An Overview of Composites as Construction Materials for the Development of Sustainable Structures

AMAECHI, Chiemela Victor <http://orcid.org/0000-0001-6712-2086>, BEDDU, Salmia Binti <http://orcid.org/0000-0001-9451-0690>, JA'E, Idris Ahmed <http://orcid.org/0000-0002-9366-9779>, OYETUNJI, Abiodun Kolawole <http://orcid.org/0000-0002-5396-4722>, SALIA, Raqib Abu <http://orcid.org/0000-0002-7558-1351>, OYEWOLE, Obafemi M <http://orcid.org/0009-0005-0728-942X>, OJEDOKUN, Olalekan <http://orcid.org/0000-0002-9573-4976> and HUANG, Bo <http://orcid.org/0000-0003-2888-9326>

Materials Today Sustainability 33 (2026) 101298

Contents lists available at ScienceDirect

Materials Today Sustainability

journal homepage: www.journals.elsevier.com/materials-today-sustainability

An overview of composites as construction materials for the Development of sustainable structures

Chiemela Victor Amaechi [a,b,c,*], Salmia Binti Beddu [c], Idris Ahmed Ja'e [c,d,e], Abiodun Kolawole Oyetunji [f,g,b], Raqib Abu Salia [b], Obafemi M. Oyewole [b], Olalekan O. Ojedokun [h], Bo Huang [i]

[a] School of Engineering, Lancaster University, Bailrigg, Lancaster, LA1 4YR, UK
[b] Department of Construction Management, Global Banking School, Devonshire Street North, Manchester, M12 6JH, UK
[c] Institute of Energy Infrastructure, Universiti Tenaga Nasional, Jalan IKRAM-UNITEN, Selangor, Malaysia
[d] Department of Civil Engineering, Ahmadu Bello University, Zaria, 810107, Nigeria
[e] Centre for Innovative Construction Technology (CICT), Department of Civil Engineering, Faculty of Engineering, Universiti Malaya, Kuala Lumpur, 50603, Malaysia
[f] Lancaster Environment Centre (LEC), Lancaster University, Lancashire, Lancaster, LA1 4YQ, UK
[g] London Metropolitan University - School of the Built Environment, London, UK
[h] Centre for Infrastructure Management, Materials and Engineering Research Institute, Sheffield Hallam University, Sheffield, S1 1WB, UK
[i] Department of Civil Engineering, Hunan University of Science and Technology, Xiangtan, Hunan, 411201, China

ARTICLE INFO

Keywords:
s: construction material
Composites
Building material
Construction industry
Built environment
Sustainable structures
Sustainability
Material science

ABSTRACT

There are numerous environmental impacts associated with the construction industry because it consumes significant energy and other resources. The design and construction of civil structures such as residential buildings require several construction materials. This paper presents an overview of sustainable composite materials for construction projects such as buildings, factories, public structures and offshore structures. The construction materials that are used to produce structural elements, or build houses, as well as other structures include composites and conventional materials. New construction technologies using composite materials, have been developed in the construction sector to promote sustainability. The advantages of using composites as construction materials over traditional materials are highlighted in this paper. There are increasing implementation of composite materials on construction sites as they incorporate fewer materials, light-weight materials, newer designs and time-saving materials. Also, composite materials offer a promising option when it comes to architecture and sustainable construction, as they guarantee high performance. Thus, this paper provides an overview of composites as construction materials for the development of sustainable structures in the construction industry with some recommendations given. This review is to enhance policies for industry application of composites geared towards sustainability.

1. Introduction

Considering that the construction sector involves material development and material handling, it also holds one of the most safety-conscious engineering professions with process-product driven practices [1–6]. Due to the high use of building materials in the construction sector, there is high production and consumption of the various construction materials which have been sustainably developed [7–9]. Though the growing focus on sustainable development has sparked interest in novel construction materials, there is a need to meet the demands of sustainability as well as fulfilling the changing requirements of the built environment [3,9–13]. There are numerous environmental impacts associated with the construction industry due to high consumption of energy and other resources. Currently, there are a range of developments recorded on composite materials. While various authors are reviewing issues concerning the use of composites for sustainable construction [11,12,14–18], others are developing innovative composite materials like geopolymers, biocomposites and cementitious

* Corresponding author. School of Engineering, Lancaster University, Bailrigg, Lancaster, LA1 4YR, UK.
E-mail addresses: chiemelavic@gmail.com (C.V. Amaechi), salmia@uniten.edu.my (S.B. Beddu), idris.ahmad@uniten.edu.my (I.A. Ja'e), abiodunoyetunji@gmail.com (A.K. Oyetunji), rabu@globalbanking.ac.uk (R.A. Salia), ooyewole@globalbanking.ac.uk (O.M. Oyewole), daniely2kus@yahoo.com (O.O. Ojedokun), bohuang@hnust.edu.cn (B. Huang).

https://doi.org/10.1016/j.mtsust.2025.101298
Received 30 October 2024; Received in revised form 23 June 2025; Accepted 23 December 2025
Available online 8 January 2026

composites [19–24]. The design and construction of civil structures, such as residential buildings, require several construction materials and novel strategies.

Though the construction industry is experiencing a significant transformation, there are transactional changes in the construction sector which include construction management, sustainability, organisational approach and business outlook. This transition is motivated by the necessity to reduce environmental harm, increase energy efficiency, improve existing systems, develop risk mitigation strategies and reduce climate change impact. The growing interest in the sustainable structures in the built environment has helped to minimize the negative impacts on the earth by reducing green house gas (GHG) emissions, enhance resource conservation and promote energy efficiency [25–28]. Additionally, conventional building materials like steel, concrete, and lumber are being reassessed due to their environmental impact, high carbon emission, and resource depletion leading to scarcity of resources, hence the need for sustainable materials. To that end, various studies on sustainability have been carried out on these building materials. More recent construction works consider sustainability impact, which others consider the assessment of the construction materials using different models like the Material Flow Analysis (MFA), Life Cycle Assessment (LFA), the circular economy theory, systematic reviews, alongside exploratory reviews [9,11,29–31]. Sustainable materials, like recycled building materials, employ eco-friendly materials, utilize renewable energy sources, recycling of building materials, and reuse of construction and demolition waste (CDW), alongside reduction in carbon emissions [28,32–34]. Howbeit, composite materials are considered as sustainable construction materials since they have become a practical option in the built environment, and other areas [10,35,36]. Considering that the assessment of the construction materials are crucial, their benefits are highlighted. Composite materials provide a blend of superior performance, adaptability, and environmental friendliness. Construction experts believe that composite materials are excellent choices for modular, portable, prefabricated, and civil engineering structures due to their advantages over the conventional construction materials [22,37,38]. Sustainable composite materials that mimic masonry or stone may be used for external claddings, wall panels and acoustic. Likewise, these materials exist in a variety of designs to suit users' needs either commercial, residential or public structures [9,39,40]. Although, the fast growth rate seen in the expansion in industrialization and urbanisation has led to an increasing demand for sustainable materials [6,9,11,12,31,39]. It has also led to increased newly built houses and other residential structures that are sustainable, thereby creating economic growth in the construction industry. The adaptation of sustainability in the construction industry involves planning, design, construction, and maintenance of a wide range of facilities for different clients as well as material development for different purposes [1,41,42]. However, the trend in the development of composites as construction materials has seen the utilization of various sustainable composite materials in the construction industry [11,12,18,22]. Some of the trend include sustainable modular integrated construction and prefabricated composites [37,38]

With the aforementioned, this paper provides an overview of composites as construction materials forthe development of sustainable structures in the construction industry. This paper is structured as follows: Section 1 introduces the review, while section 2 presents a preview of sustainable construction materials. Section 3 presents the classification and applications of composites while Section 4 presents the implications of composites in the construction industry. Section 5 presents the concluding remarks. It is important to state that the methodology for the literature reviewed is based on the selected structure of the subject, and it considers recent advances in the subject area.

2. Preview on sustainable construction materials

2.1. Composite materials

Composites are widely used in the building sector in different applications such as flooring materials from plastic wastes [43], engineered fibre mats [14], polymer composites [44], bio-fibrous concrete composites [45], cementitious composites [46], recycled construction waste composites [47,48]. Composites, being engineered materials consisting of many constituent elements with diverse qualities, offer a chance to tackle significant issues in the construction sector, such as resource depletion, greenhouse gas emissions, and waste generation. By definition, a composite is a multiphase substance made up of two or more components that differ in form or composition but retain their identities and qualities after being bonded together. The newly created substance has superior qualities to the separate components as a result of this "composition." FRP, or Fibreglass Reinforced Polymer, is an example of such material. FRP is a common composite that is utilised in a variety of applications, from space and aeronautics to watercraft and automobiles, as well as marine composites [11,35,36,49,50]. According to Williams [51], there are different criteria to consider for utilising composite materials. Thus, the following considerations illustrated in Fig. 1, were suggested when selecting composite materials for sustainable structures.

- ❖ Is the task now being done with less expensive carbon steel? If this is the case, cost-competitiveness with composites will be challenging.
- ❖ Is corrosion a serious concern? Composites will almost certainly be the preferable option in this case.
- ❖ Is it worthwhile to lose weight? Composites could typically save 25 %–50 % in weight when compared to steel.
- ❖ Will composites give enablement or result in a system solution that is less costly than a metal design?
- ❖ Will composites enable the design of sustainable structures to be more cost-effective, energy-efficient and more serviceable?

Also, composites are applied in different things – from composite

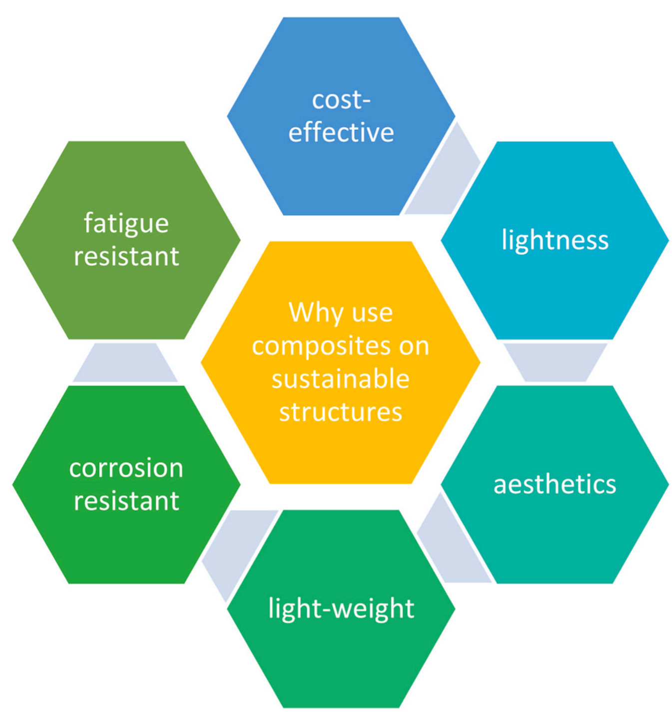

Fig. 1. Justification for practical application of composites for sustainable construction.

marine risers to leisure boats and hand-rail pipes [11,12,18,52] down to domestic building materials [53,54]. Though, it is noteworthy to state that, the production of composite materials is enhanced as composites can be formed using matrix materials, and across different layers as they are easily customizable [18,55,56]. Due to the importance of composites, there are increasing research areas on it. For instance, studies on cement-matric composites suggested that rubber mixtures offer promising options, such as those achieved using crumb rubber [57–59]. The reviews presented in earlier studies show that fibre-reinforced polymeric composites are emerging as strong alternatives for deepwater applications - light weight, strength, and durability [11,12,18,52]. However, these materials can be developed using different configurations of micro-composites with unique material combinations [22,60–62], which have great structural use in constructing sustainable structures.

