw and Jones 2015). This controlled expansion is designed to offset the subsequent drying shrinkage that the concrete will experience. The implementation of a slight pre-stress within the concrete's internal structure has been demonstrated to be a successful method of mitigating the risk of shrinkage cracks. This is achieved by enabling the concrete to absorb the tensile stresses caused by shrinkage. This approach has been demonstrated to offer high performance, particularly in applications where reduced joint density is desired or water resistance is critical (Huang et al. 2019, Yu et al. 2018, Zhuge 2020).

Self-Healing Concretes

The utilisation of biologically inspired self-healing systems, which intervene only after the formation of cracks, signifies a novel advancement in the field of concrete durability. Conventional concrete has been shown to possess limited autogenous repair capabilities, whereby it can seal very small cracks through the hydration of unreacted cement particles (Chen, Zhou and Cheng 2022, Zhao et al. 2022). The capacity for self-healing in concrete is enhanced through the implementation of advanced engineering methodologies. In the bacteria-based repair method that has been most successful in this field, specific bacterial spores and nutrient sources are added to the concrete mix specific bacterial spores and nutrient sources are added to the concrete (Vishal, Chepuri and Chandana 2025).

Figure 3 ESEM image of alkali-resistant Bacillus bacteria and spores



Jonkers, 2021

The formation of a crack initiates the activation of the dormant spores through the infiltration of water and oxygen. The bacteria metabolize the nutrient source, thereby precipitating calcium carbonate as a byproduct. The application of calcite has been demonstrated to fill the crack, thereby restoring structural integrity and reducing water permeability to a level close to zero (Jonkers 2021, Luhar, Luhar and Shaikh 2022). Another common approach, capsule-based repair, involves the dispersion of microcapsules or hollow, brittle glass tubes containing a restorative chemical agent into the concrete matrix. The propagation of a crack results in the rupture of the capsules, thereby releasing the restorative agent into the crack. The released agent reacts with surrounding moisture or a catalyst embedded in the matrix to polymerise and chemically glue the crack (Salimi, Kamboozia and Aliha 2024).

Self-Cleaning and Air-Purifying Coatings

In urban areas, road pavements have been identified as the most significant source of ambient air pollution resulting from vehicular exhaust emissions. An innovative approach in functional pavements aims to transform these large, passive surfaces into photocatalytic systems that actively interact with their environment and can improve air quality (Chouhan and Chandrappa 2023). Technology is predicated on the use of titanium dioxide (TiO_2), typically in the form of anatase, which is incorporated into the cement matrix or applied to the surface of the coating. When exposed to ultraviolet (UV) radiation in sunlight, TiO_2 produces powerful oxidising agents on its surface. These highly reactive radicals are capable of chemically breaking down harmful organic and inorganic contaminants that encounter the concrete surface. This reaction converts harmful gases into harmless, water-soluble salts such as nitrate, which are easily washed away by rainwater (Chen and Chu 2011, Shen et al. 2012). The photocatalytic effect endows the coating with two primary functions. The initial function of the device is to purify the ambient air. The coating functions as an extensive surface filter, thereby enhancing the quality of the ambient air and contributing to the mitigation of urban smog (Yang 2019). The second of these is self-cleaning. In addition to the decomposition of organic contaminants on the surface, the photocatalytic effect of TiO_2 also renders the surface superhydrophilic (Rabajczyk et al. 2021, Awadalla et al. 2011). This property is attributed to the capacity of the material to facilitate the diffusion of rainwater as a thin film, thereby preventing the accumulation of droplets on the surface. This water film has been shown to penetrate beneath the broken-down dirt, 'scraping' it from the surface, thereby providing effective cleaning. This ensures that the coating maintains its aesthetic appearance over time and reduces maintenance costs (Tang et al. 2024). Photocatalytic coating has been successfully applied to urban plazas, tunnel interiors, and noise barriers, where aesthetic considerations are particularly important. However, the effectiveness of technology is contingent upon several factors, including the surface TiO_2 concentration, the intensity of UV light, the level of pollution, and the frequency of rainfall. It has been demonstrated that surface erosion over time, or the coating of TiO_2 particles with other contaminants, are challenges that have the potential to affect long-term performance (Hassan et al. 2010). Photocatalytic concrete pavements represent a functional innovation, whereby infrastructure materials are transformed into an environmental agent. It has been demonstrated that such structures serve a dual function: in addition to supporting traffic loads, they also improve air quality and maintain surface aesthetics. This technology offers significant potential for achieving sustainable urban development goals and protecting public health.

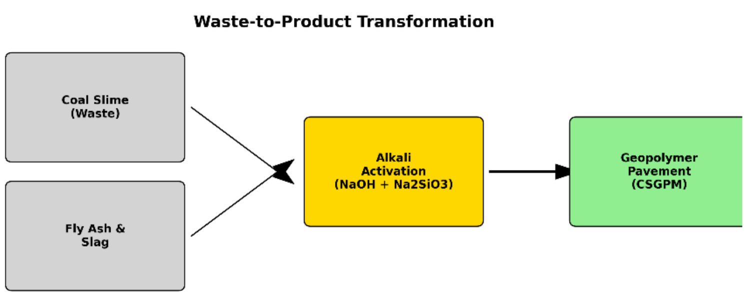
Inclusive Design Vision

The development of advanced technologies for road pavements is frequently oriented towards the provision of a particular functional benefit. However, the complex urban and environmental challenges of the present day require an overarching design vision that goes beyond single solutions and integrates the objectives of sustainability, performance and functionality. The "Inclusive Design Vision" delineated in this study offers a novel interpretation of road pavements, redefining them not as passive layers that merely bear traffic loads, but as dynamic systems that manage environmental interactions, optimise their performance throughout their service life, and provide added value to the user. This vision signifies a multifaceted pursuit of equilibrium, amalgamating advancements in materials science with structural design. In contradistinction to conventional single-parameter optimisations, such as strength or cost, this approach encompasses a more comprehensive evaluation of structural integrity. To comprehend the practical functionality of this phenomenon, it is imperative to analyse the way particular technologies address the intricate interplay between material selection, performance objectives, and functional outcomes.

Case Studies

Case studies in literature provide concrete examples of how this inclusive design process works in practice. It is therefore appropriate to initiate the discussion with RCC pavements, which are distinguished by their proven advantages, including rapid construction, high density, and affordability in comparison to traditional concrete (Alam et al. 2022). RCC is defined as a stiff-consistency concrete that can be compacted by a roller and is typically used in the surface and base courses of pavements (Krishna and Tadi 2022). While the primary ingredients of RCC are equivalent to those of traditional Pavement Quality Concrete (PQC), the mix proportions differ significantly. The higher proportion of fine aggregate in RCC results in a denser concrete matrix. From a functional perspective, the utilisation of dowels or steel reinforcement is not a prerequisite for RCC pavements, thereby engendering substantial cost reductions in comparison with traditional concrete pavements (BAV and G 2022). A salient feature of RCC technology regarding sustainability is its capacity to accommodate a diverse range of waste and industrial by-products. The utilisation of these materials has been demonstrated to engender conservation of natural resources, whilst concomitantly engendering environmental benefits by reducing carbon footprints and addressing issues of waste landfill (Selvam and Singh 2022, Hassanshahi et al. 2025). The functional effects of sustainable materials in RCC can be examined in two main categories: aggregate replacement and binder replacement. In terms of aggregate replacement, Recycled Asphalt Pavement (RAP) can be utilised as a substitute for natural aggregates, with a maximum proportion of 50%. However, the presence of a residual bitumen layer on the surface of RAP aggregates has been shown to result in a weak interfacial transition zone (ITZ), thereby reducing the mechanical properties, particularly the compressive strength. Furthermore, the utilisation of Recycled Concrete Aggregates (RCA) has been demonstrated to enhance water absorption, a consequence of the presence of an aged mortar layer on the surface. This results in the formation of a compromised ITZ, which has the potential to diminish compressive strength. Consequently, RCCs comprising RCA are widely considered appropriate for base courses necessitating reduced strength (BAV and G 2022). Conversely, materials such as Electric Arc Furnace (EAF) Slag have been shown to enhance the maximum dry density (MDD) of RCC mixes, attributable to their high density when utilised in lieu of natural coarse aggregates (Rooholamini et al. 2019). In the context of binder substitutes, SCMs assume particular significance from a sustainability perspective, given that cement production contributes approximately 5–7% of global CO_2 emissions (Li, Ma and Wang 2023). Materials such as fly ash, silica fume, GGBS, rice husk ash, and sugarcane ash are utilised to partially substitute for cement (Aghaeipour and Madhkhan 2017, Bayqra, Mardani-Aghabaglou and Ramyar 2022, Pandey, Gandhi and Murthy 2023, Villena, Trichês and Prudêncio 2011). These SCMs have been shown to enhance the mechanical properties and durability of concrete through pozzolanic reactions or by forming additional Calcium Silicate Hydrate (C-S-H) gels (BAV and G 2022). Consequently, it is evident that RCC pavements offer considerable potential for sustainable construction by enabling the utilisation of various waste materials without compromising performance requirements. The overarching design vision is not confined to external sustainability objectives, such as the utilisation of waste materials, as evidenced by the RCC case study; it also encompasses the identification and mitigation of the inherent vulnerabilities inherent in the concrete itself. The most significant of these is shrinkage cracking, which directly impacts the pavement's service life. It is evident that a significant body of pioneering work has been undertaken in the field of material-performance-function synergy, with the objective of addressing the issue of concrete cracking. This work has been driven by the proactive and reactive modification of the internal chemistry of concrete. The overarching vision in reinforced concrete design necessitates a synergy between the material's intrinsic properties, structural performance, and intended function. MgO expansion agent serves as a prime illustration of this synergistic effect. The primary function of the additive is to prevent shrinkage cracks, which are a significant problem in concrete. The performance of this material is contingent on a fundamentally distinct mechanism when compared with other expansion agents. The fundamental property of MgO is its delayed hydration capacity, which occurs at a rate that is less rapid than cement hydration. A study revealed that during the investigation process, MgO reacts with water to form Mg $(OH)_2$, resulting in a 117% molar solid volume increase (Zhang 2022). The concept of synergy, as it pertains to the material under discussion, is best exemplified by its role within the overarching design vision. This is most clearly illustrated by the material's reactivity control. As Mo et al. (2014) demonstrate, the performance of MgO can be precisely tuned by the calcination temperature during production (Mo et al. 2014). One of the most advanced examples of material synergy is composite expansion agents. It is notable that agents combining CaO and MgO offer holistic performance. In this system, calcium oxide (CaO) reacts rapidly to compensate for early-stage shrinkage, while MgO compensates for later thermal shrinkage through its delayed hydration. This synergy ensures concrete protection throughout all shrinkage stages. Moreover, it has been ascertained that the cost-effective production of these composite agents can be achieved through the calcination of industrial raw materials, such as dolomite ($CaMg(CO_3)_2$) (Onyekwena et al. 2023). The functional synergy of MgO is not limited to crack compensation but extends to its capacity for self-healing. Unreacted MgO particles within the concrete matrix are activated upon the formation of a crack, resulting in the infiltration of water. The hydration of MgO, which is subject to delay, has been shown to trigger the formation of brucite, hydromagnesite, and other magnesium carbonate products. These products have been observed to expand within the crack walls. These reactions physically fill and seal the crack. This is an inclusive design example that demonstrates how the material's fundamental performance translates into a secondary, adaptive function. Consequently, MgO-based systems have the potential to broaden the scope of modern concrete technology by enhancing the synergy of material, performance and function in diverse applications, including dams, oil well cement, road pavements and concrete fillings in steel pipes (Du 2005, Qureshi and Al-Tabbaa 2016, Srivastava, Ahmed and Shah 2018). In the pursuit of enhancing the intrinsic performance of concrete, the utilisation of inorganic expansion agents, such as MgO, along with organic polymer technologies, which effect a fundamental alteration to the binding matrix itself, has been employed. The overarching design vision employs polymers in two primary ways: to enhance the substructure of the pavement and to fortify the pavement itself (BAV and G 2022). In the field of soil and foundation stabilization, nanopolymers have been demonstrated to exhibit remarkable efficacy in coating and binding aggregate and soil particles when dispersed in water. These polymers interlock, forming a bond that gains strength under mechanical compression. Hydrophobic dry powder polymers are utilised to enhance the quality of substandard aggregates, such as clay gravel. These polymers are sometimes utilised in conjunction with hydrated lime, a process in which the lime serves to agglomerate the clay particles, thereby preparing them for adhesion to the polymer (Kannan et al. 2024). Fiber-reinforced polymers (FRPs) are utilised for the purpose of pavement reinforcement. These composites consist of fibres such as glass, aramid, or carbon within a resin matrix, which can be polyester, epoxy, or vinyl ester. The integration of these materials fosters a synergistic effect, thereby ensuring enhanced corrosion and fatigue resistance. These superior properties render them a suitable replacement for traditional steel reinforcement in concrete bridge and highway pavements (Chen, Zhou and Kun 2013). The utilisation of polymers in ground improvement or structural reinforcement exemplifies the capacity for contemporary material synergies to optimise pavement system performance. However, it should be noted that these approaches are typically reliant upon the utilisation of petroleum-derived resins. Another strand of the inclusive design vision focuses on the development of entirely waste-based binders, replacing cement or resins, with the objective of maximising sustainability while improving performance. This approach is particularly effective in industries such as mining, where the management of waste volume is a critical issue. One study utilising this waste-based binder approach concentrates on the accumulation of solid wastes such as coal slime, slag dust, and fly ash, which represent one of the most significant environmental and operational challenges in coal mining (Qin et al. 2024). The primary function of the design is to efficiently treat and utilise coal slime, a silt-like mixture found on mine road surfaces that is particularly challenging to clean and represents a new type of solid waste that consistently damages the roadbed. This vision is predicated on a material synergy that combines three mining solid wastes as raw materials. The activation of these materials was achieved through the utilisation of sodium sulfate and sodium hydroxide as alkaline stimulants, thereby facilitating the preparation of a novel functional material designated as Coal Sludge-Based Geopolymer Pavement Material (CSGPM). The transformation of these industrial waste streams into a functional pavement binder through alkali activation is illustrated in Figure 4.

Figure 4 Sustainable synergy process



Illustrated by the author based on Qin et al., 2024

The design's performance is focused on optimising two critical objectives: namely, short setting time and high early compressive strength. Numerical simulations have demonstrated that, in terms of load-bearing function, an optimal pavement thickness of 5 cm is sufficient for transport with a maximum slump of only 0.33 cm under vehicle loads. In the composite performance evaluation, acoustic emission tests revealed that after 24 hours of curing, CSGPM exhibited mechanical properties analogous to those of standard concrete and demonstrated stable load transfer. The failure mode transitioned from tensile damage (at 6 hours) to shear damage (at 24 hours), indicating enhanced internal compaction. In conclusion, an economic analysis of the CSGPM revealed that its total cost was only 63.2% of that of conventional C30 concrete, thus confirming its status as a highly economical solution. Geopolymer design is a direct contribution to the objectives of zero waste and sustainability, as it involves the transformation of three distinct solid waste materials into a durable, economical, and rapidly setting paving material through the process of alkali activation synergy, thereby demonstrating efficiency and performance. The valorisation of solid waste from the coal industry through the implementation of geopolymer technology exemplifies a robust model of sustainability synergy, wherein the conventional 'waste' is metamorphosed into 'raw material' (Qin et al. 2024). The practical application of this material has been validated through simulation and testing. A comprehensive design vision must address these material optimisations, as well as the physical and thermal vulnerabilities that often go overlooked and impact the pavement's service life. A study focusing on these physical vulnerabilities offers an approach that leverages material-performance synergy to address thermal stress and cracking, one of the most significant functional challenges of concrete pavements (Pancar and Akpınar 2016). Concrete road pavements are subject to stress known as curling due to temperature differences between the top and bottom surfaces across the slab thickness. This has been shown to increase the risk of thermal cracking, which in turn reduces the lifespan of the pavement (Westergaard 1927). The material selected for the purpose of reducing this gradient in the study was glass beads, which are utilised in road markings to substitute for conventional fine aggregate. The selection of this material was based on two specific performance characteristics: first, thermal performance, and second, reflectivity. In terms of thermal performance, the design objective is to reduce the thermal conductivity and heat capacity of the concrete; indeed, glass beads have been found to have a low thermal conductivity of approximately 0.0014 W/mK, well below that of standard aggregate. Reflective performance has been determined to reduce solar heat absorption by increasing the surface reflectivity (albedo) of the coating. This is due to the glass beads' ability to reflect light back to their source. However, the utilisation of this material must be balanced against two critical trade-offs: mechanical performance and durability. The elevated silicon dioxide (SiO_2) content of the glass is known to pose a risk to its strength, while an augmented glass bead ratio has been observed to result in a reduction in mechanical strength. The optimisation confirmed that a design incorporating 19% of the total aggregate glass beads met the minimum strength requirements for Class C30/37 concrete while remaining within acceptable limits for ASR expansion. Field tests of this optimal design demonstrated that its low thermal conductivity and increased reflectivity reduced the thermal gradient by 75% compared to standard concrete without compromising mechanical or durability performance. This case demonstrates how a specific material (glass beads) addresses a functional problem by leveraging its thermal/optical performance while meeting critical engineering constraints (Pancar and Akpınar 2016). The study demonstrates how a specific manufactured material, such as glass beads, can successfully optimize its thermal gradient function by utilizing its thermal and optical performance, while also meeting mechanical and chemical durability requirements. The utilisation of glass in material-function synergy has prompted research not only on thermal management but also on the potential of waste glass to impart entirely novel aesthetic and energetic functions to the coating, such as light transmission (Li et al. 2021). LTC technology exemplifies the innovative potential of integrating waste glass with functionality. The primary function of this study is to explore the potential of a light-transmitting layer for future photovoltaic pathways. The design is predicated on the synergy of two key materials: waste tempered glass, which contributes to environmental sustainability, and a high-performance binder, epoxy resin, which provides yellowing resistance. The combination of these materials gives rise to a design challenge that must balance two fundamental, conflicting performance metrics. Light transmission performance is contingent on a large aggregate particle size, which facilitates the establishment of numerous light paths. Conversely, critical compressive strength performance is optimised by a small aggregate particle size, owing to the enhancement of interlocking and surface area. The ability to navigate these two conflicting demands is the crux of inclusive design. The study's findings indicate that a specific gradation was identified as the optimal gradation, which exhibited the optimal balance between light transmittance and compressive strength, while concurrently achieving maximum utilisation of waste glass. This case exemplifies a holistic design process that takes waste material, balances conflicting performance metrics, and makes it suitable for next-generation applications (Li et al. 2021). This series of case studies provides concrete evidence that the "Inclusive Design Vision" is not merely an abstract concept, but rather a fundamental practice within the domain of materials engineering. In each case examined, the design process is shown to be the art of managing the complex relationship between material performance and performance. This relationship may necessitate the optimisation of a trade-off between conflicting objectives, as evidenced by the

LTC+waste glass or Thermal+glass beads illustrations (Li et al. 2021, Pancar and Akpınar 2016). Alternatively, it may engender a mutually beneficial scenario where materials offer synergistic benefits that transcend expectations, as exemplified by the secondary self-healing functionality of geopolymer or MgO (Qin et al. 2024, Onyekwena et al. 2023). The case studies demonstrate that the functional coatings of the future will not emerge from a single innovative material, but rather from the meticulous engineering of such ingenious synergies and optimised trade-offs.

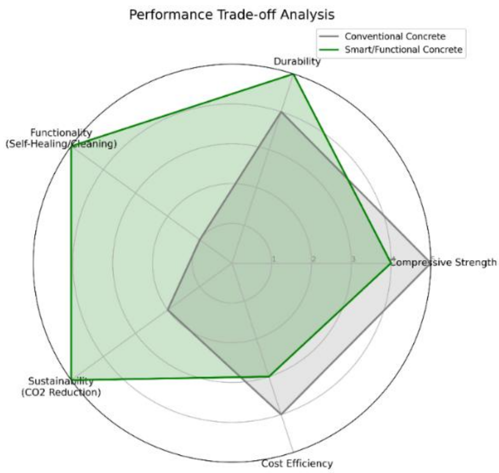
Restrictions, Difficulties and Obstacles

The case studies examined demonstrate the considerable potential that can be achieved through material-performance-function synergies. Nevertheless, the transition and proliferation of these advanced technologies from laboratory scale to field applications poses significant challenges. The most salient challenge confronting the project is the high initial cost. Typically, polymer resins, manufactured glass beads, or alkali activators have a significantly higher unit cost than traditional Portland cement and natural aggregates (Makul 2020). It is evident that decision-makers frequently prioritise lower initial costs over superior long-term performance. Moreover, the absence of standardisation and regulatory frameworks represents a significant impediment, given the construction industry's adherence to established standards and specifications. Internationally recognised design codes and testing procedures for geopolymer concrete, LTC, or self-healing systems are virtually non-existent, thereby posing a significant risk to designers and contractors (Loubouth et al. 2024). A further significant limitation is the absence of long-term performance data on the behaviour of these materials in real-world road conditions over a period of 20 or 30 years. Whilst the laboratory results are encouraging, concerns regarding UV degradation of polymers and the abrasion of LTC remain unresolved (Abera 2024). Finally, the supply chain and production scalability of these specialised materials is also a challenge (Qu and Kim 2024). In contrast to conventional materials, the precise control of reactivity exhibited by MgO, in addition to the collection and processing of waste glass, poses significant challenges to existing logistics and quality control processes. In this context, the necessity of a multi-layered strategy is evident if the current limitations are to be overcome and this potential realised. Such a strategy must include sectoral collaborations and holistic policy changes, as well as innovations in materials science.

Future Perspectives and Research Directions

The challenges inherent in the utilisation of advanced technologies also provide a roadmap for future research. The overarching design vision is predicated on the concept of multifunctionality, which is intended to serve as a means of overcoming the obstacles. Future research will aim to overcome the cost barrier by enabling a single material to fulfil multiple functions simultaneously (Roshan and Gomes Correia 2025). For instance, the transformation of road pavements into multifunctional platforms that serve both transportation and energy generation purposes, utilising piezoelectric materials or photovoltaic surfaces, will represent the forefront of this innovative approach. The functionality of the pavement will not be confined to material properties; it will also encompass sensor integration, thereby transforming the pavement into a smart system. The integration of fibre optic or piezoelectric sensors within the pavement infrastructure will facilitate the autonomous reporting of its condition, thereby enabling proactive identification of maintenance requirements (Song, Pu and Horri 2025). The data flowing from these sensor networks will be used to feed digital twin models, i.e. virtual replicas of the physical infrastructure. This will result in a transformation of maintenance strategies from reactive to fully predictable. In the domain of sustainability, the transition from a linear to a circular economy model is expected to accelerate. Research will focus not only on waste management but also on the end-of-life recyclability of pavements (Amudjie et al. 2025). In addition, in response to the global climate crisis, climate-resilient designs are set to become increasingly prevalent. To meet the challenges of the future, pavement design will need to evolve to incorporate environmental adaptation capabilities. Examples of such capabilities could include cool pavements, which mitigate the urban heat island effect, and permeable structures, which can manage flash floods.

Figure 5 Inclusive Design Vision



Illustrated by the author

Finally, it is evident that Artificial Intelligence (AI) and Machine Learning will play a critical role in this complex optimization process. The employment of AI algorithms is set to facilitate the management of the intricate trade-offs observed in the case studies, with the objective being the prediction of the most optimal mixture designs that ensure the highest function is achieved at the lowest possible cost prior to their entry into the laboratory setting (Chong et al. 2024, Konapure et al. 2025). A comparative analysis of the trade-offs and synergies between conventional and functional concrete systems is presented in Figure 5. Ultimately, the inclusive design vision illustrated in this figure serves as a blueprint for the next generation of infrastructure, synthesizing these technological advancements and sustainability goals.

Conclusion

The present study examined the radical transformation in pavement design from the traditional approach, where materials are viewed solely as passive structural components, to a multifunctional, intelligent system that actively interacts with its environment. The present age is characterised by mounting environmental pressures, diminishing resources, and escalating demands for infrastructure durability. Consequently, pavements are compelled to meet the dual objectives of "sustainability" and "functionality" in conjunction with "performance". The "Inclusive Design Vision" that underlines this study aims to demonstrate how these three objectives can be addressed simultaneously. The hypothesis that this vision is not an abstract concept but rather a fundamental practice of materials engineering is supported by detailed case studies which provide concrete evidence. The extant literature demonstrates that, at the core of inclusive design, the art of intelligently managing trade-offs between competing performance objectives and maximising synergies between material components is crucial. The Translucent Concrete case demonstrates the necessity of optimising the opposing relationship between translucent and compressive strength (Loubouth et al. 2024). The cases also provide compelling examples of synergies. A geopolymer case study demonstrates how three different industrial wastes can be utilised to create a fast-setting and economical coating that serves the goal of zero waste (Li et al. 2021). The vision is confronted by considerable challenges, including substantial initial expenses, an absence of standardisation, and the necessity for long-term performance data. The present limitations have the effect of restricting the extensive utilisation of these innovative materials in the field. Nevertheless, these challenges also serve as driving forces for research. The focus of future functional coatings is set to be multifunctionality, circular economy principles, and smart sensor integration, the purpose of which is to overcome the obstacles. The optimisation of materials, particularly driven by artificial intelligence and machine learning, will enable the more effective management of complex synergies and trade-offs. This study demonstrates that the functional pavements of the future will not emerge from a single miracle material. It is asserted that genuine progress will be achieved through the intelligent combination of disparate materials, including waste materials, nanoadditives, polymers, and geopolymers, alongside the engineering optimisation of these synergies. The case studies examined demonstrate that sustainability, performance, and functionality goals should no longer be considered separately, but rather as mutually reinforcing or balancing elements within a single, overarching design vision. Notwithstanding the present challenges, this vision will serve as the foundation for the development of more durable, environmentally sustainable, and intelligent road infrastructures.

