Open Access

Recent Progress in Materials

LIDSEN Publishing Inc.

Review

Revolutionizing Infrastructure Development: Exploring Cutting-Edge Advances in Civil Engineering Materials

Michael Toryila Tiza [1,*], Samson Imoni [2], Ebenezer Ogırıma Akande [3], Onyebuchi Mogbo [4], Victoria Hassana Jiya [5], Collins Onuzulike [5]

1. Physical Planning Unit, Federal Polytechnic Wannune, Benue State, Nigeria; E-Mail: tizamichael@gmail.com
2. Department of Monitoring and Evaluation, Tertiary Education Trust Fund (TETFUND), Abuja, Nigeria; E-Mail: imonisam@gmail.com; ORCID: 0009-0005-0826-016X
3. Department of Civil Engineering, Bells University of Technology, Ogun, Nigeria; E-Mail: besteben2000@gmail.com
4. Department of Civil Engineering, Nile University of Nigeria, Abuja, Nigeria; E-Mail: mogbo.nwabueze@nileuniversity.edu.ng; ORCID: 0000-0002-8124-8571
5. Department of Civil Engineering, Air Force Institute of Technology, Kaduna, Nigeria; E-Mails: hassvics@gmail.com; collinsonuzulike@gmail.com

* **Correspondence:** Michael Toryila Tiza; E-Mail: tizamichael@gmail.com

Academic Editor: José Ignacio Álvarez Galindo

Special Issue: New Trends on Construction Technologies and Sustainable Building Materials

Recent Progress in Materials
2024, volume 6, issue 3
doi:10.21926/rpm.2403023

Received: July 04, 2023
Accepted: September 11, 2024
Published: September 26, 2024

Abstract

This study addresses the evolving challenges in infrastructure development by exploring recent advancements in civil engineering materials. The problem lies in the limitations of traditional materials such as concrete and steel, which, while foundational, may not fully meet the demands of modern construction in terms of sustainability, durability, and resilience. The objective of this review is to assess the role and impact of both traditional and emerging materials, including supplementary cementitious materials, nanotechnology-based materials, and novel reinforcement options, on the performance and sustainability of infrastructure. The scope of the study includes an analysis of the performance characteristics, applications, and limitations of these materials. It also covers the integration of recycled materials, geopolymer-based composites, and biomimetic materials as viable, sustainable alternatives. The review further highlights the significance of functional materials for enhanced performance and energy efficiency and examines advancements in materials testing and evaluation techniques. The methodology involves a comprehensive literature review, synthesizing findings from recent studies to identify key trends, challenges, and research gaps in the field. Results indicate that these advanced materials contribute significantly to improving the sustainability, durability, and resilience of construction projects. However, the study also identifies existing research gaps, particularly in the long-term performance and large-scale application of these materials. The conclusion emphasizes the potential of these innovations to transform civil engineering by creating more robust, sustainable, and efficient infrastructure. Recommendations include continued research and development efforts to address identified knowledge gaps, fostering innovation, and adapting to the rapidly changing demands of the built environment.

Keywords

Civil engineering materials; recent advances; infrastructure development; traditional materials; supplementary cementitious materials; nanotechnology; self-healing concrete

1. Introduction

Civil engineering materials play a vital role in the construction and maintenance of infrastructure. These materials form the building blocks of various civil engineering projects, including buildings, bridges, roads, dams, and tunnels [1]. The selection and utilization of appropriate materials are crucial for ensuring the structural integrity, durability, and safety of these projects. Civil engineering materials encompass a wide range of substances, including traditional materials such as concrete, steel, and timber, as well as advanced materials like fiber-reinforced polymers (FRPs), shape memory alloys, and geopolymer-based composites. Each material possesses unique properties and characteristics that make it suitable for specific applications within the field of civil engineering [2].

Concrete is one of the most widely used civil engineering materials due to its versatility, affordability, and ability to withstand compressive forces. It consists of cement, aggregates (such as sand and gravel), water, and sometimes admixtures [3]. Steel is another essential material in civil engineering, known for its strength, ductility, and resistance to tension. Timber has been used for centuries in construction, particularly for its availability and renewable nature [4]. Over time, advancements in material science and engineering have led to the development of new and improved civil engineering materials. These innovations aim to address challenges associated with traditional materials, such as low durability, susceptibility to corrosion, and environmental impact. Recent research has focused on enhancing the performance, sustainability, and resilience of civil engineering materials, leading to significant advancements in the field [5].

The exploration and understanding of these recent advances in civil engineering materials are crucial for engineers, researchers, and industry professionals [5, 6]. By staying informed about the latest developments, professionals can make informed decisions regarding material selection, design optimization, and construction practices, ultimately contributing to the improvement of infrastructure worldwide [6, 7]. In this literature review, we will examine the recent advances in civil engineering materials, exploring the novel materials, technologies, and methodologies that have emerged. We will delve into their applications, benefits, and challenges, providing a comprehensive overview of the advancements that have the potential to shape the future of civil engineering.

1.1 The Objectives

The objectives of the literature review are to analyze recent developments in key civil engineering materials, explore their applications, benefits, and challenges, and provide a comprehensive overview of the subject matter. The scope of the review encompasses a wide range of materials, both traditional and advanced, and focuses on their properties, performance, and potential applications in civil engineering.

2. Role of Materials in Infrastructure Development

The role of materials in infrastructure development is fundamental, as they serve as the essential components that dictate the performance, safety, and longevity of civil engineering projects [8]. The selection and proper use of materials have a significant impact on the overall quality and functionality of infrastructure, ranging from small-scale residential buildings to large-scale transportation systems [9]. The following points highlight the key roles that materials play in infrastructure development:

Materials are the primary determinants of the structural integrity and stability of infrastructure [10]. They must be capable of withstanding various loads, forces, and environmental conditions over the intended lifespan of the structure. For instance, steel and reinforced concrete are commonly used in bridges and high-rise buildings due to their high tensile strength and load-carrying capacity [11]. Figure 1 shows a typical pictorial representation of concrete, highlighting its use as a fundamental material in civil engineering for constructing durable structures like buildings, bridges, and pavements.

Figure 1 Typical pictorial representation of concrete as a civil Engineering material. Source [2].

Infrastructure projects are intended to have long service lives, often spanning decades or even centuries. The durability of materials directly influences the lifespan of the structure, reducing the need for frequent repairs and replacements [12]. Durable materials such as high-performance concrete and corrosion-resistant alloys extend the life of infrastructure and reduce life-cycle costs [12, 13].

The safety of infrastructure is of paramount importance. Materials used must exhibit reliable performance and maintain their properties under various operating conditions [13]. Engineers carefully assess material properties to ensure that structures can withstand anticipated loads, environmental exposures, and potential hazards [13].

With increasing concerns about environmental sustainability, materials play a vital role in promoting eco-friendly infrastructure [13]. Sustainable materials, such as recycled aggregates and geopolymer-based concrete, reduce resource depletion, greenhouse gas emissions, and waste generation [14].

Materials also play a significant role in the aesthetics and architectural appeal of structures. The choice of materials can influence the visual appearance of buildings and public spaces, contributing to the overall character of the infrastructure [14, 15].

Different infrastructure projects have specific functional requirements. Materials are chosen to meet these functional needs, whether it be providing thermal insulation, acoustic performance, fire resistance, or specific mechanical properties [16]. The selection of materials also impacts the economic viability of infrastructure projects. The cost of materials, along with their installation and maintenance expenses, must be carefully considered to ensure projects remain financially feasible [17].

Materials used in infrastructure must be able to adapt to changing conditions, such as temperature fluctuations, seismic events, and dynamic loads. Advanced materials, like shape memory alloys and self-healing concrete, offer unique adaptive capabilities to enhance structural performance [18].

The role of materials in infrastructure development is multifaceted and pivotal to the success of civil engineering projects [19]. The use of appropriate materials not only ensures the structural stability and safety of infrastructure but also influences its environmental impact, aesthetics, functionality, and economic viability [20]. The continuous advancement of materials science and engineering contributes to the development of innovative solutions that enable the construction of more resilient, sustainable, and efficient infrastructure for the future [21, 22]. Table 1 summarizes the Role of Materials in Infrastructure Development. Figure 2 illustrates a typical pictorial representation of fiber-reinforced polymers (FRPs), emphasizing their application in civil engineering for enhancing structural strength, durability, and flexibility in projects such as bridges, buildings, and retrofitting.

Table 1 A Summary of the Role of Materials in Infrastructure Development.

Material	Advancements	Applications	Effects	References
Concrete	Self-healing properties	Buildings, bridges, roads	Enhanced durability and reduced maintenance costs	[8]
Steel	Corrosion-resistant alloys	High-rise buildings, bridges	Increased lifespan and structural integrity	[9]
Timber	Engineered wood products	Residential construction	Improved strength and sustainability	[10]
FRPs	Increased strength and durability	Retrofitting, seismic upgrades	Enhanced load-bearing capacity and resilience	[11]
Shape Memory Alloys	Shape memory effect for structural control	Earthquake-resistant structures	Improved energy dissipation and structural control	[12]
Geopolymer-based Composites	Lower carbon footprint	Sustainable construction	Reduced environmental impact and increased sustainability	[13]

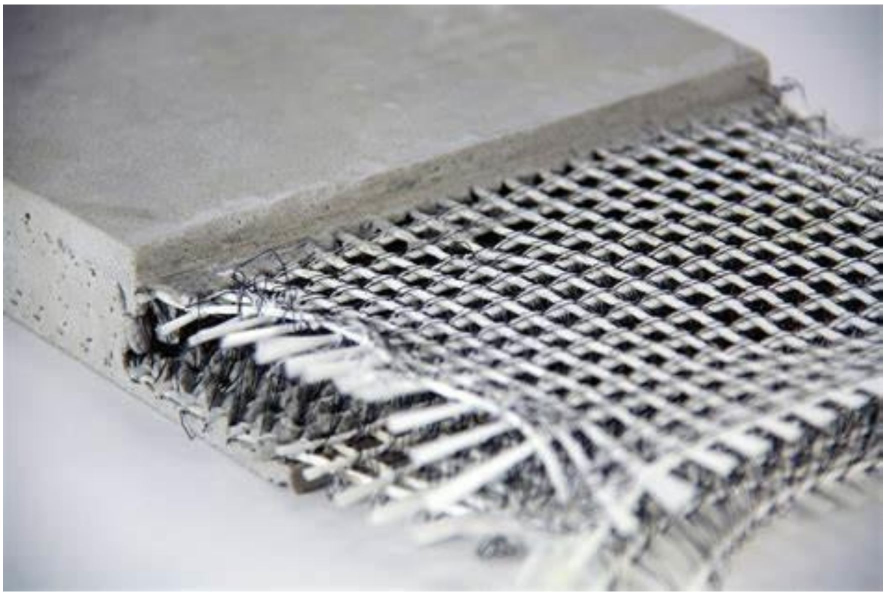

Figure 2 Typical pictorial representation of fiber-reinforced polymers (FRPs) as a civil Engineering material. Source [23].

3. Significance of Recent Advances in Civil Engineering Materials

Recent advances in civil engineering materials have significant implications for the field, offering numerous benefits and opportunities for improving infrastructure development [22]. These advancements have the potential to revolutionize the way structures are designed, built, and maintained. The following paragraphs discuss the significance of recent advances in civil engineering materials:

Recent advances in materials science and engineering have led to the development of high-performance materials with improved mechanical properties [22, 23]. These materials exhibit enhanced strength, durability, and resistance to various forces, such as compression, tension, and shear. The use of advanced materials, such as fiber-reinforced polymers (FRPs) and carbon nanotubes, allows for the construction of lighter and stronger structures that can withstand higher loads, resulting in increased structural performance and safety [23]. Figure 3 presents a typical pictorial representation of Shape Memory Alloys (SMAs), showcasing their use in civil engineering for applications such as seismic dampers and adaptive structures, where their ability to return to a pre-defined shape after deformation improves resilience and structural performance.

Figure 3 Typical pictorial representation of Shape Memory Alloys as a civil Engineering material. Source [24].

Durability is a critical factor in infrastructure development, as structures are expected to have long service lives. Recent advances in civil engineering materials have focused on developing more durable and corrosion-resistant materials, such as self-healing concrete and stainless-steel reinforcement [24]. These materials mitigate the effects of environmental factors, chemical degradation, and wear and tear, thereby extending the service life of infrastructure and reducing maintenance and repair costs [25]. Figure 4 depicts a typical pictorial representation of the application of geopolymer, illustrating its use as a sustainable civil engineering material in construction projects like pavements, precast structures, and fire-resistant coatings, offering enhanced durability and reduced environmental impact compared to traditional cement.

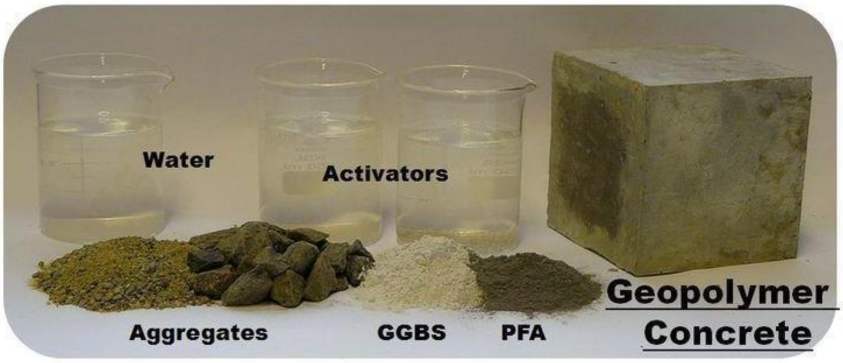

Figure 4 Typical pictorial representation of application of Geopolymer as a civil Engineering material. Source [25].

Environmental sustainability is a growing concern in the field of civil engineering. Recent advances in materials have introduced sustainable alternatives to traditional construction materials [25, 26]. For example, geopolymer-based composites and recycled aggregates offer reduced carbon emissions, lower energy consumption, and decreased reliance on non-renewable resources. These materials contribute to sustainable development by minimizing environmental impact and promoting resource conservation [26].

Recent advances in civil engineering materials have paved the way for innovative construction techniques. Prefabricated and modular construction methods, combined with advanced materials, offer benefits such as faster construction time, improved quality control, and reduced labor and material waste. These advancements enhance efficiency and productivity in the construction industry, leading to cost savings and timely project completion [27].

Advanced materials play a crucial role in enhancing the resilience of infrastructure to natural disasters, such as earthquakes, hurricanes, and floods [27, 28]. Materials like shape memory alloys and fiber-reinforced composites exhibit excellent ductility, impact resistance, and self-repair capabilities. Incorporating these materials into structural elements can improve the ability of infrastructure to withstand extreme events, reducing the risk of catastrophic failures and minimizing damage [28].

Recent advances in civil engineering materials are often accompanied by technological advancements. For instance, the use of smart materials embedded with sensors allows for real-time monitoring of structural health, enabling early detection of defects or potential failures [29]. This integration of materials and technology enables proactive maintenance strategies, leading to improved safety, reduced downtime, and optimized life-cycle management of infrastructure [29].

New materials offer exciting opportunities for architectural expression and innovative design. Advanced materials can be manipulated to create unique forms, textures, and aesthetics, allowing for the realization of architectural visions that were previously challenging to achieve [30]. The availability of diverse materials with distinct properties expands the design possibilities and promotes creativity in the field of civil engineering [30].

Advances in civil engineering materials hold great significance for the field. These advancements provide opportunities to enhance structural performance [30], extend the service life of infrastructure, promote sustainability [31], improve construction techniques, increase resilience to disasters, integrate technology, and foster innovation in design and architecture. By embracing and implementing these advances, civil engineers can create more robust, sustainable, and efficient infrastructure that meets the evolving needs of society [31, 32]. As detailed in Table 2, the role of materials in infrastructure development encompasses various critical aspects. This table provides a comprehensive overview of how different materials contribute to the advancement and sustainability of infrastructure projects, highlighting their respective benefits and applications.