Composite technology which entails the use of composite materials in engineering, is slowly but steadily making inroads into the fields of materials engineering, civil engineering and construction management. Even though composites are often more expensive than conventional construction materials, they have the advantage of being lightweight, corrosion-resistant, and stronger. Current applications of composites are seen in cement composites and rubber-composites as sustainable construction materials, which can be self-healing, self-sensing or energy absorbing [21,63–66]. The fibre reinforcements provide good damping properties as well as great fatigue resistance. Generally, composite materials are made up of two or more materials that are mixed to attain attributes (physical, mechanical, chemical, etc.) that are superior to those of their separate elements. Reinforcing agents and matrices are the two basic components of composites. Fibers, particles, and whiskers act as reinforcement, providing the majority of stiffness and strength. The reinforcement is bound together by the matrix, resulting in load transmission from matrix to reinforcement. Other materials, like fillers, are employed to cut costs while improving processing and dimensional stability. Fibre-reinforced composites are classified as either discontinuous or continuous fibre-reinforced composites. The matrix used is often classified as polymer, metallic, and ceramic [62,67,68].

Structural material experts are involved in the optimal designs using composite components. Unlike conventional materials (such as steel), the structural performance of composite materials are engineered in accordance to the required structural need. Under the supervision of the designer, composite qualities (such as stiffness and thermal expansion) can be adjusted continuously over a wide range of values. A thermosetting resin matrix is combined with a fibre reinforcement in most polymer matrix composites. Mineral filler reinforcements, either alone or in combination with different fibre kind, are employed in some composites. In addition to cellular reinforcements, ultra-lightweight materials (foams and honeycombs) are standard to provide rigidity. Glass, carbon, and aramid fibres are the most often used reinforcements, and they come in several forms (continuous, chopped, woven & non-woven, multi-axial) as well as combinations of these.

Another key aspect of the design is the material selection for the composites. The features of the finished product can be practically utilised to mostly tailored and specific technical requirements by carefully selecting the reinforcing type. The names “GRP” (glass-reinforced plastic), “Fibreglass,” and “FRP” (fibre-reinforced plastic) are typically used to classify or identify key materials made from composites, particularly for used in civil engineering.Glass fibre is by far the most widely used fibre reinforcement. While the use of composites will be obvious in many cases, material selection in others will be influenced by factors such as the working lifetime requirements, number of items to be produced (run length), complexity of the product shape, potential assembly cost savings, designer's experience and skills in identifying the potential of composites. In some cases, using composites in conjunction with traditional materials might produce the optimum results (see Table 1 for a comparison of different properties).

Presently, the use of composites in the European market is predicted to expand at a pace of about 2 % per year from 2018 to 2023 [75]. This utilization includes the offshore industry, the built environment and the construction industry. High-performance fibre-reinforced polymers (FRP) are already trying to replace traditional steel as the most widely used material in civil infrastructure 76,77]. Despite the use of the high-performance FRP in rehabilitation of civil infrastructures, and most recently in new construction, they are not yet replacing traditional steel. However, recent reports identified that the high-performance steel has lightweight nature, high tensile strength, and superior corrosion resistance, hence makes it appear as a likely "next-generation" replacement, but its penetration remains relatively low in some construction areas [76,77]. Continuous improvements in FRP production technology and performance have increased competition in a growing number of applications, resulting in significant market acceptability. Each type of composite has its own set of performance characteristics that are best suited to particular applications. The adaptation of these sophisticated materials as seen by increased volume and constant usage, is due to the advent of newer polymer resin matrix and high-performance reinforcing fibres of glass, carbon, and aramid. Cost savings are predicted as a result of the higher volume. High-performance FRP is now used in a wide range of applications, including composite armouring engineered to withstand explosive impacts, natural gas vehicle fuel cylinders, windmill blades, industrial drive shafts, highway bridge support beams, and even paper-producing rollers. In the construction industry, composite materials refer to any building constructed from numerous incompatible elements. Composite materials are frequently employed in the construction of aircraft, boats, buildings and tubular structures. With the increased research on sustainability, composites as construction materials for sustainable infrastructures have an increased interest in the construction and building industry [78–80]. Despite the importance of composite as construction materials, more work needs to be done to determine the feasibility of composite materials within the framework of a sustainable environment. Thus, the three pillars of sustainability are considered in this review, which include social, economic and environment (see Fig. 2).

Table 1
The Mechanical Properties of some Composites compared to Conventional Materials.

Material	Density (kg/m^3)	Youngs Modulus (Pa)	Bulk Modulus (Pa)	Shear Modulus (Pa)	Compressive Yield Strength (Pa)	Tensile Yield Strength (Pa)	Tensile Ultimate Strength (Pa)	Poisons Ratio
Resin Polyester[a]	1200	3×10^9	2.7174×10^9	1.1398×10^9	1.41×10^8	1.28×10^8	5.18×10^7	0.316
Nylon PA66[a]	1140	1.06×10^9	1.1778×10^9	3.9259×10^8	2.32×10^9	4.31×10^7	4.97×10^7	0.35
Epoxy Composite	1400	2.5×10^9	3.16×10^9	4.12×10^9	7.36×10^8	1.23×10^8	9.19×10^8	0.3
Carbon fibre Composite (290Gpa)[a]	1810	2.9×10^{11}	2.45×10^{11}	9×10^9	5.7×10^8	4.2×10^9	6×10^8	0.3
Wood	400	11.0×10^9	10.0×10^9	0.69×10^9	2.0×10^6	0.5×10^6	20.0×10^6	0.4
Aluminium	2690	8.2×10^{10}	4.275×10^{11}	2.4×10^{10}	5.8×10^7	5.0×10^7	11×10^7	0.3
Structural Steel[a]	7850	2.0×10^{11}	1.6667×10^{11}	7.6923×10^{10}	2.5×10^8	2.5×10^8	4.6×10^8	0.3

[a] Note: material properties data were obtained from material databases- Matweb [73] and Granta [74].
Sources: ([69–71]; Meyers, & Chawla, 2008; [72]).

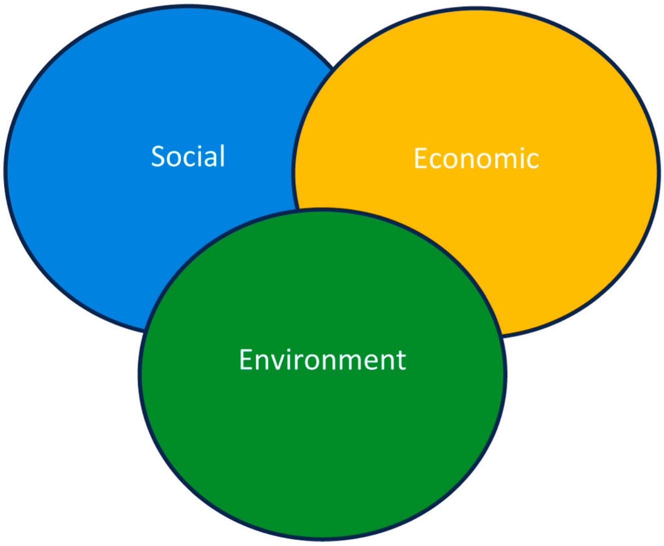

Fig. 2. The three pillars of sustainability considered for developing sustainable structures.

2.2. Cementitious composites

It has been identified that there are different types of construction materials such as composites, geopolymer and Portland cement concrete which is produced from cementitious materials. Advances in the construction industry have considered modified forms of sustainable construction composites such as geopolymers, which can be produced from waste plastics [81], as well as fly ash, slag, bauxite residue and red mud [82,83]. Overviews on geopolymers have been presented in recent studies to have benefits for commercialization and sustainability [28,83,84]. Geopolymers are a third-generation cement, which follows gypsum cement and ordinary Portland cement (OPC), [28,84]. These cement products are used for preparing concrete for a range of construction purposes, although more developments are made on cementitious composites. Hasan et al. [21] developed a novel material from beetroot that has binding properties and utilised as a cementitious composite. This was further developed using composite sensing techniques [22–24]. Other recent works involve the use of lightweight materials like kenaf-polypropylene fibre-reinforced concrete and basalt fibre-reinforced concrete [11,12,85–88]. In Birgin et al. [89]'s study, cementitious composites were prepared using different components that include cement, water, aggregates, CMF fillers, and clay, as illustrated in Fig. 3.

The fact that concrete is weak in compression, is a major concern in construction, thus newer materials are seen in sustainable structures. However, more recent studies on concrete suggested that there are unique behaviours for different cementitious composites like alkali activated cementitious material (AACM) concrete [19,20,89]. In an article by *Guardian*, Watts [90] stated that concrete is "the most destructive material on earth", and cement is the second-most used construction material after water. The entire process of making concrete accounts for 4–8 % of global CO_2 emissions, as well as having far-reaching effects in terms of water use and a propensity to amplify the urban heat island effect [90]. However, this statement has been countered by the Cement Industry in ACI-130-PRC-19 [91], which is an ACI report with justifications for the limitations of cement related to unique applications. Concrete, itself, is a composite material often used in building by combining aggregate with cementitious materials. This is, however, different from cementitious composites which are a mixture of different composite materials that has binding properties [19–21,92]. Though cement is highly utilised in most construction works, it is the leading causes of CO_2 emissions in the construction industry, which is further exacebated by rise in cement production [90,93].

In another study, Val et al. [94] found that carbonation-induced corrosion that leads to damage during the use of reinforced concrete structures impact on its durability to meet its intended design life. Thus, researchers have considered the use of cementitious composites. Cementitious composites can store CO_2 as calcium carbonate precipitates and calcites within its matrix through a slow carbonation processes, however their carbon sequestration efficiency is relatively poor [95]. Enhancing CO_2 uptake in concrete using accelerated carbonation curing and other CO_2 capture and storage (CCS) technology is a practical way to lower net CO_2 emissions during concrete production. Biochar has a high capacity for CO_2 adsorption, a green and low-carbon production technique, and a low production cost, all of which has significant economic advantages [95]. Biochar is a useful cementitious material to enhance the mechanical characteristics, longevity, and usability of cementitious composites in construction.