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CHAPTER 5

Applications of Image Processing and Digital Analysis Methods in Geotechnical Engineering

Onur SARAN[1]

Introduction

In recent years, the rapid development of digital technologies has radically transformed data collection and analysis methods in engineering sciences. One of the most significant effects of this transformation is that image processing and digital analysis methods have become an integral part of experimental and numerical geotechnical studies. While traditional measurement techniques are often time-consuming, prone to operator error, and provide superficial information, image-based analyses offer the advantages of high accuracy, repeatability, and detailed data production (White et al., 2003; Shin & Santamarina, 2011).

The study of soil behavior in geotechnical engineering often has a complex and multi-scale structure. In this process, which requires observation at various levels from the grain level to the macroscale, image processing techniques stand out as a very powerful tool. Digital analysis of data obtained, particularly with

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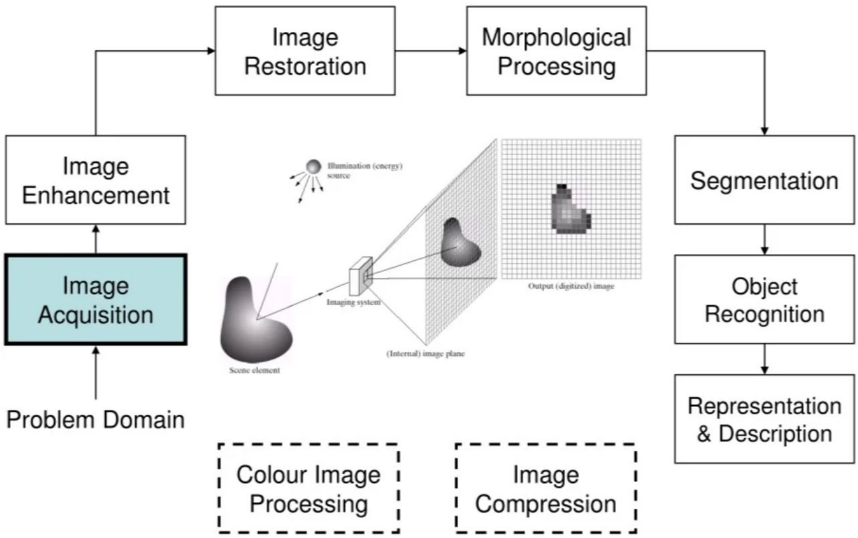
high-resolution camera systems, microscopy devices, and unmanned aerial vehicles (UAVs), allows us to more accurately understand soil behavior in both laboratory and field conditions (Mugnai et al., 2023; Sun et al., 2024).

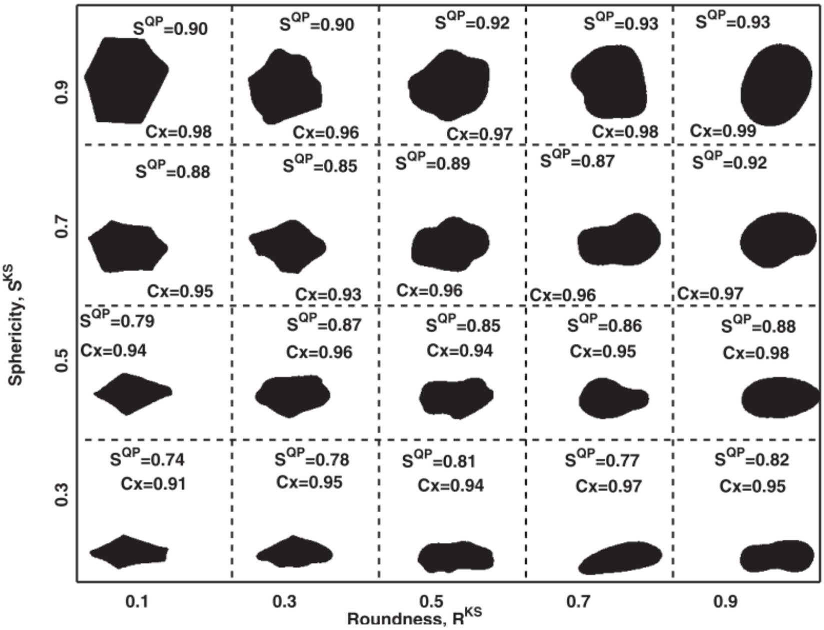
Figure 1: Image capture, preprocessing, segmentation and analysis steps



Gonzalez and Woods, 2018

At present, image processing-based techniques can be found in many branches of soil mechanics. Estimation of grain shape and size distribution in granular soils (Altuhafi et al., 2013, Altuhafi et al., 2016) (Figure 2), modeling the drying/cracking process of fine-grained soils (Tang et al., 2024) accurately, as well as evaluating deformations and strain distribution through digital image correlation (DIC) (Nishimura et al., 2022) analysis, are merely some of them. Also, with more imaging technology such as scanning electron microscopy (SEM), X-ray computed tomography (CT) imaging, or nuclear magnetic resonance (NMR) imaging being increasingly utilized, the properties of soil microstructure can also be investigated more accurately (Ghosh et al., 2023, Noaman et al., 2024).

Figure 2: Grain shape, circularity and angularity measurement



Altuhafi et al., 2013

One of the primary reasons image processing algorithms have been widely applied is that they provide non-destructive, fast, and repeatable measurements. This helps researchers analyze soil properties in real-time, enabling them to see instantaneous changes in soil cracks, soil deformation, as well as the changes in the soil's void ratio. Moreover, with the application of machine and deep learning algorithms in recent years, soil image processing algorithms have enabled automated classification, soil pattern recognition, and other applications (Shao et al., 2023).

Thus, image processing tools are finding increasing applications not only in the field of scientific research but also in engineering applications. Image processing technology, with its vast applications from laboratory-based studies to field measurements, is on the verge of being used as standard tools for measurements in geotechnical engineering. This study explores the fundamental principles of image processing and digital analysis methods, their main applications in geotechnical engineering, innovative developments in recent years.

Fundamentals of Image Processing Technologies

Image processing is the process of analyzing a digital image obtained from a physical object or surface using computer-aided algorithms. The primary goal is to extract meaningful information from the image, convert it into quantitative data, and evaluate this data as a basis for engineering interpretations (Gonzalez & Woods, 2018).

A digital image is typically composed of pixels (picture elements). Each pixel has a specific location and gray tone (or color value). Image processing techniques consist of pre-processing, segmentation, feature extraction, and analysis stages performed on these pixel matrices.

Image Pre-Processing

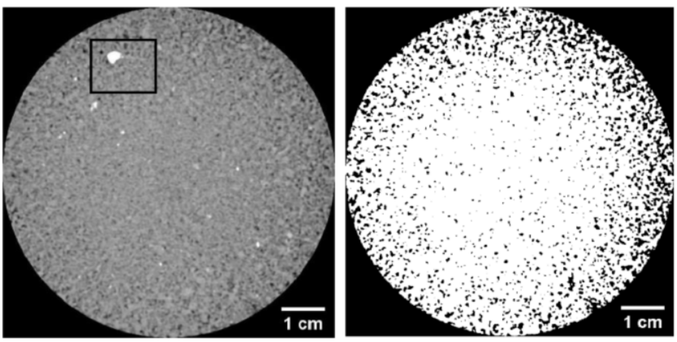
This stage aims to make the raw image suitable for analysis. Operations such as noise filtering, contrast enhancement, and histogram equalization are applied. This step is critical, especially in laboratory soil sample images, as lighting differences and surface reflections often cause problems (Alshibli & Reed, 2010; Hossain et al., 2023) (Figure 3).

Figure 3: Example of filtering and contrast enhancement in image pre-processing stage

Image Segmentation

Segmentation divides the image into distinct regions, enabling the separation of objects to be analyzed (e.g., soil grains or cracks). The most common method is thresholding. A threshold value is determined based on the grayscale histogram and converted into a binary image with black below and white above this value. In the next step, morphological operations (erosion, dilation, opening and closing) are applied to remove noise from the image (Otsu, 1979) (Figure 4).

Figure 4: Segmentation of soil grains using thresholding method



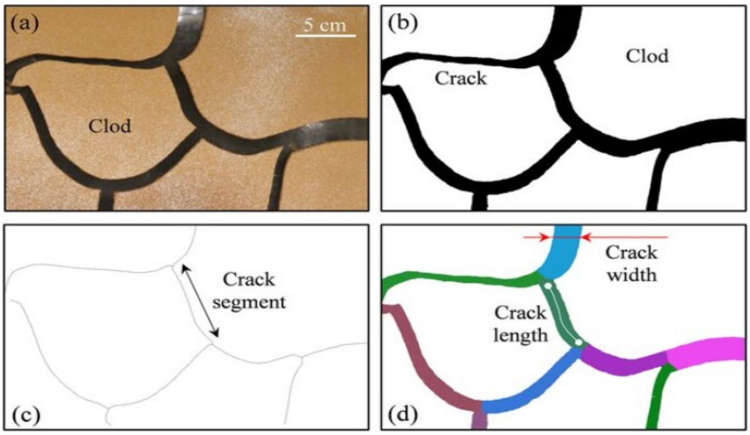
(a) Grayscale image (b) Binary image with threshold number 120

Ramesh & Thyagaraj ,2022

Feature Extraction and Quantitative Analysis

Geometric or topologic properties can be derived from the binarized images. In granular soils, these measurements typically include parameters such as area, perimeter, circularity, aspect ratio, and angularity (Zheng & Hryciw, 2015). In crack analysis studies, parameters such as crack density, length, orientation, and degree of connectivity are calculated (Tang et al., 2021). These properties can further allow the calculation of soil properties, such as porosity or the amount of cracks, from the image (Figure 5).

Figure 5: Crack image processing: (a) Original pattern; (b) Binarization; (c) Skeletonization; (d) Identification of crack segments.



Zeng et all., 2022

Software and Hardware Used

Image processing analysis used in geotechnical studies is performed with tools such as MATLAB, ImageJ, Python (with libraries such as OpenCV and scikit-image), or NI Vision (Schneider et al., 2012; Schindelin et al., 2012; van der Walt et al., 2014). MATLAB is widely preferred in academia due to its powerful filtering and segmentation algorithms, while ImageJ is commonly used in micrograph analysis due to its open-source structure (Otsu et al., 2021). Python libraries assist classification algorithms thanks to their interface with machine learning libraries (Hossain et al., 2023). In recent years, the integration of these software packages with artificial intelligence libraries such as TensorFlow and PyTorch has ushered in a new era in the automatic classification of land images and the detection of anomalies (Gao et al., 2024).

In terms of imaging hardware, high resolution DSLRs, as well as microscopes, are mostly used in labs, whereas drone-based photogrammetry or ground-based LiDAR scanning is widely used in the field (Colomina & Molina, 2014; Singh et al., 2023).

Advantages and Limitations of Image Processing

The main benefits of image processing analysis are as follows:

- Non-destructive and non-contact measurement: This technique does not require physical contact with the material.
- Time efficiency: Large data sets can be processed quickly.
- Objectivity: Prevents operator errors.
- Spatial resolution: Microscopic details are resolved.
- Ease of archiving: Digital images can be stored and analyzed.

Despite its strengths, image processing applications come with some limitations:

- Light sensitivity,
- Loss of detail at low resolution,

- The need for appropriate parameterization in thresholding and image segmentation.
- Recalibration requirements for different soil types (Pan et al. 2009, Stanier et al. 2016).

Therefore, the establishment of standard protocols in image processing is considered an important area for future work.

Image Processing Approaches in Geotechnical Applications

Grain Size and Shape Analysis

Grain size distribution analyzes of soils are based on the sieve and hydrometer method performed in the laboratory. However, these experimental methods are time-consuming and prone to error risk (Zheng and Hryciw, 2015). On the other hand, the use of image processing algorithms allows for the rapid analysis and evaluation of soil particle size, shape, and distribution (Altuhafi et al., 2016). Thus, the morphology of soil grains can be quantitatively analyzed by calculating values such as circularity, roundness, and length using images (Gao et al., 2024).

In particular, it provides high accuracy in the classification of granular soils. This method also allows for the high accuracy and examination of geometric changes that occur in grains following the fracture and abrasion processes (Zheng and Hryciw, 2015; Mahmood et al., 2020).

Identification of Drying Cracks

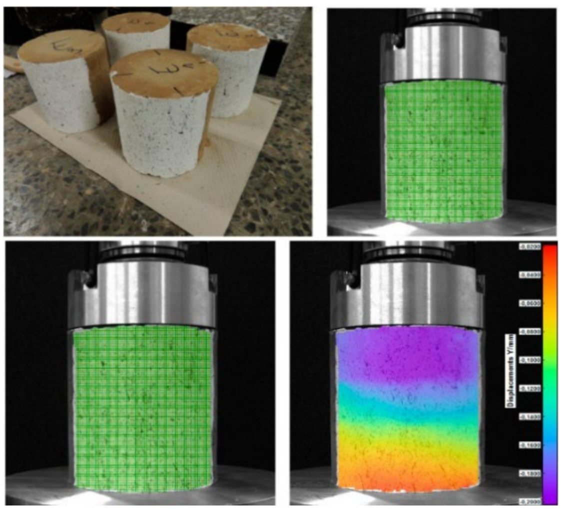
Drying cracks due to water loss in fine-grained soils can cause significant problems in engineering structures (Tang et al., 2021). Image processing techniques offer the advantage of monitoring crack development over time (Safari et al., 2021).

Crack images are typically converted from grayscale to binary format, and then the crack network is extracted through morphological operations (Otsu, 1979). Parameters such as crack area, length, orientation, and degree of connectivity can be automatically calculated from the resulting binary images (Shin & Santamarina, 2011). In some studies, the complexity of crack networks has been assessed using the fractal dimension (D), and significant correlations have been reported between different soil types (Zhao et al., 2020).

Soil Deformation and Strain Monitoring

The deformation characteristics of soils under load are of great importance in engineering applications. Image analysis techniques are useful in that they enable non-contact and highly accurate deformation analysis (White et al., 2003; Pan et al., 2009). Digital Image Correlation (DIC) and Particle Image Velocimetry (PIV) techniques are based on image comparison that calculates deformation and strain through pixel motion analysis in image sequences (Stanier et al., 2016; Nishimura et al., 2022) (Figure 6).

Figure 6: Determination of vertical deformations in unconfined compression tests using the DIC method



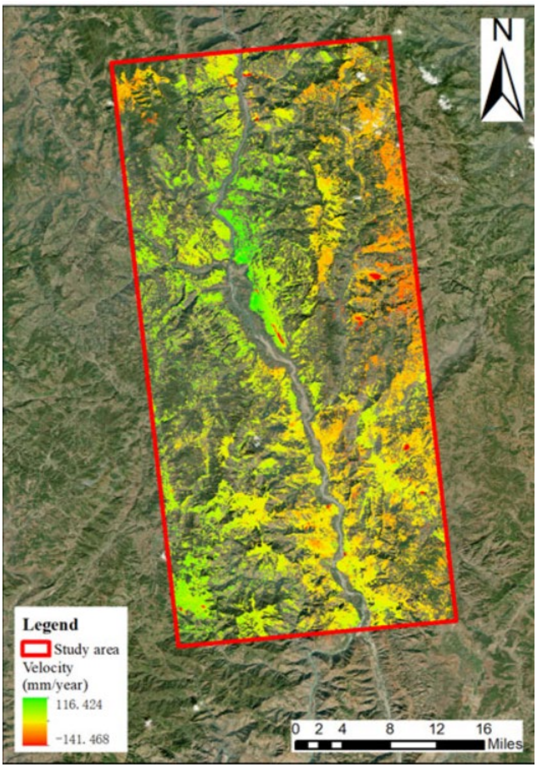
Górszczyk et all., 2019

These methods enable the precise analysis of the spatial distribution of deformation, particularly in triaxial compression and direct shear tests (Chen et al., 2022).

Landslide and Surface Deformation Monitoring

At the field level, image processing methods are often combined with drone or satellite observations (Colomina and Molina, 2014; Sun et al., 2024). LiDAR/InSAR or photogrammetry methods can detect surface deformation at the centimeter scale (Liu et al., 2022; Singh et al., 2023). These methods are crucial in landslide early warning systems (Li et al., 2023) (Figure 7).

Figure 7: InSAR deformation rate map

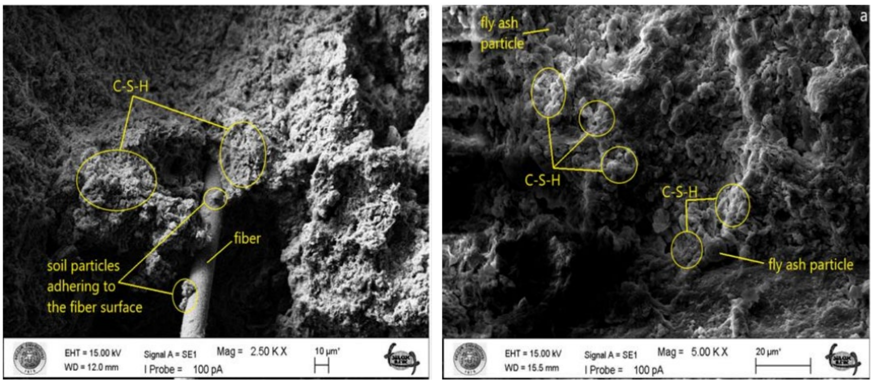


Liu et all., 2022

Microstructure Analyses

Digital analysis of SEM (Scanning Electron Microscope) images greatly facilitates the determination of soil microstructural properties (Alshibli & Reed, 2010). Thanks to image processing algorithms, indicators such as porosity, fiber distribution, and bond density can be calculated automatically (Khosravi et al., 2021). Microstructure analysis, especially in soils containing additives (fly ash, silica fume, basalt fiber, etc.), is an important tool in understanding the stabilization mechanism (Noaman et al., 2024) (Figure 8).

Figure 8: Investigation of the microstructure of soils by SEM analysis.



Demiröz & Saran, 2024

Conclusions

Image processing and analysis tools have proved to be innovative solutions that significantly improve the efficacy of laboratory and field investigations for geotechnical engineers. In light of the limitations and challenges of traditional measurement methods, benefits such as high resolution, non-contact measurement, the automation of quantitative data extraction, and the monitoring of temporal variations make such tools indispensable.

The accuracy of imaging analyses performed in laboratory conditions, such as grain-size and grain-shape analysis, drying-crack growth observation, and deformation and strain distribution analysis, allows for the creation of more precise and detailed data. Live observation of soil deformation characteristics when subjected to loading, achieved through the use of tools such as digital image correlation (DIC) and particle image velocimetry (PIV) analyses, makes it easier to obtain a complete deformation map, which would not be as easily achieved through the use of sensor-based data. Conversely, micro-analysis analyses performed using advanced imaging tools such as scanning electron microscopy (SEM) and X-ray Computed Tomography (X-ray CT) analyses enable the direct observation of the mineral and structure characteristics of soils, which are especially important for improved soil.

Large-scale drone-based photogrammetry, which integrates the use of LiDAR and InSAR, makes major contributions to the field of engineering, such as deformation measurement, landslide monitoring, subsidence analysis, and the identification of dangerous zones. Drone-based photogrammetry tools and technologies are instrumental for faster and higher-resolution coverage for disaster management and warning compared to land surveying.

Although there are some limitations concerning the processing of images, such as the sensitivity of processing algorithms to light intensity, the possible degradation of resolutions, and the difficulty faced regarding the choice of proper threshold values, rapid and continuous progress in the development of software and hardware technology is helping assuage such limitations. Future applications, such as automatic image classification, crack/ deformation analysis, and the identification of microstructures, will benefit significantly from the development of machine learning algorithms. In general, the use of image processing and analysis techniques appears poised to become the norm for the future of geotechnical engineering. This appears particularly true because the data-driven nature of the research technique and tools allows for much faster and more objective analyses to be performed, and as such, their use would help create much safer and more sustainable soil-structure interaction designs.

Acknowledgement

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CHAPTER 6

DETERMINATION OF PARTICLE SIZE DISTRIBUTION OF CRUSHED AGGREGATES BY IMAGE PROCESSING METHODS

İBRAHİM YİĞİT[1]

Introduction

Aggregates constitute the primary component of a wide range of civil engineering materials, including road base layers, embankments, asphalt mixtures, concrete, and railway ballast. Mechanical behavior of granular materials is governed by particle size distribution (PSD), particle shape, surface texture and packing characteristics. Among these, PSD is traditionally regarded as a fundamental descriptor and forms the basis of widely used soil classification systems such as the Unified Soil Classification System (USCS) and the AASHTO classification system. These systems rely almost exclusively on mechanically obtained gradation curves to distinguish between coarse and fine-grained soils. Although mechanical sieving provides standardized and repeatable grading information, it is based on simplified geometric assumptions that treat particles as idealized spheres passing through square sieve

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apertures. This assumption is particularly problematic for crushed aggregates, which exhibit highly angular, elongated, and irregular shapes as a result of blasting and crushing processes. Consequently, reliance on PSD alone may lead to incomplete or misleading characterization of granular materials. Particle shape descriptors such as roundness, sphericity, and angularity have long been recognized as important parameters influencing the mechanical response of granular soils. However, traditional methods for evaluating particle shape including manual caliper measurements and visual comparison charts are time-consuming, subjective, and limited in their ability to represent the full statistical distribution of particle morphology within a sample.

These limitations have motivated the development of objective, automated techniques capable of simultaneously capturing both particle size and shape characteristics. (Masad, 2001; Al-Rousan et al., 2007). Advances in digital image processing (DIP), computational geometry, and computer vision have provided powerful tools for the non-contact characterization of granular materials. Image-based approaches enable high-resolution measurement of particle geometry using two-dimensional or three-dimensional representations and allow large numbers of particles to be analyzed efficiently. Previous research has shown that image-derived PSDs can be correlated with mechanically obtained gradation curves when appropriate geometric correction factors are applied, while also providing access to detailed shape information that is otherwise unavailable through conventional laboratory testing. By synthesizing experimental methodologies and computational approaches reported in the literature with validated image analysis techniques, the chapter demonstrates how area-based particle measurements can be transformed into mass-based gradation curves and how shape descriptors such as roundness and sphericity can be quantified in a systematic and repeatable manner.

Image Processing Methodology

Digital image processing for aggregate analysis consists of a sequence of well-defined stages, including image acquisition, preprocessing, segmentation, feature extraction and post-processing analysis. The reliability of image-based measurements depends critically on the quality of the acquired images and the robustness of the segmentation and calibration procedures. Therefore, careful consideration must be given to camera configuration, lighting conditions, background selection, and spatial resolution during the image acquisition stage.

In aggregate imaging applications, uniform and shadow-free illumination is essential to ensure clear separation between particles and the background. Ring-shaped or coaxial lighting systems are commonly employed to minimize directional shadows and specular reflections. Images are typically captured with the camera axis-oriented perpendicular to the sample plane, and particles are arranged in a single layer without overlap to avoid segmentation ambiguity. Spatial calibration is performed using reference objects of known dimensions, allowing pixel-based measurements to be converted into physical units. (Zheng & Hryciw, 2015).

Following image acquisition, preprocessing operations such as grayscale conversion and noise reduction are applied to enhance image quality and suppress irrelevant features. Segmentation is then performed to distinguish particles from the background, most commonly through global or adaptive thresholding techniques. Morphological operations, including erosion, dilation, opening, and closing, are frequently used to eliminate small artifacts, fill internal voids, and refine particle boundaries. The outcome of this stage is a binary image in which individual particles are clearly identified.

Once particles have been segmented, geometric feature extraction is carried out to quantify particle size and shape.

Commonly extracted features include projected area, perimeter, major and minor axis lengths, equivalent circular diameter, and boundary curvature. These parameters form the basis for both particle size estimation and the calculation of shape descriptors. For PSD analysis, particle size is typically defined using equivalent diameters derived from projected areas, while shape descriptors are computed using ratios of geometric measures or curvature-based indices.

A key limitation of two-dimensional image analysis is the absence of direct information regarding particle thickness. To address this issue, image-based PSDs are commonly transformed from area-based to mass-based distributions using geometry-informed correction factors that relate particle width and thickness (Mora et al. 1998).

These correction approaches enable meaningful comparison between image-derived gradation curves and conventional sieve analysis results and represent a critical step in the application of image processing techniques to practical engineering problems.

Image-based determination of particle size distribution

Image-based determination of particle size distribution (PSD) relies on the quantitative analysis of particle geometries extracted from digital images. Unlike mechanical sieving, which classifies particles according to their ability to pass through standardized apertures, image-based methods characterize particles based on measurable geometric properties obtained from two-dimensional or three-dimensional representations. As a result, the definition of particle size in image analysis differs fundamentally from that used in conventional sieve analysis and must be carefully interpreted to ensure meaningful engineering comparisons.

In two-dimensional image analysis, particle size is most commonly defined using projected area. After segmentation, the number of pixels enclosed by the particle boundary is counted and converted to a physical area through spatial calibration. An equivalent particle diameter is then computed as the diameter of a circle having the same projected area as the particle. This equivalent diameter provides a consistent and orientation-independent size measure for irregularly shaped particles and forms the basis for constructing area-based PSD curves.

Area-based PSDs describe the relative contribution of particles to the total projected area within a sample and therefore differ conceptually from mass-based PSDs obtained through mechanical sieving. For granular materials with uniform thickness and density, area-based distributions may approximate mass-based distributions reasonably well. However, for crushed aggregates exhibiting significant variability in thickness and shape, direct comparison between area-based and sieve-based PSDs can lead to systematic discrepancies unless appropriate correction procedures are applied.