Table 2 Role of Materials in Infrastructure Development.

Material	Advancements	Applications	Effects	References
Steel	High-strength and ductility	Bridges, high-rise buildings	Improved load-bearing capacity and structural flexibility	[22]
Concrete	Durability and corrosion resistance	Roads, bridges, buildings	Extended lifespan and reduced maintenance needs	[23]
Timber	Sustainability and renewable nature	Residential construction	Enhanced environmental benefits and lower carbon emissions	[24]
Geopolymer-based Composites	Lower carbon footprint	Sustainable construction	Reduced greenhouse gas emissions and increased sustainability	[25]
Shape Memory Alloys	Adaptive and self-healing properties	Seismic-resistant structures	Enhanced seismic performance and improved structural safety	[26]
Recycled Aggregates	Resource conservation and waste reduction	Construction materials	Minimized environmental impact and conservation of natural resources	[27]

4. Traditional Civil Engineering Materials

Traditional civil engineering materials have been widely used in construction for many years and have played a crucial role in shaping infrastructure worldwide [33]. This section of the literature review examines the key traditional materials used in civil engineering, their properties, applications, and limitations. The focus is on materials such as concrete, steel, and timber.

4.1 Concrete

Concrete is one of the most commonly used construction materials in civil engineering. It is composed of a mixture of cement, aggregates (such as sand and gravel), and water. Concrete offers several advantages, including its high compressive strength, fire resistance, and durability [34]. It can be cast into various shapes and sizes, making it suitable for a wide range of applications, including building foundations, bridges, and dams. However, concrete also has limitations, such as low tensile strength and susceptibility to cracking, which can impact its long-term performance and require additional reinforcement [34, 35].

4.2 Steel

Steel is another vital material in civil engineering, valued for its high strength, ductility, and versatility. It is commonly used in structural applications, including beams, columns, and reinforcing bars [35]. Steel structures offer significant benefits, such as superior load-carrying capacity, flexibility in design, and ease of construction. Moreover, steel is a recyclable material, making it environmentally friendly. However, steel structures may be prone to corrosion if not properly protected, and their high cost can be a limitation in certain projects [36]. Figure 5 shows a typical pictorial representation of steel, highlighting its widespread use in civil engineering for constructing high-strength structures such as bridges, skyscrapers, and reinforcement in concrete, due to its durability, flexibility, and load-bearing capacity.

Figure 5 Typical pictorial representation of steel as a civil Engineering material. Source [37].

4.3 Timber

Timber has a long history of use in construction and is still utilized for various civil engineering applications. Wood offers natural warmth and aesthetic appeal, making it suitable for both structural and decorative purposes. Timber is relatively lightweight, renewable, and possesses good thermal and acoustic properties. It can be used in building frames, bridges, and other structures. However, timber is susceptible to moisture, pests, and fire, requiring proper treatment and maintenance to ensure its long-term durability and safety [36]. Figure 6 illustrates a typical pictorial representation of timber, emphasizing its use as a renewable civil engineering material in construction for structures like residential buildings, bridges, and frameworks, valued for its strength, lightweight nature, and sustainability.

Figure 6 Typical pictorial representation of Timber as a civil Engineering material. Source [38].

4.4 Masonry

Masonry materials, such as bricks, stones, and concrete blocks, have been used for centuries in civil engineering. Masonry offers strength, durability, and thermal insulation. It is commonly employed in building walls, facades, and retaining structures [37, 38]. The modular nature of masonry allows for ease of construction and versatility in design. However, masonry structures may be susceptible to cracking and water infiltration, requiring proper design and construction techniques to ensure stability and longevity [38].

4.5 Asphalt

Asphalt, or bitumen, is a widely used material for constructing roadways, parking lots, and pavements. It is a composite material consisting of aggregates, binder, and filler. Asphalt offers excellent flexibility, resistance to heavy traffic, and durability. It provides a smooth and comfortable riding surface and contributes to road safety. However, asphalt is subject to aging, cracking, and deformation over time due to traffic loads, temperature variations, and environmental factors. Regular maintenance and repair are necessary to preserve its performance [38]. Figure 7 displays a typical pictorial representation of asphalt, highlighting its use as a vital civil engineering material for constructing durable road surfaces, highways, and pavements due to its flexibility, weather resistance, and ability to withstand traffic loads.

Figure 7 Typical pictorial representation of Asphalt as a civil Engineering material. Source [2].

Traditional civil engineering materials, such as concrete, steel, timber, masonry, and asphalt, have been fundamental in the construction of infrastructure projects worldwide. These materials offer a range of properties and applications that have shaped the built environment. Understanding their characteristics, advantages, and limitations is crucial for informed decision-making in civil engineering projects. While these traditional materials have proven their reliability and suitability over time, ongoing research and advancements aim to address their limitations and enhance their performance in various aspects [39]. Table 3 presents a detailed overview of traditional civil engineering materials. This table outlines the characteristics, applications, and limitations of commonly used materials in civil engineering, providing valuable insights into their role and impact on infrastructure development.

Table 3 Traditional Civil Engineering Materials.

Material	Properties	Applications	Limitations	References
Concrete	High compressive strength, fire resistance, durability	Foundations, bridges, dams	Low tensile strength, susceptibility to cracking	[34, 35]
Steel	High strength, ductility, recyclability	Structural elements, reinforcing bars	Corrosion if not protected, high cost	[35, 36]
Timber	Natural warmth, lightweight, renewable	Building frames, bridges	Susceptible to moisture, pests, fire	[36, 37]
Masonry	Strength, durability, thermal insulation	Walls, facades, retaining structures	Susceptible to cracking, water infiltration	[37, 38]
Asphalt	Flexibility, resistance to heavy traffic	Roadways, parking lots, pavements	Aging, cracking, deformation over time	[38]

5. Strengths and Limitations of Traditional Materials

Concrete, one of the most widely used traditional materials in civil engineering, possesses several strengths that contribute to its popularity [40]. Firstly, concrete exhibits high compressive strength, making it suitable for supporting heavy loads and withstanding compression forces. This strength allows for the construction of durable and structurally sound infrastructure. Additionally, concrete offers versatility in terms of form and shape, enabling engineers to create complex structures and architectural designs [40]. Its mold ability and ability to be cast into different shapes allow for customized construction solutions. Moreover, concrete provides inherent fire resistance, making it a reliable choice for enhancing the safety of structures in the event of a fire [40, 41].

However, concrete does have certain limitations that need to be considered. One of the main limitations is its relatively low tensile strength [41]. Concrete is prone to cracking under tensile loads, which can weaken its structural integrity. To overcome this limitation, reinforcement in the form of steel bars or fibers is often incorporated to create reinforced concrete structures. Additionally, concrete is susceptible to shrinkage and expansion due to changes in temperature and moisture, which can result in cracking and reduced durability. Proper curing and moisture control techniques are necessary to mitigate these issues [41, 42].

Steel, another important traditional material in civil engineering, possesses several key strengths-that contribute to its widespread use [42]. One of the primary strengths of steel is its high strength-to-weight ratio. Steel structures can carry significant loads while remaining relatively lightweight, allowing for efficient design and construction. Steel also exhibits excellent ductility, which enables it to deform under excessive loads without sudden failure. This ductility provides buildings and other structures with the ability to absorb and dissipate energy during seismic events or other dynamic loads [43]. Moreover, steel is a highly recyclable material, making it an environmentally friendly choice.

Despite its many strengths, steel has certain limitations. One significant limitation is its susceptibility to corrosion. If not properly protected, steel structures can deteriorate due to exposure to moisture and aggressive environments. The corrosion of steel can weaken the structure and necessitate costly maintenance and repairs. Additionally, the high cost of steel compared to other materials can be a limiting factor in certain projects with budget constraints [44].

Timber, a traditional construction material known for its natural warmth and aesthetic appeal, possesses unique strengths. Timber is lightweight yet strong, making it suitable for a variety of structural and decorative applications. It offers good thermal and acoustic insulation properties, providing comfort and energy efficiency in buildings. Timber is also a renewable resource, contributing to sustainability in construction practices [45].

However, timber has its limitations. It is susceptible to moisture, pests, and fire. Without proper treatment and maintenance, timber can be prone to decay, insect infestation, and structural degradation. Fire resistance is a crucial consideration when using timber in construction, and fire protection measures must be implemented to ensure the safety of occupants and the structural integrity of timber structures [45, 46].

Masonry materials, such as bricks and concrete blocks, also have their strengths and limitations. Masonry structures offer excellent strength and durability, making them suitable for load-bearing applications and providing long-lasting performance. Masonry provides good thermal insulation properties, contributing to energy efficiency in buildings. The modular nature of masonry allows for ease of construction and versatility in design [46].

However, masonry has limitations, including its vulnerability to cracking and water infiltration. Careful design and construction techniques are required to ensure stability and prevent water damage. In seismic regions, additional reinforcement and design considerations are necessary to enhance the earthquake resistance of masonry structures [46].

Traditional civil engineering materials, including concrete, steel, timber, and masonry, possess several strengths that have made them widely used in construction. These materials offer unique properties and advantages that contribute to the durability [47], versatility, and aesthetic appeal of infrastructure. However, they also have limitations that need to be carefully addressed through proper design, construction techniques, and maintenance. The selection of materials for a specific project should consider the project requirements, environmental factors, and long-term performance considerations to ensure the successful and sustainable implementation of civil engineering structures [48]. As shown in Table 4, the strengths and limitations of traditional civil engineering materials are thoroughly examined. This table highlights the key advantages and drawbacks of these materials, offering a nuanced perspective on their performance and suitability for various applications in infrastructure development.

Table 4 Strengths and Limitations of Traditional Civil Engineering Materials.

Material	Strengths	Limitations	References
Concrete	High compressive strength, versatility, fire resistance	Low tensile strength, susceptibility to cracking, shrinkage	[40-42]
Steel	High strength-to-weight ratio, ductility, recyclability	Susceptibility to corrosion, high cost	[42, 44]
Timber	Natural warmth, aesthetic appeal, lightweight, good insulation properties	Susceptibility to moisture, pests, fire	[45, 46]
Masonry	Strength, durability, thermal insulation, ease of construction	Vulnerability to cracking, water infiltration	[46]

6. Performance Characteristics and Applications of Traditional Materials

Concrete is a versatile material widely used in civil engineering due to its performance characteristics [48, 49]. It exhibits excellent compressive strength, allowing it to bear heavy loads and provide stability to structures. Concrete is commonly used in applications such as foundations, columns, beams, slabs, pavements, and retaining walls. Its durability and fire resistance make it suitable for constructing buildings, bridges, dams, and other infrastructure [49]. However, concrete has low tensile strength and can be prone to cracking, necessitating the use of reinforcement techniques such as steel rebars to enhance its structural integrity [50].

Steel is renowned for its high strength-to-weight ratio, ductility, and resilience. It offers exceptional tensile and compressive strength, making it an ideal material for structural applications [51]. Steel is extensively used in the construction of steel-framed buildings, bridges, industrial facilities, and offshore structures. It also plays a crucial role in reinforcing concrete structures, providing strength and stability. With its ability to withstand extreme temperatures and exhibit good seismic performance, steel is a preferred choice in areas prone to earthquakes [52].

Timber, a natural and renewable material, possesses unique performance characteristics. It is lightweight yet offers high strength-to-weight ratio, making it suitable for various structural and decorative applications [53]. Timber provides good thermal and acoustic insulation properties, contributing to energy-efficient buildings. It is commonly used in residential and commercial construction, including framing, flooring, roofing, and interior finishes. However, timber is susceptible to moisture, pests, and fire, necessitating proper treatment and maintenance to ensure its durability and safety [54].

Masonry materials, such as bricks, concrete blocks, and stones, offer exceptional strength, durability, and thermal insulation properties. They are commonly used in load-bearing walls, partitions, facades, arches, and paving. Masonry provides good fire resistance and sound absorption, making it suitable for residential, commercial, and institutional buildings. However, masonry can be vulnerable to cracking and water infiltration, requiring careful design and construction techniques to ensure stability and prevent damage [54].

Asphalt, a mixture of aggregates and bitumen, is primarily used in road construction. It offers flexibility, durability, and good resistance to heavy traffic and weather conditions [55]. Asphalt provides excellent waterproofing and soundproofing properties, enhancing the longevity and performance of roads, highways, parking lots, and airport runways. However, it can be susceptible to UV radiation and temperature-induced deformations, necessitating periodic maintenance and repairs [56].

Glass is a unique traditional material known for its transparency and aesthetic appeal. It allows natural light to enter spaces, contributing to energy-efficient designs. Glass is resistant to corrosion, chemicals, and UV radiation. It is widely used in windows, doors, facades, skylights, and interior partitions. Glass enhances visual aesthetics and provides a connection between indoor and outdoor environments. However, glass is brittle and can shatter under impact or excessive loads, requiring appropriate safety measures and considerations in its application [57].

In summary, traditional civil engineering materials possess distinct performance characteristics that make them suitable for various applications. Concrete provides strength and durability, steel offers high tensile strength and resilience, timber provides natural aesthetics and thermal insulation, masonry materials offer strength and sound absorption, asphalt provides flexibility and durability for road construction, and glass offers transparency and visual aesthetics. Understanding the performance characteristics and applications of these materials is crucial in selecting the appropriate material for specific construction projects, ensuring the desired performance, durability, and functionality of the structures. Table 5 provides an in-depth analysis of the performance characteristics and applications of traditional civil engineering materials. This table details how these materials perform under different conditions and their specific uses in various infrastructure projects, offering valuable information for evaluating their effectiveness and suitability.

Table 5 Performance Characteristics and Applications of Traditional Civil Engineering Materials.

Material	Performance Characteristics	Applications	References
Concrete	Excellent compressive strength, durability, fire resistance	Foundations, columns, beams, slabs, pavements, bridges, dams	[48-50]
Steel	High strength-to-weight ratio, ductility, resilience	Steel-framed buildings, bridges, industrial facilities, reinforcing concrete structures	[51, 52]
Timber	Lightweight, high strength-to-weight ratio, thermal and acoustic insulation	Framing, flooring, roofing, interior finishes in residential and commercial construction	[53, 54]
Masonry	Strength, durability, thermal insulation, sound absorption	Load-bearing walls, facades, partitions, paving	[54]
Asphalt	Flexibility, durability, resistance to heavy traffic and weather conditions	Roads, highways, parking lots, airport runways	[55, 56]
Glass	Transparency, aesthetics, resistance to corrosion and UV radiation	Windows, doors, facades, skylights, interior partitions	[57]

7. Durability and Maintenance Challenges of Traditional Materials

While traditional civil engineering materials have been widely used in construction for their strengths and benefits, they also present certain durability and maintenance challenges. Understanding these challenges is essential for ensuring the long-term performance and sustainability of infrastructure [58]. The following are some common durability and maintenance challenges associated with traditional materials:

Despite its high compressive strength, concrete can be susceptible to various factors that affect its durability. One challenge is the potential for cracking due to shrinkage, thermal expansion, or external loads. Concrete is also prone to degradation caused by chemical attacks, such as from aggressive substances like sulfates and chlorides [58, 59]. To mitigate these challenges, proper mix design, use of quality aggregates, and appropriate curing techniques are crucial. Regular maintenance and repair of concrete structures, including crack sealing and surface coatings, are essential to prevent further deterioration [59].

While steel is highly durable and resistant to various forces, it is vulnerable to corrosion. When exposed to moisture and oxygen, steel can undergo rusting, compromising its strength and structural integrity. This is especially true in corrosive environments, such as coastal areas with high salt content in the air or structures immersed in water [60]. Protective measures, such as coatings and galvanization, are commonly employed to prevent corrosion. Regular inspection, maintenance, and timely repairs, such as replacing corroded sections and applying anti-corrosion treatments, are necessary to prolong the lifespan of steel structures [61].