2.3. Properties of Composite materials

The significance of sustainable construction materials includes green building materials and other aesthetic structures. One advantage of composites in sustainable construction is that it enhances their development. Reducing the environmental impact of buildings and

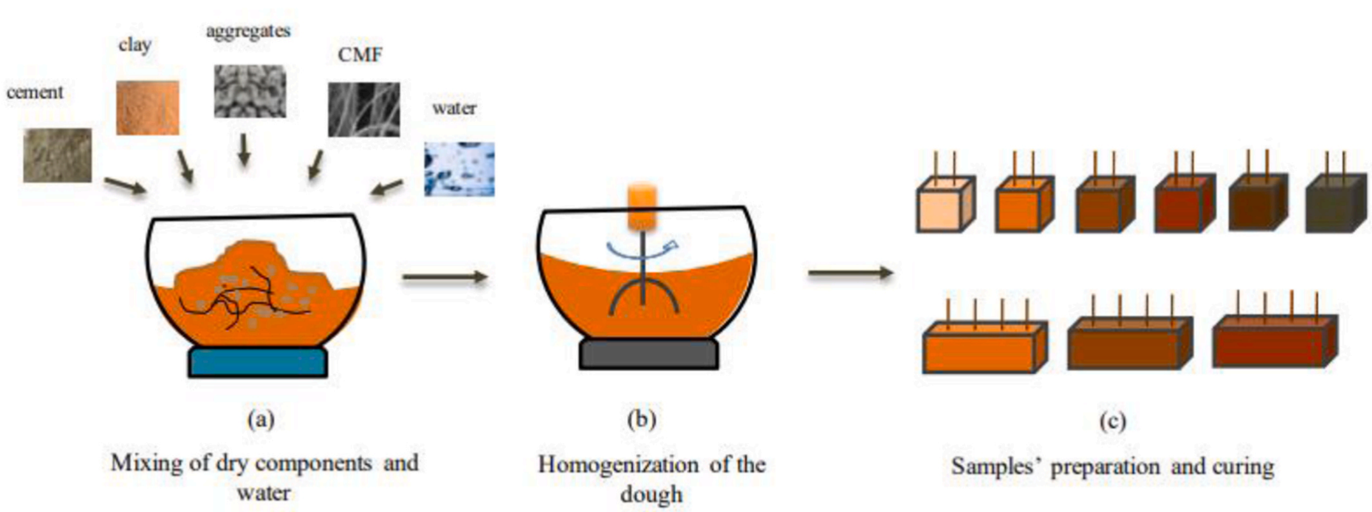

Fig. 3. Typical procedure for preparing a cementitious sample (Source: [89]).

infrastructure, minimising energy consumption, enhancing resilience as well as improving the lifetime of structures all depend on the use of sustainable construction materials. As a result of their energy-efficient, robust, and lightweight characteristics, composites are becoming more and more popular as practical substitutes for conventional building materials. (See Table 2 for a comparison on the physical properties of different materials).

Composite materials are a versatile and useful class of materials for various engineering applications. The unique characteristics of composite materials make them a promising solution for various engineering challenges. However, the following are more characteristics of composites.

1. Composite Structure: Composite materials are composed of two or more distinct materials, each with their own unique properties, combined to form a new material with properties distinct from the individual components. The combination of materials can be engineered to produce specific properties, such as high strength or stiffness, making composite materials highly versatile.
2. Strength and Stiffness: Composite materials can provide high strength and stiffness compared to traditional materials, making them ideal for use in applications requiring high loading capacity, such as aerospace and defense applications.
3. Lightweight: Composite materials are often lightweight compared to traditional materials, making them ideal for applications where weight is a concern, such as the aerospace and transportation industries.
4. Resistance to Environmental Factors: Composite materials are often resistant to environmental factors such as corrosion and weathering, making them suitable for use in harsh environments where traditional materials may fail.
5. Tailored Properties: The properties of composite materials can be tailored through the use of different fibers, resins, and manufacturing processes. This allows for the creation of composites with specific properties, such as high electrical conductivity or thermal resistance, making them suitable for a wide range of engineering applications.
6. Energy Absoring and Self-Sensing: Even though composites are often more expensive than traditional construction materials, they have the advantage of being lightweight, corrosion-resistant, and stronger. Current application of composites are seen in cement composites and rubber-composites as sustainable construction materials, which can be self-healing, self-sensing or energy absorbing [21,63–66].
7. Fatigue Resistance: The fibre reinforcements provide good damping properties as well as great fatigue resistance. Generally, composite materials are made up of two or more materials that are mixed to attain attributes (such as physical, mechanical, chemical) which are superior to those of their separate elements. Reinforcing agents and matrices are the two basic components of composites. Fibers, particles, and whiskers act as reinforcement, providing the majority of stiffness and strength. The reinforcement is bound together by the matrix, resulting in load transmission from matrix to reinforcement. Other materials, like fillers, are employed to cut costs while improving processing and dimensional stability.
8. Failure modes: Composites materials are known to have two compression failure modes namely delamination and shear crippling, which involves micro buckling of the fibres. However, the matrix and fibre characteristics can influence failure modes and strength. Thus with the use of digital technologies, these mechanical behaviour are considered while conducting the simulations on the composite for the development of sustainable structures.

Table 2
The Physical Properties of Composites compared to Conventional Materials.

Characteristics	Composite	Metal
Corrosion	Corrosion Resistant	Corrosion Prone
Stiffness	Tailorable	Fixed
Propensity to Cyclic Loading	Low	High
Stress-Strain Behaviour	Elastic	Elastic-Plastic
Stiffness-to-Weight Ratio	High	Low
Strength-to-Weight Ratio	High	Low
Directional Property	Anisotropy	Isotropy
Properties of Material	Process Dependent	Fixed
Composite Production Process	Tailorable	Standardized

2.4. *Sustainable structures and sustainable materials*

The concept of sustainability in the construction industry has led to nuances in the significance of sustainable construction materials, sustainable structures, geopolymers, green buildings, innovative materials and other aesthetic structures. With environmentalism and sustainability at the forefront, as well as the need to repair or replace ageing infrastructure, there is growing pressure on the construction sector to make progress toward an innovative, more environmental friendly construction material. The use of new alternatives to conventional building materials, like Portland cement concrete, is gaining attention due to improve structural performance in a number of ways. With recent technological advancements, attention has shifted to promotion of construction materials that can function under extreme situations such as high temperature and pressure, highly corrosive environments, changing climatic conditions, and increased strength without compromising weight and other desireable properties [10,18,94,96–98]. This ushered in the age of 'engineered materials,' called composites which devises material qualities tailored to the required application. Composite materials are gradually gaining acceptance as a new class of materials that are superior in many aspects to conventional construction materials for construction works [99]. These are required to realise their potential in the rehabilitation and upgrading of existing structures and the construction of more durable and sustainable new structures [11,12,18,68,100]. On the other hand, the construction industry covers materials including those for buildings and road networks.

The standardization of these materials, the design codes for the materials, databook on composites are another aspect that has improved in recent times. Understanding the behaviour of composite materials, and the failure modes, has enhanced the development of standards on composite materials. These include detailed codes and guidelines, covering the key areas on composite materials' development, including material development, component application, process modification, material specification and design [101–103]. These are required to fully understand their potentials in the rehabilitation and retrofitting of existing structures and the new construction of more durable and sustainable structures [100]. In the offshore industry, different offshore assets such as offshore platforms, boats and ships are examples [18,68,104–106]. On the other hand, the construction industry covers materials for buildings and road networks. Different types of sustainable materials in the construction industry are illustrated in Fig. 4.

2.5. *Composite materials and sustainable construction materials*

The significance of sustainable construction materials includes advancing green building materials and other aesthetic structures. An advantage of composites in sustainable construction is that it enhances their development. Reducing the environmental impact of buildings and infrastructure, minimising energy consumption, enhancing resilience as well as improving the lifetime of structures, all depend on the use of sustainable construction materials. As a result of their energy-efficient, robust, and lightweight characteristics, composites are becoming more and more popular as practical substitutes for conventional building materials.

2.5.1. *Composite materials for sustainable development*

Composite materials are used for a variety of purposes, including enhanced strength, beauty, and environmental sustainability. This study

Fig. 4. Different wastes for developing sustainable materials in the construction industry.

found that the application of composite materials can be seen in composite construction, which involves various materials including reinforced concrete [107,108]. The historical use of concrete has been reported in ancient structures like pyramids, dams, aqueducts and modern structures [109–113]. Table 3 gives a comparison of different composite materials.

Table 3
The tabular comparison of different Composites Materials.

Composite	Matrix	Reinforcement	References
Carbon Fibre Reinforced Polymer (CFRP)	Polymer resin	Carbon fibres	[11,12,18, 49,68,114]
Fibre Glass Reinforced Polymer (GFRP)	Polymer resin	Glass fibres	[115,116]
Geopolymer composite	Geopolymer binder	Fly ash, Slag, or Metakaolin	[82,83]
Reinforced concrete	Concrete	Steel	[94]
Chipboard	Resin glue	Wood chips	[7];
Hybrid Composite	Epoxy Resin or Polyester	Carbon fibres + Glass fibres, and/or Kevlar fibre	[11,12,18, 68,117]
Natural Fibre Reinforced Polymer	Polypropylene or PLA	Hemp, Flax, or Jute fibre	[87,118, 119];
Boron Fibre Reinforced Polymer	Epoxy Resin	Boron fibre	[120];
Kevlar Fibre Reinforced Polymer	Epoxy Resin	Kevlar fibre	[49];
Wood Plastic Composite (WPC)	Polyethylene	Wood fibre	[7,8]
Metal Matrix Composite (MMC)	Silicon Carbide, Boron Carbide	Aluminum or Magnesium	[121]
Ceramic Matrix Composite (CMC)	Silicon Carbide or Alumina	Carbon fibre, Silicon Carbide fibre	[122]
Bio-based Polymers (e.g. carrot-beetroot cementitious composites)	Concrete + Bio-based polymers (e.g.PLA)	Carrot fibre, beetroot fibre, depending on the bio-based reinforcing material used	[21–24,66]
Advanced Polymer Composites (PMC)	High-performance polymers	Carbon fibre, Kevlar, or Glass fibre	[11,12,18, 49,68,123]
3D Printing Composites	Thermoplastic Polymers	Carbon fibre, Glass fibre, or Metal Powders	[124,125]

2.5.2. Environmental advantages of composite materials

The use of composites in construction has been shown to have considerable environmental benefits when compared to the use of traditional building materials. These benefits include decreased energy consumption, lowered emissions of greenhouse gases, and less waste formation. The lightweight nature of composites is another factor that adds to the energy efficiency of structures during transit, installation, and operation [121,126–129].

2.5.3. Thermal performance and energy efficiency

Performance in terms of thermal efficiency and energy efficiency is a very important aspect of sustainability. Through the provision of efficient insulation, the reduction of heat transfer, and the maintenance of minimal thermal bridging, composites have the potential to improve the energy efficiency and thermal performance of buildings. Composite materials with low thermal conductivity are beneficial as construction materials [8,66,114]. In a recent study by Vagtholm et al. [8], different types of construction materials including wood with different timber compositions were presented, such as cross-laminated timber (CLT), oriented strand board (OSB), and modified fibre board (MFB). Table 4 shows the comparative data on thermal performance of different construction materials, the composite materials used and their methods of construction.

The utilization of composites in developing sustainable structures have been increased due to their thermal conductivity properties and thermal response [130–133]. Currently, the thermal and energy efficiencies are used in measuring the building's performance [8]. Howbeit, energy efficiency is very important in building engineering, which is the reason there are increased green buildings and other sustainable designs. While there are building regulations that govern the maintenance of buildings there are other guidelines for the residents. For instance, to keep internal temperatures of buildings at a reasonable level, it is advisable to reduce the amount of heating and cooling loads, and reduce the amount of energy that is consumed over the course of a structure's lifetime. In recent years, smart meters are very useful in energy monitoring, which helps to control the usage of heating and cooling in homes.

2.5.4. Environmental impact and life cycle assessment

Life cycle assessment (LCA) techniques examine the environmental impact of composite materials across their entire lifecycle, beginning with the extraction of raw materials and continuing through the manufacturing process, use, maintenance, and disposal of the material product [114,115]. When compared to conventional materials, life cycle assessment (LCA) studies reveal that composites offer environmental benefits in terms of resource efficiency, reduction in emissions, as well as waste minimization [9,31,114,115]. LCA is a critical tool for evaluating the sustainability of construction materials. In the LCC research by Ascione et al. [115], the structural performance and economic feasibility of industrial structures constructed using GFRP pultruded profiles were assessed. A standardised along with exportable LCC model was then used to compare their performances with those of comparable steel constructions. According to Ascione et al. [115], f our stages were included in the development of the LCC model in their study. Firstly, the structural analysis as well as technical-mechanical features of the buildings; secondly was the cost estimation as well as modelling; thirdly, the assessment of the LCC indicator; and fourthly is comparing the performance with other design options. As opined by Ascione et al. [115], industrial GFRP structures can ensure cheaper maintenance costs over time, while having a greater initial investment cost than

Table 4
Thermal performance of different construction materials, the composite materials used and their methods of construction (Source: [8]).