To enable comparison with conventional gradation curves, image-derived area-based PSDs are commonly transformed into mass-based distributions using geometry-informed conversion approaches. These approaches typically involve estimating particle volume from two-dimensional measurements by incorporating assumptions or empirical relationships regarding particle thickness.

A common strategy is to relate particle thickness to measured particle width through a shape-dependent correction factor, thereby allowing particle volume to be approximated as the product of projected area and estimated thickness. When particle density is assumed constant, relative particle masses can then be calculated and used to construct mass-based PSD curves.

Another important consideration in image-based PSD determination is the relationship between image-defined particle size and equivalent sieve aperture size. Mechanical sieving classifies particles based on their minimum cross-sectional dimension relative to the geometry of the sieve opening, whereas image analysis measures particle dimensions directly. For square-mesh sieves, the effective sieve size is often smaller than the particle width measured in images, particularly for elongated or flat particles that may pass through the sieve diagonally. To address this issue, size correction factors are introduced to convert image-based particle dimensions into equivalent sieve sizes, ensuring consistency between the two measurement approaches.

The accuracy of image-based PSD determination depends not only on geometric assumptions but also on statistical representativeness. Because image analysis enables rapid measurement of large numbers of particles, it offers a significant advantage over manual methods in capturing the full distribution of particle sizes within a sample.

Nevertheless, care must be taken to ensure that the imaged particles constitute a representative subset of the material and that particle overlap and occlusion are minimized during image acquisition. Single-layer particle arrangement and adequate sample size are therefore essential requirements for reliable PSD estimation.

Despite these challenges, numerous experimental studies have demonstrated that image-based PSDs, when properly corrected and calibrated, show strong agreement with mechanically obtained gradation curves. Moreover, image-based methods provide additional flexibility by allowing PSD to be analyzed in conjunction with particle shape descriptors derived from the same dataset. This integrated capability represents a key advantage of image processing techniques and supports their use as both an alternative and a complement to traditional sieve analysis in geotechnical and civil engineering practice.

Materials and methods

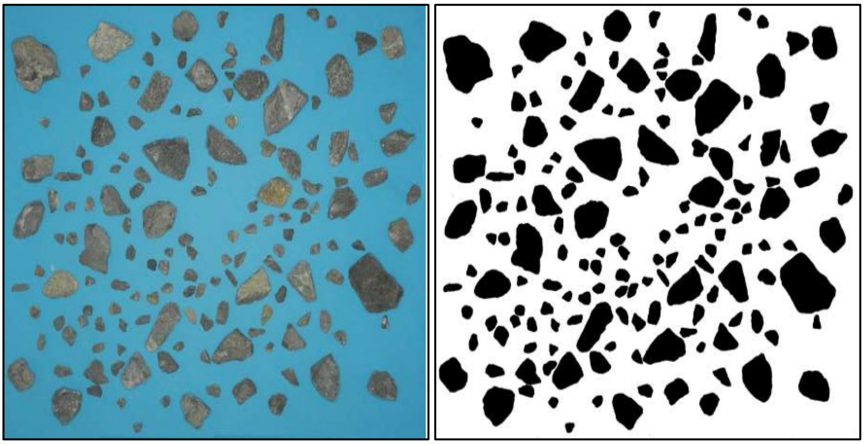
Crushed aggregate samples obtained from two different quarries located in the province of Zonguldak were subjected to sieve analysis tests using standard square-mesh sieves (ASTM D 5821-95). As the result of these sieve analyses, the gradation curves shown in Figure 2 were obtained (Yiğit and Kurt, 2019).

Subsequently, photographs of the same samples were taken under laboratory conditions (Figure 1a). A blue-colored background was used in the photographs to allow the aggregates to be easily distinguished from the background. In the method used in this study, since the aggregates were not in contact with each other, they could be easily separated from the background during the image processing stage. For this purpose, the open-source software ImageJ was used (Schneider et al., 2012a, b). The use of ImageJ for image analysis of aggregate particles has been explained in detail by Kumara et al. (2012) and Ohm and Hryciw (2013). A similar method was also employed in the study by Yiğit and Kurt (2019), Kurt (2018).

After converting the images of the crushed aggregates on the blue background into a single band, the background and the aggregates could be easily separated using the blue channel. At this stage, the photographs, originally consisting of 256 grayscale levels, were converted into binary images using the automatic thresholding algorithm available in ImageJ. The binary image obtained using the automatic thresholding algorithm is shown in Figure 1b.

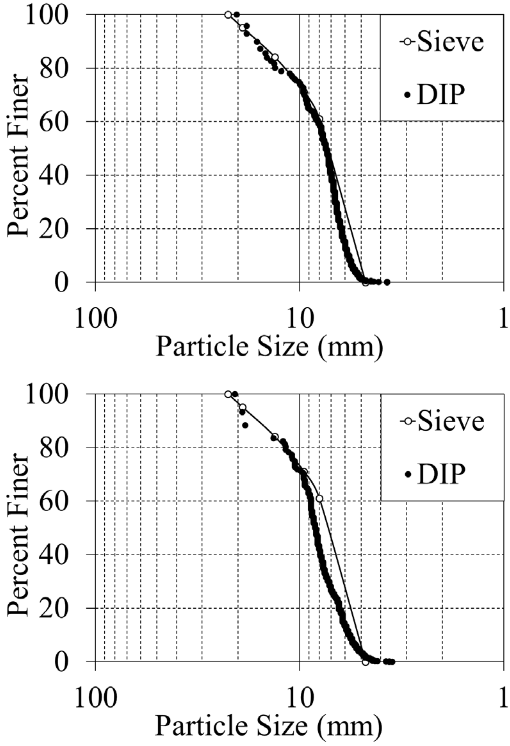
The granulometric curves obtained from sieve analysis and digital image processing for the samples from the two different quarries are presented in Figure 2. It is observed that, for both quarry samples, the granulometric curves obtained by sieve analysis and by the digital image processing method are in close agreement with each other.

Fig. 1.a) Photo of crushed aggregate, b) Binary image of the photo



Reference: Yiğit and Kurt (2019)

Fig. 2 PSD of two different crushed aggregate quarries



Results and conclusions

Comparison between image-based and mechanically obtained particle size distributions indicates that, when appropriate geometric corrections are applied, the overall gradation trends are in good agreement. Image-derived PSD curves successfully reproduce key features of sieve-based gradation, including dominant size fractions and general curve shape. Minor discrepancies are typically observed at the coarser and finer ends of the distribution, which can be attributed to limitations inherent in two-dimensional imaging, such as particle orientation effects and uncertainties associated with thickness estimation.

Despite these discrepancies, the level of agreement achieved is considered satisfactory for engineering applications, particularly given the additional morphological information provided by image analysis. The ability to capture large numbers of particles rapidly enhances the statistical reliability of the PSD, reducing sensitivity to sample selection and operator variability. This represents a significant advantage over traditional manual methods, especially for materials exhibiting wide particle size ranges and heterogeneous morphology.

Comparisons between aggregates obtained from different quarry sources indicate that, while overall PSDs may be similar, subtle differences in shape descriptor distributions can still be identified. These differences reflect variations in parent rock properties, crushing mechanisms, and processing conditions. Although the absolute magnitude of these differences often falls within the range of natural aggregate variability, they may nonetheless influence engineering behavior in applications sensitive to particle interlocking and surface roughness.

The combined analysis of PSD and particle shape highlights the limitations of conventional gradation-based classification systems in fully capturing aggregate behavior. Materials with similar PSDs but differing shape characteristics may exhibit different compaction responses, shear strength envelopes, and susceptibility to particle breakage. Image-based characterization provides a means to identify and quantify these differences, enabling more informed material selection and performance assessment.

From a methodological perspective, the results confirm that image processing techniques offer a robust framework for aggregate characterization when implemented with appropriate calibration and quality control procedures. Careful control of image acquisition conditions, representative sampling, and the use of geometry-informed correction factors are essential to achieving reliable results. When these requirements are satisfied, image-based methods can serve as both a complement to and, in certain contexts, a viable alternative to traditional laboratory testing.

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CHAPTER 7

PLASTIC WASTE AND ITS MANAGEMENT TECHNIQUES

1. FİDAN GÜZEL [1]

Introduction

Plastic waste has become a global problem largely due to its difficulty in naturally decomposing. In developing countries, the lack of advanced technological infrastructure and adequate legal regulations regarding plastic production, use, and waste management exacerbates this problem (Eze et al., 2021). Because plastics pollute both terrestrial and marine ecosystems, the United Nations has described it as "Plastic is one of the most serious environmental threats facing the world" (Khan et al., 2019). Today, the transformation of plastics from useful objects to hazardous waste has become a significant topic of global discussion.

The first comprehensive discussions regarding plastic waste began in the 1980s and have continued since then (Kedzierski et al., 2020). The increase in global plastic waste generation can be

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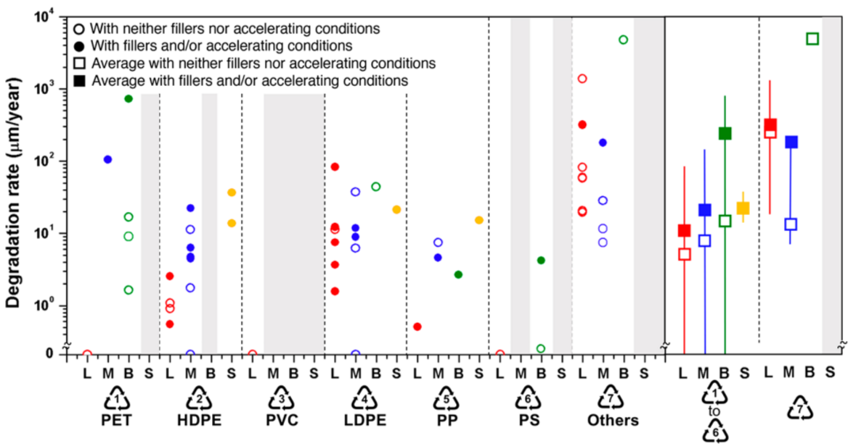
attributed to three main factors: (i) the ability of plastic to replace traditional materials such as ceramics, wood, and glass; (ii) the accelerated increase in the world's population, from 2.5 billion in 1950 to 7.7 billion by 2019; and (iii) the ease of access to consumer society. Intensive migration from rural to urban areas has led to an increase in the urban population from 751 million to 4.2 billion. This demographic shift is characterized by a population with easy access to consumer society.

Figure 1 Annual degradation rate of different plastic types ('L' represents landfill, 'M' represents the sea, 'B' represents biological pollution, and 'S' represents sunlight)



Kaynak: Chamas et al., 2020

The short lifespan of plastic (e.g., single-use products) increases plastic accumulation in the environment. Approximately two-thirds of global plastics have a lifespan of less than one month (Panda et al., 2010). It is estimated that approximately 6.30 billion tons of plastic waste were produced worldwide between 1950 and 2015, with about 80% of this waste accumulating in the natural environment. In 2016 alone, plastic waste production was estimated at approximately 242 million tons. The decomposition time of plastics in nature varies between 100 and 1000 years (Welden, 2020).

Therefore, it is likely that the first plastics produced are still present in nature. The figure shows the decomposition time of different types of plastics. According to estimates by Stubbins et al. (2021), by 2035, the amount of plastic waste in the oceans will reach a level equal to the amount of fish in the seas. These plastics, found in different sizes in nature, include: Plastics are classified as macro (>25 mm), meso (5–25 mm), large micro (1–5 mm), small micro (20 μm–1 mm), and nano (1–1000 nm) plastics (Chen et al., 2021; Gabbott et al., 2020; Hurley et al., 2020). The sources of plastic waste can be classified according to their area of use (e.g., bottles/caps: 14.9%, PET bottles: 12.5%, supermarket/shopping bags: 9.3%, food packaging: 6.5%, food containers: 2.1%, etc.) and their origin (e.g., urban solid waste and agricultural-industrial waste) (Egun and Evbayiro, 2020; Oehlmann et al., 2009).

Due to their high durability and stability, plastics are only naturally biodegradable to a limited extent in the environment. The degradation process of plastics depends on environmental factors such as sunlight, heat, and chemical/biological activity, as well as physical properties such as polymer size, density, and molecular weight. Weathering and degradation of plastics are classified under four main headings: physical/mechanical degradation, photodegradation/photo-oxidative degradation, chemical and thermal degradation, and biological degradation (Nayanathara Thathsarani Pilapitiya and Ratnayake, 2024). Physical/mechanical processes (e.g., wave action and abrasive effects in coastal environments) cause changes in the structural integrity of plastics, such as cracking and brittleness. These physical changes also bring about chemical changes at the molecular level, such as polymer oxidation and the formation of short-chain molecules. Photodegradation, or photo-oxidative degradation, involves the breakdown of polymer chains, a decrease in molecular weight, and the formation of free radicals as a result of exposure to ultraviolet

(UV) radiation (Gunawardhana et al., 2023). Chemical degradation (e.g., corrosive chemicals such as nitric, sulfuric, and hydrochloric acids, and atmospheric pollutants) and thermal degradation (heat-induced chemical changes) can lead to the breakdown and oxidation of polymer chains. Microorganisms such as bacteria, fungi, and yeasts can alter the physical and chemical properties of plastics by converting carbon in polymer structures into carbon dioxide or by incorporating it with biomolecules. This process is defined as "biological degradation".

The environmental impacts of plastic waste

Plastics collected from homes, offices, business centers, and industrial facilities are generally transported to a secondary transfer station where the necessary sorting takes place. After this process, depending on existing infrastructure arrangements and technologies, the plastics are either recycled or reused; otherwise, plastic waste is dumped in open areas or landfills, or incinerated in open areas. When plastics integrate with the soil matrix, they can affect soil aggregation and water dynamics by altering soil porosity and soil binding properties. Plastic waste, especially microplastics, can interact with many soil properties. Microplastics contain toxic additives and hazardous pollutants such as polybrominated diphenyl ethers (PBDEs), perfluorochemicals (PFOS), and heavy metals such as copper, zinc, and lead. Due to their high dispersion capacity, microplastics mix with soil, significantly reducing soil fertility (Brennecke et al., 2015; Hodson et al., 2017). Furthermore, plastics indirectly lead to soil degradation by inhibiting the growth of earthworms and other beneficial microorganisms. The emergence of plastics as ecosystem suppressors affects soil health and alters soil biophysical properties, leading to a complex change in the environmental behavior of other pollutants in the soil (Alimi et al., 2018; Wang et al., 2018). The addition of microplastics to the soil can also stimulate soil enzymes.

When plastics are discarded in open-air landfills, microplastics, formed under the influence of environmental factors (pressure, humidity, temperature, etc.), can mix with the environment (soil, water, rainwater, etc.) and accumulate in the human body through various means (food consumption, dust inhalation, water pollution, etc.). Microplastic pollution in the soil has become a serious concern and a matter that needs to be addressed appropriately, as it leads to health and ecological risks. It is estimated that microplastic ingestion from dust is approximately 3223 and 1063 particles for children and adults, respectively (Dehghani et al., 2017). In addition, many marine creatures such as crabs, oysters, mussels, and sea cucumbers are known to ingest microplastics. Microplastics are indirectly introduced into the human body through the consumption of these creatures. The microplastics found in these seafood products not only spoil the taste of food but also become more toxic due to the presence of components such as formaldehyde, benzene, and dioxins in these plastic products. Some also contain additives such as ultraviolet stabilizers and artificial pigments. These substances can lead to serious health problems such as weight gain, endocrine disorders, insulin resistance, and cancer, posing a major threat to human health (Kibria et al., 2023).

It is estimated that there are approximately 150 million tons (MT) of plastic waste in the marine environment. Furthermore, approximately 8 million tons of plastic waste are added to the marine environment every year (Mazhandu et al., 2020). This massive accumulation of plastic waste threatens marine life and thus damages the marine ecosystem. It is known that microorganisms in the oceans (e.g., copepods and zooplankton) contribute to reducing greenhouse gas emissions by absorbing 30% of CO_2 from the environment. However, ocean waves cause plastics to accumulate in the centers of ocean eddies or ocean basins. Therefore, plastic pollution is more concentrated in the ocean centers, and a dispersal occurs from the center depending on the wind direction (Eriksen et al., 2014).

However, microplastics are ingested by copepods. This reduces their CO2 absorption efficiency and, over time, impairs their reproductive capabilities (releasing smaller eggs with a lower hatching rate) (Cole and Galloway, 2015). In particular, rivers flowing through Asia contribute more to marine pollution than others. This is because many of these rivers flow through Asian countries, and population density in the region plays a vital role in this increase in plastic pollution. Furthermore, coastal populations in the Northern Hemisphere have a significant impact on the increase in plastic accumulation in ocean gyres and basins in this region. Although the coastal population of the Southern Oceans is smaller than that of the Northern Hemisphere, it shows similar levels of plastic pollution. Therefore, the intrinsic movement of plastic waste between ocean gyres and basins has become a serious issue today.

Plastic Waste Management Techniques

Plastics are not biodegradable and cannot be easily incorporated into the carbon cycle of the environment. Therefore, the end of their life cycle usually occurs either on land or in marine environments (Luo et al., 2000). For this reason, proper management of plastic waste is of great importance from environmental and economic perspectives. Various methods are used for the disposal of increasing industrial and municipal plastic waste. In general, plastic waste management can be examined in two parts: traditional and new technological methods, as shown in Figure 2. Traditional methods can be classified as: collection of plastic waste in landfills, mechanical, biological, and thermochemical recycling. New technologies, which are still under development, can be listed as plasma pyrolysis technology, polymer-modified bituminous roads, co-processing in cement kilns, and liquid gas or rapid pyrolysis processes. Table 1 shows which types of plastic waste these recycling methods are applicable to and their level of application.

Figure 2 The main diagrams of commonly used and newly developed plastic waste management systems are shown below.

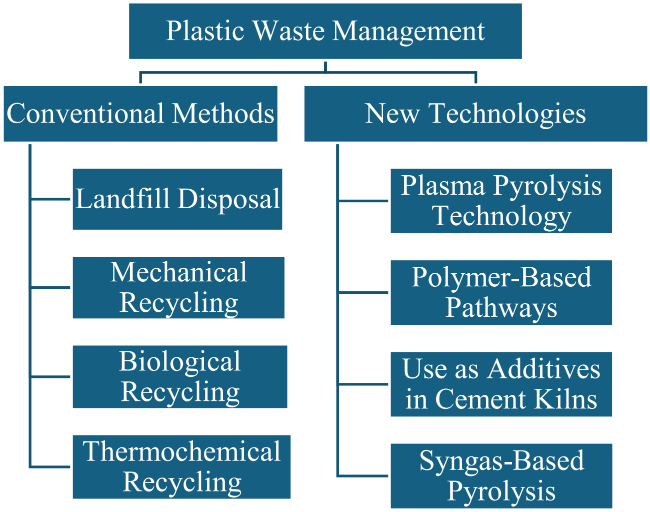


Table 1 Types of plastic waste that can be recycled using different recycling methods and their application levels.

Recycling Process	Input Material	Output	Decontamination	Ability to Process Mixed Plastics	Application Level
Mechanical recycling	PE, PET, PP, PS	Plastic (composed of one or more polymers)	Plastic (composed of one or more polymers)	Yes	Industrial scale
Solvent bazlı saflaştırma	PVC, PS, poliolefinler (PE, PP)	Polymer	Yes	No	Pilot phase
Chemical depolymerization	PET, PU, PA, PLA, PC, PHA, PEF	Monomers	Yes	No	Existing pilot plants for PET, PU, and PA.
Cracking (pyrolysis and gasification)	Plastic mixture	Hydrocarbon mixture	Yes	Yes	Pilot phase
Cracking (pyrolysis and gasification)	PMMA, PS	Monomers	Yes	No	Pilot phase

1.Landfilling

Plastics constitute a significant portion of municipal solid waste (MSW) and are often disposed of in landfills without any treatment. However, this method has become a serious environmental threat due to regulatory pressures, infrastructure and maintenance deficiencies, greenhouse gas (GHG) emissions, and the low biodegradability of commonly used polymers (Garforth et al., 2004).

Because of this hazardous waste management problem, environmental protection agencies have tightened federal and state regulations regarding the use of landfills. In this context:

• The use of landfill beds has been standardized,

• Groundwater testing has been made mandatory,

• Post-landfill maintenance processes have been regulated.

Since plastic waste has a high volume-to-weight ratio, landfilling in suitable areas creates a significant space problem. Therefore, other waste management methods can be considered as a more appropriate approach as an alternative to landfilling.

2.Energy Recovery by Incineration

The process of obtaining energy from plastic waste is carried out through a method called incineration. During this process, energy is recovered from non-biodegradable plastic waste. Since the octane number of some plastic materials is similar to that of crude oil derivatives (Eriksson and Finnveden, 2009), this method is quite effective. According to projections, approximately 50% of total plastic waste will be disposed of by incineration by 2050 (Geyer et al., 2017).

As can be seen from Table 2, the calorific values of polyethylene, polypropylene, and polystyrene are almost the same as fossil fuels such as gasoline, oil, and kerosene. Therefore, the main byproducts of the incineration process, water and carbon dioxide, make this method a viable alternative to traditional fossil fuels (Thanh et al., 2011).

Table 2 Calorific values of plastic materials and some fuel sources.

Plastic Material / Fuel Type	Calorific Value (MJ/kg)
Polyethylene	43,3 – 47,7
Polystyrene	41,6 – 43,7
Polyethylene terephthalate (PET)	21,6 – 24,2
Polyurethane foam	31,6
Polypropylene	42,6 – 46,5
Polyvinyl Chloride (PVC)	18,0 – 19,0
Polyamide	31,4
Gasoline	46,0
Petroleum	42,3
Gazyağı (Kerosene)	46,5

3.Mechanical Recycling

Mechanical recycling is the process of reprocessing used thermoplastics into a similar or new product. This method is one of the primary and secondary recycling types and begins with the classification of the thermoplastics to be used. Homogeneous waste thermoplastics, in particular, are generally transformed into new products with similar characteristics to the original product. After raw materials such as natural gas, crude oil, and salt are extracted from nature, these materials are sent to petrochemical plants. Here, plastic materials are produced by polymer engineers through various processes. Then, these polymers are customized according to properties such as color, thickness, and size before being presented to the consumer.

When the first life cycle of the plastic ends, the product is considered waste. At this point, the waste collection process, which is the first step of mechanical recycling, begins. After the collected waste is separated, it is sent to recycling facilities and transformed into either the same or different types of products. Then it reaches the consumer again, and this cycle continues. However, this recycling process is not cost-effective because:

- High energy demand
- Separation, cleaning, transportation, and processing technologies
- It requires environmentally friendly application costs.

4.Biological Recycling

Many studies are being conducted on biodegradable plastics (bioplastics) to meet the need for organic recycling. To meet future needs, it is necessary to develop the biorecycling infrastructure along with technical expertise.

Biorecycling can be done especially in the following ways:

- Aerobic composting (decomposition in an oxygenated environment),
- Decomposition of polymers through aerobic bacteria and fungi.

These microorganisms use polymers for energy production and reproduction. In this process, organic carbon materials are also converted into biomass. This biomass has energy potential and protects the environment.

However, some biodegradable plastics may not decompose in this process. In this case, non-decomposable plastics are considered non-biodegradable waste.

5.Thermal Recycling or Incineration

In general, composite materials containing carbon fiber and polymer matrix are subjected to high temperatures during thermal recycling (Verma et al., 2018). This temperature usually ranges from 450°C to 700°C and depends on the properties of the resin (Verma et al., 2018).

Although thermal recycling is costly in terms of energy and labor, it has become a more common and preferred method compared to other methods due to the ease of reusing and reprocessing mixed plastics as raw materials.

6.Chemical Recycling

Although plastic is a general term, the way polymers are used to obtain different types of plastics varies. Furthermore, each polymer has its own unique melting point. Therefore, it is technically impossible to recycle different types of polymers at the same temperature. This necessitates that the recycling process be not only physical but also chemically decomposed. Considering limitations such as the inability to separate additives and uncontrolled contaminants found in polymers, chemical recycling is seen as a much more effective and comprehensive method than mechanical recycling.

Chemical recycling is compatible with the principles of sustainable development because it provides not only material but also energy recovery (Ragaert et al., 2017). This method can even process mixed and contaminated polymers. The degraded polymer structure can be re-arranged and reused according to the application and the properties of the target product. Thus, both environmental pollution is reduced and valuable raw materials are recovered. The chemical recycling process is divided into three main categories according to the degradation mechanism to which plastics are subjected:

1. Solvent-Based Purification: In this method, plastic waste is dissolved with suitable solvents and converted back into polymer form. The chemical structure of the polymer is preserved and purified without undergoing physical degradation.

2. Chemical Depolymerization: Plastic waste is broken down into its original monomer structures through chemical reactions.

These monomers can be repolymerized to become raw materials for new products.

3. Thermal Depolymerization: This method includes pyrolysis and gasification processes. Polymer chains are broken at high temperatures and converted into hydrocarbons and other chemical products. These products can be used for energy production or as fuel. Thermal depolymerization is considered a method close to chemical recycling.

7.Pyrolysis

Pyrolysis is the process of converting large-chain polymers into smaller chains through thermal decomposition. In this process, plastics are heated in an inert gas atmosphere at temperatures ranging from 300–900 °C (Chen et al., 2014). Pyrolysis yields energy recovery products (WtE – Waste-to-Energy) such as liquid oils and gases. This method is particularly suitable for hydrocarbon polymers such as PE (polyethylene), PP (polypropylene), and PET (polyethylene terephthalate) (Wong et al., 2015).