The main durability challenge for timber is its susceptibility to moisture, pests, and fungal decay. Excessive moisture can lead to wood rot, weakening the material and compromising its structural integrity. Termites and other wood-boring insects can cause significant damage to timber structures [62]. Proper design considerations, treatment with preservatives, and regular inspection for signs of decay or infestation are essential for maintaining timber structures. Regular maintenance, including sealing, staining, and replacing damaged sections, helps to preserve the durability of timber materials [63].

Masonry materials, such as bricks and stones, are generally durable. However, they can be susceptible to moisture-related issues, including water penetration, efflorescence, and freeze-thaw cycles. Water infiltration can cause degradation and deterioration, leading to the loss of structural integrity. Proper design detailing, adequate waterproofing measures, and routine maintenance, such as repointing mortar joints and sealing cracks, are necessary to prevent water-related damage in masonry structures [64].

While asphalt offers durability, it is not immune to challenges. Over time, asphalt can undergo aging and deterioration due to environmental factors, such as UV radiation, temperature variations, and heavy traffic loads. Cracking, potholes, and surface deformation are common issues that require regular maintenance and repair. Resurfacing, patching, and sealcoating are common maintenance practices to extend the lifespan of asphalt pavements and ensure their functionality and safety [65].

Glass is a relatively durable material, but it can still face maintenance challenges. Scratches, chips, and cracks can occur due to impact or mishandling. Proper cleaning and maintenance are required to prevent the buildup of dirt, stains, and mineral deposits on glass surfaces. Additionally, glass requires careful installation and maintenance of seals and weatherproofing measures to prevent water infiltration and ensure its long-term performance [66]. Figure 8 presents a typical pictorial representation of glass, showcasing its application in civil engineering for creating aesthetically pleasing and functional elements such as windows, facades, and structural glazing in buildings, valued for its transparency, strength, and durability.

Figure 8 Typical pictorial representation of Glass as a civil Engineering material. Source [67].

Addressing the durability and maintenance challenges of traditional materials involves proactive measures, routine inspections, and timely repairs. Implementing proper construction practices, employing suitable protective measures, and conducting regular maintenance programs are crucial for maximizing the lifespan and performance of infrastructure constructed with traditional materials. Additionally, advancements in protective coatings, sealants, and maintenance techniques can help mitigate these challenges and enhance the durability and longevity of traditional materials. Table 6 addresses the durability and maintenance challenges associated with traditional civil engineering materials. This table outlines common issues and concerns related to the longevity and upkeep of these materials, providing essential insights into their performance over time and the strategies needed for effective maintenance.

Table 6 Durability and Maintenance Challenges of Traditional Civil Engineering Materials.

Material	Durability and Maintenance Challenges	Mitigation Strategies	References
Concrete	Cracking, chemical attacks, degradation	Proper mix design, quality aggregates, appropriate curing techniques, regular maintenance, crack sealing, surface coatings	[58, 59]
Steel	Corrosion due to moisture and oxygen exposure	Coatings, galvanization, regular inspection, maintenance, timely repairs, anti-corrosion treatments	[60, 61]
Timber	Moisture-related issues, wood rot, pests, fungal decay	Design considerations, treatment with preservatives, regular inspection, sealing, staining, replacing damaged sections	[62, 63]
Masonry	Water infiltration, efflorescence, freeze-thaw cycles	Proper design detailing, waterproofing measures, routine maintenance, repointing mortar joints, sealing cracks	[64]
Asphalt	Aging, deterioration, cracking, potholes, surface deformation	Resurfacing, patching, sealcoating, regular maintenance, repair	[65]
Glass	Scratches, chips, cracks, dirt buildup, water infiltration	Proper cleaning, maintenance, careful installation, seals and weatherproofing measures	[66]

8. Recent Advances in Cementitious Materials

Cementitious materials, particularly concrete, play a vital role in the construction industry. In recent years, there have been significant advancements in cementitious materials, aimed at improving their performance, durability, and sustainability [66]. This section explores some of the recent advances in cementitious materials:

1. High-Performance Concrete (HPC): High-performance concrete is a type of concrete that exhibits superior mechanical properties and durability compared to conventional concrete [67, 68]. It is achieved through the use of advanced admixtures, mineral additives, and optimized mix designs [69, 70]. HPC offers higher strength, enhanced resistance to cracking and chemical attacks, and improved workability [71]. It finds applications in high-rise buildings [72], bridges, and infrastructure projects that require exceptional performance and durability [73].

2. Self-Healing Concrete: Self-healing concrete is an innovative development that aims to address the issue of cracking in concrete structures. Microcapsules or other self-healing agents are incorporated into the concrete mix, which release healing agents when cracks occur. These agents react with the surrounding environment, filling the cracks and restoring the integrity of the concrete. Self-healing concrete improves the durability and service life of structures, reducing the need for frequent repairs and maintenance [74].
3. Ultra-High Performance Concrete (UHPC): Ultra-high performance concrete is a class of cementitious material that exhibits exceptional strength, high ductility, and enhanced durability. It is achieved by incorporating high amounts of cement, fine aggregates, and steel or polymer fibers [75]. UHPC offers outstanding resistance to compression, tension, and impact, making it suitable for a wide range of applications, including precast elements, infrastructure repair, and seismic-resistant structures [76].

Geopolymer concrete is an alternative to traditional Portland cement-based concrete. It is produced by activating industrial by-products, such as fly ash or slag, with alkali solutions. Geopolymer concrete offers similar or even superior mechanical properties compared to ordinary concrete while reducing carbon emissions and energy consumption. It is considered a more sustainable option and has applications in various construction projects, including roads, buildings, and infrastructure [77].

Carbon capture and utilization is an emerging field that aims to capture carbon dioxide (CO_2) emissions from industrial processes and incorporate them into building materials. In the case of cementitious materials, CO_2 can be utilized in the production of synthetic aggregates or as a binder in concrete mixtures. This approach not only reduces the carbon footprint of the construction industry but also contributes to the circular economy by reusing captured CO_2 [77].

Additive manufacturing, or 3D printing, has gained traction in the construction industry, including the production of concrete structures. 3D-printed concrete allows for precise and intricate geometries, reducing material waste and construction time [77]. It enables the fabrication of complex shapes, customized components, and optimized structures. Advances in 3D printing technology and the development of specialized concrete mixtures have opened up new possibilities for construction and architectural design [78].

Traditional Portland cement production is known to be energy-intensive and a significant contributor to carbon emissions. Recent advances have focused on developing sustainable cement alternatives, such as calcium sulfoaluminate cement, magnesium-based cement, and novel binders using industrial waste materials [78]. These alternatives offer reduced environmental impact and lower carbon emissions while maintaining comparable performance to conventional cement [79].

The recent advances in cementitious materials have paved the way for more sustainable, durable, and high-performance construction practices. These materials address the challenges of traditional cementitious systems while offering enhanced properties and environmental benefits. By incorporating these advancements into construction projects, engineers and architects can create structures that are not only structurally robust but also more sustainable and resilient in the face of evolving demands and environmental concerns [78]. Table 7 highlights recent advances in cementitious materials. This table provides a summary of the latest developments and innovations in cementitious materials, showcasing improvements in performance, sustainability, and application techniques that are shaping the future of civil engineering.

Table 7 Recent Advances in Cementitious Materials.

Cementitious Material	Description	Applications	References
High-Performance Concrete (HPC)	Concrete with superior mechanical properties and durability achieved through advanced admixtures, mineral additives, and optimized mix designs	High-rise buildings, bridges, infrastructure projects	[67-73]
Self-Healing Concrete	Concrete containing microcapsules or self-healing agents that release healing agents when cracks occur, restoring the integrity of the concrete	Structures requiring improved durability and reduced maintenance	[74]
Ultra-High Performance Concrete (UHPC)	Cementitious material with exceptional strength, ductility, and durability achieved through high cement content, fine aggregates, and fibers	Precast elements, infrastructure repair, seismic-resistant structures	[75, 76]
Geopolymer Concrete	Alternative to Portland cement-based concrete, produced by activating industrial by-products with alkali solutions	Roads, buildings, infrastructure project	[77]
Carbon Capture and Utilization in Cementitious Materials	Incorporating captured CO_2 emissions into building materials, reducing carbon footprint and promoting circular economy	Production of synthetic aggregates, binder in concrete mixtures	[77]
3D-Printed Concrete	Concrete structures produced through additive manufacturing, enabling precise geometries, reduced waste, and customized components	Complex shapes, customized components, optimized structures	[77, 78]
Sustainable Cement Alternatives	Calcium sulfoaluminate cement, magnesium-based cement, and novel binders using industrial waste materials as alternatives to conventional cement	Reduced environmental impact, lower carbon emissions	[78, 79]

9. Nanotechnology in Cement-Based Materials

Nanotechnology has emerged as a promising field in materials science and engineering, offering new possibilities for enhancing the properties and performance of cement-based materials. The integration of nanotechnology into cementitious systems has opened up avenues for improving strength, durability, sustainability, and functionality [79]. This section explores the application of nanotechnology in cement-based materials:

The addition of nano-scale particles, such as nanoparticles, nanofibers, and nanotubes, to cement-based materials can significantly enhance their mechanical properties [79]. These particles have a high surface-to-volume ratio, allowing for improved interfacial interactions with cementitious matrix components. Nanoparticles, such as nano-silica, nano-titania, and nano-alumina, can enhance the strength, toughness, and durability of concrete, while nanofibers and nanotubes, such as carbon nanotubes, can provide reinforcement and improve the flexural and tensile properties [78, 79]. Figure 9 illustrates a typical pictorial representation of nanomaterials, demonstrating their use in civil engineering to enhance the properties of construction materials, such as increasing strength, durability, and self-healing capabilities in concrete, coatings, and other advanced applications.

Figure 9 Typical pictorial representation of Nanomaterials as a civil Engineering material. Source [80].

The incorporation of nanomaterials in cement-based materials leads to improved mechanical performance. Nano-scale particles act as nucleation sites for the hydration of cement, resulting in denser microstructures with reduced porosity and enhanced strength. They can also improve the packing and dispersion of cement particles, leading to improved workability and reduced water demand. The enhanced mechanical properties offered by nanotechnology contribute to the development of more robust and durable concrete structures [79].

Nanotechnology plays a crucial role in improving the durability of cement-based materials. The addition of nano-scale particles can enhance the resistance of concrete to chemical attacks, such as sulfate attack and alkali-silica reaction [79, 80]. The incorporation of nanoscale additives can also reduce the permeability of concrete, making it less susceptible to moisture ingress and reinforcing steel corrosion. This increased durability results in extended service life and reduced maintenance requirements [80].

Nanotechnology offers the potential for self-healing capabilities in cement-based materials. Microcapsules containing healing agents, such as polymers or crystalline compounds, can be incorporated into the cementitious matrix. When cracks form, these capsules rupture, releasing the healing agents that can fill the cracks and restore the structural integrity of the material. Self-healing properties enabled by nanotechnology have the potential to enhance the longevity and sustainability of cement-based materials [81]. Nanotechnology has the potential to contribute to sustainable cement production. By incorporating nano-scale additives, the reactivity of cementitious materials can be enhanced, allowing for the reduction of cement content while maintaining or improving the mechanical properties. This reduction in cement consumption leads to a lower carbon footprint and reduced energy consumption during cement production, making it more environmentally friendly [82].

Nanotechnology enables the functionalization of cement-based materials, expanding their applications beyond traditional structural uses. Functional nanoparticles can be incorporated into cementitious systems to achieve specific properties, such as enhanced photocatalytic activity, self-cleaning surfaces, improved thermal insulation, or enhanced electromagnetic shielding. These functionalized cement-based materials have the potential to contribute to sustainable and energy-efficient building designs [82, 83].

Nanotechnology can also be utilized for monitoring and sensing applications in cement-based materials [83]. The integration of nano-sensors and nanomaterials with sensing capabilities, such as carbon nanotubes or graphene, allows for real-time monitoring of structural health, strain, and other parameters. This enables early detection of defects or structural changes, facilitating proactive maintenance and ensuring the safety and integrity of concrete structures [84].

In conclusion, nanotechnology has revolutionized the field of cement-based materials by offering new opportunities for enhancing strength, durability, sustainability, and functionality. The incorporation of nano-scale particles, self-healing capabilities, and functionalization of cement-based materials through nanotechnology have the potential to transform the constructionindustry. By leveraging the unique properties of nanomaterials, engineers can develop more advanced and sustainable cementitious systems that meet the evolving demands of modern infrastructure.

10. Self-Healing Concrete and Its Potential in Infrastructure Maintenance

Self-healing concrete, also known as autonomous or bio-inspired concrete, is an innovative material that has the potential to revolutionize infrastructure maintenance practices. It possesses the ability to repair cracks and restore its structural integrity without the need for human Intervention [85]. This section explores the concept of self-healing concrete and its potential applications in infrastructure maintenance:

Self-healing concrete incorporates various mechanisms to repair cracks. One common approach is the inclusion of microcapsules filled with healing agents, such as polymers or crystalline compounds, within the concrete matrix [86]. When cracks form, these capsules rupture, releasing the healing agents that react and fill the cracks, effectively sealing them. Another approach involves the use of vascular networks embedded within the concrete, through which healing agents can flow and repair cracks [87].

The ability of self-healing concrete to repair cracks autonomously leads to an extended service life for infrastructure. Cracks in concrete are typically pathways for moisture ingress and reinforcement corrosion, which can significantly compromise the durability and structural integrity of the material [88]. By self-healing cracks, self-healing concrete mitigates these issues and maintains the functionality and longevity of structures, reducing the need for frequent repairs and replacements [88].

Self-healing concrete has the potential to reduce maintenance and repair costs associated with infrastructure. Traditional concrete structures often require regular inspections, crack repairs, and maintenance interventions to ensure their integrity and safety [88]. Self-healing concrete minimizes the need for such interventions, as it can autonomously repair cracks as they occur. This reduces the need for manual repairs and associated labor costs, saving time and resources [89].

The self-healing capability of concrete enhances its durability by preventing crack propagation and minimizing the ingress of moisture, aggressive chemicals, and environmental pollutants. By sealing cracks promptly, self-healing concrete prevents further damage and degradation, preserving the material's strength and structural integrity. This results in longer-lasting and more resilient infrastructure that can withstand harsh environmental conditions and service loads [90].

Self-healing concrete aligns with sustainability goals by reducing the environmental impact associated with maintenance and repair activities [91]. It minimizes the consumption of repair materials, such as epoxy resins or external sealants, which often have a significant carbon footprint. Additionally, self-healing concrete reduces waste generation by eliminating the need for frequent crack repairs and replacements, promoting a more sustainable and resource-efficient approach to infrastructure maintenance [92].

Self-healing concrete enhances the safety and reliability of infrastructure by proactively addressing cracks and potential structural weaknesses. Cracks in concrete can compromise the stability and load-bearing capacity of structures, posing safety risks. With self-healing capabilities, concrete structures can maintain their integrity and performance, ensuring the safety of occupants and the public [92].

Self-healing concrete holds potential applications in various types of infrastructure, including buildings, bridges, tunnels, and roads. It can be particularly beneficial in structures exposed to aggressive environments, such as coastal areas with high chloride exposure or regions prone to freeze-thaw cycles. The development of self-healing concrete can also pave the way for more advanced and intelligent infrastructure systems, where sensors and monitoring technologies work in synergy with self-healing capabilities to provide real-time feedback and optimize maintenance strategies [92].

Self-healing concrete has the potential to revolutionize infrastructure maintenance practices by autonomously repairing cracks and extending the service life of structures. It offers benefits such as cost reduction, enhanced durability, sustainability, improved safety, and future applications in diverse infrastructure projects [93]. By incorporating self-healing concrete into construction practices, engineers can create more resilient, long-lasting, and sustainable infrastructure systems. Table 8 examines the potential benefits of self-healing concrete in infrastructure maintenance. This table outlines how self-healing concrete can enhance the longevity and durability of infrastructure by addressing common issues such as cracks and damage, providing valuable information on its advantages for maintaining and extending the life of structures.

Table 8 Potential Benefits of Self-Healing Concrete in Infrastructure Maintenance.