Parameters				Values for Building Envelope Property			
Category		Type	Material	Thermal Conductivity (W/m-K)	Thickness (mm)	Thermal Resistance (m^2K/W)	Calculated U-Value (W/m^2K)
Traditional	Earth	Rammed Earth	Earth	1.5	300	0.2	2.70
		Cob	Lime render	0.8	35	0.044	1.12
			Cob	0.73	500	0.68	
	Wood	Straw Bale	Lime render	0.8	35	0.044	0.11
			Straw	0.051	450	8.82	
			Lime render	0.8	35	0.044	
		Cordwood	Wood	0.13	600	4.62	0.21
			Cement mortar	2.15	600	0.28	2.2
	Masonry	Adobe	Earth render	1.5	35	0.023	0.81
			Adobe Brick	0.24	250	1.04	
		Clay Brick	Brick	0.77	102.5	0.13	1.18
			Air cavity	0.18	75	0.42	
			Brick	0.77	102.5	0.13	
		Hempcrete	Lime render	0.8	15	0.019	0.39
			Hempcrete	0.09	210	2.33	
			Lime render	0.8	15	0.019	
		Sandstone	Sandstone	2.3	550	0.24	2.44
Modern	Masonry	Concrete	Reinforced (2 % steel and 2400 kg/m^3)	2.5	200	0.08	4
			High density (2400 kg/m^3)	2	200	0.075	3.7
			Medium (2000 kg/m^3)	1.35	200	0.11	3.14
	Wood	Timber Frame	Brick	0.77	102.5	0.13	0.25
			Air cavity	0.18	50	0.28	
			Mineral fibre	0.04	140	3.5	
			Brick	0.77	102.5	0.13	0.6
			Air cavity	0.18	50	0.28	
			Timber stud/frames	0.13	140	1.08	
		Structural insulated panel (SIP)	Brick	0.77	102.5	0.13	0.13
			Air cavity	0.18	50	0.28	
			oriented strand board (OSB)	0.13	12	0.09	
			Mineral fibre board (MFB)	0.04	270	6.75	
			oriented strand board (OSB)	0.13	12	0.09	
		cross-laminated timber (CLT)	Timber (500 kg/m^3)	0.13	100	0.77	1.06

Note: The values for the thermal conductivity are from research. Source: Vagtholm et al. [8].

comparable steel constructions.

2.5.5. Resilience and disaster control

Composite materials provide intrinsic resilience and endurance, which contribute to the enhancement of the safety and performance of structures in the face of extreme weather, seismic activity, and other natural calamities. Composite materials have the ability to endure severe wind loads, seismic forces, and corrosion, which helps to reduce the risk of structural damage and improves the long-term resilience of buildings and infrastructure. The measures used in road construction and disaster controls is carried out with fences as well as paths (see Fig. 5 (a)). Different sustainable construction materials can be seen in Fig. 5.

3. Classification and advantages of composites

3.1. Classification of composites

In recent times, the utilization of composites has gained popularity in sustainable structures like green buildings, residential properties, smart buildings, office buildings, and commercial buildings. A particular type of composite called marine composites is used for ships, marine hoses, floating offshore wind turbines (FOWT), composite marine risers, and flowlines [11,12,18,49,68,69,104,117,137–140]. However, the composites considered in this study are for construction purposes or connected to the construction industry. Thus, it is important at this point to classify composites and describe them as it will be necessary due to recent advances [114,118,123,141–145]. By definition, composite materials are defined as a composition of two or more separate materials that are chemically combined to form a distinct material having mechanical properties that differ significantly from its constituents [68,69,146,147]. By classification, composites are classed by matrix and by reinforcements, as presented in Fig. 6.

Generally, composites differ from standard materials like steel in several ways, due to certain reasons but yet have increased usage. Firstly, more material scientists, engineers and designers now have a more excellent grasp of composite materials, reflected in recent advances in composites. Secondly, these composite materials have weight savings and a comparative stiffness-to-strength ratio, which could be advantageous in marine science, material science and engineering. Thirdly, the construction and offshore industries have grown in response to newer innovations in composite structures like composite taps, composite pipes and composite riser pipes. In the offshore industry, these composites have been applied in hybrid structures, as seen in thermoplastic composite pipes (TCP) [11,12,18,117,137,148,149]. Thus, there are various approaches to classify composite materials for sustainable construction. A recent classification on the applications of FRP Composites in concrete structures was presented by Ortiz et al. [118], as seen in Fig. 7.

Since composites have failure concerns, there is a need for proper understanding of the mechanics of composite materials which will aid proper designs[62,68,147,150,151]. One area of concern is debonding in composites, as the failures affects the bonds holding the composite layers together. Debonding also occurs when there is loading in a direction that would increase the load carried by the matrix. Hence, the fibre/matrix interface is critical in achieving the structural integrity of the composite structure [62,68,147,151]. The matrix also protects the fibres from physical and chemical damages while keeping the component's ideal shape. Since fibres are very anisotropic, their orientation has a significant impact on the macro-mechanical structure's properties. Also, anisotropy is established by favouring distinct orientations, which

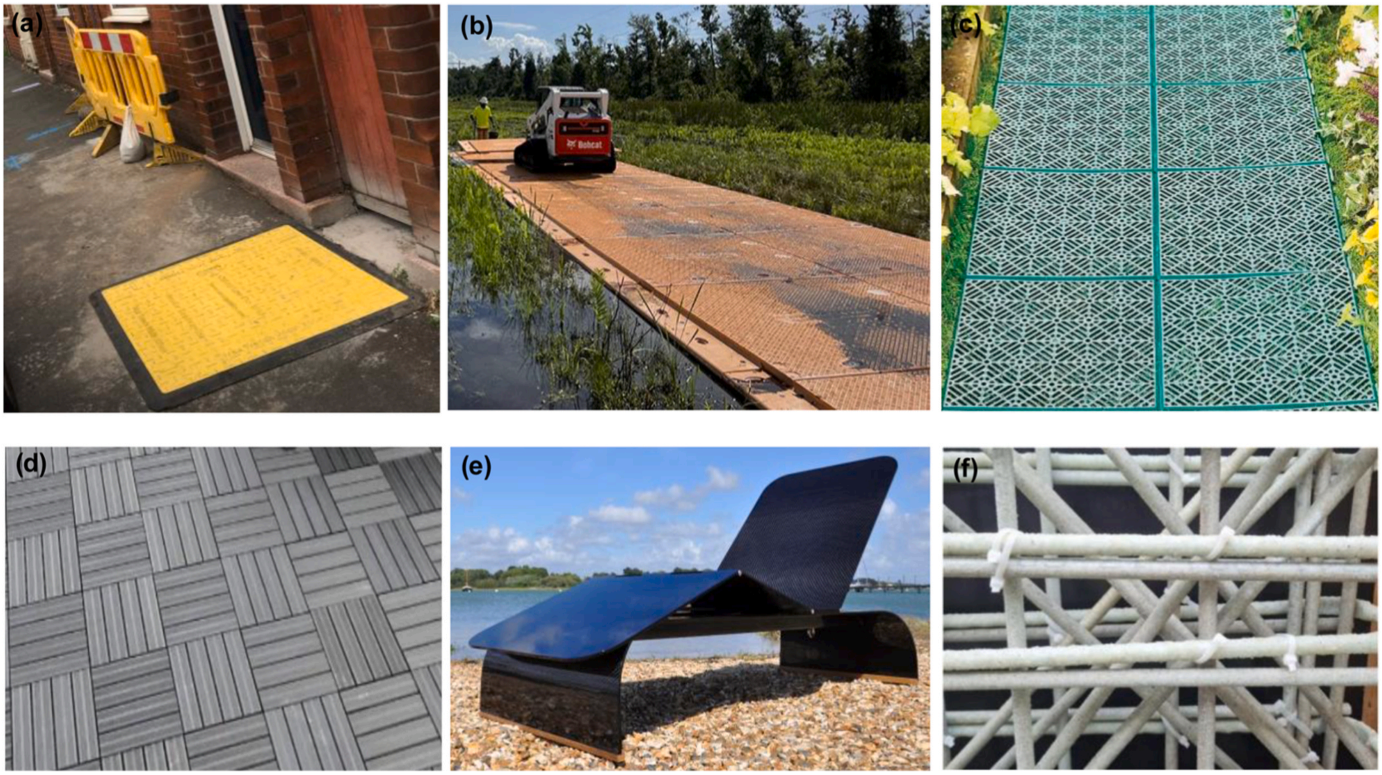

Fig. 5. Different sustainable construction materials showing (a) Composites used in making construction floor mats and moveable fences, (b) Typical composite mat used in a waterlogged area (Source: [134]), (c) Composite garden tiles, (d) Composite deck tiles (e) A composite furniture made using carbon from Epoxycraft (Source: [135]); (e) Composite decks for landscape paths, and (f) Composite rods for reinforcements using FIBERNOX® V-ROD reinforcing bars (Image credit: PohlCon. Source: [136]).

have both benefits and drawbacks. Although it is possible to impart strength and stiffness in load-bearing zones, the complexity of heterogeneity can make the prediction of mechanical behaviour and production challenging. By characterization, fibre-reinforced composites are made up of high-strength and stiffness fibres impregnated with a polymer matrix that binds the fibres and transfers the load efficiently [49,68,69,114]. An illustration of the fibre and matrix that formas a composite material is shown in Fig. 8.

3.2. Advantages of composites as construction materials

Application of composite materials are seen in space shuttles, space ships, aeronautical vessels, aircrafts [152,153] to watercraft, boats, ships, offshore vessels, yatchs [10,18,36,68] as well as to automobiles [51,154] and defence structures in ballistic protection [155] to general construction materials [22,35,45,46]. Different standards like the International Standards Organisation (ISO) as well as the American Society for Testing and Materials (ASTM)'s international standards can be used to evaluate the strength and durability of these novel construction materials as they provide benchmarks for mechanical testing [18,20,156–161].

When compared to conventional materials, composites can suit a wide range of design requirements while reducing weight and providing a high strength-to-weight ratio [49,162]. The advantages of composite materials over conventional materials are far-reaching due to their diverse properties. Composites have a tensile strength that is about four to six times that of steel or aluminium, but weaker in compression strength [49,68]. The torsional stiffness and impact characteristics of composites can be improved [159,163–165]. The fatigue endurance limit of composites is higher (up to 60 % of the ultimate tensile strength) [166].

Composite materials are 30–45 % lighter than aluminium structures with the same functional requirements [154,167]. Composites are more adaptable than metals, allowing them to be adapted to specific performance and design requirements [168–170]. Long life means less maintenance and better fatigue, impact, and environmental resistance [171,172]. When compared to metals, composites have a lower life cycle cost. However, composites also have good behaviour when mixed with reinforced concrete [116,173,174] considering the high durability requirements of the reinforced concrete [94]. Composites are also corrosion resistant and lightweight [11,12,18,49,154]. Studies have also found that composites have an advantage of weight reduction of approximately 20 %–50 % compared to conventional materials [121,175].

Composites provide a better appearance with smooth surfaces and inbuilt decorative melamine that is easily incorporated, as seen in metal matrix composites [122,176,177]. When compared to typical metallic parts, composite parts can reduce the number of joints and fasteners, resulting in part simplification and integration, such as composite lap joints [178,179]. Embedded energy in composites is lower than steel, aluminium, and other structural materials [180]. When compared to metals, composites are quieter in operation and transmit less vibration, so composites are currently highly utilised in developing various roof materials, road mats, doors and windows [143,154].