8.Hydrocracking

Hydrocracking, or hydrogenation, is the process of converting long-chain hydrocarbons into smaller molecules such as kerosene and gasoline by adding hydrogen under high pressure in the presence of catalysts (Al-Salem et al., 2017). Compared to pyrolysis, hydrocracking technology has several advantages. Firstly, plastic waste can be converted into high-quality liquid fuels. Secondly, it is more efficient than pyrolysis because it allows the production of gasoline derivatives in the C6–C12 range (Munir et al., 2018).

Hydrocracking also increases efficiency by improving heat and mass transfer. Some problems can arise due to the high viscosity and large molecular structure of the products formed during the pyrolysis process (Miranda et al., 2013). However, it should be noted that hydrogen gas used in hydrocracking is much more expensive than gases used in pyrolysis, such as nitrogen. For example, while a ton of nitrogen costs around $200, a ton of hydrogen produced using electricity costs approximately $2800 (Ragaert et al., 2017). Furthermore, because hydrofracturing takes place under high pressure, it requires expensive equipment. For these reasons, it is not as common as pyrolysis in terms of cost.

9.Gasification

Gasification is another thermal decomposition method that can be an alternative to pyrolysis and hydrocracking. In this method, various plastic wastes are processed at high temperatures in the presence of oxygen, along with light hydrocarbons such as carbon dioxide, water vapor, and methane, to be converted into synthesis gas (Krapivin et al., 2017).

10.Chemolysis

Chymolysis, also known as depolymerization or solvolysis, is a raw material recovery technology. In this method, plastics are chemically decomposed into their monomers at temperatures ranging from approximately 80–280 °C (Payne et al., 2019). Chymolysis is generally suitable for unsaturated resins and polyester-based polymers (e.g., PET, polyamides, polycarbonate, polyurethane) (Oliveux et al., 2015).

However, since the chymolysis method is highly dependent on the type of plastic, it is difficult to obtain monomers from different plastic mixtures. Therefore, the applicability of this method is limited, and consequently, it is not generally preferred as the main recycling method.

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CHAPTER 8

INVESTIGATION OF FLUID–STRUCTURE INTERACTION OF THE HISTORICAL THREE-SPAN BRIDGE UNDER FLOOD EFFECTS USING A COUPLED EULERIAN–LAGRANGIAN APPROACH

MUHAMMET ENSAR YİĞİT[1]

Introduction

Historical stone arch bridges, as one of the oldest engineering achievements in human history, are not only structures that meet transportation needs but also monumental works that embody the technical knowledge, aesthetic understanding, and cultural tradition of societies. As an important part of the masonry construction tradition, these bridges hold a special place in both engineering and cultural heritage literature due to their material properties, construction techniques, proportional geometry, and long-lasting performance. The original design principle of stone arch bridges is based on the fact that stone is a building material that only works under compression. Thanks to the arch geometry, loads are largely transferred along the compression line; this

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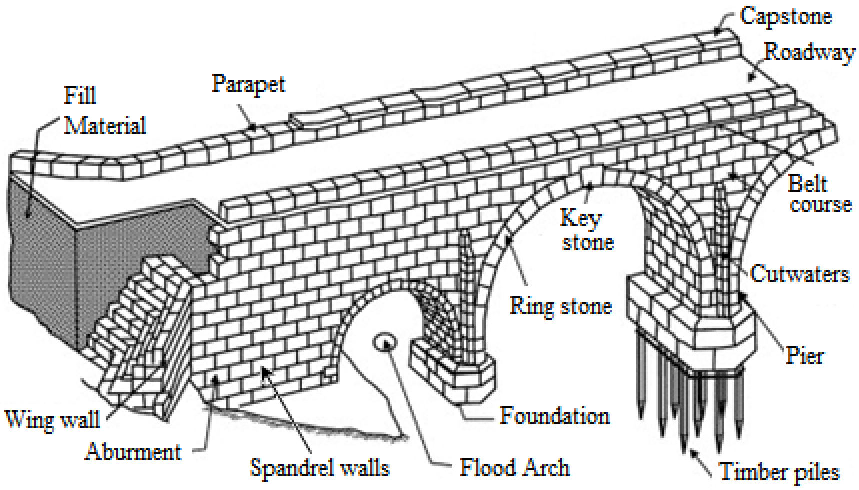
increases the durability of the stonework, whether mortared or mortarless. This construction technique has been applied unchanged for centuries, developing in different geographies depending on local material and craftsmanship traditions, and has been used intensively, especially in Anatolia and the Caucasus (Figure 1).

Figure 1 a) Akköprü Bridge, b) Ortacalar Twin Bridges.

Reference: URL-1, (2025); URL-2, (2025).

The preservation of traditional stone bridges is one of the priority areas of cultural heritage management today. Many of these structures, located on historical trade routes, rural settlement networks, or military routes, have shaped the socio-economic development of their regions and ensured the continuity of local life. The names of the structural and non-structural elements of stone arch bridges are shown in Figure 2, and these structures were built using stone masonry techniques. Therefore, the destruction or damage of stone bridges is not only a physical loss but also creates a significant gap in social memory, identity, and settlement fabric. In particular, hydrodynamic effects such as sudden rainfall, floods, and the impact of floating debris/wood, which are increasing due to the effects of climate change, increasingly threaten the reliability of such historical structures (Figure 3).

Figure 2 Some definitions used for stone arch bridge.



Reference: Ural et al. (2008).

From a structural engineering perspective, historical stone bridges require different analytical approaches compared to modern reinforced concrete or steel bridges because they consist of masonry components, a heterogeneous and crack-prone material. The assumption of elasticity and homogeneous material approach often does not reflect the actual behavior. In recent years, advanced numerical modeling methods such as nonlinear finite element analysis (FEM), discrete element method (DEM), cohesive zone modeling, and limit-equilibrium analyses have enabled more realistic investigation of complex behaviors in stone bridges, such as cracking, crushing, arch displacement, the role of infill, foundation settlements, and scour effects. In this context, a vast literature has developed concerning the seismic behavior of stone bridges, vibration characteristics under traffic loads, effects of humidity and freeze-thaw cycles, and multiple impacts such as flooding and debris impact.

Figure 3 Examples of damaged stone bridges

Reference: Tubaldi et al. (2022); Bayraktar et al. (2021); URL-3, (2025).

The literature contains significant articles and reports addressing numerical modeling of stone arch bridges, scouring/flood effects, dynamic/seismic analyses, model updating, and heterogeneous material behavior.

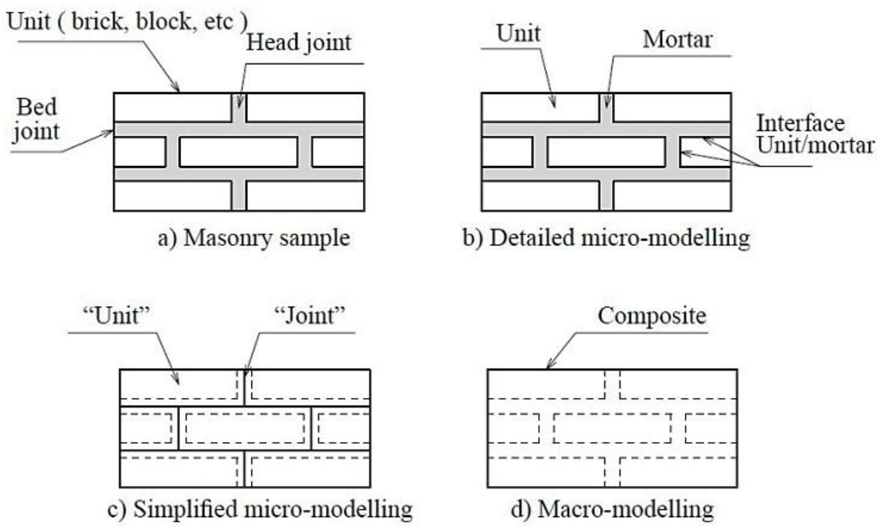
Ural et al. (2008) also aimed to present the architectural and engineering characteristics of historical arch bridges in Türkiye. The deterioration, damage, and collapse patterns in the structural materials of masonry arch bridges were classified and discussed using some illustrated photographs. Pulatsu et al. (2019) presented a methodology that can comprehensively simulate the behavior of three-dimensional masonry arch bridges and incorporate various possible damage mechanisms. The results showed that soil properties have a significant effect on the behavior and load-carrying capacity of masonry arch bridges. Silva et al. (2022), in their study, they simulated the damage situation in masonry arch bridges under service load using FE models. By combining a continuous homogeneous model with a discrete crack model, a better representation of longitudinal cracking, particularly the transverse motion of the arch and spandrel walls, was achieved. These simplified, calibrated numerical FE strategies were found to be quite effective in nonlinear dynamic analysis under service load. Karalar and Çufalı (2023) investigated the effects of changes in arch form thickness and height on a bridge using numerical analysis. The analysis showed that increasing the arch thickness under the bridge's own weight reduced displacements. Furthermore, under the effects of live loads and earthquakes, displacements decreased with increasing arch thickness. Silva et al. (2024) reported a numerical study focusing on the characterization of the wall and infill material behavior of stone arch railway bridges. They presented experimental data obtained from testing campaigns conducted on the materials of two granite stone bridges. Varró et al. (2025) investigated eight different vaulted stone bridges with 1, 2, 3, and 4 spans. Using the data obtained, numerical analyses were conducted to determine the load-carrying capacity of the structures. They stated that the most important factors affecting the load-carrying capacity were the geometric dimensions and the frictional interaction between the elements.

Material and Method

This study will examine the architectural features and demolition process of the Historical Three-Span Bridge in Borçka/Artvin/Turkey. Subsequently, numerical modeling methods specific to the structure, analysis results, and possible strengthening/conservation proposals will be discussed. The aim of the study is both to examine a concrete demolition event from an engineering perspective using the Historical Three-Arched Bridge as an example, and to provide a scientific basis for the sustainable preservation of stone bridges. The wall elements of historical arched bridges consist of stone/brick and mortar. Numerical modeling of wall structures is quite complex due to the interaction between wall units and mortar. Depending on the size of the structural system, detailed micro, simplified micro, and macro modeling techniques are used in modeling the wall units (Figure 4) (Hökelekli and Yılmaz, 2019).

In detailed micro-modeling, wall units (stone/brick) and mortar are modeled separately. Therefore, different material properties are defined for the elements forming the wall units. In the simplified micro-modeling technique, wall units are constructed with half the width of the mortar layer, and the mortar layer is neglected. In the finite element model, arches, side walls, and infill are modeled separately. In the macro-modeling technique, the wall unit and mortar are modeled as a whole. The material properties of the wall masonry are determined using empirical formulas obtained from the literature, taking into account the material properties of the stone units and mortar components of the wall masonry. Due to their complex geometric features, macro modeling techniques are used in the modeling of mosques, churches, minarets, towers, and bridges.

Figure 4 Material modeling techniques



Reference: Lourenço, (1996).

Formulation of Eulerian-Lagrangian Coupled Approach

The Eulerian-Lagrangian Coupled Approach offers a robust framework for examining the complex interactions within structures, accounting for both the larger spatial context and the behavior of individual elements. In the realm of fluid dynamics and continuum mechanics, the Eulerian and Lagrangian descriptions serve as foundational methods for analyzing the motion and characteristics of materials. The relationship between material and spatial time derivatives can be expressed as follows (Skrzat, 2012):

$$\frac{D\Phi}{Dt} = \frac{\partial\Phi}{\partial t} + v.(\nabla\Phi) \qquad (1)$$

Where, Φ represents the arbitrary solution variable, v denotes the velocity. $D\Phi/Dt$ the material time derivative, and $\partial\Phi/\partial t$ the spatial time derivative.

The conservation equations for mass, momentum, and energy, initially formulated in the Lagrangian framework, are converted into Eulerian conservation equations (involving spatial derivatives) as detailed in the provided Benson and Okazawa, (1997).

$$\frac{\partial\rho}{\partial t} + v.(\nabla.\rho) + \rho\nabla.v = 0 \qquad (2)$$

$$\frac{\partial v}{\partial t} + v.(\nabla.v) = \frac{1}{\rho}(\nabla.\sigma) + b \qquad (3)$$

$$\frac{\partial e}{\partial t} + v.(\nabla e) = \sigma{:}D \qquad (4)$$

Where, ρ represents density, b is the vector of body forces, σ denotes the Cauchy stress, D represents velocity strain and e stands for strain energy.

The equations within the Eulerian framework (Eq. 2-4) can be reformulated in conservative formats as follows (Benson, 1997):

$$\frac{\partial\rho}{\partial t} + \nabla.(\rho v) = 0 \quad (5)$$

$$\frac{\partial\rho v}{\partial t} + \nabla.(\rho v \otimes v) = \nabla.\sigma + \rho b \quad (6)$$

$$\frac{\partial e}{\partial t} + \nabla.(ev) = \sigma : D \quad (7)$$

The Eulerian governing Eq. (5-7) have a general form:

$$\frac{\partial\phi}{\partial t} + \nabla.\varphi = S \quad (8)$$

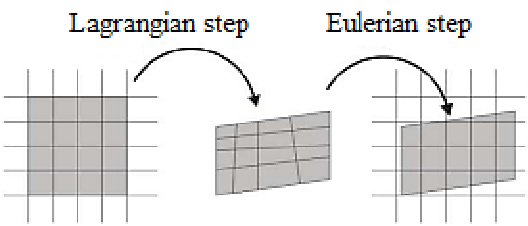
Where, S represents the source term and ϕ represents the flux function. Eq. (*8*) is divided into two equations and solved sequentially using operator splitting, as described in reference.

$$\frac{\partial\phi}{\partial t} = S \quad (9)$$

$$\frac{\partial\phi}{\partial t} + \nabla.\varphi = 0 \quad (10)$$

Eq. (*9*) includes the source term, which signifies the Lagrangian step, whereas Eq. (10) incorporates the convective term, symbolizing the Eulerian step. A visual depiction of this split operator is presented in Figure 5.

Figure 5 The use of the split operator in the CEL formulation



Reference: (Skrzat, 2012).

To solve Eq. (10), the distorted mesh from the Lagrangian step is moved to the fixed Eulerian mesh, and the volume of material transferred between neighbouring elements is computed.

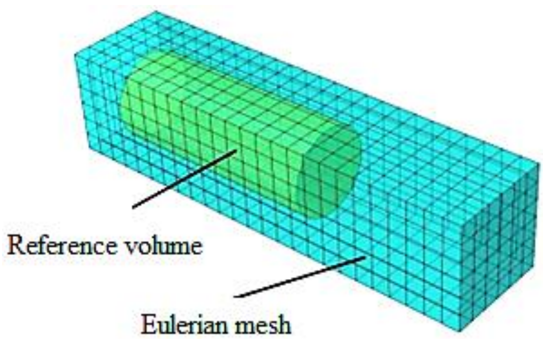
The principle of virtual work is employed in the Lagrangian step as described in reference Bathe, (1996).

$$\int_v \rho a.\delta u dv + \int_v \sigma: \delta\varepsilon dV = \int_S \tau.\delta u dS + \int_v \rho b.\delta u dV \qquad (11)$$

Where, $\delta\varepsilon$: the virtual strain, δu: the virtual displacement resulting from virtual displacements, τ : the surface traction and α: the spatial acceleration. In the Lagrangian step, the updated Lagrangian formulation is suitable because it corresponds to the current configuration in the Eulerian approach, aligning with the reference configuration at time t. However, predicting the configuration of the body at $t+\Delta t$, as described in Eq. (11), is generally challenging. Moreover, determining the Cauchy stress at $t+\Delta t$ isn't straightforward, as it can't be obtained by merely adding the stress increment to the Cauchy stress at t. These measures are employed in the principle of virtual displacements (Equation 11) to accurately represent the behaviour of the material under deformation (Belytschko, 2014).

In the context of simulations involving the Eulerian mesh, understanding the presence or distribution of materials is crucial. To achieve this, a parameter called the volume fraction (VF) is introduced Al-Athel and Gadala, (2011) (Figure 6) (Skrzat, 2012).

Figure 6 Volume ratios in finite element analysis.

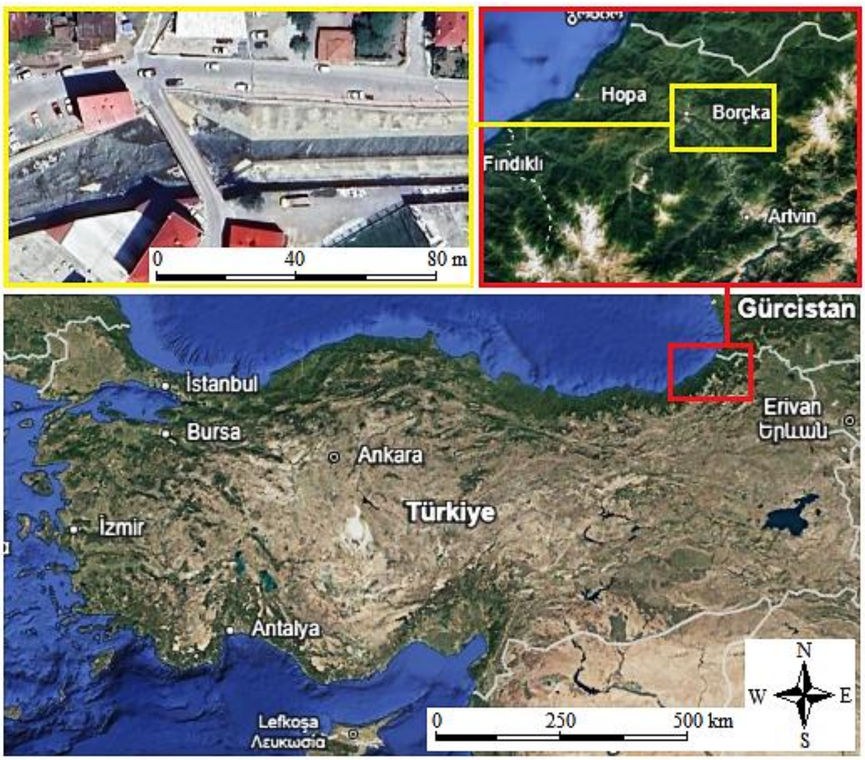


Reference: (Skrzat, 2012).

Model Description

This study focuses on the historical Three-Span Bridge located on the Aksu Stream, which flows east-west in Borçka district of Artvin province in northeastern Turkey (Coordinates: 41°21'37"N, 41°40'48"E) (Figure 7). Cultural inventory records indicate that the bridge's arches are constructed of finely cut stone, its body of rough-hewn stone, and that recent interventions (railings, iron supports, widenings) have been made to accommodate pedestrian and vehicle traffic (Figure 8). The bridge is approximately 35 m long, 8.5 m high, and has an arch width of 3 m. With additions to the bridge, the road width has been increased to 6 m (Url-4, 2025).

Figure 7 Location of the historic Three-Span Bridge



While there are no definitive records regarding the bridge's construction date, local narratives and cultural inventory data suggest that the structure may have been built during the Ottoman period, between the late 18th and early 19th centuries. The bridge, which has undergone numerous repairs over time, has largely preserved the originality of its pier and arch form. However, it is known to have undergone partial interventions such as railings, fill arrangements and surface repairs (Url-5: 2025; Url-6: 2025).

Figure 8 The historic Three-Span Bridge before it was demolished

Reference: Url-5, (2025); Url-6, (2025).

In the autumn of 2025 (September), the extreme rainfall caused the water level in the Aksu Stream to reach critical levels in a short time, resulting in intense flooding downstream (possibly floating wood and debris) and increased flow velocity, severely affecting the structural integrity of the bridge (Figure 9). Damage and debris impact, particularly on the upstream side of the piers, resulted in the partial collapse of the bridge. This event revealed that the Borçka bridge, like many stone bridges in the region, is vulnerable to hydrodynamic forces and that the structures need to be re-evaluated under current climatic conditions.

Figure 9 The historic Three-Span Stone Bridge after its collapse

Reference: Url-7: (2025); Url-8, (2025)

Finite Element Model

In this section of the study, a linear 3D finite element model of the historical Three-Span Bridge was created and analyses were performed for flow height (h) of 1 m, 1.5 m, and 2 m. 3D FEM analyses were performed using ABAQUS software (Abaqus, 2016) (Figures 10, 11).

Figure 10 Stone bridge and fluid FE model

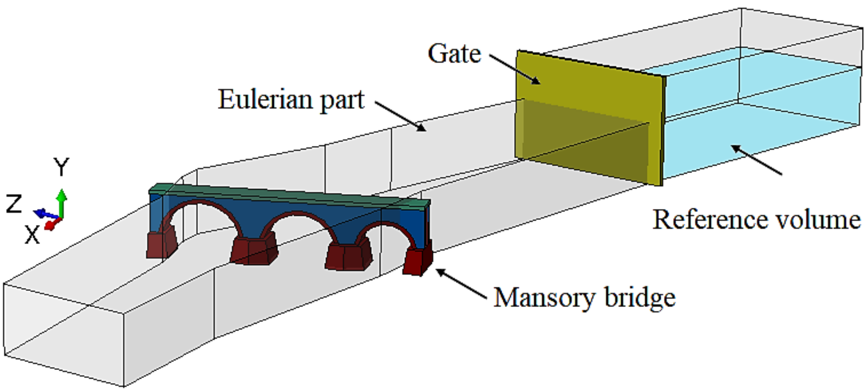
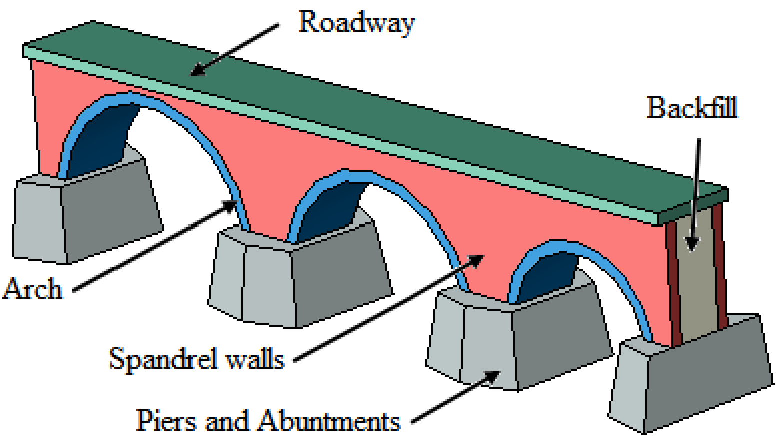


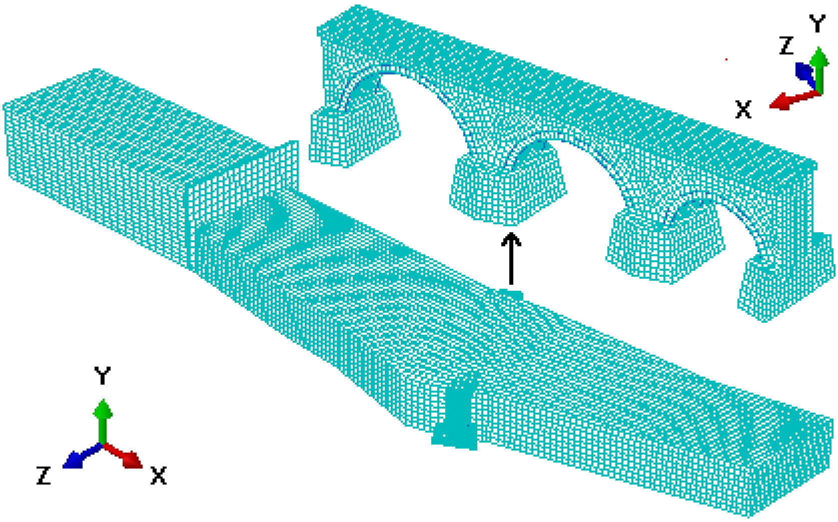
Figure 11 Stone bridge components and FE model detail



The flow form around the piers and the tensile and compressive stresses at the bridge piers obtained under the influence of different flows are compared in the 'Result' section.

The Three-Span Bridge was modeled using 8-node high-order hexahedron elements. The fluid is modeled using a linear brick 8-node Eulerian element (EC3D8). Arches, spandrel walls, rubble walls, and piers were simulated with 8-node linear brick elements (C3D8R). The interaction between the fluid and the bridge is defined as a hard contact interface that can transmit compressive forces in the normal direction but cannot sustain tensile forces, together with a frictional contact interface capable of transferring tangential forces. Macro-modeling was used in the selection of mesh size and type. In the modeling of the historical Three-Span Bridge, the mesh spacing was taken as 0.7 m for fluid elements and 0.5 m for solid elements. In the analysis, 221,031 elements, 243,307 nodes, and a total of 729,921 variables were included in the calculations (Figure 12).

Figure 12 Three-Span Bridge mesh detail



Material Properties

When determining the material properties to be used in the FE model, the Elastic modulus, Density, and Poisson ratio values used in 10 case studies of stone bridges between 2011 and 2025 were examined. Table 1 presents the properties of the fluid affecting the stone bridge (Yiğit, 2024; Tuskan and Yiğit, 2025). These values are summarized in Table 2, covering various sections of the stone bridge. Table 3 details the properties used in the FE model.

Table 1 The material properties for flood

Density (t/m^3)	Sound velocity in fluid (m/s)	Viscosity (Pa.s)
1300	1700	0.05

Table 2 Material properties used in the literature for sections of masonry stone bridges.