Aspect	Description	Benefits	References
Mechanisms	- Microcapsules filled with healing agents - Vascular networks for agent flow	- Autonomous crack repair - Improved structural integrity	[86, 87]

Extended Service Life	- Prevents moisture ingress and reinforcement corrosion - Maintains durability and functionality	- Longer lifespan - Reduced need for repairs and replacements	[88]
Cost Reduction	- Minimizes inspections and manual repairs - Saves time and resources	- Lower maintenance costs - Reduced labor expenses	[88, 89]
Durability and Sustainability	- Prevents crack propagation and ingress of chemicals and pollutants - Preserves strength and structural integrity	- Resilient infrastructure - Reduced environmental impact	[90-92]
Safety and Reliability	- Addresses cracks and structural weaknesses proactively - Ensures stability and safety	- Enhanced occupant and public safety	[92]
Applications	- Buildings, bridges, tunnels, roads - Aggressive environments (coastal, freeze-thaw cycles)	- Versatility in infrastructure projects	[92]
Potential Impact	- Autonomous crack repair and extended service life - Cost reduction, durability, sustainability, safety	- Revolutionize infrastructure maintenance	[93]

11. Novel Reinforcement Materials

Novel reinforcement materials have emerged as promising alternatives to traditional steel reinforcement in civil engineering applications. These materials offer unique properties and characteristics that enhance the performance, durability, and sustainability of reinforced concrete structures [94]. This section focuses on the advancements and applications of novel reinforcement materials:

Fiber-reinforced polymers, such as carbon fibers, glass fibers, and aramid fibers, have gained significant attention as reinforcement materials. FRPs offer high strength-to-weight ratios, excellent corrosion resistance, and low thermal conductivity compared to steel. They are used in various applications, including strengthening of existing structures, construction of lightweight bridges, and seismic retrofitting. FRPs also provide design flexibility due to their high tensile strength and the ability to tailor their properties to specific structural requirements [95].

Basalt fiber reinforced polymer is a relatively new reinforcement material that is gaining popularity due to its excellent mechanical properties and environmental sustainability [96]. Basalt fibers are derived from volcanic rocks and exhibit high tensile strength, good resistance to alkali, and excellent thermal stability. BFRP reinforcement offers advantages such as increased durability, reduced maintenance, and improved resistance to environmental degradation. It finds applications in infrastructure projects, including bridge decks, marine structures, and corrosion-prone environments [96].

Glass fiber reinforced polymer is another widely used reinforcement material in civil engineering. GFRP reinforcement consists of high-strength glass fibers embedded in a polymer matrix. It offers high tensile strength, corrosion resistance, and electrical non-conductivity [97]. GFRP reinforcement is commonly employed in applications requiring lightweight and non-magnetic properties, such as rehabilitation of concrete structures, parking garages, and seawalls. It also has excellent fatigue resistance and can enhance the durability and service life of structures [97].

Natural fiber reinforced polymer composites have gained attention as sustainable alternatives to traditional reinforcement materials. NFRP uses natural fibers, such as hemp, flax, or bamboo, embedded in a polymer matrix [97]. These materials offer low carbon footprints, biodegradability, and good mechanical properties. NFRP reinforcement finds applications in non-structural elements, such as cladding panels, partitions, and formwork. However, further research is needed to optimize the mechanical properties and durability of NFRP composites for structural applications [98].

Shape memory alloys are a unique class of materials that exhibit the ability to recover their original shape after deformation. SMAs, such as nickel-titanium (NiTi) alloys, can provide active reinforcement and self-repair capabilities in civil engineering structures. They can be embedded in concrete elements to provide additional flexural strength, crack closing, and damage recovery. SMAs find applications in seismic-resistant structures, adaptive structures, and smart infrastructure systems [99].

Carbon nanotubes are cylindrical carbon structures with exceptional mechanical, thermal, and electrical properties. They offer high tensile strength, low density, and excellent electrical conductivity. CNTs can be incorporated into cementitious materials to enhance their mechanical properties and improve electrical conductivity for applications such as sensing and self-monitoring. However, challenges related to cost, dispersion, and scalability limit their widespread implementation [99].

The use of novel reinforcement materials in civil engineering offers numerous advantages, including enhanced mechanical properties, improved durability, corrosion resistance, and sustainability. These materials contribute to the development of lightweight and high-performance structures, reduce maintenance needs, and extend the service life of infrastructure. Continued research and development in this field will further expand the applications and optimize the performance of these novel reinforcement materials, enabling the construction of more resilient and sustainable infrastructure systems [100]. Table 9 below provides a comprehensive overview of recent innovations in reinforcement technologies and their practical applications, highlighting how these novel materials contribute to enhanced performance and durability in civil engineering projects. Table 10 discusses advancements and applications of novel reinforcement materials in civil engineering.

Table 9 Advancements and Applications of Novel Reinforcement Materials in Civil Engineering.

Material	**Description**	**Applications**	**References**
Fiber-Reinforced Polymers (FRPs)	- Carbon fibers - Glass fibers - Aramid fibers	- Strengthening existing structures - Lightweight bridge construction - Seismic retrofitting	[95]
Basalt Fiber Reinforced Polymer (BFRP)	- Derived from volcanic rocks - High tensile strength - Good alkali resistance and thermal stability	- Bridge decks - Marine structures - Corrosion-prone environments	[96]
Glass Fiber Reinforced Polymer (GFRP)	- High-strength glass fibers in a polymer matrix - High tensile strength, corrosion resistance, and electrical non-conductivity	- Concrete structure rehabilitation - Parking garages - Seawalls	[97]
Natural Fiber Reinforced Polymer Composites (NFRP)	- Natural fibers (hemp, flax, bamboo) in a polymer matrix - Low carbon footprint and biodegradability	- Non-structural elements (cladding panels, partitions, formwork)	[97, 98]
Shape Memory Alloys (SMAs)	- Nickel-titanium (NiTi) alloys - Ability to recover original shape after deformation	- Seismic-resistant structures - Adaptive structures - Smart infrastructure systems	[99]
Carbon Nanotubes (CNTs)	- Cylindrical carbon structures with exceptional properties - High tensile strength, low density, excellent electrical conductivity	- Cementitious material enhancement - Sensing and self-monitoring	[99]
Advantages	- Enhanced mechanical properties - Improved durability - Corrosion resistance - Sustainability	- Lightweight and high-performance structures - Reduced maintenance needs - Extended service life of infrastructure	[100]

Table 10 Bio-Based Materials as Sustainable Alternatives for Reinforcement in Civil Engineering.

Material	Description	Applications	References
Bamboo	- High strength-to-weight ratio - Excellent tensile strength - Rapid growth rates	- Reinforcing concrete and structural elements	[100]
Natural Fibers	- Derived from hemp, flax, jute, etc. - Renewable nature and low environmental impact	- Biocomposite reinforcement with bio- based polymers or lime	[101]
Straw, Straw Bales, Timber	- Natural materials for reinforcement - Load-bearing walls, roof structures	- Load-bearing construction applications	[102]
Bio-based Polymers	- Renewable sources (bio-based polyesters, PLA) - Reduced carbon footprint compared to traditional materials	- Reinforcement in bio-composites with natural fibers	[102]
Advantages	- Renewable and low-carbon materials - Improved indoor air quality - Enhanced thermal performance and acoustic insulation - Resistance to fire	- Sustainable construction practices	[103]
Challenges	- Durability and resistance to environmental factors - Standardization of manufacturing processes and quality control - Cost considerations and availability on a large scale	- Ensuring long-term performance and cost-effectiveness	[104, 105]

12. Bio-Based Materials as Sustainable Alternatives for Reinforcement

Bamboo is a versatile and sustainable material that has gained attention as a potential reinforcement option in civil engineering [100]. It possesses high strength-to-weight ratio, excellent tensile strength, and rapid growth rates, making it an attractive alternative to traditional reinforcement materials. Bamboo can be used as a whole or processed into strips or fibers to reinforce concrete or other structural elements. Additionally, natural fibers derived from sources like hemp, flax, and jute are being explored as reinforcement materials due to their renewable nature and low environmental impact. These natural fibers can be incorporated into biocomposite materials, where they are combined with a matrix material, such as bio-based polymers or lime, to create sustainable reinforcement options [101].

In the pursuit of sustainable construction practices, researchers and engineers are exploring various renewable and low-carbon reinforcement options. One example is the use of natural materials like straw, straw bales, or timber in construction [102]. These materials can be employed as reinforcement in certain applications, such as load-bearing walls or roof structures. Additionally, bio-based polymers, such as bio-based polyesters or polylactic acid (PLA), are being investigated as potential reinforcement materials due to their renewable sources and reduced carbon footprint compared to traditional materials. These bio-based polymers can be reinforced with natural fibers to create bio-composites with improved mechanical properties [102].

The use of bio-based materials as sustainable alternatives for reinforcement offers several advantages. Firstly, these materials are renewable, meaning they can be replenished and do not deplete finite resources. Secondly, they often have a lower carbon footprint compared to traditional reinforcement materials, as they are derived from natural sources and require less energy-intensive manufacturing processes. Moreover, bio-based materials can contribute to improved indoor air quality as they do not release harmful chemicals or volatile organic compounds. Additionally, bio-based reinforcement materials can provide enhanced thermal performance, acoustic insulation, and resistance to fire [103].

However, there are some challenges associated with the use of bio-based materials as reinforcement. One challenge is ensuring their long-term durability and resistance to environmental factors, such as moisture, insects, and decay [104]. Proper treatment and protection methods are required to enhance the durability of bio-based reinforcement materials. Another challenge is the standardization of manufacturing processes and quality control, as bio-based materials may exhibit more variability compared to traditional materials. Additionally, cost considerations and availability of bio-based materials on a large scale need to be addressed for widespread adoption [105].

Overall, bio-based materials, including bamboo, natural fibers, and biocomposites, offer sustainable alternatives for reinforcement in civil engineering. These materials provide renewable and low-carbon options that can contribute to the reduction of environmental impact and promote sustainable construction practices [106]. Continued research, development, and standardization efforts are essential to optimize the performance, durability, and cost-effectiveness of these bio-based reinforcement materials and ensure their successful integration into mainstream construction practices [107]. Table 10 explores bio-based materials as sustainable alternatives for reinforcement in civil engineering. This table outlines the characteristics, benefits, and potential applications of bio-based materials, emphasizing their role in promoting sustainability and reducing environmental impact in reinforcement practices.

13. Advances in Steel Reinforcement for Enhanced Durability

Corrosion-Resistant and High-Strength Steels: Corrosion is a major concern for steel reinforcement in civil engineering, as it can lead to structural deterioration and reduced service life. Recent advancements in steel reinforcement have focused on developing corrosion-resistant and high-strength steels to address these challenges. Corrosion-resistant steels, such as stainless steels and weathering steels, are specifically designed to resist corrosion in aggressive environments [108]. These steels contain alloying elements that form a protective layer, preventing the penetration of corrosive agents. High-strength steels, on the other hand, offer improved tensile strength and yield strength, allowing for the design of lighter and more efficient structural elements. These advanced steels enhance the durability and performance of reinforced concrete structures, particularly in corrosive environments or high-stress applications [108].

Innovations in Reinforcement Design and Manufacturing: Advancements in reinforcement design and manufacturing techniques have contributed to improved durability and performance of steel reinforcement. The use of computer-aided design (CAD) and finite element analysis (FEA) has facilitated the development of optimized reinforcement configurations and geometries, ensuring efficient load transfer and enhanced structural behavior. Additionally, advancements in manufacturing processes, such as hot-rolling, cold-twisting, and microalloying, have enabled the production of steel reinforcement with superior mechanical properties and improved bond characteristics. These innovations have led to the development of reinforcement systems that offer higher load-carrying capacity, improved ductility, and enhanced resistance to fatigue and deformation [109].

The use of corrosion-resistant and high-strength steels in reinforcement offers several benefits. Firstly, corrosion-resistant steels provide enhanced durability and resistance to aggressive environments, minimizing the risk of corrosion-related damage and the need for frequent maintenance and repair. This improves the overall service life of reinforced concrete structures. Secondly, high-strength steels allow for the design of more slender and efficient structural elements, reducing material consumption and construction costs. They also offer improved structural performance, allowing for increased load-carrying capacity and better resistance to dynamic loads and seismic events [109].

Innovations in reinforcement design and manufacturing techniques have also contributed to enhanced durability. Optimized reinforcement configurations and geometries ensure effective load transfer and reduce the potential for localized stress concentrations. Improved bond characteristics between the reinforcement and concrete matrix enhance the structural integrity and resistance to cracking [110]. These advancements in design and manufacturing techniques enable the development of reinforcement systems that are better tailored to meet the specific requirements of different structural applications [110].

Despite these advancements, challenges remain in the use of advanced steel reinforcement. The cost of corrosion-resistant and high-strength steels may be higher compared to conventional reinforcement, impacting the economic feasibility of their widespread use [111]. Adequate quality control and inspection protocols are essential to ensure the proper manufacturing and installation of advanced reinforcement systems. Additionally, long-term performance and durability assessments of these advanced reinforcement materials are necessary to validate their effectiveness in real-world applications [112].

In conclusion, recent advances in steel reinforcement have focused on developing corrosion-resistant and high-strength steels, as well as innovations in reinforcement design and manufacturing techniques. These advancements offer enhanced durability and performance for reinforced concrete structures, improving their resistance to corrosion, increasing their load carrying capacity, and optimizing their structural behavior. By incorporating these advances into construction practices, civil engineers can enhance the longevity, sustainability, and performance of infrastructure projects [112]. Table 11 highlights advances in steel reinforcement aimed at enhancing durability in civil engineering. This table details recent developments in steel reinforcement technologies and their impact on improving the performance and longevity of structural elements, providing valuable insights into how these advancements contribute to more resilient and durable infrastructure.

Table 11 Advances in Steel Reinforcement for Enhanced Durability in Civil Engineering.

Advancement	Description	Benefits	References
Corrosion-Resistant Steels	- Stainless steels, weathering steels - Designed to resist corrosion in aggressive environments	- Enhanced durability and resistance to corrosion - Reduced maintenance and repair needs	[108]
High-Strength Steels	- Offer improved tensile strength and yield strength - Design of lighter and more efficient structural elements	- Design flexibility and material savings - Improved load-carrying capacity and resistance to high-stress applications	[108]
Innovations in Reinforcement Design	- Computer-aided design (CAD), finite element analysis (FEA) - Optimization of reinforcement configurations and geometries	- Efficient load transfer and enhanced structural behavior - Improved bond characteristics and resistance to fatigue	[109]
Innovations in Manufacturing	- Hot-rolling, cold-twisting, microalloying - Production of reinforcement with superior mechanical properties	- Superior reinforcement performance and bond characteristics - Enhanced resistance to deformation and cracking	[109]
Benefits	- Corrosion resistance reduces maintenance and repair needs - High-strength steels allow for efficient and lighter structural design - Improved structural performance and resistance to dynamic loads	- Extended service life and reduced life-cycle costs - Increased load-carrying capacity and seismic resistance	[108, 109]

Challenges	- Higher cost compared to conventional reinforcement - Quality control and inspection protocols - Long-term performance and durability assessment	- Economic feasibility and cost-effectiveness - Ensuring proper manufacturing and installation - Validating real- world effectiveness	[112]

13.1 Prefabricated and Modular Construction Materials

Prefabricated and modular construction materials have gained significant attention and popularity in recent years due to their numerous advantages in the construction industry. These materials involve the off-site manufacturing of building components or entire modules, which are then transported to the construction site for assembly. The following paragraphs discuss the strengthsand limitations of prefabricated and modular construction materials:

Prefabricated and modular materials offer significant time savings in construction projects. Since the components are manufactured off-site, site preparation and construction activities can proceed simultaneously, resulting in faster project completion [113]. The controlled environment of the manufacturing facility also allows for more efficient production, reducing construction time.

The manufacturing process of prefabricated and modular materials involves rigorous quality control measures. Factory-controlled conditions ensure consistent and high-quality production. Additionally, the use of standardized components and assembly methods minimizes variations and improves the overall quality of the final structure [114].