As stated earlier, composite materials have seen tremendous advancements. Composite materials are continually being adapted to the way they are utilised, thanks to today's technological know-how. Due to the ever-changing technological developments that make composite engineering feasible, there are a vast variety of composites to choose from. As a result, each type of composite has its own set of performance characteristics that are best suited to certain applications [154,155,181]. Furthermore, today's construction issues include the need for reinforced structures that can withstand human and natural disasters (such as earthquakes, floods, storms, fires and hurricanes) [182–184].

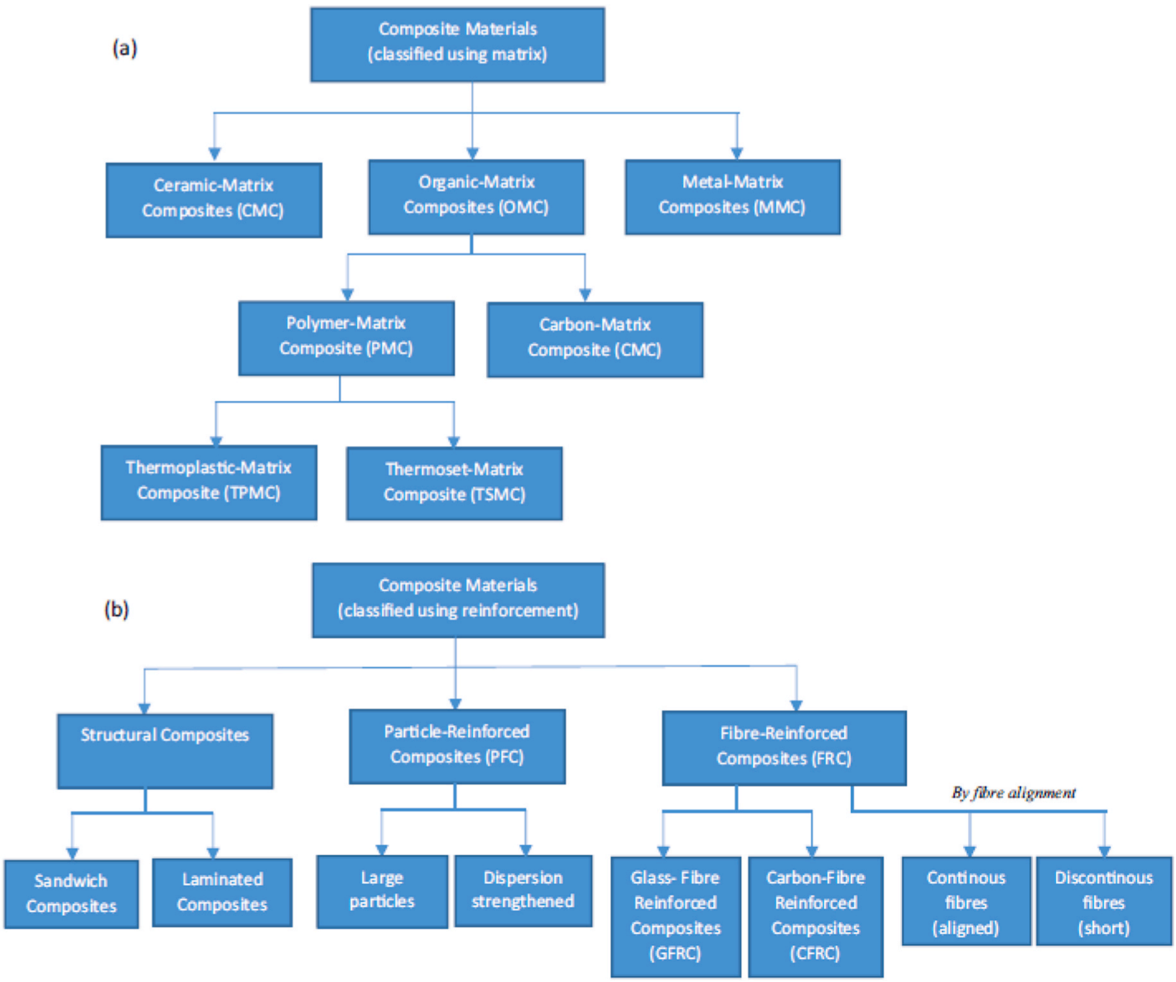

Fig. 6. Classification of composites by: (a) matrix, and (b) reinforcements. (Permission was obtained to reuse the image. Copyright year: 2020; Publisher: Elsevier; Source: [126]).

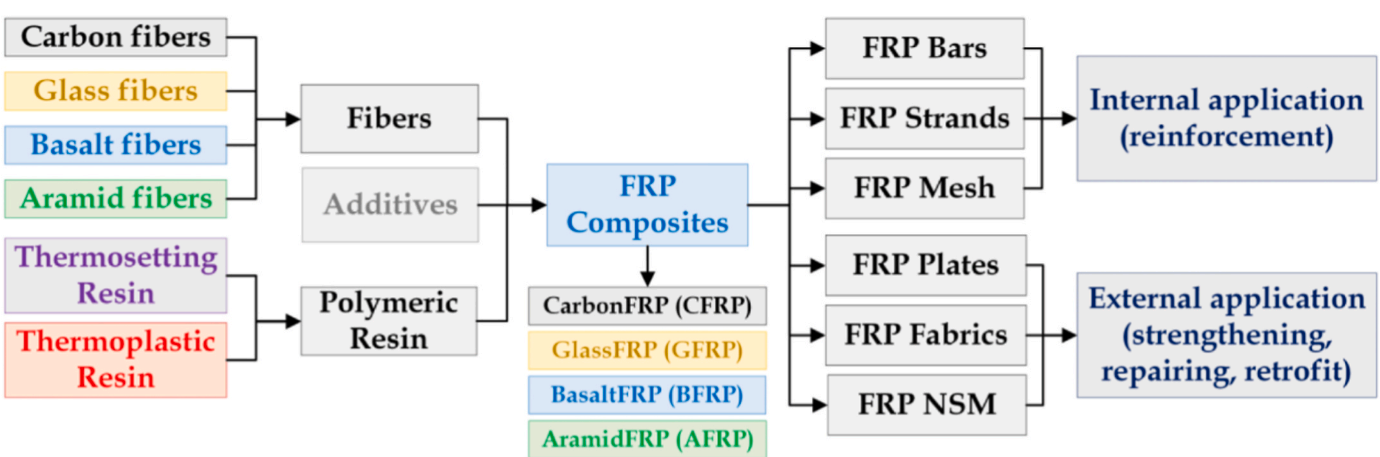

Fig. 7. Applications of FRP composites in concrete structures using a tree diagram (Source: [118]).

This necessitates innovative use of composite materials in existing structures, different sustainable designs and structural systems. Globally, composites are now being used to make additive manufactured concrete constructions alongside geopolymer concretes to be more stable and seismic-resistant [181,185–188].

In a nut shell, composite engineering is predicted to make further inroads into building engineering, automobile engineering as well as offshore engineering [11,12,18,68,154,181]. Composite engineering plays a larger role in pushing the future of the building and construction process to new heights. Moreso, composite engineering has also been used in smart buildings and other sustainable designs in the built environments because they have proven to be processed under different material mixes, with an agreeable limit of design [189,190]. Table 5 gives a comparison on the advantages and disadvantages of composite

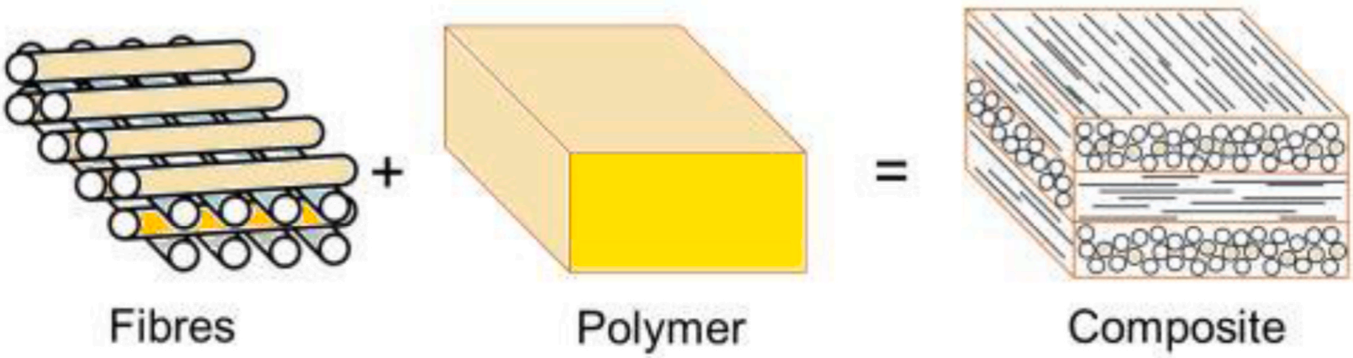

Fig. 8. Illustrative of fibre and matrix for forming a composite material.

Table 5
The advantages and disadvantages of Composite Materials.

S/N	Advantages	Disadvantages	References
1	Corrosion Resistant	Temperature Resistance is dependent on the matrix materials	[11,12,18,117,137,149]
2	High fatigue strength	The fatigue strength also depends on the type of composite material	[11,12,18,117,143,154]
3	Supports part integration by providing capabilities	Absorb moisture that affects the properties and dimensional stability of the composites	[119,191–194]
4	Reduction in assembly cost	High cost of repairs	[11,12,18]
5	Weight reduction (approximately 20 %–50 % compared to conventional materials)	High material costs	[49,121,162,175]
6	High specific stiffness	Non-visible impact damage	[195,196]
7	Light weight	There are multiple quality checks against fracture damage during part assembly	[11,12,18,117,137,149]

materials.

3.3. Application of composites as construction materials

A few areas where composite material can be applied are.

3.3.1. Pultruded profiles

These structural profiles, such as handrails, solid pipes, cable trays, solid rods, ladders and gratings, are employed in many engineering applications with Class I flame retardancy among a wide range of Composite goods. Pultrusion is one of the most cost-effective way to make fiber-reinforced polymer (FRP) composite engineering members [68,87,123,196–198]. It offers high-performance composites for commercial applications like offshore platforms, high-performance helidecks, ship decks, boats, electrically non-conductive systems, lightweight corrosion-free buildings, and a slew of different cutting-edge goods.

In industralised countries, pultruded sections are well recognized as an acceptable alternative to aluminium, wood, and steel [12,68,123,197–199]. Also, they are quickly increasingly popular in different locations globally. Oil exploration rigs, civil construction fences, chemical companies, and other sectors have ready markets for structural sections. In comparison to conventional materials like steel and aluminium, the amount of energy required to create FRP composite materials for structural purposes is smaller, which would work to its advantage in the end [49,115,200]. Pultruded items are already being acknowledged as a commodity in the global building sector. Since pultruded profiles are able to withstand heavy impacts, resistant to chemicals, fire-resistant, as well as being lightweight, they have high demand for sustainable structures in the construction industry [87,195,196,201]. Additionally, pultruded sections have low electrical conductivity, with good thermal conductivity [130,131] and the structural strength of these pultuded composites enable their use in fencing [202]. Typical pultruded profiles could be glass-reinforced plastic profiles of high-performance E23 grade with a characteristic wall thickness featured as 5 mm (see Fig. 9).