Author(s)	Bridge units	Elastic modulus (MPa)	Density (kg/m^3)	Poisson ratio
Shabani and Kioumarsi, 2023	Arch	818.4-1078.4	1936-2750	0.29
	Spandrel	1064-1088	2103-2192	0.30
	Backfill	466	2408	0.25
	Pier and Abutment	462-977	2195-2243	0.30
Hökelekli and Yılmaz, 2019	Arch	2800-3000	1600	0.20-025
	Spandrel	2400-2500	1400	0.2
	Backfill	500	1800	0.25
Sevim et al, 2011	Arch	3000	1600	0.25
	Spandrel	2500	1400	0.20
	Backfill	1500	1300	0.05
Zahra et al, 2025	Arch, Spandrel, Pier	7800-16100	1981	-
Özmen and Sayın, 2020	Arch	2500	2300	0.20
	Spandrel	2000	2200	0.20
	Backfill	1200	1400	0.20
Ercan et al, 2015	Arch, Spandrel, Pier	1164	2100	0.17
Öztürk et al, 2023	Arch	2109	2350	0.20
	Spandrel	2209	2350	0.20
	Backfill	1800	1600	0.15
	Slab	2209	2350	0.20
Shabani et al, 2023	Arch, Spandrel, Pier	1001	2200	0.29
	Backfill	300	2000	0.30
Altunışık et al. (2015)	Arch, Abutment	3250	2000	0.20
	Spandrel	1950	2000	0.20
	Backfill	390	1800	0.20
Gönen and Soyöz, 2021	Arch,	6700	2540	0.22
	Spandrel	6200	2500	0.22
	Backfill	1150	1900	0.27
	Pier and Abutment	6200	2500	0.22

Table 3 Material properties for bridge units.

Mechanical properties	Arch	Piers and Abuntments	Spandrel wall	Backfill	Roadway
Modulus of elasticity (Mpa)	7700	10000	5000	3000	28000
Unit weight (kN/m^3)	22.0	23.0	21.0	18.0	25.0
Poisson’s ratio	0.17	0.2	0.2	0.25	0.2

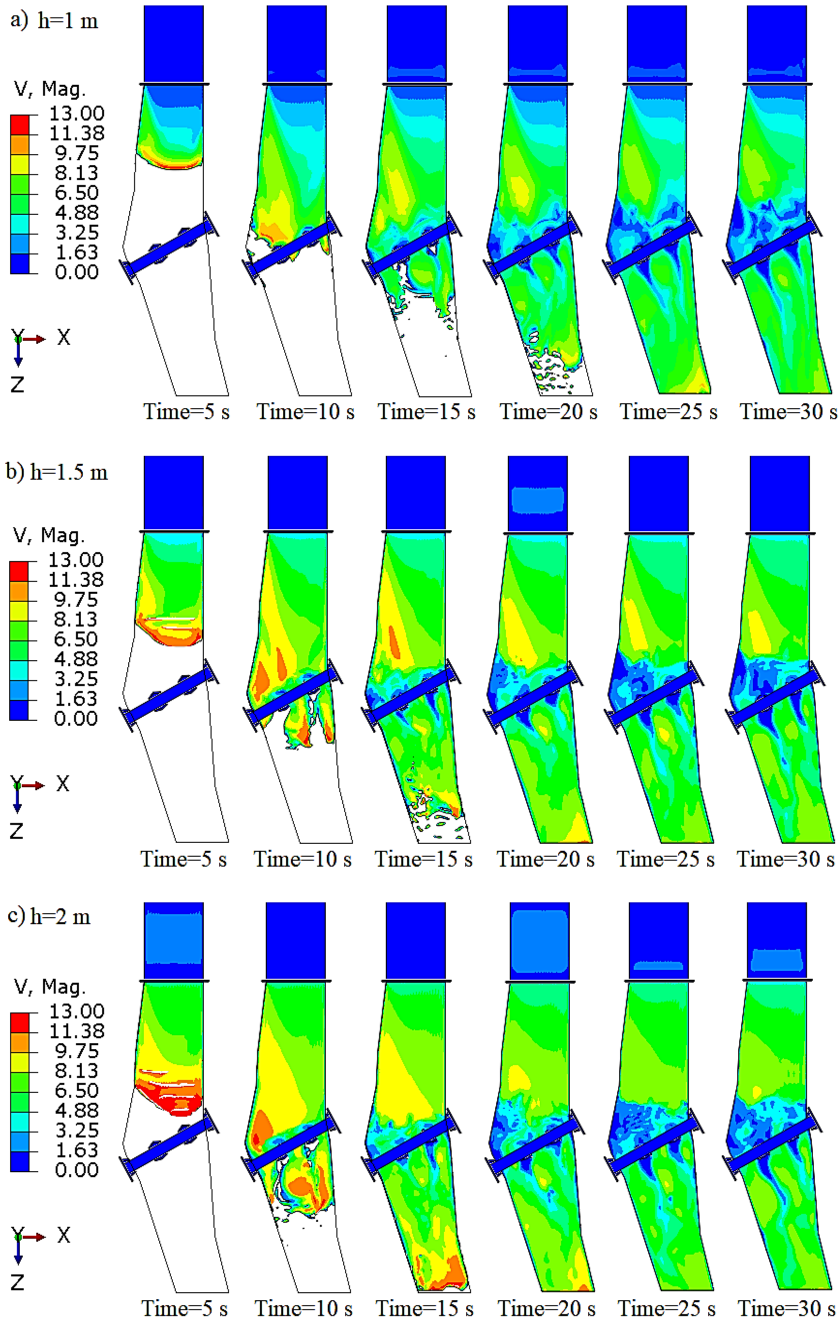
Results

The results obtained from analyses conducted on the historical Three-Span Bridge under the influence of floodwaters flowing at heights of h=1 m, 1.5 m, and 2 m are presented in two parts. The first shows the water surface shapes at different time points 't' and includes velocity contour diagrams illustrating flood flow around the bridge piers. The second shows the contour diagrams of the maximum principal tensile and maximum principal compressive stresses occurring on the bridge structure at different time points 't'.

Flood Speeds

In the FE model, flow was initiated by opening the gate, which holds the fluid at a certain height, sequentially from the base at h=1 m, 1.5 m, and 2 m. The flow reached the bridge pier from the gate in approximately 8.15 s for h=1 m, 6.25 s for h=1.5 m, and 5.3 s for h=2 m. In all three cases, the flow stabilized after approximately 30 seconds. It is observed that the flow velocities around the bridge piers decrease and a bulge occurs in the upstream direction (Figure 13). The length of the upstream bulge zone was measured as 16.95 m for h=1 m, 13.22 m for h=1.5 m, and 16.73 m for h=2 m. On the downstream side of the piers, the flow velocities decrease, creating tail water.

Figure 13. Velocity contour diagrams for different water heights.



Stresses

Figures 14-16 show that in all three analyses at different heights, the maximum principal tensile stress value read on the bridge before the flood was S_{max}=0.172 MPa, and the maximum principal compressive stress value was S_{min}=-0.658 MPa. A review of the literature reveals that the tensile and compressive strength values of the stone material are quite sufficient for these values. Considering the initial contact moments of the stone bridge with the flood, these values are observed as follows: for h=1 m, the maximum principal tensile stress value was S_{max}=0.296 MPa, and the maximum principal compressive stress value was S_{min}=-1.255 MPa; for h=1.5 m, the maximum principal tensile stress value was S_{max}=0.383 MPa, and the maximum principal compressive stress value was S_{min}=-1.045 MPa; and for h=2 m, the maximum principal tensile stress value was S_{max}=0.392 MPa, and the maximum principal compressive stress value was S_{min}=-0.947 MPa. This situation shows that as the flow height increases, there is an increase in tensile stresses and a decrease in compressive stresses.

After 30 seconds from the start of the analysis, when the flow stabilizes, the stresses are observed to be: for h=1 m, the maximum principal tensile stress value is S_{max}=1.035 MPa, and the maximum principal compressive stress value is S_{min}=-5.750 MPa; for h=1.5 m, the maximum principal tensile stress value is S_{max}=0.937 MPa, and the maximum principal compressive stress value is S_{min} =-5.514 MPa; and for h=2 m, the maximum principal tensile stress value is S_{max}=2.37 MPa, and the maximum principal compressive stress value is S_{min}=-8.296 MPa. In stone bridge piers and arches, tensile stress strength is taken as 0.50-0.75 MPa and compressive stress strength as 5-10 MPa, as examples from the literature (Hökelekli and Yılmaz, 2019; Yiğit, 2025). Therefore, tensile and compressive damage is likely to occur in the structure.

Figure 14. Time-varying stresses on the bridge for h=1 m.

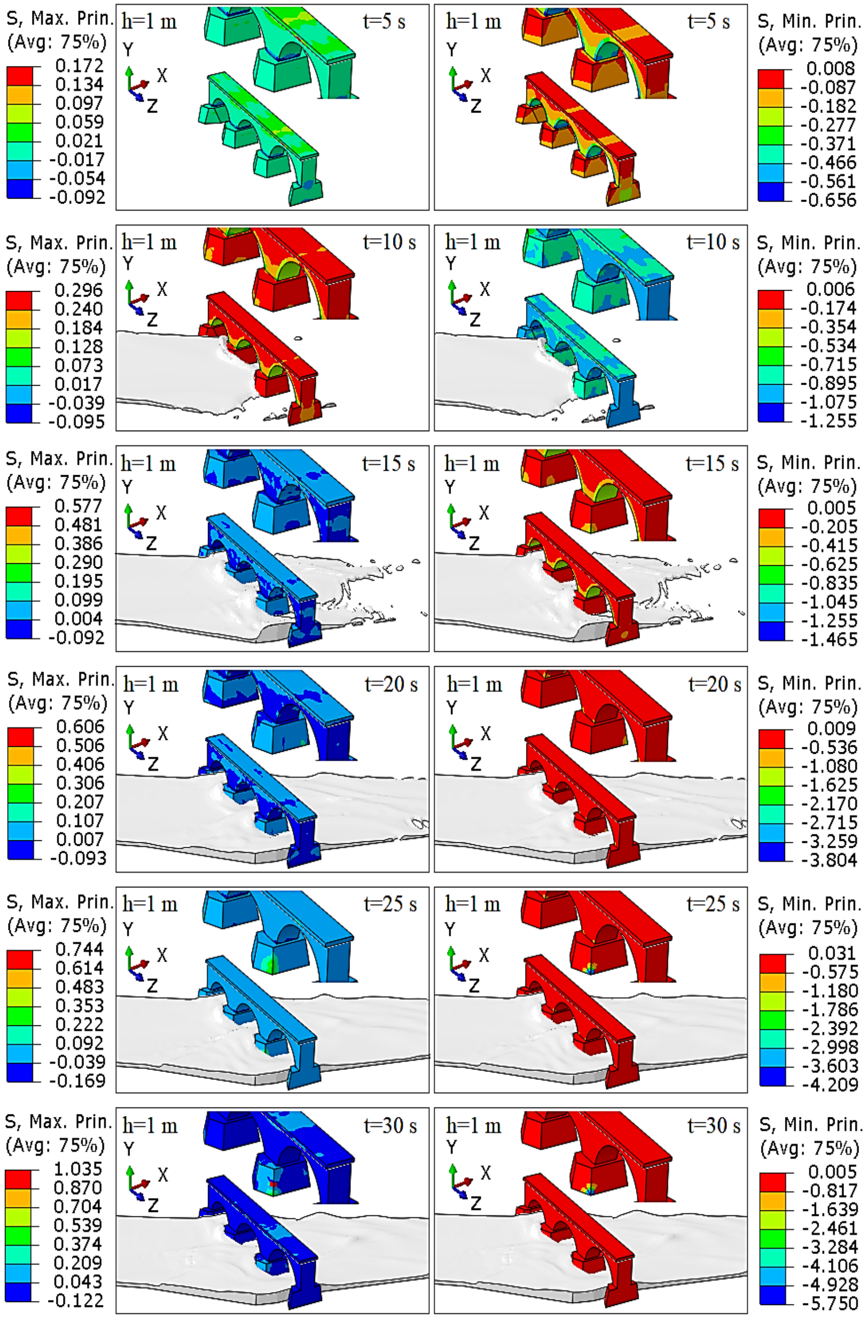


Figure 15. Time-varying stresses on the bridge for h=1.5 m.

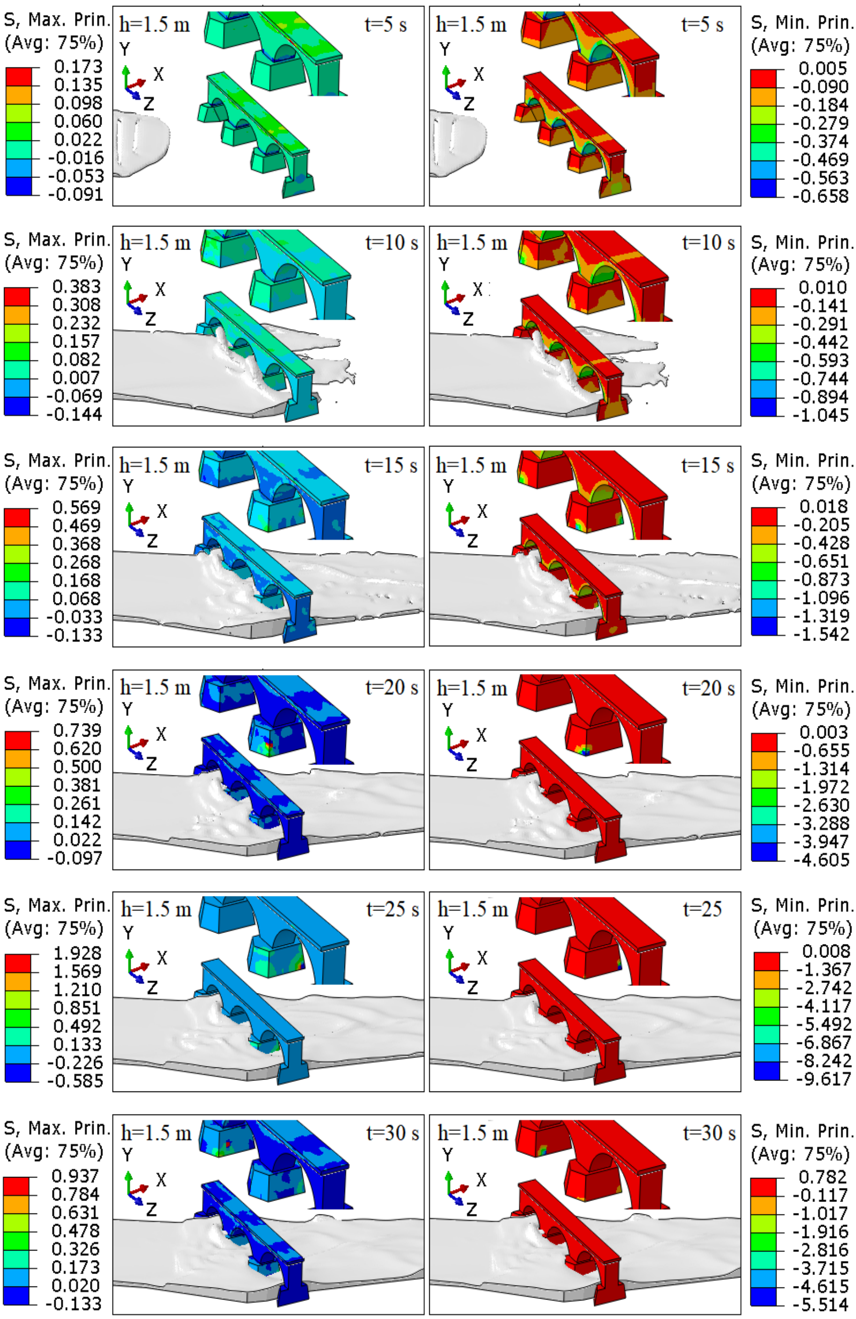
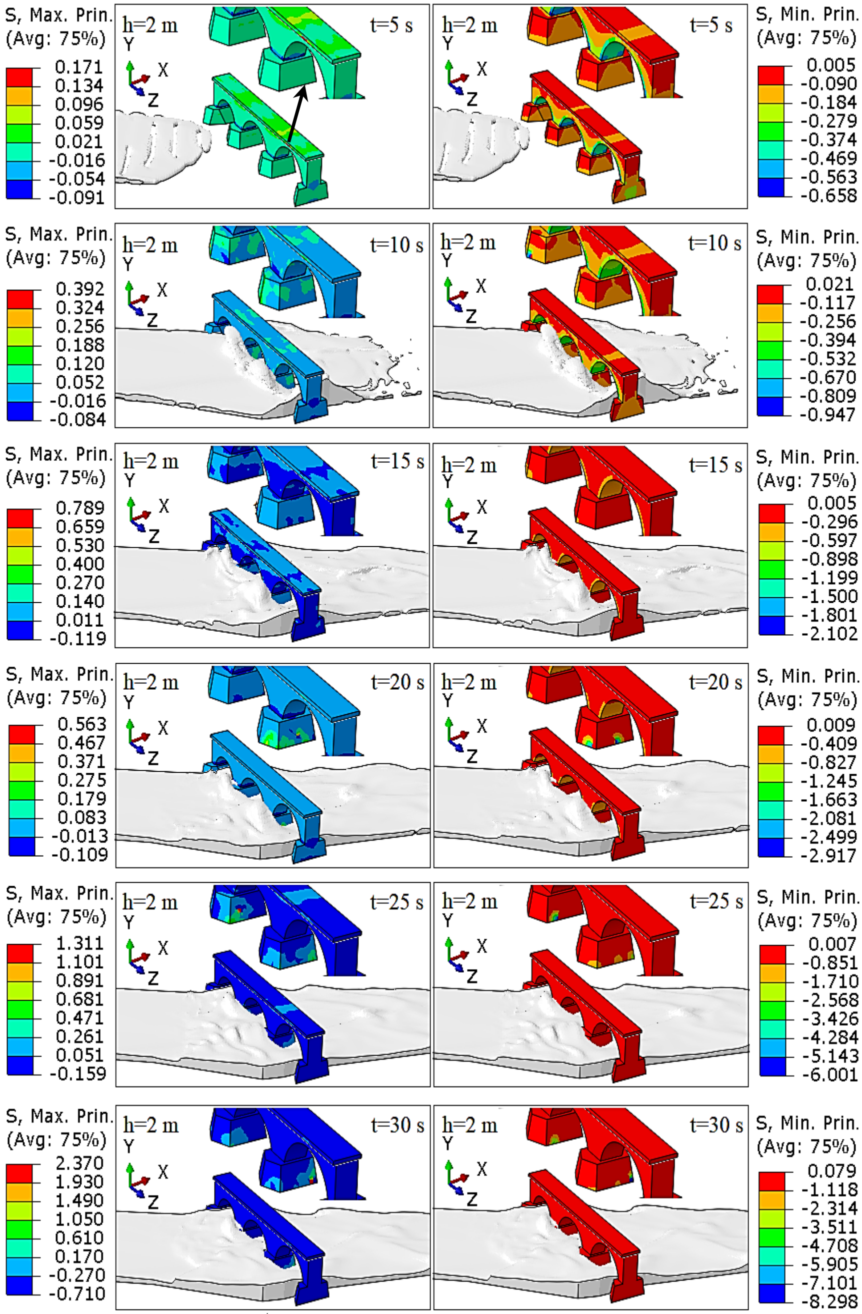


Figure 16. Time-varying stresses on the bridge for h=2 m.



Discussion

The morphological structure of Artvin and the Eastern Black Sea region, the steep river regimes, sudden increases in flow due to short but intense rainfall, and the intense sediment-debris transport indicate that the stone bridges in this region are under serious threat under hydrodynamic loads. When the bridge's collapse mechanism is examined, it is understood that the following effects are predominantly critical:

- Excessive scour in the central piers,
- Debris load and blockage effect,
- Loss of the holistic behavior of the arch geometry,
- Low tensile strength of the masonry material,

When the engineering and conservation conclusions drawn from this event are evaluated, the following points stand out:

- Regular hydraulic risk analyses of historical bridges are mandatory.
- Numerical analyses and flow-structure interaction models play a critical role in understanding the behavior, especially under flood regimes.
- Conservation and strengthening strategies should also include hydraulic measures such as flow regulation structures (guide walls, base protection structures, energy dissipators).

Consequently, the partial collapse of the three-arched bridge in Borçka serves as a significant warning for similar masonry bridges, both regionally and nationally.

Conclusion

The structural damage suffered by the three-arched historical stone bridge in Borçka, Artvin, following the extreme rainfall and flood in 2025, clearly revealed the fragility of traditional masonry bridges in the face of hydrodynamic effects. The critical levels of flow velocity during the flood, along with the heavy load of debris and floating timber, caused significant stress, particularly on the two central piers of the bridge. The resulting scouring around the piers led to a loss of load-bearing capacity; the imbalance in the load-bearing system resulted in the complete collapse of one of the central piers and, consequently, the complete collapse of both arch spans. The gradual erosion caused by floods in previous years reduced the bridge's initial resistance during floods. Furthermore, the design of the spurs with inclined surfaces during recent restoration work on the bridge piers caused the flow to be diverted towards the bridge wall. This geometric change resulted in the structure exhibiting behavior inconsistent with its original historical flow distribution. In addition, the flood protection walls built in the stream where the bridge is located narrowed the riverbed cross-section, altering the flow regime and causing a high-velocity flow approaching the bridge at an angle of approximately 45°. This narrowing increased the flow velocity and amplified the impact of flood loads, particularly on the central piers.

Consequently, the bridge's collapse is the result of a complex hydraulic-structural interaction stemming from the combined effects of natural aging, inappropriate restoration geometry, and modern interventions in the riverbed. This situation highlights the need for a holistic approach to the preservation of historical stone bridges, addressing not only the structure itself but also the engineering structures that determine the surrounding flow conditions.

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CHAPTER 9

EARTHQUAKE PERFORMANCE AND DAMAGE MECHANİSMS OF MASONRY STRUCTURES: A COMPARATİVE REVİEW OF 2007 AND 2018 TURKİSH EARTHQUAKE CODES

ELİFNUR ŞAKALAK[1]

Introduction

Throughout history, humankind has felt the need to build structures to meet basic needs such as protection and shelter. From ancient times to the present day, they have created living spaces using various materials, using the conditions, resources, and technologies of that era.

The first masonry structures date back to the Neolithic period. During this period, people constructed their homes using natural stones and adobe bricks. Over time, this construction system evolved with the use of bricks and concrete blocks (Çoban & Başaran, 2023: 928). The history of masonry structures dates back to the transition of people to settled life. In our country, masonry structures are preferred in the construction of low-rise buildings.

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Masonry structures are particularly prevalent in rural areas of Turkey (Ay et al., 2012: 41).

Masonry structures, which are one of the oldest types of structures and do not have a skeleton system, are structural systems formed by combining materials such as stone, brick, adobe, briquette, wood and autoclaved aerated concrete with binders.

In masonry structures, walls not only function as dividing elements but also as load-bearing elements. They both transmit vertical loads to the foundation and provide structural integrity against horizontal loads. In masonry systems, load transfer occurs through the interaction between the material units and the binding mortar. In these structures, which generally do not have a supporting skeleton, the walls work together with the floor and roof systems to form a whole. Therefore, material selection, wall thickness, binder type and workmanship quality are among the basic factors that directly affect the strength and seismic behavior of masonry structures.

Masonry buildings constitute a significant portion of Turkey's building stock. Since they are generally constructed without engineering services, some masonry buildings suffer moderate or severe damage and loss of life in earthquakes with instrumental magnitudes of 5.5~6.0 (Güler, 2021: 6).

Masonry structures are structural systems composed of brittle materials such as stone, brick, and wood, with high compressive strength but low tensile strength. Because these materials lack ductility, masonry structures offer limited resistance to tensile stresses generated during earthquakes and ground movements; this can cause structures to exhibit brittle fracture behavior and suffer sudden strength losses. The geometry of load-bearing walls, the quality of the materials used, and the way they are assembled directly affect the performance of structures under vertical and horizontal loads. Because masonry buildings are heavy and rigid, the earthquake loads acting on them are large, which can lead to increased brittle behavior in structures with limited plastic deformation capacity. Furthermore, while the compressive strength of the blocks forming the wall is a determining factor in structural behavior, low tensile strength weakens flexural strength in the wall plane and perpendicular to it. Conversely, these materials have high fire resistance, but water absorption and porosity affect resistance to frost damage. All these features reveal both the advantages and the limitations of masonry buildings in terms of earthquake safety (Arun, 2005: 69-70; Akgül & Doğan, 2019: 73; Yılmaz, 2024: 338).

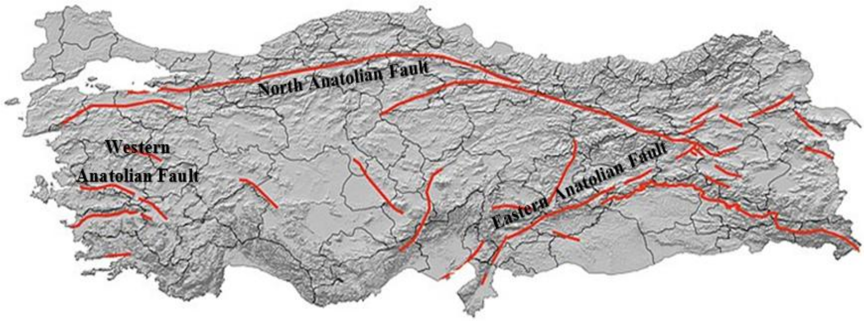
Turkey's location in an earthquake zone and the severe damage suffered by masonry buildings in past major earthquakes necessitate understanding the seismic behavior of these types of structures. Therefore, examining the seismic performance and damage mechanisms of masonry structures is critical for structural safety and disaster risk reduction.

The aim of this study is to examine the mechanical behavior of masonry structures under earthquake effects, damage types, and damage formation mechanisms. The study examines the stress distributions, crack development processes, and potential damage mechanisms induced by earthquake loads in masonry structures. Furthermore, the provisions related to masonry structures in the 2007 and 2018 Turkish Earthquake Regulations are compared to reveal the innovations these regulations provide in terms of damage prevention and performance assessment.