Prefabricated and modular materials can lead to cost savings in several ways. The controlled manufacturing process reduces material waste and optimizes resource utilization. The speed of construction also reduces labor costs. Additionally, the use of standardized components can result in economies of scale and bulk purchasing benefits [115].

Prefabricated and modular materials offer design flexibility, allowing for customization and adaptability. These materials can be easily configured and assembled in different ways to meet specific project requirements. They also enable the integration of various architectural styles, finishes, and functional features [116].

Prefabricated and modular construction materials can contribute to sustainable construction practices. The controlled manufacturing environment allows for efficient use of resources and minimizes material waste. Additionally, the ability to disassemble and reuse these materials in different projects enhances their sustainability profile [116]. Table 12 provides an overview of prefabricated and modular construction materials. This table outlines the key features, benefits, and applications of these materials, illustrating their role in modern construction practices and their impact on efficiency, cost-effectiveness, and overall project delivery.

Table 12 Prefabricated and Modular Construction Materials.

Strengths	Description	Limitations	References
Time Savings	- Off-site manufacturing allows concurrent site preparation and construction - Faster project completion	- Transportation logistics and coordination - Limited on-site customization	[113]
Quality Control	- Rigorous quality control measures in factory-controlled environments - Consistent and high-quality production	- Dependence on manufacturer expertise and certification - Limited flexibility for on-site adjustments	[114]
Cost Savings	- Reduced material waste and optimized resource utilization - Labor cost reduction due to faster construction - Economies of scale and bulk purchasing benefits	- Initial investment in manufacturing facilities and equipment - Transportation costs for large modules	[115]
Design Flexibility	- Easy configuration and assembly of components for customization - Integration of architectural styles, finishes, and functional features	- Design limitations based on module sizes and structural constraints - Potential challenges in adapting to site- specific conditions	[116]
Sustainability	- Efficient use of resources and reduced material waste - Potential for disassembly and reuse in different projects	- Transportation-related carbon footprint - Challenges in recycling and repurposing certain materials	[116]

14. Functional Materials for Enhanced Performance and Energy Efficiency

Functional materials play a crucial role in enhancing the performance and energy efficiency of structures. These materials have unique properties and functionalities that contribute to improved thermal insulation, acoustic control, energy generation, and storage. The following paragraphs discuss some of the recent advancements in functional materials for enhanced performance and energy efficiency:

Insulation is essential for reducing heat transfer and maintaining comfortable indoor temperatures. Recent advancements have led to the development of high-performance insulating materials, such as aerogels, vacuum insulation panels, and phase change materials. These materials offer superior thermal insulation properties, allowing for better energy efficiency in buildings and reduced heating and cooling costs [117].

Glass is a widely used material in modern architecture, and recent advancements have focused on improving its energy efficiency. Low-emissivity (low-E) coatings are applied to glass surfaces to minimize heat transfer while allowing visible light transmission. Additionally, smart glass technologies, such as electrochromic and thermochromic glass, can dynamically control the amount of light and heat passing through, optimizing energy consumption in buildings [118].

Materials that can convert renewable energy sources, such as solar or kinetic energy, into usable electricity are gaining attention. Solar panels made from advanced photovoltaic materials, such as perovskites and organic solar cells, offer higher efficiency and lower production costs. Similarly, piezoelectric materials can harness mechanical energy from vibrations and convert it into electrical energy, potentially powering small-scale devices within structures [119].

Phase Change Materials (PCMs) are substances that can store and release thermal energy during phase transitions. These materials can absorb heat during the day and release it at night, contributing to passive cooling and heating in buildings. PCMs integrated into building elements, such as walls or ceilings, can help regulate indoor temperatures, reduce reliance on heating and cooling systems, and enhance energy efficiency [120].

Functional coatings and surfaces with self-cleaning and air-purifying properties are becoming more prevalent. These materials can break down organic pollutants, neutralize harmful gases, and resist dirt and stains, leading to improved air quality and reduced maintenance requirements in buildings. Examples include titanium dioxide coatings and photocatalytic materials that harness sunlight to initiate self-cleaning and air-purifying processes [121].

Advances in nanotechnology have led to the development of smart materials embedded with sensors for structural health monitoring. These materials can detect changes in temperature, humidity, strain, or other physical parameters, providing real-time feedback on the condition of structures. This enables proactive maintenance and optimized performance, ensuring structural integrity and safety [122]. Energy storage is crucial for balancing intermittent renewable energy sources and managing peak demand. Innovative materials, such as advanced batteries and super capacitors, offer high energy density, rapid charging and discharging capabilities, and long cycle life. These materials facilitate the efficient storage and utilization of renewable energy, promoting sustainability and resilience in the built environment [123].

These recent advancements in functional materials offer promising opportunities to enhance the performance and energy efficiency of structures. By incorporating these materials into building design and construction, engineers can create more sustainable, comfortable, and technologically advanced environments. Continued research and development in this field will further expand the range of functional materials and their applications, driving the transition towards energy-efficient and environmentally friendly buildings [124]. Table 13 examines functional materials designed for enhanced performance and energy efficiency. This table details the properties, advantages, and applications of these materials, highlighting how they contribute to improved functionality and energy savings in civil engineering projects.

Table 13 Functional Materials for Enhanced Performance and Energy Efficiency.

Functional Materials	Description	Applications	References
High-Performance Insulating Materials	- Aerogels, vacuum insulation panels, phase change materials - Superior thermal insulation properties	- Building insulation - Energy-efficient construction	[117]

	- Energy-efficient buildings, reduced heating and cooling costs		
Energy-Efficient Glass	- Low-emissivity (low-E) coatings, smart glass technologies - Minimize heat transfer while allowing visible light transmission - Dynamic control of light and heat	- Windows, facades - Efficient building envelopes	[118]
Advanced Photovoltaic Materials	- Perovskites, organic solar cells - Higher efficiency, lower production costs - Conversion of solar energy into electricity	- Solar panels - Renewable energy generation	[119]
Piezoelectric Materials	- Harvest mechanical energy from vibrations - Conversion of mechanical energy into electrical energy	- Structural energy harvesting - Powering small-scale devices	[119]
Phase Change Materials (PCMs)	- Store and release thermal energy during phase transitions - Passive cooling and heating - Regulating indoor temperatures	- Building elements (walls, ceilings) - Energy-efficient climate control	[120]
Self-Cleaning and Air-Purifying Coatings	- Titanium dioxide coatings, photocatalytic materials - Breakdown of pollutants, resistance to dirt and stains - Improved air quality, reduced maintenance	- Building surfaces, facades - Indoor air purification	[121]
Smart Materials for Structural Health Monitoring	- Embedded sensors for real-time monitoring - Detection of temperature, humidity, strain, etc. - Proactive maintenance, optimized performance	- Structural health monitoring - Condition assessment, safety	[122]
Advanced Energy Storage Materials	- Advanced batteries, supercapacitors - High energy density, rapid charging and discharging	- Energy storage systems - Balancing intermittent	[123]

	- Efficient storage and utilization of renewable energy	renewable sources

14.1 Sustainable Materials for Civil Engineering

Sustainable materials in civil engineering refer to the use of environmentally friendly, socially responsible, and economically viable materials that minimize negative impacts on the environment and human health throughout their life cycle. These materials aim to reduce resource depletion, minimize waste generation, and promote sustainable development in the construction industry. This section explores the various sustainable materials used in civil engineering and their benefits [124, 125].

14.2 Recycled and Reclaimed Materials

Recycled and reclaimed materials play a significant role in sustainable construction practices. These materials include recycled aggregates, reclaimed timber, and recycled plastics. By diverting waste from landfills and reusing materials, these sustainable alternatives reduce the need for extracting and processing virgin resources. Recycled materials can be used in a variety of applications, such as road construction, concrete production, and structural elements, providing comparable performance to traditional materials while reducing environmental impact [126].

14.3 Low-Carbon Concrete

Concrete production is a major contributor to carbon emissions due to the high energy consumption involved in cement production. Low-carbon concrete aims to reduce carbon dioxide emissions by using alternative cementitious materials, such as fly ash, slag, or calcined clay, to partially replace Portland cement [127]. These materials have lower carbon footprints and contribute to the circular economy by utilizing industrial by-products as cementitious materials. Low-carbon concrete can be used in various construction applications and offers comparable strength and durability to traditional concrete [127].

14.4 Timber as a Sustainable Alternative

Timber is a renewable and environmentally friendly material that is increasingly being recognized for its sustainability in civil engineering. Responsibly sourced timber offers benefits such as low embodied energy, carbon sequestration, and reduced environmental impact compared to conventional construction materials. Timber can be used in structural elements, such as beams, columns, and floors, and its use can contribute to a lower carbon footprint and promote sustainable forestry practices [128].

14.5 Geopolymer-Based Materials

Geopolymer-based materials are gaining attention as a sustainable alternative to traditional cement-based materials. Geopolymer are formed by activating industrial by-products, such as fly ash or slag, with alkali solutions, resulting in a binder with properties similar to traditional cement.

Geopolymer-based materials offer lower carbon emissions, improved chemical resistance, and enhanced durability compared to conventional cementitious materials. They can be used in applications such as concrete production, coatings, and repair materials, providing sustainable solutions for infrastructure development [129].

14.6 Bio-Based Materials

Bio-based materials, derived from renewable resources such as agricultural waste, bamboo, or hemp, are emerging as sustainable alternatives for construction. These materials offer benefits such as low embodied energy, reduced carbon emissions, and biodegradability. Bamboo, for example, is a fast-growing and renewable resource that can be used as a structural material, offering high strength-to-weight ratio and versatility. Bio-based materials can be utilized in various applications, including insulation, paneling, and structural components, contributing to a more sustainable and circular economy [130].

14.7 Green Concrete and Self-Healing Materials

Green concrete refers to concrete that incorporates sustainable materials and technologies to reduce its environmental impact. This includes the use of recycled aggregates, alternative cementitious materials, and innovative admixtures to improve performance and reduce carbon emissions. Self-healing materials, on the other hand, have the ability to repair cracks and damage autonomously, extending the service life of infrastructure and reducing maintenance needs. These materials utilize microorganisms, capsules, or other mechanisms to release healing agents when damage occurs [130].

Sustainable materials in civil engineering offer numerous advantages, including reduced environmental impact, resource conservation, and improved life cycle performance. The use of these materials promotes sustainable construction practices, supports the circular economy, and contributes to the overall resilience and longevity of infrastructure. As research and technological advancements continue, the range of sustainable materials available for civil engineering applications will expand, leading to more sustainable and environmentally friendly construction practices [131]. Table 14 explores sustainable materials for civil engineering. This table outlines various materials that contribute to environmentally friendly construction practices, detailing their benefits, applications, and impact on sustainability in the field of civil engineering.

Table 14 Sustainable Materials for Civil Engineering.

Sustainable Materials	Description	Applications	References
Recycled and Reclaimed Materials	- Recycled aggregates, reclaimed timber, recycled plastics - Waste diversion and material reuse - Road construction, concrete production, structural elements	- Sustainable construction - Reduced environmental impact	[126]

Low-Carbon Concrete	- Alternative cementitious materials (fly ash, slag, calcined clay) - Reduced carbon dioxide emissions - Various construction applications	- Construction industry - Sustainable concrete production	[127]
Timber as a Sustainable Alternative	- Responsibly sourced timber - Low embodied energy, carbon sequestration - Structural elements, sustainable forestry practices	- Beams, columns, floors - Lower carbon footprint	[128]
Geopolymer-Based Materials	- Activation of industrial by-products (fly ash, slag) with alkali solutions - Lower carbon emissions, improved chemical resistance - Concrete production, coatings, repair materials	- Sustainable infrastructure development - Cementitious alternatives	[129]
Bio-Based Materials	- Derived from renewable resources (agricultural waste, bamboo, hemp) - Low embodied energy, reduced carbon emissions - Insulation, paneling, structural components	- Sustainable construction - Circular economy	[130]
Green Concrete and Self-Healing Materials	- Sustainable concrete incorporating recycled aggregates, alternative cementitious materials - Self-repairing materials extending service life - Reduced environmental impact, improved durability	- Construction industry - Infrastructure maintenance	[130]

15. Recycled Materials and Their Use in Construction

Recycled materials play a vital role in sustainable construction practices by reducing the demand for virgin resources and minimizing waste generation. One prominent example of recycled materials in construction is the use of recycled aggregates, crushed concrete, and reclaimed asphalt [132].

Recycled aggregates are derived from the processing of construction and demolition waste, including concrete, bricks, and asphalt. These materials undergo a crushing and screening process to produce aggregates with similar properties to natural aggregates. They can be used as a replacement for traditional aggregates in various construction applications, such as road base and subbase layers, drainage systems, and concrete production [133].

Crushed concrete is produced by crushing and processing old concrete structures or waste concrete generated during construction and demolition activities. The resulting crushed concrete can be used as a replacement for natural aggregates in road construction, embankments, and as a base material for new concrete [133].

Reclaimed asphalt refers to the recycling of asphalt pavement materials. During road resurfacing or reconstruction projects, the existing asphalt pavement is milled and reclaimed. The reclaimed asphalt is then processed and mixed with new asphalt binder and aggregates to produce recycled asphalt pavement (RAP). RAP can be used as a cost-effective alternative to virgin asphalt in road construction and maintenance [134].

The use of recycled aggregates, crushed concrete, and reclaimed asphalt offers several benefits. Firstly, it helps conserve natural resources by reducing the need for virgin materials. This contributes to waste reduction and landfill diversion. Secondly, it reduces energy consumption and carbon emissions associated with the extraction and processing of virgin aggregates and asphalt. By recycling these materials, the carbon footprint of construction projects can be significantly reduced. Thirdly, the use of recycled materials can lead to cost savings in construction projects, as recycled materials are often more affordable than their virgin counterparts [135].

However, it is important to consider the limitations and challenges associated with the use of recycled materials. Quality control and proper processing techniques are crucial to ensure that recycled aggregates meet the required specifications and perform satisfactorily in construction applications. Some challenges include potential variability in material properties, such as particle size distribution and contamination, which may require additional testing and quality assurance measures. Additionally, awareness and education among industry professionals and stakeholders are essential to promote the use of recycled materials and overcome any perceived barriers [136].

Overall, the utilization of recycled aggregates, crushed concrete, and reclaimed asphalt in construction contributes to sustainable development by reducing resource depletion, minimizing waste, and lowering environmental impact. With proper management and implementation, recycled materials offer a viable and environmentally friendly option for construction projects.

16. Geopolymer-Based Materials for Sustainable Infrastructure

Geopolymer-based materials have emerged as a sustainable alternative to traditional cementitious materials in the construction industry [137]. Geopolymer are inorganic binders formed by the reaction of alum inosilicate materials with alkaline activators. These materials offer several advantages in terms of sustainability, durability, and reduced environmental impact. Here, we explore the use of geopolymer-based materials for sustainable infrastructure:

Geopolymer-based materials have a significantly lower carbon footprint compared to conventional cement-based materials. The production of Portland cement, a key component of traditional concrete, is responsible for substantial carbon dioxide emissions. In contrast, geopolymer binders can be synthesized using industrial byproducts such as fly ash, blast furnace slag, and met kaolin, which are rich in reactive alum inosilicates. By utilizing these waste materials, geopolymer-based materials help reduce greenhouse gas emissions and minimize the environmental impact of construction activities [138].

Geopolymer exhibit excellent durability characteristics, making them suitable for various infrastructure applications. They possess high chemical resistance, minimizing degradation in harsh environments and protecting against corrosion. Geopolymer-based materials also demonstrate better resistance to sulfate attack, alkali-silica reaction, and chloride penetration compared to traditional cement-based materials [139]. Their enhanced durability contributes to the longevity and sustainability of infrastructure, reducing the need for frequent repairs and maintenance.