3.3.2. Composite furniture

Composite materials are used in designing and constructing various furniture sets for offices, houses, hotels and recreation. This type of furniture can be used for resting by the pool sides and also for leisure in fields, flower beds or gardens. Composite furniture can come in different colours, shapes and designs because of the ease at which they can be designed sustainably. They are also made from different types of composites such as the composite furniture made using carbon from Epoxycraft. An article showed one of these state-of-the-art furniture by Epoxy craft was designed by Nicholas Spens using composites [135], as seen in Fig. 5 (e).

3.3.3. Cement-polymer composites

As an alternative to ordinary Portland cement, cement-polymer composites are being developed and tested. Stucco made of conventional cement deteriorates quickly. Due to the deterioration, the material cracks readily and becomes porous to water, rendering it structurally unsound. The Environmental Protection Agency (EPA) alongside Materials and Electrochemical Research (MER) Corporation investigated a cement-polymer composite material formed from crumb and recycled rubber tyres and cement [203]. It was discovered that 20 % crumb rubber can be added to the cement mixture without changing the cement's look, after testing with an ASTM standard [203]. Research has found that the strength of concrete can be improved by mixing it with rubber scraps to achieve cement-matric composites [204–208].

3.3.4. Composite-wood decking

Pressure-treated wood is the typical decking material. Composite decking is the current material of choice for many contractors. Wood-plastic composite or Fiberglass Reinforced Plastic are commonly used in this material (FRP). These materials are as adaptable as typical pressure-treated wood and do not warp, crack, or split. Composite decking can be created in a variety of sizes, forms, and strengths due to a variety of manufacturing procedures. Decking materials can be utilised for a variety of additional building projects, including fences and sheds, depending on the type of composite material used, as seen in Fig. 5(a–d).

3.3.5. Composite-steel decking

The dissimilar materials in a composite steel deck are steel and

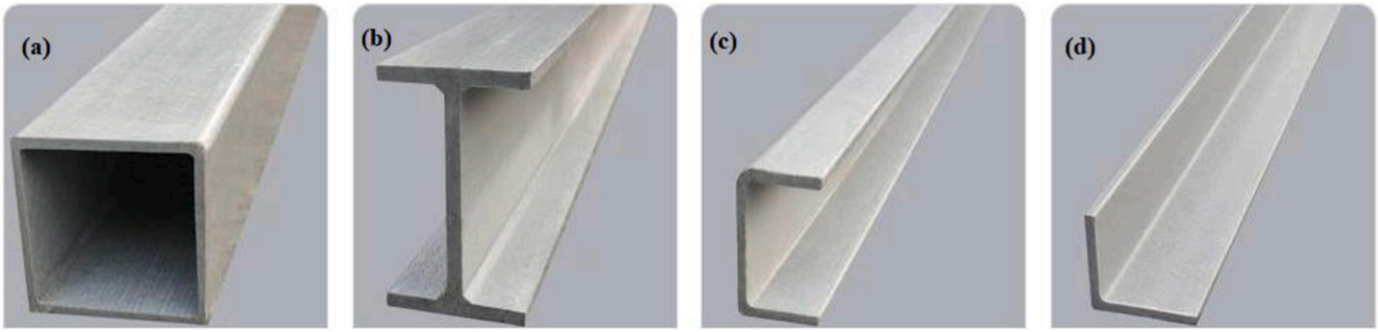

Fig. 9. Typical pultruded composite profiles showing (a) Box pultruded profile, (b) I-beam pultruded profile, (c) C-channel pultruded profile and (d) equal-angle or L-beam pultruded profile.

concrete. To increase design efficiency and reduce the amount of material required to cover a given area, a composite steel deck blends the tensile strength of steel with the compressive strength of concrete. In comparison to prior construction technologies, composite steel decks supported by composite steel joists can span greater distances between supporting parts and have lower live load deflection.

3.3.6. *Composite decks*

High-performance decking composite building materials from businesses like Trex Decking, Fiberon and Tecwood include some new products on the advances in the composite construction industry [209]. In recent years, high-performance composite decking has arisen to counteract older generations of composite deckings, such as wood plastic composite (WPCs), which struggled to maintain market credibility. With the addition of the shell, also known as "cap-stock," capped composite decks have a high-performance finish. Depending on the brand, this shell covers all four sides of the composite board or only the top and sides. The cap is applied to the board via a method known as co-extrusion. The majority of capped composite decking comes with a stain and fade warranty. Typical composite deck products can be seen in Fig. 10.

3.3.7. *Composite mats*

The use of composite mats as a temporary roadway and site access solution is a safe and reliable option that is ideal for heavy-duty construction sites. Composite mats, which are constructed from high-density polyethylene (HDPE), provide higher strength and dependability, which enables crews and equipment to obtain access to isolated project locations in a secure manner. Among the many applications that may be found for composite construction mats are the covering of manholes and culverts, the construction of temporary roadways, and the construction of access roads for farms. Other areas include accessways that are constructed over exceptionally soft ground, staging areas, work platforms, laydown yards, ground protection for sensitive regions, and protection of prepared subgrade [134]. These composite mats are classified based on the load-bearing capacity, as heavy-duty composite mats, medium-duty composite mats and light-duty composite mats, however, there are others like the trackout composite mats. Fig. 5 (b) shows a typical heavy-duty composite mat used for access in a waterlogged area.

3.3.8. *Road bridges and decks*

Bridges are a large part of the construction industry, and the use of high-performance FRP has sparked a lot of interest. FRP has been demonstrated to be an ideal material for repairing, seismic retrofitting,

Fig. 10. Typical composite deck showing different products with their top surface finishes and the connection ends.

and upgrading concrete bridges to extend their service life. Polymer composites are thought to provide advantages over conventional materials, notably in terms of corrosion resistance in locations where de-icing salts are used to keep roads open. The design techniques and manufacturing economies developed for road bridge applications will be useful in a wider range of civil construction areas. Understanding the deck performance under traffic loads is essential when building highway bridges with modular FRP decks. During the service life of a bridge, traffic loads cause repetitive stress cycles on the deck. Due to the intrinsic method (pultrusion technique), the composite bridge decks are modular in design and can be produced in continuous lengths, which can then be reduced to size according to the user's requirements. As a result, it gives room for more flexibility in the manufacture of composite bridge decks to accommodate diverse product dimensions. Applicable construction areas include construction sites where FRP materials are used, such as residential constructions and road constructions. (See Fig. 5 (a)).

3.3.9. Composite structures for bridges

Truss and pre-stressed cable bridges are made of structural composite. Standard pultruded profiles make up the components. The design is particularly appealing for places where construction impact must be reduced. The pultruded composite components of the bridges provide crucial mechanical qualities at a fraction of the weight of steel. As a result, installing a bridge span without heavy equipment or huge work crews is simple. These bridges were designed for far-flung sites such as zoos, historic mountain access and national parks. An example is the bridge line ascending toward the historical lighthouse off the Golden Gate on Maui's island. Nehls [210] presented another example of the composite lightweight pedestrian bridge, as shown in Fig. 11 (a).

3.3.10. Composite plates for rebar, retrofit, and repair

Composite plates have been successfully used for construction works and for repairing structural members like residential buildings, columns, masonry beams, and other structural designs that have been damaged or weakened by settlement, subsidence, seismic loadings (earthquake), or impact. They can usually be attached in place by hand without the use of heavy lifting equipment. Traditional approaches would take significantly longer to complete such repairs. Composite reinforcement rods could be utilised to replace steel in traditional reinforced concrete to avoid "concrete cancer" issues caused by internal reinforcement corrosion. These composite reinforcement bars have been applied in some constructions and have shown positive progress. Although they were initially more expensive, the use of composite rebars is justifiable when the nature of the structure makes future repairs impossible or otherwise prohibitively expensive.

3.3.11. FRP doors & FRP door frames

Given the scarcity of wood for building offshore products, one option worth considering is to promote the production of low-cost FRP building materials to satisfy the needs of the housing and construction sectors. FRP skins layered between core materials such as expanded polystyrene, paper honeycomb, stiff polyurethane foam, coir/jute felt, and others can be used in hospitals, residential structures, office buildings, laboratories, and educational institutions. FRP doors can be built in a variety of sizes and designs using structural sandwich construction, which has gained widespread approval and use for principal load-bearing constructions. The use of additives correctly gives the doors fire retardant qualities. Furthermore, because the doors are made of composite material, they are completely water and termite-resistant. FRP doors are significantly less expensive than wooden doors. Contact moulding can also be used to make FRP door frames, but sometimes these FRP doors are prepared with woodgrain finishes and leather finishes [212]. Fig. 12 shows different types of FRP doors.

3.3.12. Composite microstructures

Composite materials have also seen some recent advances in development to support other construction materials like wood, concrete, steel and aluminium. To increase the strength of the construction material, the design efficiency and the capacity to withstand high loads, there is a need to have a sustainable construction material. These are also seen in various structural materials that are developed using micro-composites [60–62,89]. Composite materials can be quite minute that they need to be viewed with a microscope, such as a scanning electron microscope (SEM) and optical microscope. Fig. 13 shows typical

Fig. 11. Different structures designed using composite materials, showing (a) Composite lightweight pedestrian bridge. (Image credit: Bedford Reinforced Plastics. Source: [210]), (b) Glass Fiber Pultrusion Bridge, Washington, USA, (c) Composite lightweight bridge in Morgan County (Image credit: IACMI. Source: [211]), and (d) The East Span of the San Francisco-Oakland Bay Bridge, USA (Image credit: TyLin).

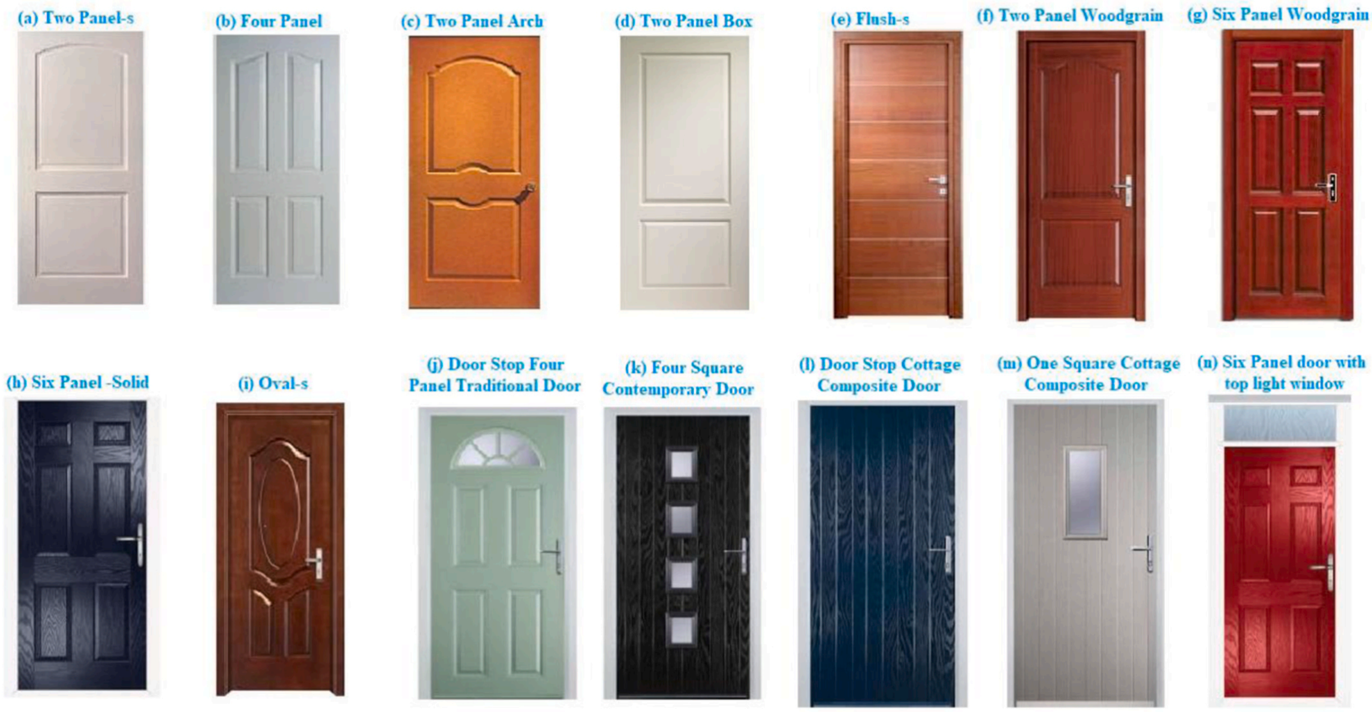

Fig. 12. Different types of FRP Composite doors, showing (a) Two Panel-s, (b) Four Panel, (c) Two Panel Arch, (d) Two Panel Box, (e) Flush-s, (f) Two Panel Woodgrain, (g) Six Panel Woodgrain, (h) Six Panel -Solid, (i) Oval-s, (j) Door Stop Four Panel Traditional Door, (k)Four Square Contemporary Door, (l) Door Stop Cottage Composite Door, (m) One Square Cottage Composite Door, and (n) Six Panel Door with top light Window.

micrographs of cementitious composite material showing pieces of hardened materials.