Turkey's Earthquake Reality and The Importance Of Masonry Buildings

Due to its tectonic location, Turkey lies within an active earthquake zone. Located between the Eurasian, African, and Arabian plates, Turkey experiences numerous destructive earthquakes as a result of the interaction between these plates. Turkey's major fault lines—the North Anatolian Fault (NAF), the East Anatolian Fault (EAF), and the West Anatolian Graben System—are the most significant tectonic zones that determine the country's earthquake hazard (Figure 1).

Figure 1. Turkey's main fault lines



These fault systems have been focal points of intense seismic activity throughout history and today, creating a high earthquake risk nationwide. Therefore, Turkey is among the countries with a high earthquake risk. Numerous earthquakes have occurred since the 1900s, causing thousands of deaths (Altun, 2018:5; Edemen et al., 2023:726). Table 1 lists some of the earthquakes with magnitude 5 and above in the last 10 years.

Table 1. Selected earthquakes of magnitude 5 and above that occurred in Turkey in the last 10 years

Date	Type	Magnitude	Depth	Location
27.10.2025	MW	6.1	6.07	Sındırgı (Balıkesir)
10.08.2025	MW	6.1	12.89	Sındırgı (Balıkesir)
15.05.2025	MW	5.2	18.27	Kulu (Konya)
27.10.2024	MW	5	9.7	Kozan (Adana)
16.10.2024	MW	5.9	10.48	Kale (Malatya)
7.09.2024	MW	5	7	Pazarcık (Kahramanmaraş)
18.04.2024	MW	5.6	5.25	Sulusaray (Tokat)
25.01.2024	MW	5.2	13.88	Battalgazi (Malatya)
23.11.2023	MW	5.2	7	Battalgazi (Malatya)

24.08.2023	MW	5	7	Yeşilyurt (Malatya)
10.08.2023	MW	5.3	7.89	Yeşilyurt (Malatya)
1.08.2023	MW	5	7.83	Selçuklu (Konya)
23.03.2023	MW	5.3	12.9	Göksun (Kahramanmaraş)
27.02.2023	MW	5.6	6.15	Yeşilyurt (Malatya)
27.02.2023	MW	5	8.51	Gölbaşı (Adıyaman)
25.02.2023	MW	5.3	2.28	Bor (Niğde)
20.02.2023	MW	5.8	6.64	Samandağ (Hatay)
20.02.2023	MW	6.4	21.73	Yayladağı (Hatay)
18.02.2023	MW	5.1	6.2	Göksun (Kahramanmaraş)
10.02.2023	MW	5	10.45	Yeşilyurt (Malatya)
8.02.2023	ML	5	16.69	Nurhak (Kahramanmaraş)
8.02.2023	ML	5.3	13.18	Doğanşehir (Malatya)
8.02.2023	MW	5.1	9.06	Göksun (Kahramanmaraş)
7.02.2023	MW	5	10.22	Göksun (Kahramanmaraş)
7.02.2023	MW	5.2	11.48	Göksun (Kahramanmaraş)
7.02.2023	ML	5.1	6.85	Sincik (Adıyaman)
7.02.2023	MW	5.3	6.93	Pütürge (Malatya)
7.02.2023	MW	5.4	8.44	Gölbaşı (Adıyaman)
7.02.2023	MW	5	6.87	Doğanşehir (Malatya)
6.02.2023	MW	5.2	5.82	Yeşilyurt (Malatya)
6.02.2023	MW	5.5	5.96	Pazarcık (Kahramanmaraş)
6.02.2023	MW	5	7.03	Göksun (Kahramanmaraş)
6.02.2023	MW	5.2	12.79	Göksun (Kahramanmaraş)
6.02.2023	MW	5.3	11.15	Yeşilyurt (Malatya)
6.02.2023	MW	5	7.04	Doğanşehir (Malatya)
6.02.2023	MW	5.1	8.76	Nurhak (Kahramanmaraş)
6.02.2023	MW	5.3	7.2	Doğanşehir (Malatya)
6.02.2023	MW	5.2	3.94	Göksun (Kahramanmaraş)
6.02.2023	ML	5.5	10.93	Ekinözü (Kahramanmaraş)
6.02.2023	ML	5.8	6.89	Yeşilyurt (Malatya)
6.02.2023	MW	7.6	7	Elbistan (Kahramanmaraş)
6.02.2023	MW	5	7	Çağlayancerit (Kahramanmaraş)
6.02.2023	MW	5.3	11.81	Nurdağı (Gaziantep)
6.02.2023	MW	5.1	6.95	Çelikhan (Adıyaman)
6.02.2023	MW	5.6	10.23	Doğanşehir (Malatya)
6.02.2023	MW	5.3	16.44	Pazarcık (Kahramanmaraş)
6.02.2023	MW	5.3	7	Gölbaşı (Adıyaman)
6.02.2023	MW	5.3	10.21	İslahiye (Gaziantep)
6.02.2023	MW	5.3	6.63	İslahiye (Gaziantep)
6.02.2023	MW	5	7	İslahiye (Gaziantep)

6.02.2023	ML	5.7	11.19	İslahiye (Gaziantep)
6.02.2023	MW	6.6	6.2	Nurdağı (Gaziantep)
6.02.2023	ML	5.6	6.98	Nurdağı (Gaziantep)
6.02.2023	MW	7.7	8.6	Pazarcık (Kahramanmaraş)
23.11.2022	MW	5.9	6.81	Gölyaka (Düzce)
11.10.2022	MW	5.1	7	Düziçi (Osmaniye)
27.09.2022	MW	5	9.45	Göle (Ardahan)
12.06.2022	MW	5	18.62	Tusba (Van)
9.04.2022	MW	5.2	6.72	Pütürge (Malatya)
19.11.2021	MW	5.1	5.18	Köprüköy (Erzurum)
17.11.2021	MW	5	18.29	Merkez (Düzce)
8.11.2021	MW	5.1	6.82	Meram (Konya)
31.08.2021	MW	5	12.07	Altintas (Kütahya)
25.06.2021	MW	5.2	15.51	Kigi (Bingöl)
27.12.2020	MW	5.3	15.94	Merkez (Elazig)
3.12.2020	MW	5	14.02	Kurtalan (Siirt)
20.09.2020	MW	5.1	6.2	Bor (Nigde)
4.08.2020	MW	5.2	8.16	Pütürge (Malatya)
26.06.2020	MW	5.5	9.29	Saruhanli (Manisa)
25.06.2020	MW	5.4	7.48	Saray (Van)
15.06.2020	MW	5.6	7.01	Karliova (Bingöl)
14.06.2020	MW	5.7	8	Karliova (Bingöl)
19.03.2020	MW	5	13.2	Sivrice (Elazig)
18.02.2020	MW	5.2	6.98	Kirkagaç (Manisa)
25.01.2020	MW	5.1	16.4	Sivrice (Elazig)
24.01.2020	MW	6.8	8.06	Sivrice (Elazig)
22.01.2020	MW	5.4	10.35	Akhisar (Manisa)
19.01.2020	MW	5.1	7.7	Iyon Denizi
26.11.2019	MW	6.2	6.9	Tiranë (Arnavutluk)
21.09.2019	MW	5.4	7	Tiranë (Arnavutluk)
8.08.2019	MW	6	10.92	Bozkurt (Denizli)
4.04.2019	MW	5.2	8.92	Sivrice (Elazig)
20.03.2019	MW	5.5	10.76	Acipayam (Denizli)
20.02.2019	MW	5	5.8	Ayvacik (Çanakkale)
24.04.2018	MW	5.1	9.79	Samsat (Adiyaman)
24.11.2017	MW	5.1	24.46	Ula (Mugla)
22.11.2017	MW	5	24.75	Ula (Mugla)
27.05.2017	MW	5.1	11.03	Saruhanli (Manisa)
13.04.2017	MW	5	11.33	Ula (Mugla)
2.03.2017	MW	5.5	9.76	Samsat (Adiyaman)
12.02.2017	MW	5.3	7	Ayvacik (Çanakkale)

10.02.2017	ML	5	7.01	Ayvacik (Çanakkale)
7.02.2017	MW	5.2	6.24	Ayvacik (Çanakkale)
6.02.2017	MW	5.3	8.72	Ayvacik (Çanakkale)
6.02.2017	MW	5.3	14.16	Ayvacik (Çanakkale)
10.01.2016	MW	5	13.6	ÇIÇEKDAGI (KIRSEHIR)

Reference: AFAD, 2025

These earthquakes in recent years are a result of Turkey's geologically active structure and make it necessary to increase the sensitivity to building safety.

The continuity of earthquake hazard necessitates the evaluation of the earthquake performance of building types and especially the examination of the strength properties of masonry structures.

Masonry structures are one of the most common types of buildings in Turkey, especially in rural areas. They have been preferred for many years due to the use of easily available local materials, low cost and fast construction. However, despite these advantages, most of the masonry structures were built without engineering services, traditional construction methods and without adequate detailing. This situation seriously increases the likelihood of damage to such structures under the influence of earthquakes.

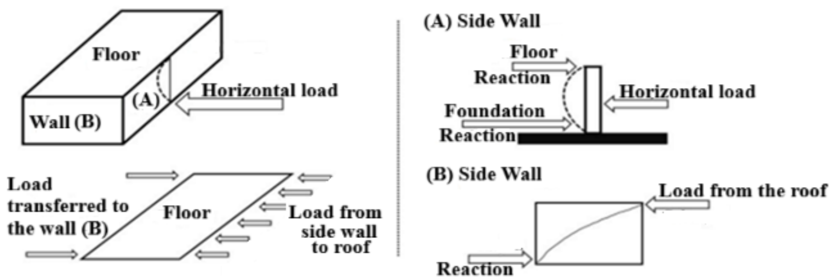
Most of the masonry buildings, which constitute a significant part of Turkey's building stock, do not meet the design requirements of the current regulations and exhibit poor performance that can cause serious loss of life and property in earthquakes. Therefore, understanding the earthquake behavior of masonry structures, scientifically explaining the damage mechanisms observed in these structures, and developing measures to strengthen the existing building stock are of great importance in terms of reducing earthquake risk in Turkey.

Earthquake Behavior and Damage Mechanisms of Masonry Structures

In masonry structures that do not have a load-bearing skeleton system, load transfer is achieved by the combined work of wall units and binding mortar. Masonry structures, which generally have high compressive strength, have low tensile strength. This can lead to the structure being unable to withstand the tensile stresses caused by horizontal forces occurring within the structure during an earthquake, potentially leading to sudden damage.

Seismic resistance in masonry buildings varies depending on the compressive strength of the materials used and the strength properties of the mortar. In masonry structures with rigid floor slabs, horizontal loads generated during an earthquake are distributed to the vertical load-bearing wall elements in proportion to the wall stiffness. Wall stiffness depends on the ratio of the length of the wall segment to the wall height. The horizontal load distribution in a masonry structure with walls of same thickness is given in Figure 2 (Yılmaz, 2024: 340).

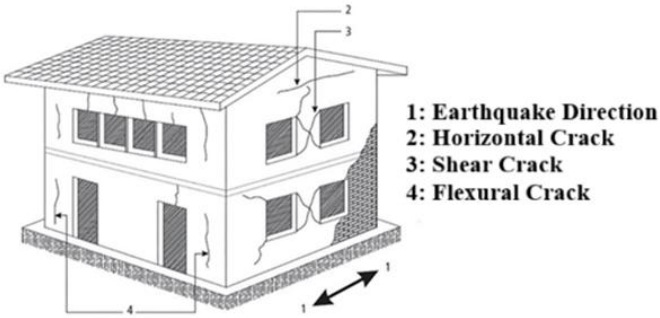
Figure 2. Horizontal load distribution model of masonry building



Reference: Bayülke, 2011:7

To accurately assess the damage, it's necessary to determine the cause of the cracks. Whether the damage or crack is structural is crucial. Figure 3 shows cracks that may occur after an earthquake, depending on the direction of the earthquake (Güleç, 2023:636).

Figure 3. Types of cracks that may occur in masonry structures after an earthquake



Reference: Güleç, 2023:636

Damages in masonry structures are mostly in the form of cracks in the walls, deterioration of the materials used (loss of physical and mechanical properties) and settlements in the foundation (Çırak, 2011: 56; Erçolak, 2021: 25).

Damage is classified into different levels depending on the impact it has on the structural system of the building.

<u>Light Damage</u>: Small-scale plaster cracks, peeling plaster, fine separations, and slight deformations may occur in the structure. The carrier system of structural is generally unaffected, and structural integrity is not compromised, but maintenance may be required.

<u>Moderate Damage</u>: Larger, significant cracks, peeling plaster, deformations, and material losses may be observed in the walls. The structure's load-bearing walls may be affected. The structure may require reinforcement.

<u>Heavy Damage</u>: Large cracks, separations, collapses, and great deformations may occur in the walls. The arrier system of

structural may be significantly damaged, reducing its load-bearing capacity. There is a risk of collapse.

Complete Demolition: The masonry structure suffers great losses and may collapse completely. Walls collapse. The structure becomes unusable. The structure cannot be saved or repaired, and must be rebuilt.

Figure 4 shows examples of damage in masonry buildings classified as light, medium and heavy.

Figure 4. Examples of masonry structures classified as light, moderate or heavy damaged

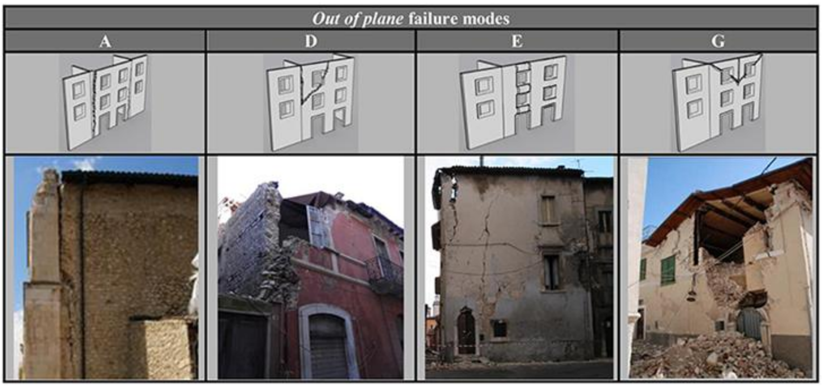
Reference: Yılmaz & ark., 2023: 45

There are two basic damage mechanisms in masonry structures under the influence of earthquakes: in-plane and out-of-plane (Güleç, 2023:637).

- **Out-of-Plane Damage Mechanism:**

Out-of-plane behavior occurs as a result of earthquake forces acting perpendicular to the wall surface. This effect usually occurs in the form of overturning outwards on walls that are not well connected to the flooring or roofing system. Out-of-plane collapse is usually sudden and disruptive; Therefore, it is one of the most critical types of damage in terms of life safety. The out-of-plane failure mechanisms are illustrated in Figure 5.

Figure 5: Out of plane failure modes



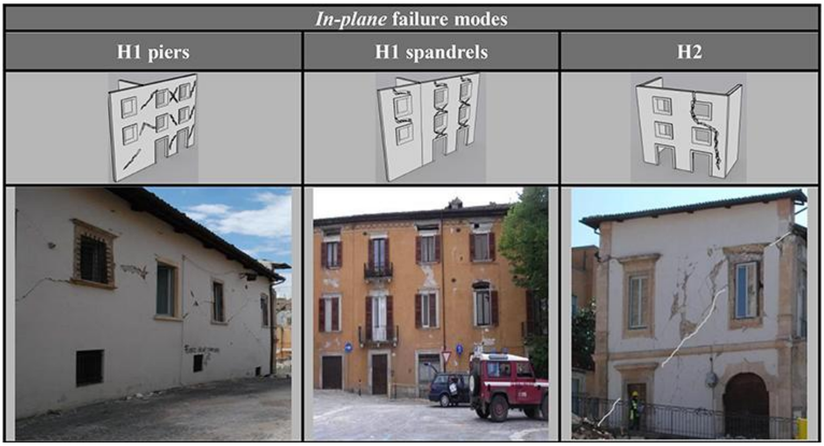
Reference: Novelli & D'ayala, 2019: 4; D'Ayala & Paganoni 2011: 88

- **In-Plane Damage Mechanism:**

In masonry structures, load-bearing walls behave like shear walls in order to resist the in-plane lateral forces caused by earthquakes. Shear cracks form in the form of diagonal or inclined tensile cracks in load-bearing walls. These cracks progress in the form of planar shear cracks along the horizontal soil joints and spread gradually from the heads to the base connection points (Günaydin & ark., 2021: 2448; Yılmaz, 2024: 340).

During an earthquake, the inertial forces generated by the weight of the structure and the seismic forces exert opposing forces on the structure. As a result of these forces, shear and bending effects often occur simultaneously in masonry structural elements. These effects can lead to cracks or separations in the masonry structural element, and these types of damage are generally referred to as in-plane damage (Güleç, 2023:640). The in-plane failure modes are illustrated in Figure 6.

Figure 6: In plane failure modes



Reference: Novelli & D'ayala, 2019: 4; D'Ayala & Paganoni 2011: 88

The resistance of masonry structures to in-plane stresses is higher than to out-of-plane stresses. This is generally due to the high compressive strength of the materials used in masonry structures. For this reason, masonry structures are more resistant to in-plane stresses (Güleç, 2023:637).

Throughout history, Turkey has experienced numerous earthquakes with instrumental magnitudes ranging from 5.0 to 7.7. Many structures have sustained varying degrees of damage.

A review of past earthquakes reveals that existing masonry buildings are inadequately capable of withstanding earthquakes of magnitudes 5.5 to 6.0. Masonry buildings in rural areas, in particular, have been observed to have sustained severe damage (Güler, 2021:9). When earthquake zones are examined, the primary causes of damage to masonry structures can be listed as follows.

Poor workmanship and application errors:

- They were built by local craftsmen, using local materials, based on experience, without the need for any engineering services
- Irregular wall construction, improper application of bond beams and connection details, and incomplete filling of joint gaps

Inadequate fasteners:

- Lack of sufficient anchors and binding elements at wall-flooring, wall-roof, and wall-wall joints

Lack of bond beams:

- Failure to use horizontal bond beams at flooring and roof levels to ensure walls work together

Poor material quality:

- The binding mortar is generally made of materials with poor adherence

Improper or asymmetric arrangement of openings

- Excessive or irregular placement of window and door openings

Irregular Plan and Geometry:

- Irregularities in the building's plan or vertical alignment

Insufficient Rigid Diaphragm Effect:

- Inability to achieve rigid diaphragm behavior in wooden or weak flooring systems

Figure 7, Figure 8 and Figure 9 show examples of masonry structures damaged by earthquakes in Turkey.

Figure 7. Examples of masonry structures damaged in the 2011 Van Earthquake

Reference: Güler, 2021: 7

Figure 8. Examples of masonry structures damaged in the February 6 Pazarcık Earthquake

Reference: Yetkin, 2024: 827-829

Figure 9. Examples of masonry structures damaged in the 2020 Bingöl-Karlıova Earthquake

Reference: Kocaman & Kazaz, 2021: 157-158

Masonry Buildings In 2007 and 2018 Turkish Earthquake Regulations

The first earthquake code used in our country came into force in 1940 after the Erzincan Earthquake that occurred on December 26, 1939. Together with the 2018 Turkish Building Earthquake Regulation, which entered into force on January 1, 2019, a total of 10 earthquake regulations have entered into force in Turkey (Özkat & Kuruşcu, 2019:120).

The 2018 Turkish Building Earthquake Code addresses masonry structures in greater detail. Compared to the 2007 Regulation on Buildings to be Constructed in Earthquake Zones, there are numerous changes. Below, a summary of the key differences and key amendments between the two codes is provided.

- The most important difference between the two regulations is the change in the calculation method. While the safety stress calculation method was used in the 2007 earthquake regulation, the bearing capacity calculation method began to be used with the entry into force of the 2018 earthquake regulation.
- The types of masonry structures have increased in the 2018 earthquake code. While the concept of unreinforced masonry building existed in the 2007 earthquake code, the concepts of unreinforced, confined, reinforced, and reinforced panel system masonry buildings have been introduced in the 2018 earthquake code.
- While it was stated in the 2007 earthquake regulation that the concrete class to be used in masonry buildings should be at least C16, in the 2018 earthquake regulation this class is foreseen as at least C25 (Özkat & Kuruşcu, 2019:125-126).
- In the 2018 earthquake regulations, it is seen that the concrete quality has been improved, the stirrup spacing has been reduced, the longitudinal reinforcement diameter has been increased, and the stirrup length has been increased (Özkat & Kuruşcu, 2019:125-126).
- While the 2007 earthquake code allowed the use of low-strength materials such as adobe brick as masonry units, this was abolished in the 2018 earthquake code. The 2007 earthquake code stated that the "Equivalent Earthquake Load" calculation method should be applied in earthquake calculations. The 2018 earthquake code stated that structural analysis should be performed using either finite elements or equivalent bar methods (Özkat & Kuruşcu, 2019:125-126).

Conclusion

Masonry structures have been a widely preferred building type in Turkey throughout history for both economic and cultural reasons. However, due to their lack of a structural frame and their brittle material properties, these structures exhibit a high degree of vulnerability to earthquakes. Studies indicate that a significant portion of masonry buildings in Turkey have sustained severe damage or completely collapsed in medium- and large-scale earthquakes. This demonstrates that masonry structures require a more comprehensive approach to earthquake safety in both their design and implementation.

A comparison of the 2007 Regulation on Buildings to be Constructed in Earthquake Zones and the 2018 Turkish Building Earthquake Code reveals that the engineering understanding of masonry structures has evolved significantly over the years. The 2018 Turkish Building Earthquake Code significantly improved the definitions, material specifications, calculation methods, and performance criteria for masonry structures. These updates allow for a more realistic assessment of the seismic performance of masonry structures. However, the effectiveness of the codes depends not only on the technical regulations themselves but also on the level of implementation of these provisions on site. Buildings constructed without engineering supervision, particularly in rural areas, remain in the high-risk group.

Accurately understanding the seismic behavior of masonry structures requires the development of numerical modeling methods, material testing, and experimental analyses specific to this type of structure. Furthermore, expanding engineering services and integrating traditional construction techniques with contemporary engineering principles in rural areas are critical to improving the seismic safety of masonry structures.

Ultimately, improving the seismic safety of masonry structures requires not only engineering design but also the integration of material selection, inspection, maintenance, and traditional building culture with modern methods. This holistic approach will significantly contribute to improving the resistance of both historic and contemporary masonry structures to future earthquakes and creating safer building stocks.

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CHAPTER 10

BÖLÜM I

Transformation of Construction Cost Management in Türkiye within the Scope of the 2053 Net Zero Emission Target

Başak ZENGIN[1]

INTRODUCTION

Türkiye's 2053 Net Zero Emission target necessitates a fundamental reassessment of cost structures in the construction sector through technical, quantitative, and measurable approaches. Due to its high embodied carbon, energy-intensive production processes, and large-scale material consumption, the construction sector is among the primary areas directly affected by carbon reduction policies. In this context, cost management has evolved beyond traditional budget control and unit price analyses, transforming into an integrated analytical framework that incorporates carbon pricing, energy efficiency, and life cycle costing (LCC).

Within the scope of net zero targets, carbon–cost analyses reveal the impacts of carbon-related policy instruments on construction project cost structures and identify sector-specific adaptation strategies. The promotion of energy-efficient buildings

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and low-carbon construction solutions has triggered significant transformations in construction materials and production technologies. While rising energy prices, carbon taxes, and incentive mechanisms directly influence project budgets, sustainable materials and systems—despite increasing initial investment costs—demonstrate a clear potential to reduce long-term operational expenditures.

The literature indicates that green buildings typically involve an initial cost increase of approximately 5–15%, while energy-efficient systems can reduce operational costs by 20–40% over the building life cycle (Giesekam et al., 2016; Ürge-Vorsatz et al., 2020). Although low-carbon materials are often associated with higher upfront costs, they become economically competitive under carbon pricing policies. Furthermore, the integration of Life Cycle Assessment (LCA) and Building Information Modeling (BIM) enhances the accuracy of cost estimations and supports more informed decision-making processes. The European Union Emissions Trading System (ETS) has also been shown to exert significant impacts on the costs of key construction materials such as cement and steel (Liu et al., 2020; Gao et al., 2021).

Within this framework, the present study aims to identify the differences between analytical approaches in the international literature and current practices in Türkiye, and to develop new strategies for construction cost management that simultaneously address carbon reduction and cost optimization. Accordingly, material-based embodied carbon values, energy consumption profiles, carbon pricing mechanisms, and digital cost estimation tools are evaluated within a comprehensive technical framework.

1. Carbon–Cost Analysis Methods

Carbon–cost analyses are fundamental tools that enable the integrated evaluation of costs and carbon footprints in line with sustainability targets in the construction sector. These analyses are generally based on two main approaches: cost-oriented and carbon-oriented analyses. Cost-oriented analyses compare the economic performance of alternative projects and implementation options by considering materials, labor, equipment, and technological investments, whereas carbon-oriented analyses focus on assessing emissions generated throughout the life cycle of buildings.

Within this framework, Life Cycle Assessment (LCA), scenario-based modeling, and integrated cost–carbon analyses are among the most prominent methods. Scenario analyses simulate the potential impacts of different policy and technological developments on costs and emissions, providing decision-makers with comparative evaluation capabilities. The integration of Building Information Modeling (BIM) and LCA improves the accuracy of cost estimates and reduces uncertainties in design and construction processes.

The reliability of models used in carbon–cost analyses depend on their continuous updating with current energy prices, technological advancements, and sector-specific data. Evaluating cost and carbon impacts at different stages of the construction process, both individually and holistically, enables more realistic outcomes and contributes to the development of strategies aligned with the sector's sustainability objectives (Kılıç, 2022)

2. Türkiye's Political and Economic Structure

Türkiye's political and economic framework plays a critical role in achieving the 2053 net zero emission target. The country's geographical location and economic characteristics shape energy supply and demand dynamics, while the construction sector evolves in parallel with these conditions. Dependence on energy imports and the diversity of domestic energy resources are among the key factors influencing cost management in the construction industry. In addition, economic growth rates and the scale and direction of public and private sector investments directly affect construction costs.