Geopolymer-based materials exhibit superior fire resistance properties. They have a higher fire resistance rating than conventional concrete, enabling the construction of fire-resistant structures. Geopolymer composites maintain their mechanical strength at elevated temperatures, reducing the risk of structural failure during fire events. This characteristic enhances the safety and resilience of infrastructure, particularly in high-risk areas [140].

Geopolymer technology enables the utilization of industrial byproducts and waste materials as raw materials. Fly ash, blast furnace slag, and other waste materials are often used as precursors for geopolymer binders. By diverting these materials from landfills and incorporating them into construction, geopolymer-based materials contribute to the circular economy and promote sustainable waste management practices [141].

The production of geopolymer-based materials consumes less energy compared to the production of Portland cement. The alkaline activation process used in geopolymer synthesis requires lower curing temperatures, reducing energy consumption during manufacturing. Additionally, the lower curing time of geopolymer allows for faster production and reduced energy requirements. These energy-efficient characteristics contribute to the overall sustainability of geopolymer-based materials [142].

Geopolymer-based materials offer flexibility in terms of composition and application. They can be tailored to meet specific performance requirements, allowing for customization based on project needs. Geopolymer-based materials can be used in various construction applications, including structural elements, pavement, and even 3D printing. This versatility enhances their applicability and promotes their adoption in sustainable infrastructure projects [143].

As geopolymer technology continues to advance, ongoing research and development efforts are focused on optimizing material properties, refining production techniques, and expanding applications. While challenges such as cost, standardization, and market acceptance remain, geopolymer-based materials hold significant potential for sustainable infrastructure development, offering a greener and more durable alternative to traditional cement-based materials [144].

17. Biomimetic Materials and Their Applications in Civil Engineering

Biomimetic materials, inspired by nature, have gained attention in civil engineering for their potential to improve performance, sustainability, and resilience of infrastructure. These materials mimic the structural and functional properties found in natural systems, offering unique advantages in various applications [145]. Here, we explore the applications of biomimetic materials in civil engineering:

Self-healing is a remarkable property found in many living organisms, and researchers have been working on developing materials that possess similar characteristics. Biomimetic self-healing materials have the ability to repair damage autonomously, enhancing the durability and longevity of infrastructure [146]. These materials incorporate capsules or vascular networks filled with healing agents that are released when cracks or damage occur. Self-healing materials have potential applications in concrete, asphalt, and composite structures, reducing the need for frequent repairs and maintenance [146].

Natural structures, such as bones, shells, and plant stems, possess exceptional strength, stiffness, and lightweight characteristics. Biomimetic materials aim to replicate these properties by mimicking the hierarchical structure and composition of natural materials. By integrating bio-inspired design principles into the development of structural materials, civil engineers can create lightweight and high-strength materials that optimize material usage, improve structural efficiency, and reduce environmental impact [147].

Biomimetic adaptive materials have the ability to respond and adapt to changes in environmental conditions. They can adapt their shape, stiffness, or other properties in response to external stimuli such as temperature, humidity, or mechanical stress. These materials have potential applications in adaptive building facades, smart bridges, and structures that can actively respond to changing loads or environmental conditions, improving safety, efficiency, and energy conservation [147].

Coatings inspired by natural systems offer protective and functional properties to infrastructure. For example, lotus leaf-inspired coatings provide self-cleaning properties, preventing the accumulation of dirt and reducing maintenance requirements [147]. Additionally, coatings mimicking the skin of sharks or dolphins can reduce drag and enhance the hydrodynamic performance of marine structures. Biomimetic coatings have the potential to improve the durability, energy efficiency, and sustainability of infrastructure components [148].

Biomimetic materials have found applications in geotechnical engineering, particularly in slope stabilization and erosion control. Plant root-inspired reinforcement systems can enhance the stability of slopes and reduce soil erosion by mimicking the anchoring and reinforcement mechanisms of plant roots. These biomimetic approaches can provide sustainable and cost-effective solutions for soil stabilization in geotechnical projects [149].

Nature provides inspiration for sound-absorbing and noise-reducing materials. Biomimetic materials based on the acoustic properties of animal fur, bird feathers, or insect wings can be used in building facades, sound barriers, and other noise control applications. These materials can effectively absorb and dampen sound waves, improving the acoustic performance of infrastructure and enhancing comfort for occupants [150].

Biomimetic materials offer innovative and sustainable solutions for civil engineering challenges, promoting efficiency, durability, and environmental stewardship. However, further research and development are required to refine manufacturing techniques, optimize material properties, and ensure their long-term performance and feasibility in real-world applications. Collaborative efforts between engineers, material scientists, biologists, and other disciplines are crucial to unlocking the full potential of biomimetic materials in civil engineering [151]. Table 15 discusses recycled materials in construction. This table highlights the types, benefits, and applications of recycled materials, emphasizing their role in promoting sustainability and reducing environmental impact within the construction industry. While Table 16 focuses on geopolymer-based materials for sustainable infrastructure. This table provides an overview of the properties, advantages, and applications of geopolymer materials, illustrating their potential for enhancing sustainability and reducing environmental impact in infrastructure projects and Table 17 explores biomimetic materials in civil engineering. This table outlines the principles, benefits, and applications of biomimetic materials, highlighting how these nature-inspired solutions contribute to innovative and sustainable approaches in civil engineering design and construction.

Table 15 Recycled Materials in Construction.

Recycled Materials	Description	Applications	References
Recycled Aggregates	- Derived from construction and demolition waste - Crushing and screening process - Road base, subbase layers, concrete production	- Road construction - Drainage systems - Concrete production	[133]
Crushed Concrete	- Crushing and processing of old concrete structures - Replacing natural aggregates - Road construction, embankments, base material	- Road construction - Embankments - Base material	[133]
Reclaimed Asphalt	- Recycling of asphalt pavement materials - Milling and reclaiming process - Cost-effective alternative to virgin asphalt	- Road construction - Maintenance	[134]

Table 16 Geopolymer-Based Materials for Sustainable Infrastructure.

Geopolymer-Based Materials	Description	Applications	References
Lower Carbon Footprint	- Utilizes industrial byproducts (fly ash, blast furnace slag, metakaolin) - Reduces greenhouse gas emissions - Minimizes environmental impact	- Concrete production - Coatings, repair materials	[138]
Enhanced Durability	- High chemical resistance - Resistance to sulfate attack, alkali-silica reaction, and chloride penetration	- Infrastructure construction - Longevity, reduced maintenance	[139]
Fire Resistance	- Higher fire resistance rating than conventional concrete - Maintains mechanical strength at elevated temperatures	- Fire-resistant structures - High-risk areas	[140]

Circular Economy	- Utilization of industrial byproducts and waste materials - Promotes sustainable waste management practices	- Waste diversion - Sustainable materials	[141]
Energy Efficiency	- Lower energy consumption during production and curing - Faster production with reduced energy requirements	- Sustainable manufacturing - Energy conservation	[142]
Versatile Applications	- Tailorable composition and performance - Structural elements, pavement, 3D printing	- Customized construction - Sustainable infrastructure	[143]

Table 17 Biomimetic Materials in Civil Engineering.

Biomimetic Materials	Description	Applications	References
Self-Healing Materials	- Autonomous repair of damage - Capsules or vascular networks with healing agents - Concrete, asphalt, composites	- Infrastructure durability - Reduced maintenance	[146]
Lightweight and High-Strength Materials	- Replicating natural structural properties - Hierarchical structure and composition - Improved structural efficiency	- Structural elements - Material optimization	[147]
Adaptive Materials	- Shape, stiffness, or property adaptation - Response to environmental stimuli - Adaptive facades, smart structures	- Energy conservation - Responsive infrastructure	[147]
Protective Coatings	- Inspired by natural systems - Self-cleaning, hydrodynamic, functional properties - Building facades, marine structures	- Durability enhancement - Energy efficiency	[148]
Geotechnical Engineering	- Slope stabilization, erosion control - Plant root-inspired reinforcement systems - Sustainable soil stabilization	- Slope stability - Erosion control	[149]

Acoustic Materials	- Sound-absorbing, noise-reducing properties - Inspired by animal fur, bird feathers, insect wings - Building facades, sound barriers

18. Advances in Construction Materials Testing and Evaluation

18.1 Non-Destructive Testing (NDT) Techniques

Non-destructive testing (NDT) techniques have advanced significantly in recent years, revolutionizing the way construction materials are tested and evaluated. These techniques allow for the assessment of material properties and structural integrity without causing damage to the tested samples. Here are some notable advances in NDT techniques:

UT uses high-frequency sound waves to detect flaws, measure material thickness, and evaluate the integrity of structures. Recent advances in UT technology have improved its accuracy and resolution, making it a valuable tool for detecting defects such as cracks, voids, and delaminations in concrete, steel, and other construction materials [151].

GPR is a geophysical method that uses radar pulses to image the subsurface of materials. It can be used to locate and assess the condition of reinforcement bars, detect voids or anomalies in concrete, and map subsurface features such as pipes and utilities. Recent developments in GPR equipment and data processing algorithms have enhanced its resolution and depth penetration capabilities [151].

Infrared thermography measures surface temperatures and thermal patterns to identify anomalies in materials. It can be used to detect moisture intrusion, thermal bridging, and insulation defects in buildings and structures. Advances in infrared camera technology have led to increased sensitivity and higher spatial resolution, improving the accuracy and efficiency of defect detection.AE testing involves monitoring and analyzing the acoustic signals emitted by a material or structure under stress. It can detect the presence and propagation of cracks, corrosion, and other forms of structural damage. Recent advancements in AE technology have improved signal processing techniques, enabling better identification and localization of damage sources [152].

18.2 Structural Health Monitoring (SHM) Systems

Structural health monitoring (SHM) systems have emerged as a powerful tool for continuously monitoring the condition and performance of structures. These systems integrate various sensors and data acquisition techniques to collect real-time data on structural behavior. Here are some key advances in SHM systems:

Wireless sensor networks enable the deployment of a large number of sensors for data collection, without the need for extensive wiring [152]. These sensors can measure parameters such as strain, vibration, temperature, and humidity, providing valuable insights into the structural health of buildings and infrastructure. Advances in wireless communication and energy harvesting have improved the reliability and autonomy of these networks [152, 153].

Internet of Things (IoT) integration enables the integration and analysis of data from multiple sensors and devices in real-time. It allows for centralized data management, remote monitoring, and early warning systems for structural health assessment. By leveraging IoT platforms, SHM systems can provide a comprehensive view of the structural behavior and enable proactive maintenance strategies [153].

These techniques can detect patterns, anomalies, and trends in structural behavior, facilitating accurate condition assessment and prediction of future performance. Machine learning algorithms can also automate the process of identifying and classifying different types of defects and damage in materials [154].

Remote monitoring capabilities have been improved, allowing engineers to access real-time data from SHM systems remotely. This enables prompt decision-making and efficient management of structural health [154]. Additionally, advancements in data visualization techniques provide intuitive and user-friendly interfaces for data interpretation, enabling stakeholders to understand the condition of structures easily.

The advancements in non-destructive testing techniques and structural health monitoring systems have revolutionized the field of construction materials testing and evaluation. These technologies provide valuable insights into the condition and performance of structures, enabling early detection of defects, more accurate assessments, and proactive maintenance strategies. Continued research and development in this area are essential to further improve the accuracy, reliability, and cost-effectiveness of these testing and monitoring techniques [155]. Table 18 highlights advancements in construction materials testing and evaluation, showcasing innovations such as high-precision instrumentation, non-destructive testing methods, real-time monitoring, advanced analytical techniques, improved testing protocols, and sustainability assessments that enhance the accuracy, efficiency, and reliability of material performance evaluations.

Table 18 Advances in Construction Materials Testing and Evaluation.

NDT Techniques	Advances	References
Ultrasonic Testing (UT)	Improved accuracy and resolution for defect detection	[151]
Ground Penetrating Radar (GPR)	Enhanced resolution and depth penetration capabilities	[151]
Infrared Thermography	Increased sensitivity and higher spatial resolution for defect detection	[151]
Acoustic Emission (AE) Testing	Improved signal processing techniques for damage identification	[152]
Wireless Sensor Networks	Deployment of large-scale sensor networks with improved reliability and autonomy	[152, 153]
Internet of Things (IoT) Integration	Centralized data management, remote monitoring, and proactive maintenance strategies	[153]
Data Analytics and Machine Learning	Enhanced interpretation and analysis of sensor data for condition assessment and defect classification	[154]
Remote Monitoring and Data Visualization	Improved remote access to real-time data and intuitive interfaces for data interpretation	[154]

19. Challenges and Future Directions

While recent advances in civil engineering materials have brought about numerous benefits and opportunities, there are still several challenges and areas for future exploration. Understanding these challenges and directing future research efforts can drive further advancements in the field.

Here are some key challenges and future directions:

1. Cost-effectiveness: Many advanced materials and technologies come with higher initial costs compared to traditional materials. Further research is needed to optimize manufacturing processes, scale up production, and explore cost-effective alternatives without compromising performance. Finding innovative ways to reduce material costs and improve cost-benefit ratios will be crucial for widespread adoption [156].
2. Standardization and regulations: As new materials and technologies emerge, it is essential to establish industry standards, guidelines, and regulations to ensure their safe and reliable use in construction projects. Developing standardized testing methods, performance criteria, and design codes will provide a framework for evaluating and implementing these materials. Collaboration between researchers, industry professionals, and regulatory bodies is crucial in developing comprehensive and widely accepted standards [157].
3. Long-term performance and durability: While many advanced materials exhibit excellent short-term performance, their long-term durability and service life under real-world conditions require further investigation [158]. Understanding the long-term behavior of these materials, including their resistance to environmental factors, chemical degradation, and aging, is essential to ensure the sustainability and longevity of infrastructure.
4. Integration of emerging technologies: The integration of emerging technologies, such as artificial intelligence, internet of things, and robotics, with civil engineering materials is an area of great potential. These technologies can enable real-time monitoring, predictive maintenance, and efficient construction processes. Future research should focus on exploring the seamless integration of these technologies into materials and construction practices to enhance performance, productivity, and sustainability [159].
5. Environmental impact and sustainability: While sustainable materials have gained attention, there is still room for improvement in terms of reducing the environmental impact associated with their production, use, and end-of-life disposal. Future research should focus on developing materials with lower carbon footprints, exploring recycling and reuse options, and assessing the life-cycle environmental impacts of new materials. Additionally, understanding the ecological compatibility of materials and their interactions with the surrounding environment will contribute to sustainable infrastructure development [160].
6. Collaboration and knowledge sharing: To accelerate progress in the field of civil engineering materials, collaboration and knowledge sharing among researchers, practitioners, and industry stakeholders are vital. Establishing platforms for exchanging ideas, sharing research findings, and collaborating on interdisciplinary projects will foster innovation and accelerate the adoption of advanced materials in the construction industry [161].
7. Education and training: With the rapid advancement of civil engineering materials, it is essential to equip professionals with the knowledge and skills required to effectively work with these materials. Incorporating the latest advancements in materials science and

engineering into educational curricula and providing training programs for industry professionals will ensure a skilled workforce capable of leveraging the benefits of advanced materials [162].