3.3.13. Plumbing components

Plumbing materials like toilet components made of lightweight composites are easy to install. They also add aesthetic features to the property as they are shiny, bright and corrosion-resistant. Unlike porcelain and steel, the composite surface is warm to the touch due to poor thermal conductivity. The ease with which composites may be moulded allows for more appealing designs and superior surface finishes. There are a range of various types of FRP materials and other plumbing materials used in sustainable buildings, such as FRP water taps.

3.3.14. Panel for suspended ceilings

The materials of the composite panel for suspended ceilings are used in developing sustainable structures. The veil face used in the moulding of suspended ceiling panels increases panel rigidity and prevents puncturing. The veil provides good panel aesthetics due to its ease of printing. Electrical wires, ducting, pipes, and fittings are hidden behind suspended ceilings. The veil with the best porosity improves the acoustic quality of the working or living area. There are a range of various FRP panels for suspended ceilings used in sustainable construction.

3.4. Application of composite as sustainable structures

3.4.1. The construction of buildings

There are many different applications for composites in the building construction industry. Some of these applications include structural components, facade systems, roofing materials, insulation panels, and interior treatments. As a result of their adaptability in terms of design, aesthetic diversity, and ease of installation, composite materials are suited for use in the redevelopment of properties, construction of new builds as well as renovation projects. For instance, the FRP doors used in modern buildings are mostly from composite materials.

The major stumbling blocks in the use of composites include initial expenditures owing to raw materials, as well as inefficient traditional moulding techniques. Cast composites with resin, filler, and correct processing technologies may generate realistic simulations of marble in varied colours, onyx, and granite. The presence of highly fire-resistant phenolic composites allows for the development of novel, safer, and more cost-effective construction solutions. With rising population pressures and rising labour and material prices, composite construction may to a certain extent provide cost-effective alternative solutions in place of conventional construction materials. Experts from the construction industry, the built environment and design professionals believe issues that becloud the use of conventional materials in construction can be easily solved with the use of new technology and some degree of material optimisation. Recent works using sustainable construction materials include the fly ash bricks, and recycled bricks used for interlocking tiles. (See Fig. 14).

3.4.2. Infrastructural development

There is increased research on composites in various microfibers for developing more sustainable structures [62,114,144,145,200,210]. These structures include composite plates, laminate composite walls, FRP composite tubes, and pultruded composite beams that are used in infrastructural development. Since the construction industry has seen rising trends in the use of available composites for sustainable structures, infrastructures also benefit from these materials. These include different types of building materials, such as nails, zinc roofing sheets, aluminium roofing sheets, flush panel doors, PVC doors, PVC roofing materials, acoustic ceiling materials, modified polymer boards, plywood, brass door handles, iron door handles, among others.

In the construction of various types of infrastructure, such as bridges, highways, tunnels, and railways, composites are a very important component. Composite materials provide lightweight and corrosion-resistant alternatives to conventional construction materials. These materials can increase the service life of infrastructure assets, reduce the costs of maintenance, and minimize disruptions to transportation networks, or energy efficiency. Thus, some infrastructures on energy efficiency include composite electric poles and wind turbines with composite blades.

3.4.3. Aesthetics and the design of architectural structures

Composites make it possible to create unique architectural ideas and aesthetic expressions that would not be possible with traditional materials. The visual appeal and identity of buildings and public spaces can be improved by using composite materials since they can be moulded, sculpted, and textured to create complicated geometries, curved surfaces, and customised finishes. Herr [213] considered the use of concrete in Chinese urban development to drive the material innovation and architectural design and discussed the concepts considered.

With the increase in sustainable construction practices, more composites in the construction industry are seen in cement composites and other cast composites. Generally, composites are utilised on composite flexible pipes to erect shower enclosures, shower trays, shower basins, bathtubs, bench tops, vanity units, shower taps, bath taps, sinks, troughs, and spas for interior applications. Composite materials components are widely used in shuttering supports, distinctive architectural constructions that give an aesthetic look, huge signage, and other applications, with benefits such as longer life, minimal maintenance, ease of workability, and fire retardation. Composites are utilised in developing various sustainable constructions, as seen in Fig. 15.

3.4.4. Structures for renewable energy sources

The construction of structures that generate renewable energy, such as solar panels, wind turbines, and hydroelectric facilities, requires the use of composites as an essential component. Utilising composite materials, which are characterised by their high strength, resilience to fatigue, and protection against corrosion, makes it possible to effectively capture and convert renewable energy resources while simultaneously reducing their impact on the environment. Energy efficiency can be achieved using renewable energy sources such as wind turbines.

3.4.5. Coastal and marine engineering

When it comes to marine and coastal engineering applications, composites are utilised extensively. Some examples of these applications are composite marine risers, offshore platforms, seawalls, TCP pipes, boat hulls, and marine renewable energy systems. Since the marine environment is salty, corrosion-resistance is a concern for pipelines. Thus, there is the need for proper monitoring and also having corrosion-resistant materials [18,68,214]. Composite materials provide solutions for coastal protection against corrosion. These solutions enable the offshore infrastructure to become long-lasting and they require little maintenance. Thus, composites offer high resistance to corrosion, fatigue, and harsh marine environments. Spoolable composite pipe for oil and gas transfer onshore is a rapidly increasing application. Currently, a wide range of applications has been developed in the offshore industry over the years [51,97,215–217]. Also, composite tubes have good use in wave tanks, for testing. Another application is the fluid transfer system in a tank with a tubular structure having glass and composite.

3.4.6. Ocean engineering platforms

Developments in ocean engineering include the use of composite materials. These structures include offshore platforms and tug boats. Offshore composites are increasingly being applied to different offshore assets. They are also used on the decks for offshore platforms, ships and boats. The increasing use of composites on these offshore structures is due to their lightweight which helps to reduce the load of the deck. Different reviews on composite materials have confirmed that their structural and functional use can be seen in ocean engineering [11,12,18,52,68]. Moreso, offshore platforms have various structures including composite handrails with a mix of other construction composite materials that are deployed to reduce the deck load, as seen in Fig. 16.

3.5. Case studies on application of composites in the construction industry

3.5.1. Composite lightweight bridge in Morgan County

Earlier works have presented the application of composites in constructing bridges [144,145,218]. A particular example of this application is the composite lightweight bridge in Morgan County. This bridge is a sustainable solution that will reduce the cost of energy and cost of on-site construction works, considering that the bridge is expected to have a 100-year lifespan which will be cost-effective in the long term for repair works [211,219]. This composite lightweight bridge is shown in Fig. 11 (b).

3.5.2. Glass Fiber Pultrusion Bridge, Washington, USA

There is another development made in the use of composite materials to develop sustainable structures, as seen near Duvall, in Washington, USA. It was also a cost-effective alternative to traditional bridge structures. This sustainable structure called the Glass Fiber Pultrusion Bridge, was constructed in 2021. It is an arch design that was developed with hollow pultruded composite tubes. This design is cost-saving and meets the seismic requirement for sustainable structures. Fig. 11 (c) shows the Glass Fiber Pultrusion Bridge, Washington, USA.

3.5.3. The East Span of the San Francisco-Oakland Bay Bridge (United States of America)

A seismic retrofit that makes use of fiber-reinforced polymer (FRP) composite wraps is included in the East Span of the San Francisco-Oakland Bay Bridge in the United States of America. This retrofit is intended to improve the structural resilience and seismic performance of the bridge columns. The existing concrete columns are improved in terms of their ductility and resistance to seismic stresses as a result of the FRP composite wraps, which give confinement and reinforcement to existing concrete columns. (See Fig. 11 (d)).

3.5.4. The Shard, London

The Shard is considered London's tallest building presently. It is also uniquely seen as a notable sustainable structure that has a composite steel-concrete structure. This showers it with a tapering shape which was inspired by glass shards, during the design. It is also aesthetically renowned with this glass design looking like a spiral pyramid clad with glasses which enhances it energy efficiency. Fig. 15(a) shows the Shard, in London.

3.5.5. Aberdeen Harbour Marine Operations Centre

The Harbour Marine Operations Centre in Aberdeen is a sustainable structure that is used for supply vessel bridge simulation. The structure is primarily composite steel construction, and it holds some meeting rooms and offices (see Fig. 15 (b)).

3.5.6. Taiwan's Taoyuan Airport Terminal 3

The Taiwanese infrastructure is equipped with a composite ceiling structure that is built of ETFE foil cushions and is supported by steel cables. This is seen in the Taoyuan Airport Terminal 3 as this construction is relatively lightweight and translucent. It is possible for natural daylight to penetrate deep into the terminal space thanks to the ETFE composite roof, which simultaneously reduces the need for artificial lighting and creates an indoor climate that is comfortable and efficient in terms of energy use for passengers. (See Fig. 15 (c)).

3.5.7. Biomes created for the Eden Project (United Kingdom)

Elements of ETFE (ethylene tetrafluoroethylene) foil cushions are used to form the iconic biomes that are featured in the Eden Project, which is located in the United Kingdom. According to Eden [220], According to Eden [220], the Rainforest Biome and the Mediterranean Biome are the two main biomes produced by the Eden Project in Cornwall, UK. These biomes are supported by steel space frames. These biomes are sizable, enclosed structures that support a variety of plant species and replicate particular climates. The Mediterranean Biome mimics warm, moderate, as well desert climates, whilst the Rainforest Biome mimics humid tropical regions [220]. In addition to reducing the amount of energy that is consumed and increasing the amount of natural light that is transmitted, the lightweight and translucent nature of ETFE composites makes it possible to create a one-of-a-kind indoor environment for educational exhibits and botanical gardens. (See Fig. 15 (d)).

3.5.8. Solar Decathlon House in Saudi Arabia's King Abdullah University of science and technology (KAUST)

The creative applications of composite materials in environmentally responsible residential construction are highlighted by the KAUST Solar Decathlon House, which is located in Saudi Arabia. Off-grid living in severe desert climates can benefit from the modular, prefabricated design that integrates composite panels created from recycled materials. These panels offer thermal insulation, structural stability, and energy efficiency. (See Fig. 15 (e)).