From a policy perspective, government strategies aimed at sustainability and carbon reduction may include regulatory measures that either incentivize or constrain the construction sector. In this context, the integration of low-carbon technologies and renewable energy sources necessitates new methodologies in cost planning. Furthermore, Türkiye's macroeconomic conditions—such as inflation rates, exchange rate volatility, and fluctuations in interest rates—pose significant challenges for project financing and cost calculations in construction projects.

Considering these dynamics, carbon–cost scenarios introduce new risks and opportunities for cost management, particularly through fluctuations in energy costs and material prices. Consequently, Türkiye's political and economic structure requires strategic alignment and adaptive capacity to ensure the sustainable and effective management of construction costs in line with net zero objectives (Sert et al., 2025; Demir & Altuntaş, 2024; Yıldırım, 2024; Eroğlu, 2024; Acar, 2024).

3. Methodology

This study employs scenario-based modeling approaches to analyze the impacts of transformations in energy use and carbon emissions on construction costs. In the first stage, existing data sources compatible with construction cost components and carbon emission indicators were examined. These datasets form the basis for future projections developed under different policies and economic conditions. The concept of net zero refers to balancing emitted carbon with emissions removed from the atmosphere (IPCC, 2021). Within the construction sector, carbon emissions are categorized into two main components: embodied carbon arising from material production and construction processes, and operational carbon resulting from energy consumption during the use phase of buildings.

In the second stage, multi-layered modeling tools integrating carbon and cost components were developed. Carbon taxes and incentive mechanisms were linked with material-based carbon footprint data, while parametric simulation and scenario analysis techniques were applied to assess the effects of production efficiency and material selection on cost dynamics.

In the final stage, cost and emission outputs obtained from different scenarios were comparatively analyzed, and strategies aligned with Türkiye's current policy framework were formulated. The findings demonstrate that cost–carbon integrated modeling provides a robust analytical tool for policymakers by capturing the combined effects of economic and political factors on the construction sector and supporting long-term decision-making processes.

3.1. Data Sources

Data sources constitute the foundation of this study and are critical to ensuring the reliability and validity of the analyses. Official statistics and reports published by governmental institutions were primarily used. Economic and construction sector data provided by the Turkish Statistical Institute (TURKSTAT) served as the main national reference. In addition, carbon emission inventories and sustainability reports issued by the Ministry of Environment, Urbanization and Climate Change were incorporated to analyze sectoral carbon footprints through spatial and temporal dimensions.

International datasets published by organizations such as Eurostat, the World Bank, and international environmental agencies were also utilized, particularly for comparative analyses of carbon markets and cost trends. Sectoral reports provided up-to-date information on renewable energy technologies and their cost trajectories.

Furthermore, expert opinions and sectoral insights obtained through interviews and surveys were considered to better understand construction cost structures and the adoption level of carbon-saving technologies. All datasets were cleaned, normalized, and cross-validated prior to analysis, enhancing the robustness and analytical depth of the results (Polat & Fendoglu, 2021; Torun, 2021; Akcan & Azazi, 2022).

3.2. Scenario Design

Multiple scenarios representing alternative future pathways were developed by considering current policies, economic trends, and technological advancements. Key drivers such as carbon tax levels, incentive mechanisms, regulatory changes, and sectoral adaptation capacity were incorporated into scenario assumptions. Each scenario explicitly defined emission reduction pathways and their cost implications.

Economic modeling techniques supported by real-world data were employed to ensure realistic representation of future conditions. Through this approach, the scenarios provide a framework for evaluating sectoral risks and opportunities, enabling stakeholders to develop informed cost management strategies. Scenario design thus serves as a key analytical tool guiding policy formulation and decision-making in construction cost management.

Key factors influencing the cost–carbon relationship in sustainable construction include:

- Material selection
- Energy consumption
- Transportation distance
- Production technology
- Waste management
- Life cycle assessment (LCA)
- Building type and structural system
- Renewable energy integration
- Green building certification schemes

3.3. Cost–Carbon Integration Modeling

The cost–carbon integration model enables the simultaneous evaluation of sustainability objectives and cost efficiency in the construction sector. Energy and material consumption data are integrated with greenhouse gas emission factors to quantify the impact of carbon footprints on total project costs. Carbon pricing and incentive mechanisms are analyzed in relation to material procurement, construction processes, and overall cost structures, with the model dynamically updated according to policy and market conditions.

Scenario-based comparisons assess the cost advantages and risks associated with emission reduction technologies, renewable energy solutions, energy efficiency measures, and material optimization strategies. This integrated framework allows for a holistic evaluation of the financial and environmental performance of construction projects.

In Türkiye, construction costs are largely driven by material expenditures, with cement and steel representing the primary sources of carbon emissions. Net zero targets are expected to transform existing cost distributions through increased adoption of low-carbon materials, renewable energy systems, and energy-efficient designs. While these measures may increase initial investment costs, they offer significant potential for reducing operational expenses over the building life cycle. The chart illustrates how different sustainability criteria affect both project costs and carbon emissions. All criteria significantly reduce carbon emissions (−100%), confirming their environmental benefits. However, cost impacts vary material efficiency decrease costs, while recycled materials, energy-efficient design, and renewable energy increase initial costs by approximately 100%. Building orientation has a neutral cost effect. These findings highlight the trade-off between short-term cost increases and long-term carbon reduction benefits, emphasizing the need for balanced policy and design strategies (Figure 1).

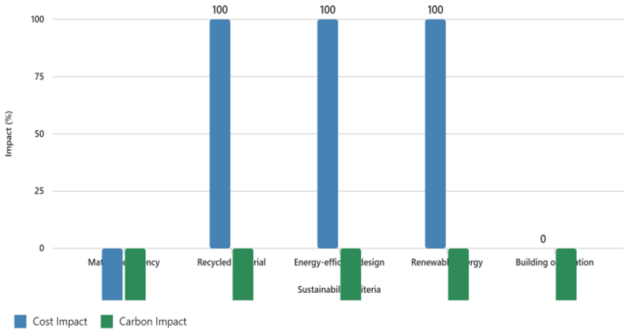

Figure 1. Impact of Sustainability Criteria on Cost and Carbon Emissions

Material costs currently account for approximately 55–65% of total construction costs, followed by labor (10–20%), machinery and equipment (5–10%), and overheads (10–15%). Net zero policies particularly influence material and energy-related cost components. The developed model enables comparative evaluation of cost and emission outcomes under different policy and economic scenarios, supporting strategic optimization of cost–carbon trade-offs (Yılmaz & Yüksel, 2025; Türker, 2021; Akbaş & Çalışkan, 2024; Altuntaş, 2024).

4. Results and Discussion

The scenario analyses reveal distinct trends in construction costs under different carbon pricing and incentive frameworks. Increased carbon taxation leads to higher energy costs and, consequently, rising total project costs. While incentives for carbon reduction partially offset these increases, their overall impact on total costs remains limited. Conversely, improvements in material efficiency and production processes indicate that sustainable technologies and low-carbon materials can reduce costs in the medium to long term.

Table 1. Impact of Sustainable Building Criteria on Project Cost and Carbon Emissions

Criterion	***Impact Mechanism***	***Cost Impact***	***Carbon Impact***
Material efficiency	Reduced material usage	Decs.	Decs.
Recycled material	Reuse	Incs.	Decs.
Energy-efficient design	Reduced heat loss	Incs.	Decs.
Renewable energy	Reduced electricity need	Incs.	Decs.
Building orientation	Passive design advantage	Neu.	Decs.

This table summarizes how key sustainability measures influence both project costs and carbon emissions in construction (Table1). All listed criteria contribute to reducing carbon emissions, demonstrating their environmental benefits. However, cost impacts vary significantly: Material efficiency lowers both cost and carbon emissions by reducing material usage. Recycled materials, energy-efficient design, and renewable energy increase initial costs due to higher implementation expenses, but they substantially reduce carbon emissions. Building orientation offers passive design advantages without affecting costs, while still decreasing carbon emissions. These findings highlight the trade-off between short-term cost increases and long-term sustainability benefits, emphasizing the need for balanced strategies in policy and design.

4.1. Scenario-Based Cost Trends

Scenario-based cost trends provide critical insights into the potential impacts of the 2053 net zero target on the construction sector. Rising carbon prices, increasing energy costs, and new regulatory requirements are examined under alternative scenarios.

Sustainability-oriented assumptions reveal future cost trajectories influenced by energy accessibility, material prices, and technological adoption. Accounting for increasing carbon mitigation costs in financial planning reduces uncertainty and supports long-term strategic decision-making.

Comparative analysis of Türkiye and selected European countries shows that sustainable material usage remains relatively low in Türkiye (10–15%) compared to Germany, the Netherlands, and Sweden, where lifecycle-based policies and circular economy practices drive higher adoption rates.

Table 2. Sustainable Material Usage Rates in Türkiye and Europe

Country	Usage Rates	Note
Türkiye	%10–15	Dominance of reinforced concrete
Germany	%35–40	Mandatory LCA
Netherlands	%40–50	Circular economic practices
Sweden	%45	Strong timber construction culture

This table compares sustainable material usage rates in Türkiye and selected European countries. Türkiye shows a relatively low adoption rate (10–15%) due to the dominance of reinforced concrete in construction (Table 2). In contrast, European countries demonstrate significantly higher rates: Germany (35–40%) enforces mandatory Life Cycle Assessment (LCA), the Netherlands (40–50%) promotes circular economy principles, and Sweden (45%) benefits from a strong timber-based building tradition. These differences highlight the need for Türkiye to accelerate policy measures and technological adoption to align with international sustainability standards.

4.2. Impacts of Carbon Taxes and Incentives

Carbon taxes directly increase energy and material costs, exerting upward pressure on construction prices. At the same time, incentive schemes promote the adoption of low-carbon materials and technologies. Although sustainable materials may entail higher upfront costs, carbon pricing and incentives enhance their long-term economic competitiveness through improved energy efficiency and reduced lifecycle costs.

Effective policy design is essential to balance cost increases and ensure financial sustainability. Well-structured incentives can mitigate cost burdens and facilitate sectoral transition toward low-carbon construction practices (Koç, 2024; Yurduseven, 2024; Karakaya et al., 2023).

4.3. Material and Production Efficiency Linkages

Material and production efficiency are closely linked to rising carbon costs and play a decisive role in cost management. Investments in low-carbon materials and efficient production technologies may increase initial costs but yield long-term economic benefits by reducing energy consumption and carbon liabilities. Modernization, automation, and optimized supply chains enhance cost control under increasing carbon pricing pressures.

Carbon pricing scenarios indicate that higher carbon prices significantly increase cement and steel costs, reinforcing the importance of material selection in cost optimization strategies.

Table 3. Material-Based Embodied Carbon – Average Values in Türkiye

Material	**Embodied Carbon** **($kgCO_2e/kg$)**	**Description**
Cement	0.7 – 0.9	High emissions
Steel	1.8 – 2.1	Production method matters
Wood	-0.1	Carbon storage
GeoplyCon.	0.2 – 0.4	Low-carbon material

This table presents the average embodied carbon values of common construction materials in Türkiye. Cement and steel exhibit the highest carbon intensities, with values ranging from 0.7–0.9 kgCO_2e/kg for cement and 1.8–2.1 kgCO_2e/kg for steel, making them major contributors to construction-related emissions. In contrast, timber shows a negative or near-zero carbon footprint due to its ability to store carbon, positioning it as a highly sustainable choice. Geopolymer concrete, with values between 0.2–0.4 kgCO_2e/kg, offers a low-carbon alternative to traditional cement. These findings underscore the importance of material choice in reducing embodied carbon and achieving net-zero targets in the construction sector.

4.4. Policy Design Insights

Policy instruments targeting net zero emissions have both direct and indirect cost implications. Carbon pricing mechanisms increase short-term costs but incentivize innovation and sustainable practices. Integrating long-term financing tools and adaptive incentives can facilitate sectoral transition while minimizing cost uncertainty. Transparent and predictable policies reduce investment risks and support sustainable construction development.

4.5. Sectoral Differences and Risks

Structural differences among construction sub-sectors significantly influence the cost impacts of net zero policies. Energy-intensive segments face greater cost pressures, while low-carbon applications experience relatively limited effects. Sustainable building practices involve higher upfront costs but deliver substantial long-term benefits through reduced lifecycle costs and carbon emissions.

Considering sectoral differences is critical for effective policy design. A comprehensive assessment of sector-specific risks enables balanced solutions that support financial sustainability and long-term alignment with net zero objectives.

5. Conclusions

This study has examined the expected transformation of construction cost structures in Türkiye within the scope of the 2053 Net Zero Emissions target through a multidimensional framework based on carbon–cost scenario analysis and life cycle costing (LCC). Considering the high carbon intensity, material dependency, and energy consumption profile of the construction sector, the findings clearly demonstrate that the impacts of carbon mitigation policies on cost management are both inevitable and structural in nature.

The analysis indicates that carbon pricing mechanisms lead to significant short-term cost increases, particularly for energy-intensive construction materials such as cement and steel. However, the results also show that energy efficiency measures, low-carbon materials, and the integration of renewable energy systems have substantial potential to reduce total costs over the life cycle of construction projects. Under scenarios where carbon prices range between €20 and €80 per ton of CO_2, project costs increase by approximately 8–35%, whereas sustainability-oriented design and technology-driven scenarios enable reductions in operating costs of 20–40% in the medium to long term.

The scenario-based carbon–cost integration model developed in this study demonstrates that construction cost management should not be limited to initial investment costs but should instead be evaluated in conjunction with life cycle costs and carbon emissions. In particular, the integration of Building Information Modeling (BIM) and Life Cycle Assessment (LCA) significantly improves the accuracy of cost estimates and enables carbon–cost optimization at the early design stage. These finding highlights digitalization as a key enabler of cost management aligned with net zero objectives.

A comparison between Türkiye and European countries in terms of sustainable material utilization reveals that the adoption rate in Türkiye remains relatively limited. In contrast, countries where LCA requirements, circular economy policies, and timber-based construction practices are well established demonstrate more favorable cost–carbon balances for sustainable materials. This outcome confirms the decisive role of regulatory frameworks and policy design in shaping sectoral behavior.

From a policy perspective, the findings suggest that treating carbon taxes and incentive mechanisms solely as cost-increasing or cost-reducing instruments is insufficient. Instead, these tools should be designed within a holistic, predictable, and sector-sensitive framework. To mitigate cost pressures during the transition period, the simultaneous implementation of financial incentives, green financing instruments, and long-term investment mechanisms is of critical importance.

In conclusion, the 2053 Net Zero Emissions target is driving a paradigm shift in construction cost management in Türkiye toward a carbon-oriented, life cycle-based, and digitally supported approach. While short-term cost increases are unavoidable, they can be effectively managed through technical optimization, material efficiency, and digitalization strategies. In the long term, this transformation offers significant opportunities for both environmental sustainability and economic rationality. In this context, analytical approaches based on carbon–cost integration emerge as indispensable decision-support tools for the construction sector within Türkiye's net zero transition roadmap.

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CHAPTER 11

PRODUCTS USED IN TIMBER CONSTRUCTION

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Introduction

Although timber has very ancient historical origins, it is a load-bearing structural material that has been reinterpreted through contemporary engineering approaches and has gained increasing importance in modern building production. The role of timber in building culture is not limited solely to material selection; rather, it is directly associated with the climatic conditions, natural resources, construction traditions, and technological capabilities of the geographical context in which it is used

In contemporary structural engineering practice, the role of timber in load-bearing systems has undergone a significant transformation with the development of engineered wood products. The inherent variability and dimensional limitations of solid timber have been largely mitigated through laminated and composite manufacturing techniques; consequently, products such as glued

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laminated timber, cross-laminated timber (CLT), and laminated veneer lumber (LVL) provide more predictable and reliable structural performance. These advancements have enabled the use of timber not only in low-rise buildings but also in multi-storey structures and structurally complex load-bearing systems.

Timberas a structural element

Historically, timber construction technology evolved in different forms across Europe and Asia. In Europe, timber frame applications dating back to the Middle Ages were primarily based on the assembly of load-bearing members through interlocking and mechanical fastening techniques. The timber frame systems of this period provided significant advantages in terms of deformation control and ease of maintenance and repair. The development of diverse connection techniques across different regions indicates that timber structural systems were optimized according to local material resources and climatic conditions (Perria, 2024).

Modern engineering has enhanced the performance of load-bearing systems by integrating historical knowledge of timber construction with advanced manufacturing techniques and experimental data. In particular, industrial wood products developed in recent years—such as cross-laminated timber (CLT) and glued laminated timber provide viable engineering solutions for long spans and multi-storey buildings. These advancements have repositioned timber not merely as a material associated with historical construction practices, but as a sustainable structural material fully integrated into contemporary engineering solutions (Perria, 2024).

Structural Timber Products Used in Buildings

The reliable use of timber in load-bearing systems requires the control of uncertainties inherent in its natural material structure. The anisotropic behavior of natural timber depending on fiber orientation, together with the presence of knots, grain deviations, and sensitivity to moisture variations, complicates the prediction of structural performance. For this reason, in modern structural engineering practice, timber is not considered solely as a solid material; instead, it is increasingly evaluated through engineered structural timber products whose mechanical properties have been enhanced and standardized through industrial manufacturing processes (Ross, 2010).

The structural timber products used in buildings can be examined by classifying them into member-based and panel-based engineered wood products.

Solid Timber

Solid timber refers to natural wood elements obtained by longitudinally sawing logs, in which the continuity of fibers is preserved. From a structural engineering perspective, the primary advantage of solid timber lies in its high compressive and tensile strength parallel to the grain. However, the presence of knots, grain deviations, and density variations within solid timber results in non-homogeneous mechanical behavior. This characteristic complicates performance prediction, particularly for load-bearing members subjected to combined bending and compressive actions (Arriaga et al., 2023).

In addition, solid timber is sensitive to moisture variations induced by environmental conditions and exhibits shrinkage and swelling behavior. These properties have limited its application in modern load-bearing systems; consequently, solid timber is now predominantly used in low-rise buildings, temporary structures, and restoration applications(Ross, 2010).

Engineered Timber Products

Structural Composite Lumber (SCL) products are engineered wood materials developed to minimize the inherent defects of natural timber and to achieve controlled mechanical properties (Singer & Özşahin, 2020). In these products, wood is processed into strand or veneer forms and bonded using resin-based adhesives, followed by pressing under high pressure. Through this manufacturing process, the modulus of elasticity, strength, and material continuity become more predictable and reliable (Ghazanfari and Malzl, 2025).

Glued Laminated Timber

Glued laminated timber is an engineered structural material produced by bonding thin timber laminations together with their grain directions aligned parallel to each other using structural adhesives. This manufacturing technique reduces the adverse effects of natural timber imperfections such as knots, grain deviations, and density variations on structural behavior, thereby enabling the achievement of more homogeneous and predictable mechanical properties (Greffier et al., 2024).

One of the most significant engineering advantages of glulam elements is the safe production of large cross-sections and long spans. Through the grading of laminations during the manufacturing process and their strategic placement within the cross-section, higher-strength laminations can be positioned in zones subjected to maximum bending stresses. As a result, glulam members exhibit superior bending strength and modulus of elasticity compared to solid timber (Ross, 2010).

In structural applications, glulam is commonly used in beam–column systems, frame structures, long-span roof systems, sports halls, and industrial buildings with high load-bearing capacity and geometric flexibility are required. Furthermore, the ability to manufacture laminations in curved shapes during production provides glulam members with considerable architectural design flexibility (Ross, 2010).

The structural behavior of glulam members provides high compressive and tensile strength parallel to the grain (Greffier et al., 2024). However, the design of connection regions is a decisive factor in the overall performance of glulam structural systems (Lee & Kim, 2000). In joints formed using mechanical fasteners and steel connection details, accurate modeling of the load transfer mechanisms and proper consideration of joint stiffness are critical to ensuring the reliability of the global structural response (Greffier et al., 2024).

Laminated Veneer Lumber (LVL)

One of the most important engineering characteristics of laminated veneer lumber (LVL) is its high bending and compressive strength. Experimental studies on LVL under both tensile and bending loading have demonstrated more predictable load–deformation relationships and high stiffness values parallel to the grain this reason, LVL members are widely preferred for primary load-bearing applications such as beams, columns, and floor systems (Romero and Odenbreit, 2023).

In the production of LVL, the grain directions of the veneer panels are arranged to be almost entirely parallel. This configuration further enhances the bending strength and modulus of elasticity of natural timber, as the parallel alignment of fibers provides more controlled and predictable behavior under loading. At the same time, the veneer-based manufacturing process allows for the efficient utilization of small-diameter or lower-grade timber resources.LVL is widely evaluated for critical load-bearing components such as floor joists, roof load-bearing members, floor headers, and prefabricated elements, particularly due to its high load-carrying capacity, dimensional stability, and ability to span long distances (Romero and Odenbreit, 2023, Li et al., 2025).

Parallel Strand Lumber (PSL)

Parallel Strand Lumber (PSL) is an engineered wood product manufactured by orienting wood strands parallel to the longitudinal direction, bonding them with high-strength structural adhesives, and consolidating the assembly under high pressure. PSL belongs to the Structural Composite Lumber (SCL) family and, through optimized fiber orientation and adhesive application, exhibits a more predictable structural response, higher strength, and improved dimensional stability compared to conventional solid timber.In the production process of PSL, veneer strands obtained through rotary peeling are commonly used and aligned longitudinally; these strands are then bonded using water-resistant structural adhesives. The assembly is subsequently consolidated through pressing to form a single large billet(Hindman and Lee, 2007).

The parallel alignment of fibers enables PSL to exhibit high mechanical performance, particularly under compressive, bending, and axial loading Compared to solid timber of the same species and other engineered wood products, PSL generally demonstrates higher characteristic strength properties (Kurt et al., 2012). Accordingly, PSL is widely preferred for beams, columns, and post-and-beam structural members. These products have been successfully applied in residential, Commercial and industrial buildings requiring high load-bearing capacity (Kurt et al., 2012; Madsen and Buchanan, 1986)

Laminated Strand Lumber (LSL)

Laminated Strand Lumber (LSL) is an engineered wood product manufactured by orienting short wood strands with their fiber directions largely parallel and consolidating them using structural adhesives under pressure. LSL belongs to the Structural Composite Lumber (SCL) family and has been developed specifically to reduce the mechanical and geometric limitations associated with solid timber and conventional sawn lumber.The wood strands used in LSL production are shorter than those employed in PSL, yet thicker than the veneer sheets used in LVL. This configuration enables the effective utilization of small-diameter or lower-grade logs, thereby improving material efficiency while promoting a more homogeneous distribution of mechanical properties. Accordingly, the literature recognizes LSL as a balanced engineered product from both economic and structural perspectives (Kurt et al., 2012).

From a mechanical behavior perspective, LSL exhibits more predictable bending strength and modulus of elasticity compared to solid timber. Experimental studies have shown that LSL members display more consistent stress–strain behavior under compression and bending loads parallel to the grain, with a significant reduction in sudden strength losses associated with material defects. Consequently, the mechanical performance of LSL is lower than that of PSL and LVL; therefore, LSL is generally preferred for structural members requiring moderate load-bearing capacity (Hasan et al., 2024; Moradpour et al., 2018).

In structural applications, LSL is commonly used as wall studs, beams, lintel elements, and components of light- to medium-load-bearing frame systems. Although LSL is not as frequently selected as PSL or LVL for primary beams and columns requiring high load-carrying capacity, it plays an important role in ensuring structural continuity in multi-storey residential buildings and prefabricated systems. In this respect, LSL represents a balanced engineered wood product that provides an effective compromise between economic efficiency and structural performance (Kurt et al., 2012).

Oriented Strand Lumber (OSL)

Oriented Strand Lumber (OSL) is a strand-based engineered wood product manufactured by orienting short and thin wood strands in predetermined proportions during production and consolidating them through pressing with structural resin adhesives. OSL is part of the Structural Composite Lumber (SCL) family and has been specifically developed for applications requiring moderate load-bearing capacity (Hassani et al., 2019).

In terms of mechanical properties, OSL provides a more homogeneous distribution of modulus of elasticity and strength compared to solid timber (Zhu et al., 2019; Hassani et al., 2019). One of the key advantages of OSL is its ability to efficiently utilize low-grade or small-diameter logs, thereby enhancing raw material efficiency and aligning with the objectives of sustainable forest management. In structural applications, OSL is commonly used as wall studs, beams, lintel elements, and components of light- to medium-load-bearing frame systems. While PSL or LVL is generally preferred for primary structural members requiring high load-carrying capacity, OSL is more frequently selected for residential and prefabricated building systems where economic solutions are prioritized (USDA Forest Service, 2015).

Panel-Based Structural Timber Products

Cross-Laminated Timber (CLT)

Cross-Laminated Timber (CLT) is an engineered wood product manufactured by arranging timber boards in layered configurations with their grain directions oriented perpendicular to each other and bonding them using structural adhesives.The fundamental engineering concept behind the development of CLT is to mitigate the grain-direction-dependent mechanical limitations of solid timber and to produce large-scale panels that are capable of carrying loads in two orthogonal directions while exhibiting high stiffness and dimensional stability. This manufacturing technique enables CLT panels to demonstrate more predictable structural behavior under both vertical and horizontal loading conditions. From a mechanical standpoint, CLT exhibits high load-bearing capacity under in-plane shear, bending, and compressive actions (Brandner et al., 2016).