20. Research Gap

Identifying research gaps in the field of recent advances in civil engineering materials is crucial for guiding future research efforts and addressing areas that require further investigation. While it is beyond the scope of this response to provide an exhaustive list of research gaps, here are a few potential areas that could be explored:

1. Long-term performance and durability assessment: There is a need for comprehensive long-term studies to evaluate the performance and durability of recently developed materials under real-world conditions. This includes monitoring the behavior of materials over extended periods, assessing their resistance to various environmental factors, and understanding their degradation mechanisms. Such studies can provide valuable insights into the long-term sustainability and maintenance requirements of infrastructure constructed using these materials.
2. Multi-scale modeling and simulation: Developing accurate and reliable models that can predict the behavior of advanced materials at different scales is an ongoing challenge. Further research is needed to refine existing models and develop new computational techniques that can capture the complex behavior and interactions of these materials. This includes incorporating multi-physics phenomena, such as coupled thermal, mechanical, and chemical processes, and considering the effects of material heterogeneity and microstructural variations.
3. Standardization and certification: As new materials emerge, there is a need for standardized testing protocols and certification procedures to ensure their quality, performance, and compatibility with existing infrastructure systems. Research efforts should focus on developing standardized testing methods, performance criteria, and certification frameworks specific to these materials. This will facilitate their wider acceptance and implementation in practice.
4. Environmental impact assessment: While sustainability is a key consideration in the development of advanced materials, further research is needed to assess their environmental impact throughout their life cycle. This includes conducting comprehensive life cycle assessments (LCA) to evaluate the carbon footprint, energy consumption, and other environmental indicators associated with the production, use, and disposal of these materials. Additionally, research can explore methods for reducing the environmental impact of materials by optimizing manufacturing processes, exploring alternative raw materials, and integrating recycling and waste management strategies.
5. Integration of advanced materials with existing infrastructure: Retrofitting and upgrading existing infrastructure using advanced materials pose unique challenges. Research is needed to develop effective retrofitting techniques, design guidelines, and compatibility assessments to ensure the seamless integration of advanced materials with existing structures. This includes understanding the behavior of hybrid systems comprising traditional and advanced materials and evaluating their structural performance, durability,

and long-term behavior.

6. Health and safety considerations: The health and safety aspects associated with the production, handling, and use of advanced materials require further investigation. Research is needed to assess potential hazards, develop guidelines for safe handling and disposal, and evaluate the occupational health risks associated with working with these materials. Understanding the potential risks and implementing appropriate safety measures will facilitate the responsible and sustainable use of advanced materials in construction projects.

It is important to note that the specific research gaps may vary depending on the specific materials, applications, and regional contexts. Therefore, conducting a comprehensive literature review and consulting with experts in the field can help identify additional research gaps that need to be addressed.

21. Conclusion

The literature review on recent advances in civil engineering materials has highlighted several key findings and implications for the field. Advances in materials have led to improved performance, safety, and durability of infrastructure. Sustainable alternatives, such as recycled materials and bio-based materials, have gained prominence, aligning with environmental concerns. The integration of materials with technology has enabled real-time monitoring and proactive maintenance strategies. Prefabrication and modular construction methods have increased efficiency and productivity. Continued research and development are crucial for addressing knowledge gaps, driving innovation, fostering collaboration, and adapting to evolving needs and challenges in the field. Overall, these advancements have the potential to create more robust, sustainable, and efficient infrastructure that meets the demands of a changing world.

Acknowledgments

We extend our heartfelt gratitude to our co-authors, Samson Imoni, Michael Toryila Tiza, Ebenezer Ogırıma Akande, Mogbo Onyebuchi, Victoria Hassana Jiya, and Collins Onuzulike, for their invaluable contributions to the success of this article. Their expertise, dedication, and collaboration have been instrumental in shaping and enriching this work. We deeply appreciate their support throughout this research endeavor.

Author Contributions

Michael Toryila Tiza: Conducted literature search, reviewed and selected relevant articles, analyzed the literature, and contributed to the writing and editing of the review. Samson Imoni: Assisted in literature search, reviewed and selected relevant articles, analyzed the literature, and contributed to the writing and editing of the review. Ebenezer Ogırıma Akande: Assisted in literature search, reviewed and selected relevant articles, analyzed the literature, and contributed to the writing and editing of the review. Mogbo Onyebuchi: Conducted literature search, reviewed and selected relevant articles, summarized key findings, and contributed to the writing of the review. Victoria Hassana Jiya: Assisted in literature search, reviewed and selected relevant articles, analyzed the literature, and contributed to the writing and editing of the review. Collins Onuzulike: Conducted literature search, reviewed and selected relevant articles, summarized key findings, and contributed to the writing of the review. All authors have read and approved the final version of the literature review.

Funding

No funding was received for this research.

Competing Interests

The authors have declared that no competing interests exist.

References

1. Nia EM, Ling L, Awang M, Emamian SS. Advances in civil engineering materials. Singapore: Springer; 2022.
2. Discoveries E. Properties of fresh concrete with PDF file [Internet]. New York, USA: Engineering Discoveries; 2019. Available from: https://engineeringdiscoveries.com/properties-of-fresh-concrete-with-pdf-file/.
3. Yuan Q, Liu Z, Zheng K, Ma C. Civil engineering materials: From theory to practice. Amsterdam, Nederland: Elsevier; 2021.
4. Wu H. Advanced civil infrastructure materials: Science, mechanics and applications. Cambridge, UK: Woodhead Publishing; 2006.
5. Somayaji S. Civil engineering materials. 2nd ed. Englewood Cliffs, NJ: Prentice-Hall; 2011.
6. Zhang P, Han S, Ng S, Wang XH. Advanced Cementitious Building Materials with Applications in Civil Engineering. Adv Civ Eng. 2017; 2017: 9654910.
7. Tong K. Application of New Concrete Materials in Civil Engineering. Insight Mater Sci. 2021; 4: 352.
8. Grosse CU. Advances in construction materials 2007. Springer Science & Business Media; 2007.
9. Chang SY, Al Bahar SK, Zhao J. Advances in civil engineering and building materials. Boca Raton, FL: CRC Press; 2012.
10. Giddey SP, Badwal SP, Kulkarni A. Review of electrochemical ammonia production technologies and materials. Int J Hydrog Energy. 2013; 38: 14576-14594.
11. Smith BH, Szyniszewski S, Hajjar JF, Schafer BW, Arwade SR. Steel foam for structures: A review of applications, manufacturing and material properties. J Constr Steel Res. 2012; 71: 1-10.
12. Sarin P, Snoeyink VL, Lytle DA, Kriven WM. Iron corrosion scales: Model for scale growth, iron release, and colored water formation. J Environ Eng. 2004; 130: 364-373.
13. Mays G, Hutchinson AR. Adhesives in civil engineering. Cambridge: Cambridge University Press; 1992.
14. Liu J, Huang B. Civil Engineering Materials for Climate Adaptation and Sustainability. J Mater Civ Eng. 2020; 32: 02020001.
15. Iyer SL, Sen R, American Society of Civil Engineers. Advanced composites materials in civil engineering structures. Proceedings of the Specialty Conference; 1991 January 31-February 1; Las Vegas, NV, USA. Reston, VA: American Society of Civil Engineers.

16. Chen WF, Liew R. The civil engineering handbook. Boca Raton, FL: CRC Press; 2003.
17. Samui P, Kim D, Iyer NR, Chaudhary S. New materials in civil engineering. Oxford, UK: Butterworth-Heinemann; 2020.
18. James AN. Soluble materials in civil engineering. Horwood; 1992.
19. Abdullah S, Singh SS, Nor NM. Structural integrity cases in mechanical and civil engineering. Cham: Springer; 2022.
20. Awoyera PO, Thomas C, Kirgiz MS. The structural integrity of recycled aggregate concrete produced with fillers and pozzolans. Duxford, UK: Woodhead Publishing; 2021.
21. Jonnalagadda K, Alankar A, Balila NJ, Bhandakkar T. Advances in structural integrity. Singapore: Springer; 2022.
22. Rethinking the Future. Alternative materials: Fibre-reinforced plastic [Internet]. New Delhi, India: Rethinking the Future; 2021 [cited date 2023 July 3]. Available from: https://www.re-thinkingthefuture.com/alternative-material/a3555-alternative-materials-fibre-reinforced-plastic/.
23. Oyguc R, Tahmasebinia F. Structural integrity and failure. London, UK: IntechOpen; 2021.
24. Mohammadi S. Shape memory alloy, memories, alloy. Pinterest; [cited date 2023 July 3]. Available from: https://www.pinterest.com/pin/837810336927584954/.
25. Huany G. Geopolymer [Internet]. Alchetron; 2017 [cited date 2023 July 3]. Available from: https://alchetron.com/Geopolymer.
26. Grandt Jr AF. Fundamentals of structural integrity: Damage tolerant design and nondestructive evaluation. Hoboken, NJ: John Wiley & Sons; 2004.
27. Ariffin AH, Latif NA, bin Mahmod MF, Mohamad ZB. Structural integrity and monitoring for composite materials. Singapore: Springer; 2023.
28. Kanellopoulos A, Norambuena-Contreras J. Self-healing construction materials: Fundamentals, monitoring and large scale applications. Cham: Springer; 2022.
29. Lidbury D, Hirsch PB. Methods for the assessment of the structural integrity of components and structures. London, UK: CRC Press; 2003.
30. Cicero S, Álvarez JA. Fracture, fatigue, and structural integrity of metallic materials. Metals. 2019; 9: 913.
31. Holtz RD, Kovacs WJ. Introduction to geotechnical engineering. Hershey, PA: IGI Global; 2015. 40p.
32. Brûlé S, Javelaud EH, Enoch S, Guenneau S. Experiments on seismic metamaterials: Molding surface waves. Phys Rev Lett. 2014; 112: 133901.
33. Montalvao D, Maia NM, Ribeiro AM. A review of vibration-based structural health monitoring with special emphasis on composite materials. Shock Vib Dig. 2006; 38: 295-324.
34. Van Den Einde L, Zhao L, Seible F. Use of FRP composites in civil structural applications. Constr Build Mater. 2003; 17: 389-403.
35. Sohail U. What's the difference between reinforcement steel & structural steel? A civil engineer answers [Internet]. Wonderful Engineering; 2017. Available from: https://wonderfulengineering.com/whats-difference-reinforcement-steel-structural-steel-civil-engineer-answers/.
36. Hollaway LC. The evolution of and the way forward for advanced polymer composites in the civil infrastructure. Constr Build Mater. 2003; 17: 365-378.
37. Tönshoff HK, Hillmann-Apmann H, Asche J. Diamond tools in stone and civil engineering

industry: Cutting principles, wear and applications. Diam Relat Mater. 2002; 11: 736-741.
38. Awad ZK, Aravinthan T, Zhuge Y, Gonzalez F. A review of optimization techniques used in the design of fibre composite structures for civil engineering applications. Mater Des. 2012; 33: 534-544.
39. Murmu AL, Patel A. Towards sustainable bricks production: An overview. Constr Build Mater. 2018; 165: 112-125.
40. Ulusoy UĞ, Yekeler ME, Hiçyılmaz C. Determination of the shape, morphological and wettability properties of quartz and their correlations. Miner Eng. 2003; 16: 951-964.
41. DRemy & Co. Timber trusses, timber frame engineering–DRemy & Co–Structural Engineers Gallery [Internet]. D.Remy & Co.; [cited date 2023 July 3]. Available from: http://www.dremy.com/structural_engineering_photos_gallery_DRemy_and_Co_north_carolina.html.
42. Vieira CS, Pereira PM, de Lurdes Lopes M. Recycled construction and demolition wastes as filling material for geosynthetic reinforced structures. Interface properties. J Clean Prod. 2016; 124: 299-311.
43. You Z, Mills-Beale J, Foley JM, Roy S, Odegard GM, Dai Q, et al. Nanoclay-modified asphalt materials: Preparation and characterization. Constr Build Mater. 2011; 25: 1072-1078.
44. Li R, Xiao F, Amirkhanian S, You Z, Huang J. Developments of nano materials and technologies on asphalt materials–A review. Constr Build Mater. 2017; 143: 633-648.
45. Knoeri C, Binder CR, Althaus HJ. Decisions on recycling: Construction stakeholders' decisions regarding recycled mineral construction materials. Resour Conserv Recycl. 2011; 55: 1039-1050.
46. Gonçalves MC, Margarido F. Materials for construction and civil engineering. Cham, Switzerland: Springer; 2015.
47. Middendorf B, Fehling E, Wetzel A. Ultra-High Performance Concrete and High Performance Construction Materials. Proceedings of HiPerMat 2020 5th International Symposium on Ultra-High Performance Concrete and High Performance Materials; March 11-13, 2020; Kassel, Germany. Norderstedt: BoD–Books on Demand. Available from: https://doi.org/10.17170/kobra-202002271026.
48. Zhou XJ. Architecture and building materials. Bäch, Switzerland: Trans Tech Publications Ltd.; 2011.
49. Shi C. High-performance construction materials: Science and applications. Singapore: World Scientific; 2008.
50. Luo Z, Li W, Wang K, Shah SP. Research progress in advanced nanomechanical characterization of cement-based materials. Cem Concr Compos. 2018; 94: 277–295.
51. Zhang H. Building materials in civil engineering. Cambridge, UK: Elsevier; 2011.
52. Connor J, Laflamme S. Structural motion engineering. Cham: Springer; 2014.
53. Konietzky H. Numerical modelling of discrete materials in geotechnical engineering, civil engineering and earth sciences. London, UK: CRC Press; 2004.
54. Eyvaz M. Textile materials in liquid filtration practices current status and perspectives in water and wastewater treatment. London, UK: IntechOpen; 2017.
55. Seracino R. FRP composites in civil engineering - CICE 2004. London, UK: CRC Press; 2004.
56. Fragomeni S, Venkatesan S. Incorporating sustainable practice in mechanics and structures of materials. London, UK: CRC Press; 2010.

57. Xu J, Deng W, Wu J. Artificial intelligence in nondestructive testing of civil engineering materials. Lausanne, Switzerland: Frontiers Media SA; 2021.
58. Hussain CM. Handbook of polymer nanocomposites for industrial applications. Amsterdam, Nederland: Elsevier; 2020.
59. Asdrubali F, Desideri U. Handbook of energy efficiency in buildings: A life cycle approach. Oxford, UK: Butterworth-Heinemann; 2019.
60. Hollaway LC, Leeming M. Strengthening of reinforced concrete structures. Cambridge, UK: Elsevier; 1999.
61. Yu CW, Bull JW. Durability of materials and structures in building and civil engineering. Whittles Publishing; 2006.
62. Liew JR, Xiong MX, Lai BL. Design of steel-concrete composite structures using high-strength materials. Woodhead Publishing; 2021.
63. Schneppa Recycled Crushed Glass. Glass in polished concrete [Internet]. Croydon, VIC: Schneppa Recycled Crushed Glass; [cited date 2023 July 3]. Available from: https://schnepparecycledcrushedglass.com.au/crushed-glass-images/glass-polished-concrete/.
64. Fangueiro R. Fibrous and composite materials for civil engineering applications. Cambridge, UK: Elsevier; 2011.
65. Chen A, Ruan X, Frangopol DM. Life-cycle civil engineering: Innovation, theory and practice. Leiden, Netherlands: CRC Press; 2021.
66. Casas JR, Frangopol DM, Turmo J. Bridge safety, maintenance, management, life-cycle, resilience and sustainability. Leiden, Netherlands: CRC Press; 2022.
67. Thompson MK. Proceedings of the 2nd International Workshop on Design in Civil and Environmental Engineering; 2013 June 28th-29th; Worcester, Massachusetts, USA. Worcester, MA: Worcester Polytechnic Institute; 2013.
68. Kawashima S, Hou P, Corr DJ, Shah SP. Modification of cement-based materials with nanoparticles. Cem Concr Compos. 2013; 36: 8–15.
69. Yokota H, Frangopol DM. Bridge maintenance, safety, management, life-cycle sustainability and innovations. Leiden, Netherlands: CRC Press; 2020.
70. Tiza MT. Sustainability in the civil engineering and construction industry: A review. J Sustain Constr Mater Technol. 2022; 7: 30-39.
71. Şahmaran M, Shaikh F, Yıldırım G. Recent advances in nano-tailored multi-functional cementitious composites. Woodhead Publishing; 2022.
72. Lago R. Quality of concrete structures and recent advances in concrete materials and testing. Farmington Hills, MI: American Concrete Institute; 2005.
73. Li Z. Advanced concrete technology. Hoboken, NJ: John Wiley & Sons; 2022.
74. Sangiorgi C, Ubertini F, Pisello AL. Recent advances in smart materials for the built environment. Basel: MDPI; 2018.
75. Kathir. Nanotechnology in Concrete - Civil Snapshot. 2018 [cited date 2023 July 3]. Available from: http://civilsnapshot.com/nanotechnology-in-concrete/.
76. Rahman RO, Rakhimov RZ, Rakhimova NR, Ojovan MI. Cementitious materials for nuclear waste immobilization. Chichester, UK: John Wiley & Sons; 2015.
77. Yilmaz S, Ozmen HB. High performance concrete technology and applications. London, UK: IntechOpen; 2016.

78. Malhotra VM. Quality of concrete structures and recent advances in concrete materials and testing. Farmington Hills, MI: American Concrete Institute; 2005.
79. Barros JA, Ferrara L, Martinelli E. Recent advances on green concrete for structural purposes: The Contribution of the EU-FP7 Project EnCoRe. Cham: Springer; 2017.
80. Gdoutos EE, Kounadis AN. Recent advances in mechanics. Netherlands: Springer; 2011.
81. Hau KK, Gupta AK, Chaudhary S, Gupta T. Recent advances in structural engineering and construction management: Select proceedings of ICSMC 2021. Singapore: Springer; 2022.
82. Zijl V, Boshoff BP. Advances in cement-based materials. London, UK: CRC Press; 2009.
83. Jiang Z. Green high-performance concrete with manufactured sand. Singapore: Springer Nature; 2022.
84. Tiza MT, Ogunleye E, Jiya VH, Onuzulike C, Akande EO, Terlumun S. Integrating sustainability into civil engineering and the construction industry. J Cem Based Compos. 2023; 4: 5756.
85. Fehling E, Middendorf B, Thiemicke J. Ultra-high performance concrete and high performance construction materials. Kassel, Germany: Kassel University Press GmbH; 2016.
86. Middendorf B, Fehling E, Wetzel A. Ultra-high performance concrete and high performance construction materials. Kassel, Germany: Kassel University Press GmbH; 2020.
87. Baseheart TM, Shahrooz BM. Use of high performance concrete for an adjacent box beam bridge, guernsey county, Ohio. Cincinnati, OH: University of Cincinnati; 2002.
88. De Rooij M, Van Tittelboom K, De Belie N, Schlangen E. Self-healing phenomena in cement-Based materials: State-of-the-art report of RILEM technical committee 221-SHC: Self-Healing phenomena in cement-Based materials. Springer Science & Business Media; 2013.
89. Hager MD, Der V, Schubert US. Self-healing materials. Cham: Springer International Publishing; 2016.
90. He J. Development, characterization and modeling of self-healing cementitious materials. Washington, DC: Washington State University; 2020.
91. Alexander MG, Beushausen HD. Concrete repair, rehabilitation and retrofitting II. Proceedings of the 2nd International Conference on Concrete Repair, Rehabilitation and Retrofitting; 2008 November 24-26; Cape Town, South Africa. Boca Raton, FL: CrcPress/Balkema.
92. Tiza MT, Jırgba K, Sanı HA, Sesugh T. Effect of thermal variances on flexible pavements. J Sustain Constr Mater Technol. 2022; 7: 220-230.
93. Fisher D. Self-healing concrete. Materials Research Forum LLC; 2021.
94. Khan A, Jawaid M, Raveendran SN, Ahmed M. Self-healing composite materials. Duxford, UK: Woodhead Publishing; 2019.
95. Huseien GF, Faridmehr I, Baghban MH. Self-healing cementitious materials technologies, evaluation methods, and applications. Boca Raton, FL: CRC Press; 2022.
96. Provis JL, Van Deventer JS. Geopolymers: Structures, processing, properties and industrial applications. Cambridge, UK: Elsevier; 2009.
97. Davidovits J. Geopolymer chemistry and applications. Institut Géopolymère; 2008.
98. Panigrahi M, Ganguly RI, Dash RR. Development of geopolymer from pond ash-thermal power plant waste. John Wiley & Sons; 2023.
99. Ban CC. Ternary and quaternary blended alkali-activated binder: Engineering properties and performance. Penerbit USM; 2021.
100. Shrestha P. Development of geopolymer concrete for precast structures. 2013. Available from: https://mavmatrix.uta.edu/civilengineering_theses/134.

101. Tiza TM, Mogbo O, Singh SK, Shaik N, Shettar MP. Bituminous pavement sustainability improvement strategies. Energy Nexus. 2022; 6: 100065.
102. Pacheco-Torgal F, Labrincha J, Leonelli C, Palomo A, Chindaprasit P. Handbook of alkali-activated cements, mortars and concretes. Cambridge, UK: Elsevier; 2014.
103. Chami D, Tabchoury R. Development of green concrete using geopolymer. Balamand: University of Balamand; 2019.
104. Teng JG, Huang YL, Lam L, Ye LP. Theoretical Model for Fiber-Reinforced Polymer-Confined Concrete. J Compos Constr. 2007; 11: 201–210.
105. Bernard O, Ulm FJ, Lemarchand E. A multiscale micromechanics-hydration model for the early-age elastic properties of cement-based materials. Cem Concr Res. 2003; 33: 1293–1309.
106. Seki Y, Sarikanat M, Sever K, Durmuşkahya C. Extraction and properties of Ferula communis (chakshir) fibers as novel reinforcement for composites materials. Compos B Eng. 2013; 44: 517-523.
107. Porras A, Maranon A, Ashcroft IA. Characterization of a novel natural cellulose fabric from Manicaria saccifera palm as possible reinforcement of composite materials. Compos B Eng. 2015; 74: 66-73.
108. Tiza TM, Kpur G, Ogunleye E, Sharma S, Singh SK, Likassa DM. The potency of functionalized nanomaterials for industrial applications. Mater Today Proc. 2023. doi: 10.1016/j.matpr.2023.03.212.
109. Mechtcherine V, Michel A, Liebscher M, Schneider K, Großmann C. Mineral-impregnated carbon fiber composites as novel reinforcement for concrete construction: Material and automation perspectives. Autom Constr. 2020; 110: 103002.
110. Ramasamy R, Obi Reddy K, Varada Rajulu A. Extraction and characterization of Calotropis gigantea bast fibers as novel reinforcement for composites materials. J Nat Fibers. 2018; 15: 527-538.
111. Han F, Yue J, Fan X, Gao T, Luo C, Ma Z, et al. High-performance all-solid-state lithium–sulfur battery enabled by a mixed-conductive Li_2S nanocomposite. Nano Lett. 2016; 16: 4521-4527.
112. Tiza TM, Singh SK, Kumar L, Shettar MP, Singh SP. Assessing the potentials of Bamboo and sheep wool fiber as sustainable construction materials: A review. Mater Today Proc. 2021; 47: 4484-4489.
113. Ammar MA. Bond durability of basalt fibre-reinforced polymers (BFRP) bars under freeze-and-thaw conditions. Québec, Canada: Université Laval; 2014.
114. Adhikari S. Mechanical properties and flexural applications of basalt fiber reinforced polymer (BFRP) bars. Akron, OH: The University of Akron; 2009.
115. Rahman A. Effect of basalt fibers on the flexural behavior of beams reinforced with BFRP Bars. Sharjah, UAE: American University of Sharjah; 2018.
116. Schaaf B, Richter C, Feldmann M, Toups E, Simon J, Reese S, et al. Material parameter determination for the simulation of hyperelastic bonds in civil engineering considering a novel material model. Int J Adhes Adhes. 2020; 103: 102692.
117. Banibayat P. Experimental Investigation of the Mechanical and Creep Rupture Properties of Basalt Fiber Reinforced Polymer (BFRP) Bars. Akron, OH: The University of Akron; 2011.
118. Karbhari VM. Durability of composites for civil structural applications. Elsevier; 2007.
119. Gu X, Dong Q. Laboratory test and numerical simulation of bond performance between basalt fiber reinforced polymer rebar and concrete. J Test Eval. 2012; 40: 1-8.

120. Singaravadivelan R. Strengthening of concrete elements using basalt fiber. Saarbrucken, Germany: LAP Lambert Academic Publishing; 2013.
121. Byrne MT, Gun'ko YK. Recent advances in research on carbon nanotube–polymer composites. Adv Mater. 2010; 22: 1672-1688.
122. Sorelli L, Constantinides G, Ulm FJ, Toutlemonde F. The nano-mechanical signature of ultra high performance concrete by statistical nanoindentation techniques. Cem Concr Res. 2008; 38: 1447-1456.
123. Sharp JH, Lawrence CD, Yang R. Calcium sulfoaluminate cements—low-energy cements, special cements or what? Adv Cem Res. 1999; 11: 3-13.
124. Mo M, Zhao W, Chen Z, Yu Q, Zeng Z, Wu X, et al. Excellent tribological and anti-corrosion performance of polyurethane composite coatings reinforced with functionalized graphene and graphene oxide nanosheets. Rsc Adv. 2015; 5: 56486-56497.
125. Feng W, Patel SH, Young MY, Zunino III JL, Xanthos M. Smart polymeric coatings—recent advances. Adv Polym Technol. 2007; 26. doi: 10.1002/adv.20083.
126. Singh G, Singh M, Saini B. Role of FRP in developing sustainable infrastructure—A review. In: 3rd International Conference on Innovative Technologies for Clean and Sustainable Development. Cham: Springer International Publishing; 2021. pp. 251-261.
127. Mo KH, Alengaram UJ, Jumaat MZ. A review on the use of agriculture waste material as lightweight aggregate for reinforced concrete structural members. Adv Mater Sci Eng. 2014; 2014: 365197.
128. Elgabbas F, Ahmed EA, Benmokrane B. Experimental testing of concrete bridge-deck slabs reinforced with basalt-FRP reinforcing bars under concentrated loads. J Bridge Eng. 2016; 21: 04016029.
129. Zhang P, Li G. Advances in healing-on-demand polymers and polymer composites. Prog Polym Sci. 2016; 57: 32-63.
130. Vaithylingam R, Ansari MN, Shanks RA. Recent advances in polyurethane-based nanocomposites: A review. Polym Plast Technol Eng. 2017; 56: 1528-1541.
131. Yadav R, Naebe M, Wang X, Kandasubramanian B. Body armour materials: From steel to contemporary biomimetic systems. RSC Adv. 2016; 6: 115145-115174.
132. Khatib JM. Sustainability of construction materials. Woodhead Publishing; 2009.
133. Dong Y. Performance assessment and design of ultra-high performance concrete (UHPC) structures incorporating life-cycle cost and environmental impacts. Constr. Build. Mater. 2018; 167: 414–425.
134. Satyanarayanan KS, Seo HJ, Gopalakrishnan N. Sustainable construction materials. Singapore: Springer Nature; 2021.
135. Gupta AK, Shukla SK, Azamathulla H. Advances in construction materials and sustainable environment: Select proceedings of ICCME 2020. Singapore: Springer; 2022.
136. Dhir RK. Sustainable construction materials: Recycled aggregates. Duxford, UK: Woodhead Publishing; 2019.
137. Kao JC, Sung WP, Chen R. Green building, materials and civil engineering. Proceedings of the 4th International Conference on Green Building, Materials and Civil Engineering; 2014 August 21-22; Hong Kong, China. Leiden, Netherlands: CRC Press/Balkema.
138. Reddy KR, Pancharathi RK, Reddy NG, Arukala SR. Advances in sustainable materials and resilient infrastructure. Singapore: Springer; 2022.

139. Biswas S, Metya S, Kumar S, Samui P. Advances in sustainable construction materials. Singapore: Springer Nature; 2021.
140. Martínez-Barrera G, González-Rivas N, Vigueras-Santiago E, Martínez-López Á, Tello-González JA, Menchaca-Campos C. Waste and recycled materials and their impact on the mechanical properties of construction composite materials. In: Composites from renewable and sustainable materials. London, UK: IntechOpen; 2016.
141. Mirza J, Hussin MW, Ismail MA. Recycled waste materials in concrete construction: Emerging research and opportunities. Hershey, PA: IGI Global; 2019.
142. Rifaie-Graham O, Apebende EA, Bast LK, Bruns N. Self-reporting fiber-reinforced composites that mimic the ability of biological materials to sense and report damage. Adv Mater. 2018; 30: 1705483.
143. Díaz Lantada A, de Blas Romero A, Sánchez Isasi Á, Garrido Bellido D. Design and performance assessment of innovative eco-efficient support structures for additive manufacturing by photopolymerization. J Ind Ecol. 2017; 21: S179-S190.
144. Pan H, She W, Zuo W, Zhou Y, Huang J, Zhang Z, et al. Hierarchical toughening of a biomimetic bulk cement composite. ACS Appl Mater Interfaces. 2020; 12: 53297-53309.
145. Grotzinger J, Beaty D, Dromart G, Gupta S, Harris M, Hurowitz J, et al. Mars sedimentary geology: Key concepts and outstanding questions. Astrobiology. 2011; 11: 77-87.
146. Kang I, Schulz MJ, Kim JH, Shanov V, Shi D. A carbon nanotube strain sensor for structural health monitoring. Smart Mater Struct. 2006; 15: 737-748.
147. Khan MJ, Bhuyan G, Iqbal MT, Quaicoe JE. Hydrokinetic energy conversion systems and assessment of horizontal and vertical axis turbines for river and tidal applications: A technology status review. Appl Energy. 2009; 86: 1823-1835.
148. Al-Tabbaa A, Lark B, Paine K, Jefferson T, Litina C, Gardner D, et al. Biomimetic cementitious construction materials for next-generation infrastructure. Proc Inst Civil Eng Smart Infrastruct Constr. 2018; 171: 67-76.
149. Qu X, Brame J, Li Q, Alvarez PJ. Nanotechnology for a safe and sustainable water supply: Enabling integrated water treatment and reuse. Acc Chem Res. 2013; 46: 834-843.
150. John G, Clements-Croome D, Jeronimidis G. Sustainable building solutions: A review of lessons from the natural world. Build Environ. 2005; 40: 319-328.
151. Yao W. Testing and evaluation of advanced building materials. Bäch, Switzerland: Trans Tech Publications Ltd.; 2013.
152. Partl MN, Bahia HU, Canestrari F, De la Roche C, Di Benedetto H, Piber H, et al. Advances in interlaboratory testing and evaluation of bituminous materials: State-of-the-art report of the RILEM technical committee 206-ATB. Springer Science & Business Media; 2013.
153. Pacheco-Torgal F, Falkinham JO, Galaj J. Advances in the toxicity of construction and building materials. Duxford, UK: Woodhead Publishing; 2022.
154. Panigrahi M, Mohanty S, Dash RR, Ganguly RI. Development of Novel Constructional Material from Industrial Solid Waste as Geopolymer. IOP Conf. Ser.: Mater. Sci. Eng. 2018; 410: 012012. doi: 10.1088/1757-899x/410/1/012012.
155. Gholizadeh S, Leman Z, Baharudin BT. A review of the application of acoustic emission technique in engineering. Struct Eng Mech. 2015; 54: 1075-1095.
156. Kot P, Muradov M, Gkantou M, Kamaris GS, Hashim K, Yeboah D. Recent advancements in non-destructive testing techniques for structural health monitoring. Appl Sci. 2021; 11: 2750.

157. Kohl C, Streicher D. Results of reconstructed and fused NDT-data measured in the laboratory and on-site at bridges. Cem Concr Compos. 2006; 28: 402-413.
158. Capozzoli L, Rizzo E. Combined NDT techniques in civil engineering applications: Laboratory and real test. Constr Build Mater. 2017; 154: 1139-1150.
159. Lim YY, Smith ST, Soh CK. Wave propagation based monitoring of concrete curing using piezoelectric materials: Review and path forward. Ndt E Int. 2018; 99: 50-63.
160. Gagliardi V, Tosti F, Bianchini Ciampoli L, Battagliere ML, D'Amato L, Alani AM, et al. Satellite remote sensing and non-destructive testing methods for transport infrastructure monitoring: Advances, challenges and perspectives. Remote Sens. 2023; 15: 418.
161. Avdelidis NP, Moropoulou A. Applications of infrared thermography for the investigation of historic structures. J Cult Herit. 2004; 5: 119-127.
162. Kylili A, Fokaides PA, Christou P, Kalogirou SA. Infrared thermography (IRT) applications for building diagnostics: A review. Appl Energy. 2014; 134: 531-549.