Connections have a significant effect on the structural behaviour of CLT systems.. Panel-to-panel and panel-to-foundation connections are typically provided by steel fasteners, and a significant portion of the structure's energy dissipation capacity is concentrated in these connection regions. For this reason, CLT buildings are generally classified as semi-ductile systems, in which ductile behavior is largely managed the performance of the connections (Ceccotti et al., 2013).

At present, CLT is widely used in a variety of structural systems, particularly in multi-storey residential buildings, office buildings, schools, and mixed-use developments. Owing to the advantages of panel-based production and prefabrication, CLT systems enable rapid construction, high levels of quality control, and a reduction in construction-site-related errors, thereby offering both structural and execution-related benefits (Yürekli & Karaman, 2023)

Structural Oriented Strand Board (OSB)

Structural Oriented Strand Board (OSB) is an engineered wood product manufactured by arranging thin and elongated wood strands in layered configurations and consolidating them through pressing with structural adhesives (Ayrılmış, 2022). The effects of knots, grain deviations, and localized defects typically observed in natural timber are largely mitigated through strand-based production. The bending strength and modulus of elasticity of OSB can be adjusted depending on its structural parameters and manufacturing configuration (Aguiar et al., 2023).

With respect to moisture effects, OSB exhibits more stable behavior than solid timber; however, it may experience swelling at panel edges when exposed to water. Therefore, OSB panels must be selected in accordance with the appropriate service class, and moisture effects should be carefully considered during detailing and design. OSB is widely used in floor sheathing, wall and roof diaphragms, temporary and permanent shear walls, and prefabricated timber structural systems (Aguiar et al., 2023).

Plywood (Structural Panel)

Plywood is a layered engineered wood panel manufactured by stacking thin wood veneer layers with their grain directions oriented perpendicular to each other and bonding them under pressure using structural adhesives. One of the primary advantages of plywood is its favorable bending and shear behavior under load. The cross-laminated arrangement of veneer layers reduces weaknesses perpendicular to the grain direction and significantly enhances panel stiffness (Kretschmann, 2010).

In timber frame construction systems, plywood is predominantly used as sheathing and as diaphragm or shear wall elements. Connection detailing plays a decisive role in the structural performance of plywood panels. Parameters such as nail type, spacing, and edge distances directly influence the shear capacity and ductile behavior of the panel system.In terms of moisture and environmental effects, plywood exhibits superior dimensional stability compared to solid timber. The cross-layered configuration effectively limits shrinkage and swelling, thereby allowing long-term deformations to be maintained within acceptable limits. Plywood is widely utilized in wall shear panels, floor and roof diaphragms, temporary and permanent sheathing applications, and prefabricated timber structural systems (Kretschmann, 2010).

Conclusion

Timber structural systems, while possessing strong historical roots, have undergone a significant transformation through advances in modern engineering and materials science. This development process, extending from solid timber to engineered wood products, has increased the diversity of structural systems, enhanced structural performance, and enabled the safe application of timber in multi-storey buildings.

In conclusion, timber structures have become a strong, reliable, and sustainable alternative in the contemporary construction sector through the use of engineered wood materials, advanced connection technologies, and performance-based design approaches. When addressed with appropriate engineering principles, it is evident that timber structures will assume a more central role in future building culture and engineering practice.

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CHAPTER 12

Influence of Geometrical Optimization in Thermal Performance of 3D Printed Walls

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1. Introduction

By the middle of this century, the world's population is expected to approach 9.7 billion, which will intensify an already serious global housing deficit and require construction of well over 20 million new homes every year for several decades (UN DESA, 2019; World Bank, 2016; UN-Habitat, 2020). At the same time, buildings already account for roughly one third of global final energy use and a comparable share of energy-related CO_2 emissions, while in the European Union the building stock represents about 40 % of total energy consumption and 36 % of energy-related greenhouse-gas emissions (IEA, 2023; European Commission, 2020). Meeting future housing demand without locking in high operating energy and carbon therefore depends on rapid improvements in the efficiency and sustainability of the built environment. Central to this effort is the enhancement of building fabric performance—above all, the

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thermal quality of insulation materials and envelope systems that govern heating and cooling loads.

As more dwellings are built and comfort expectations rise, the energy required to maintain indoor thermal conditions has grown steadily. Space and water heating alone account for almost half of the energy used in buildings worldwide, and a large fraction of this demand is met by fossil-fuel-based or electricity-intensive heating, ventilation and air-conditioning (HVAC) systems (IEA, 2023; Gonzalez-Torres et al., 2022). Strong reliance on such systems increases operating costs for households and public budgets and contributes directly and indirectly to greenhouse-gas emissions. Behind this dependence lies the limited thermal performance of many existing envelopes: low insulation levels, insufficient heat storage capacity and pronounced thermal bridges allow rapid heat exchange between indoors and outdoors. Recent studies show that poorly insulated walls in particular drive unwanted heat gains in summer and heat losses in winter, making stable indoor temperatures difficult to maintain without substantial mechanical conditioning (Ounis et al., 2022). The obvious but technically demanding response is to develop and adopt construction materials and systems with significantly better thermal insulation, so that baseline heat transfer is lowered, indoor conditions are kept closer to comfort with minimal HVAC input, and sector-wide energy use and emissions decline over the long term.

The opaque envelope—and especially the exterior wall—plays a dominant role in the building's heat balance. Its thermal resistance, inertia and moisture behaviour together determine a large part of operational energy demand and associated CO_2 emissions (Mastrucci et al., 2020; Anwajler et al., 2024). High-quality insulation limits conductive, convective and radiative heat transfer, lowering heating and cooling loads, but envelope design is inherently multi-dimensional. For intermittently occupied buildings, moderate thermal inertia can be advantageous, while in cooling-dominated or mixed climates excessive insulation, without adequate paths for heat rejection, may increase summer cooling energy (Liu et al., 2025). As a result, high-performance walls must balance: (i) low steady-state transmittance (U-value), (ii) a dynamic thermal response tuned to climate and occupancy patterns, and (iii) robust detailing that limits thermal bridges and manages moisture and air leakage.

Three-dimensional concrete printing (3DCP) has emerged as a promising route to more sustainable construction because it enables automated, formwork-free fabrication with precise material placement. Life-cycle and techno-economic assessments report that, relative to conventional casting, 3DCP can cut material use and waste by on the order of 40–60 %, shorten construction times and reduce on-site labour demand, especially for wall systems (Xu et al., 2022; Alami et al., 2023; Hasani & Dorafshan, 2024). Beyond these process efficiencies, the geometric freedom of additive manufacturing allows the design of graded cavities, lattice-like infills and layered cross-sections that actively shape heat-flow paths, transforming walls from homogeneous slabs into engineered thermal devices (Kaur & Singh, 2021; Freeman, 2023). Recent analyses show that optimized 3D-printed wall geometries can reduce effective thermal transmittance compared with conventional monolithic walls and that the performance gap widens as cross-sectional complexity and cavity optimization increase.

Process innovation alone, however, is not sufficient; the sustainability of 3D-printed construction is strongly constrained by binder choice. Many printable mixes still rely on high proportions of ordinary Portland cement (OPC), with the associated kiln energy demand and CO_2 emissions. Alkali-activated and geopolymer binders have therefore received growing attention as low-carbon alternatives. Comparative assessments indicate that geopolymer concretes can reduce cradle-to-gate CO_2 emissions by 40–80 % while delivering compressive strengths in the 30–80 MPa range, and that insulating panels based on lightweight alkali-activated matrices can reach thermal conductivities as low as 0.08–0.18 W m^{-1} K^{-1} (Provis & Bernal, 2014; Passuello et al., 2017; Nodehi et al., 2024). These binders also offer a robust route to valorising industrial by-products and construction-and-demolition waste (CDW), including brick and concrete rubble, which can serve as precursors and aggregates in printable mixtures (Elmesalami & Celik, 2022). However, a large fraction of current alkali-activated systems still depends on coal fly ash and ground-granulated blast-furnace slag, whose availability is regionally constrained and expected to decrease as coal-fired power plants are phased out and metallurgical practices evolve (Kamath et al., 2021; Ismail et al., 2014). In this context, scalable and geographically robust low-carbon construction will require binder systems based on widely available CDW streams and minimally processed clays and minerals, so that geometric efficiency in printing is matched by resilient material supply.

The combination of additive manufacturing and advanced binders also opens a rich design space for tailoring thermal properties. Biomimetic and cellular infill patterns—such as honeycomb, wood-like and other bio-inspired topologies—can be manufactured with 3DCP and have been shown to lower effective conductivity and smooth indoor temperature swings compared with solid sections of equal thickness (du Plessis, 2020; Xu et al., 2025). At the material level, porous alkali-activated composites and foamed concretes with carefully controlled pore structures routinely attain bulk densities below 1200 kg m^{-3} and thermal conductivities in the 0.05–0.20 W m^{-1} K^{-1} range while preserving several MPa of compressive strength (Nodehi, 2021). At the same time, mineral fillers such as vermiculite and other lightweight aggregates can be used to balance thermal insulation with fire resistance and mechanical capacity, enhancing the multifunctionality of these systems (Traven et al., 2022; Isaza et al., 2023; Zuda et al., 2010).

At the printed-component scale, similar principles apply. Experimental and numerical studies on 3D-printed blocks show that the shape, size and continuity of internal voids strongly influence both heat transfer and structural response; ribs, cavities and anisotropic infill can be arranged to steer heat flow and to provide structural stiffening where needed (Briels et al., 2022; Alqahtani et al., 2024; Piccioni et al., 2023). Investigations of lightweight printed concretes and clay-based mixes further confirm that appropriate combinations of porous matrices, fibers and cellular geometries can deliver usable compressive strength together with meaningful reductions in effective U-value (Rahul & Santhanam, 2020; Grzeszczyk & Janus, 2020). High-temperature stability can also be engineered through binder chemistry: certain alumina- and magnesium-rich precursors yield alkali-activated foams that retain low thermal conductivity while remaining structurally stable at temperatures approaching 1000 °C, expanding their potential role in fire-exposed elements (Peng et al., 2020; Traven et al., 2021). In summary, the literature shows that the thermal behaviour of additively manufactured building components is not a fixed property but can be shaped across scales—from nano-porous fillers and gel chemistry to pore morphology and macroscopic printed geometry.

Against this background, the present study numerically evaluates the thermal performance of 3D-printed wall systems made with alkali-activated mortars containing recycled brick waste. Two 3D-printable mortar formulations reported in earlier experimental studies were adopted as input materials for the analyses. Based on these mixes, two wall configurations with identical external dimensions but different inner infill patterns were designed and modelled. Using the experimentally reported thermal properties, steady-state and transient finite-element simulations were carried out to quantify how the alternative internal geometries and void layouts affect heat transfer through the wall.

2. Materials and Methodology

This study numerically evaluates the thermal performance of 3D-printed wall segments made from alkali-activated mortars incorporating recycled brick-based constituents. Two 3D-printable foamed geopolymer mixtures reported in the literature were adopted as reference materials, and their experimentally measured thermal properties were used as input for finite-element (FE) simulations. For each mixture, the heat transfer through two alternative 3D-printed wall configurations, differing only in their internal infill pattern, was analysed under steady-state and transient boundary conditions. The results were compared in terms of equivalent thermal transmittance and temperature distribution across the wall thickness.

Two foamed, 3D-printable alkali-activated mortars were selected from previous experimental studies: (i) Material A: a fly-ash-based 3D-printable geopolymer foam with reduced density and enhanced thermal insulation, as developed by Alghamdi and Neithalath (2019). (ii) Material B: a 3D-printed foamed geopolymer composite incorporating recycled clay-brick and aerated-concrete waste as aggregates, as reported by Balina et al. (2025).

For both mixtures, the thermal conductivity (λ) and dry density (ρ) were taken directly from the experimental results published in the respective articles. All thermal properties were assumed to be homogeneous within each material and temperature-independent over the considered temperature range.

The adopted material parameters for the FE analyses are summarised in Table 1, where Material A and Material B correspond to the selected mixtures from Alghamdi and Neithalath (2019) and Balina et al. (2025), respectively. Two reference mixtures were selected from the literature to represent the material input for the numerical thermal analyses. The first, denoted as Material A, corresponds to the 3-CBW+AACW foamed geopolymer, which incorporates both clay-brick waste and aerated-concrete waste as lightweight mineral additives. Its mixture composition and thermal properties were taken directly from experimentally measured values. The second system, Material B, is the FLC printable binder blend, which combines fly ash, slag and ordinary Portland cement in defined mass ratios and includes a small amount of sodium sulfate as an activator. For both mixtures, the proportions of the principal solid constituents and the thermal parameters used in the finite-element model—namely bulk density and thermal conductivity—are also given in Table 1. These values were assigned as homogeneous, temperature-independent properties within each simulation.

After the thermal properties of the selected mixtures were identified, the numerical study focused on evaluating how different 3D-printed wall configurations respond to heat transfer. Before analysing the proposed geometries, the modelling approach was checked for accuracy. For this purpose, the wall section examined by Alkhalidi and Hatuqay (2020) was recreated within the finite-element environment, and its thermal transmittance (U-value) was used as a benchmark for comparison.

In the validation model, the interior and exterior surface temperatures were set to 40 °C and 0 °C, matching the boundary conditions applied in the reference work. According to EN ISO 6946, convective surface heat-transfer coefficients of 7.69 W/(m^2·K) for the inner surface and 25 W/(m^2·K) for the outer surface were assigned using surface-film interactions. The domain was meshed using DC3D8 heat-transfer brick elements, and mesh refinement near cavity boundaries followed the strategy reported in the reference study, with a global 10 mm element size and 2 mm elements around edges. A steady-state heat-transfer analysis was then performed. The resulting U-value of 1.64 W/m^2K showed close agreement with the value reported in the literature (1.87 W/m^2K), confirming that the modelling setup was suitable for further investigation.

Once the validation stage was completed, different 3D-printed wall sections were designed based on the physical properties of the two printable mixtures. These cross-sections were developed to examine how cavity arrangement, internal layout and material choice influence thermal behaviour.

All major modes of heat transfer occurring through the wall—conduction, convection, and radiation—were represented in the simulations. Convection effects were introduced with the same surface coefficients used during validation. Radiative exchange inside the cavities was captured by assigning an emissivity of 0.7 to the cavity surfaces, consistent with commonly adopted values for enclosed air spaces. To account for the layered nature of additive manufacturing, tie constraints were applied between printed layers across all configurations.

Mesh generation and element selection were handled carefully to maintain numerical accuracy. The printed concrete components and the internal void zones were discretised using 3D eight-node brick elements (DC3D8). Mesh convergence was checked, and the optimal mesh density was used for the final analyses. Since the examined wall systems are non-load-bearing envelope components, the simulations were conducted as uncoupled thermal analyses. The mixture compositions and thermal parameters used in the simulations are summarized in Table 1, which presents the proportions of key constituents (e.g., fly ash, slag, cement, CBW, AACW) along with the corresponding density and thermal conductivity values for the two reference materials.

Table 1. *Material proportions and thermal analysis parameters adopted for the two reference mixtures used in the numerical simulations*

Mixture Proportions (%)											
	Fly Ash	**Slag**	**Cement**	**Sand**	**NaOH**	**Water**	**H_2O_2**	**AACW**	**CBW**	**Sodium Sulfate**	**Surfactant**
Material A	17.63	3.92	1.57	39.18	12.24	7.05	0.78	8.81	8.81	–	–
Material B	50	20	30	–	–	–	–	–	–	3	3

Analysis Parameters		
	Density (kg/m^3)	**Thermal Conductivity (W/mk)**
Material A	940	0.14
Material B	622	0.26

Note: *NaOH: Sodium hydroxide, H_2O_2: Hydrogen Peroxide, AACW: Autoclaved aerated concrete waste, CBW: Clay brick waste*

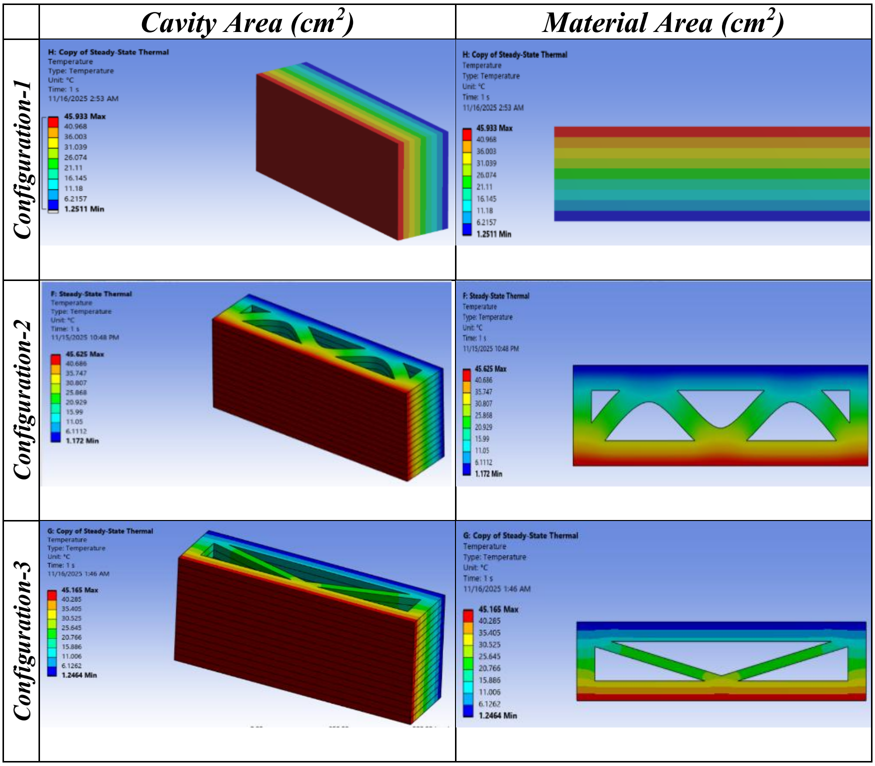
3. Results and Discussions

This study investigated the influence of internal geometry and material type on the thermal performance of 3D-printed wall elements by conducting numerical simulations on six different configurations. For all models, a temperature boundary condition of 0 °C on the exterior surface and 50 °C on the interior surface was applied. U-values were calculated based on the average heat flux at steady state. U-values results of the wall configurations are presented in Table 2.

Table 2. *U-values of 3D printed wall configurations*

	U-Value (W/m^{2}K)
Configuration-1	0.63
Configuration-2	0.60
Configuration-3	0.61
Configuration-4	1.06
Configuration-5	0.94
Configuration-6	0.89

Numerical analysis results of the wall configurations are presented in Figure 1.



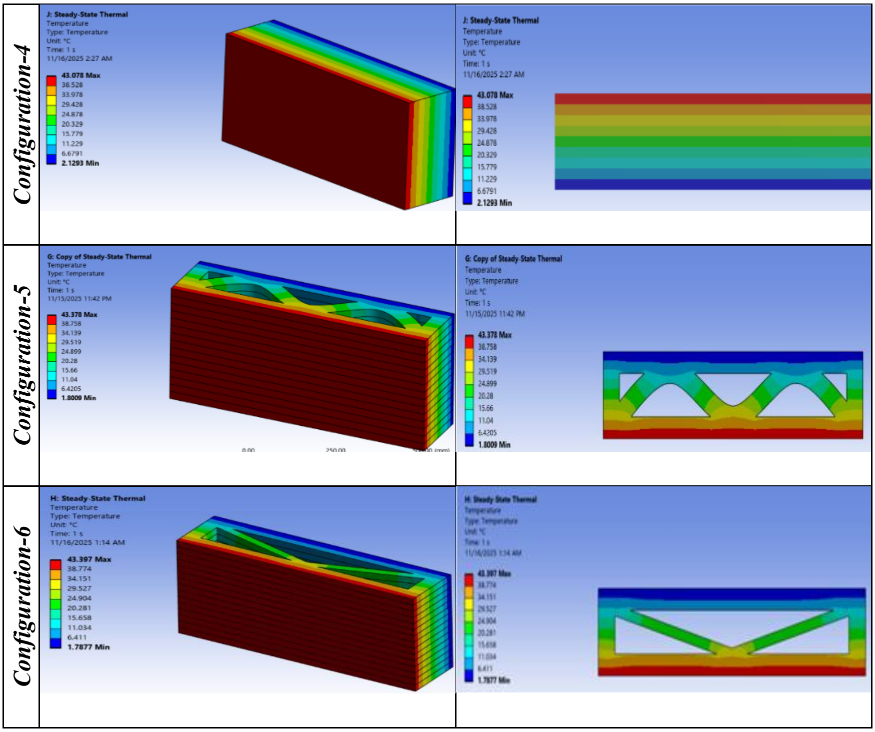


Figure 1. *Numerical analysis results of 3D printed wall configurations*

The numerical results obtained from the six 3D-printed wall configurations clearly demonstrate the combined influence of internal geometry and material type on heat-transfer behaviour. The U-values of the models range between 0.60 and 1.06 W/m²K, indicating that even small modifications in geometric arrangement can lead to significant differences in thermal resistance. This highlights the sensitivity of additively manufactured wall systems to both material selection and cavity arrangement, particularly under steady-state conditions where conduction dominates heat transfer.

Among all configurations, Configuration-2 achieved the best thermal performance, with a U-value of 0.60 W/m²K. The temperature contour plots show that its internal void layout forces heat to follow a long, fragmented, and indirect conduction path. This generates high thermal tortuosity, where diagonally oriented cavities and discontinuous material sections effectively disrupt direct thermal bridges. Configuration-3, with a U-value of 0.61 W/m^2K, exhibits a similar behaviour; although its cavity pattern differs, the sequence of interrupted conduction paths reduces heat-flow continuity. Configuration-1 also performs well (0.63 W/m^2K), where its inclined internal features help diffuse heat flow and limit the formation of linear conduction routes.

In contrast, Configuration-5, despite appearing compact and material-dense, exhibits a much higher U-value of 0.94 W/m^2K. The contour plots reveal the existence of wide, uninterrupted solid regions that allow heat to propagate efficiently through the structure. This finding confirms that dense or material-rich geometries do not necessarily provide enhanced insulation; when material conductivity is relatively high or when the geometry unintentionally forms direct conduction paths, thermal performance can deteriorate.

The poorest performance was observed in Configuration-4, which reached a U-value of 1.06 W/m^2K. The steep temperature gradients and closely spaced isotherms in its contour plots indicate strong internal thermal bridges formed by continuous, vertically aligned material ribs. Configuration-6, with a U-value of 0.89 W/m^2K, performs better than Configurations-4 and -5 but still belongs to the high-U-value group. Although its cavity structure partially disrupts heat flow, several aligned conduction paths remain active.

Collectively, these results show that the directionality, connectivity, and interruption frequency of internal material elements play a far more decisive role than total cavity area alone. Two configurations with similar void ratios may behave entirely differently depending on whether the cavities compel heat to detour or inadvertently align with the primary heat-flow direction. Designs that maximize thermal detouring—through diagonal patterns, staggered cavities, or multidirectional interruptions—consistently yield lower U-values. Conversely, designs containing continuous ribs or cavities aligned with the heat-flow direction tend to develop strong thermal bridges.

The temperature contours also reveal that 3D-printed geometries generate anisotropic thermal behaviour. Inclined and diagonally oriented print paths create directional heat-flow tendencies that differ from those in homogeneous or cast walls. This anisotropy may be strategically exploited in future wall design, particularly in climates where the direction of heat flow reverses seasonally.

A key insight from the findings is the strong interaction between material thermal conductivity and geometric optimization. In the low-conductivity group (1, 2, and 3), geometry acts as a secondary yet beneficial factor that further improves insulation. However, in the high-conductivity group (4, 5, and 6), internal geometry becomes the primary determinant of thermal behaviour. With a more conductive material, heat transfer occurs more rapidly, making geometric disruption of conduction paths far more critical. This demonstrates that effective thermal design of 3D-printed walls requires the integration of material engineering with the architectural design of internal geometry, rather than treating these aspects separately.

Overall, the best thermal performance was achieved when low-conductivity binder systems were combined with cavity arrangements that maximize thermal tortuosity. Conversely, configurations with continuous internal elements or insufficiently fragmented geometries created direct heat-transfer routes that increased U-values. These findings provide valuable guidance for developing energy-efficient, additively manufactured wall systems and point toward promising research directions, including cavity orientation optimization, multi-layered infill strategies, and the integration of functionally graded materials to further enhance thermal resistance..

4. Conclusion

This study evaluated the thermal performance of 3D-printed wall elements by examining how internal geometry and material type influence heat transfer under steady-state conditions. Two printable alkali-activated mixtures with distinct thermal properties were used to model six different wall configurations. The findings show that both material conductivity and the arrangement of internal cavities play important roles, but their relative impact depends on the characteristics of the material.

The walls produced with the low-conductivity material demonstrated the best overall thermal performance. In these configurations, geometric variations resulted in only small differences in U-value, indicating that the insulating capacity of the material largely governs heat transfer. In contrast, when the higher-conductivity material was used, the effect of geometry became more pronounced. The orientation and continuity of internal elements either restricted or facilitated heat flow, leading to noticeable differences among the configurations.

The results confirm that a high void ratio alone does not guarantee improved insulation. Instead, the direction and connectivity of the internal structural layout determine whether the voids act as thermal barriers or create unintended conduction pathways. The best-performing models were those in which cavities forced longer and more indirect heat transfer routes, particularly in the higher-conductivity material group.

Overall, the study highlights the importance of combining appropriate material selection with deliberate geometric design to optimize thermal behaviour in 3D-printed wall systems. Low-conductivity binder systems naturally offer improved insulation, while higher-conductivity materials require more careful control of internal patterns to achieve comparable performance. These insights provide a useful basis for developing energy-efficient 3D-printed building envelopes and support further research into geometry–material interaction for advanced additive manufacturing applications.

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