3.5.9. The Red Pavilion, Canada

The Red Pavilion is a typical sustainable construction made from metal composites. The Red Pavilion is situated in a plaza outside a new office building and adjacent to the Emily Carr University of Art & Design campus in Vancouver, BC, Canada. The material used includes 4 mm ALUCOBOND® PLUS Custom Rosy Starburst. Fig. 15 (f) shows the Red Pavilion, which is a typical sustainable structure.

4. The implications and future directions

4.1. Cost considerations

In most engineering projects that involve composite applications, the decision to employ composites is based on cost savings [128,191,197,221]. These cost reductions can be amplified if composites are considered at the initial design phase rather than as a retrofit, allowing composite benefits to cascade throughout the project [115,221]. Composite materials, despite the numerous benefits they offer, may have higher initial costs when compared to conventional construction materials. This lack of affordability may make it difficult for composite materials to gain widespread use. Continued efforts in research and development are required in order to decrease the costs of manufacturing, enhance the efficiency of the use of materials, and increase market competitiveness. Despite reasonable progress in composites over the last decade, large-scale projects continue to be hampered by perceived technical, emotional, and business constraints. Many factors contribute to composites' market success, including clear advantages over previous technology, superior material qualities (e.g., lightweight and fatigue resistance), increased design capabilities, safety, and, ultimately, affordability. The materials industry still depends on composites although it has been affected by some recent global challenges such as the drop in the price of oil in 2016–2017 and the COVID-19 pandemic in 2020–2022 [3,5,95]. Lastly, when comparing composites to metals for various construction applications, the designers must keep in mind that the composite application will be cost-effective for the development of that sustainable structure.

4.2. Optimisation of the design

For the purpose of optimising material selection, geometry, and manufacturing processes, the design and engineering of composite structures necessitates the utilization of specialised knowledge, expertise, and software tools [85–87,221]. There is a need for sophisticated design techniques and computational tools that may streamline the design process and maximise the performance of composite buildings. These can only be developed through collaborative efforts involving architects, engineers, material scientists, and manufacturers, via approaches like Building Information Modelling (BIM) [222]. Composites also enable structural strength and stiffness to be tailored locally. Capturing this adaptability is essential for efficient minimum-weight and minimum-cost design. This is due to significant differences in the cost of raw components (like resins and fibres) as well as the procedures that might be utilised to build the structure with the selected materials. It also depends on the careful selection of composite materials. Different sustainable buildings choose a diverse range of composite materials such as wood composites materials, all-glass materials or hybrid constructions, in which glass fibres are used in combination with carbon or aramid. The reasons for such material justifications include aesthetics, thermal consideration, green building consideration, safety consideration, and the need to follow the building regulations. Also, the designers must combine performance requirements with the need to reduce costs thus composites are justifiable building materials for sustainable structures.

4.3. Certification and standardisation of procedures

There are variations in quality assurance, performance testing, and regulatory compliance as a result of the fact that the methods of standardisation and certification for composite materials in construction differ from region to region and country to country. It is absolutely necessary to achieve a state of harmony among standards, rules, and guidelines in order to guarantee the safety, dependability, and interoperability of composite construction materials. An advantage of composites is that their structural performance can now be tested and monitored in service, as this has to be done in accordance with the related standard(s) [223–225]. Some fiber optics cables and some electrical cables can be included in the composite structure, due to the material used in developing them. These materials offer a safe, nonintrusive way to convey structural monitoring data from remote or downhole locations. It is used in structural integrity testing of buildings and it is also a key developing technology in the oil sector for demonstrating reliability.

To meet the demand for quality assurance in construction materials, there is the need to have good research conducted alongside extensive testing. The other forms of quality assurance processes that have all led to the successful development of composites include laboratory testing and field demonstrations. Though, the introduction of new composite materials has been seen in various sustainable structures due to the continued close collaboration of the manufacturers, researchers, users and regulators. The later group is very important in ensuring that there are good construction materials that are well-tested and approved. Currently, different standard groups have been identified in the construction industry to cover sustainable structures, ranging from ISO, BIS, NIS, ASME, EN, ICC, etc. However, each standard that has been elaborated by the standard body is limited to the location due to the uniqueness of the soil, building regulations and other environmental factors. The International Code Council (ICC) has been identified as very important as they developed the International Building Code (ICC) [226] and other relevant design codes used for developing sustainable structures [227]. Ortiz et al. [118] presented a detailed review of the standards that are used for FRP composites and concrete. Table 6 shows some standards used in developing sustainable structures.

4.4. Trends in material research and innovation

Composite materials are the subject of ongoing research and innovation, which is driving breakthroughs in environmentally friendly manufacturing techniques, bio-based resins, recycled reinforcements, and nanotechnology additions. These are also applied in a wide range of composites materials including composite materials for domestic use, lightweight composites for aviation use as well as offshore composites for oil and gas sector [51,97,215–217]. The characteristics, performance, and sustainability of composite construction materials have the potential to be improved through the use of emerging developments in

Table 6
Some standards and design codes for sustainable structures using composites (Source: [118]).

Standard	Material Specifications	External Applications	Internal Applications	References
CSA	CSA S807-19. Specification for fibre-reinforced polymers	CSA S806-12 (R2017). Design and construction of building structures with fibre-reinforced polymers	CSA S806-12 (R2017). Design and construction of building structures with fibre-reinforced polymers	CSA [228, 229];
ACI	ACI SPEC-440.5-22. Construction with Glass Fiber-Reinforced Polymer Reinforcing Bars	ACI 440.2R-17. Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures	ACI 440-22. Code Requirements for Structural Concrete Reinforced with Glass FRP Bars (1st ed.)	ACI [20, 230–234]
ASTM	ASTM International D7205/ D7205M-06 (2016). D7914/ D7914M. D7957/ D7957M-22	Guide Specifications for Design of Bonded FRP Systems for Repair and Strengthening of Concrete Bridge Elements (1st ed.)	LRFD Bridge Design Guide Specifications for GFRP-Reinforced Concrete (2nd ed.)	ASTM [160,161]; AASHTO [235,236]
AASHTO	–	—same—	—same—	AASHTO [228, 235–239]
JPCI	–	–	Recommendation for Design and Construction of Concrete Structures using Fiber Reinforced Polymers (FRP)	JPCI [240]
ICC	ICC-ES AC-32; Acceptance Criteria for Concrete with Synthetic Fibers.	2021 International Building Code.	2021 International Building Code.	ICC [227], IBC [226]
ISO	ISO 12439:2010 - Mixing water for concrete ISO 10406-1, 2 and 3 - Fibre-reinforced polymer (FRP) reinforcement of concrete — Test methods;	ISO 14484:2020 Performance guidelines for design of concrete structures using fibre-reinforced polymer (FRP) materials	ISO 20290–5:2023 Aggregates for concrete — Test methods for mechanical and physical properties — Part 5: Determination of particle size distribution by sieving method	ISO [20, 156–159, 241]

Source: Ortiz et al. [118].

material science, digital fabrication, and additive manufacturing. Composites have been identified as an important construction material in the construction and building industry, the aviation industry and the offshore industry, among others [138,155,242–247]. Generally, composites have the potential to save weight, reduce maintenance, increase safety, reduce negative environmental effects, and improve durability in offshore oil structures. Thus, the trends in the advances made in composite materials, their design and production procedures have addressed safety concerns while also improving performance and reliability [6, 248]. Offshore platforms now commonly specify safety-critical components made of fibre-glass and polymeric resin. Additive manufactured composite materials and recycled waste composites like recycled waste carpets have good properties that can be harnessed in developing sustainable structures [20,249,250]. However, to conduct the research on composite microstructures, the use of various material testing devices like the SEM can be deployed to identify material behaviour, as seen in Fig. 13. Another aspect that has increased demand is research on designing with polymer composites [60–62,251,252] and understanding the effect of adhesives in hybrid composite joints [253,254]. These joints are used in various applications in both primary and secondary constructions. The primary constructions are the main non-dependent construction works such as the walls, the firewater pipelines, and the garden shed while the secondary constructions depend on primary construction works such as gratings, handrails, and staircases are examples. Thus, each element of construction work is still evolving to enhance the development of sustainable structures. The literature list reflecting the research trends on composite materials for sustainable structures can be summarized in Table 7.

4.5. Incorporation of digital technologies

The development of these construction materials has also led to adaptable construction practices, such as COVID-19 protocols [3,5,222]. Building Information Modelling (BIM), parametric design, and digital manufacturing are examples of digital technologies that can be integrated with composite materials to create new potential for optimisation, automation, and customisation in the construction industry [62, 125,179,222]. BIM has helped to improve the designs developed using Computer-Aided Designs (CAD). Better decision-making, performance prediction, and lifetime management of composite structures are all made possible through the use of real-time monitoring, artificial intelligence, predictive analytics, the internet of things (IoT) and digital twin simulations. Recent studies have identified growth in BIM deployment in the construction industry [5,222].

With the use of CAD and BIM software, the designers are able to simulate the construction materials that can be used as well as the material parameters for various construction projects, in particular, sustainable structures. However, the construction industry will need to grasp the constraints of potential material systems and structural principles before they can use composites in crucial applications, such as replacing metallic water taps with composite material water taps. Each construction material has its mechanical properties with the pros and cons. One of the findings of the present study is that composites are very light-weight and also add to the aesthetics of sustainable structures. Additionally, they are intended to have their uniqueness. For example, both metals and composites have diverse failure modes. With the use of offshore composites, proper monitoring of composite pipes are necessary alonside corrosion-resistant materials in marine environment [18, 52,68,214].

5. Conclusions

This paper presents an overview of composites as a construction material for the development of sustainable structures. To achieve this, the review highlights the use of composites for construction works, its implications and the advantages of composites to ensure sustainable practices are presented on general composites, classification, advantages, state-of-the-art and case studies on composites. The application of composites in the industry involves the right application of safe construction practices. Construction presents a number of significant challenges, including energy efficiency, robustness, and environmental impact, and composites provide a sustainable approach to address these challenges. Composites play a role in the development of sustainable structures that fulfil the increasing demands of society, bolster the built environment, as well as create a more resilient and sustainable future. This is accomplished by utilising the unique qualities and versatility of composites in the construction of these structures. Composite materials

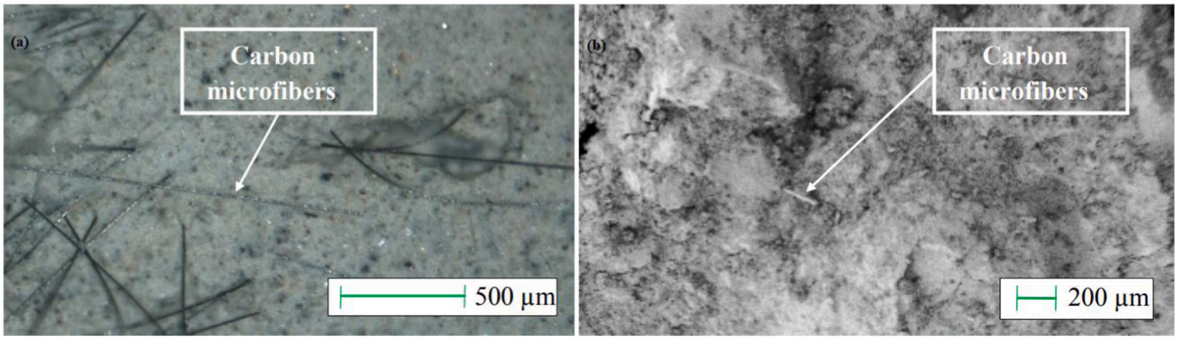

Fig. 13. Micrographs of cementitious composite material showing pieces of hardened materials, viewed with (a) optical microscope view, and (b) SEM view (Source: [89]).

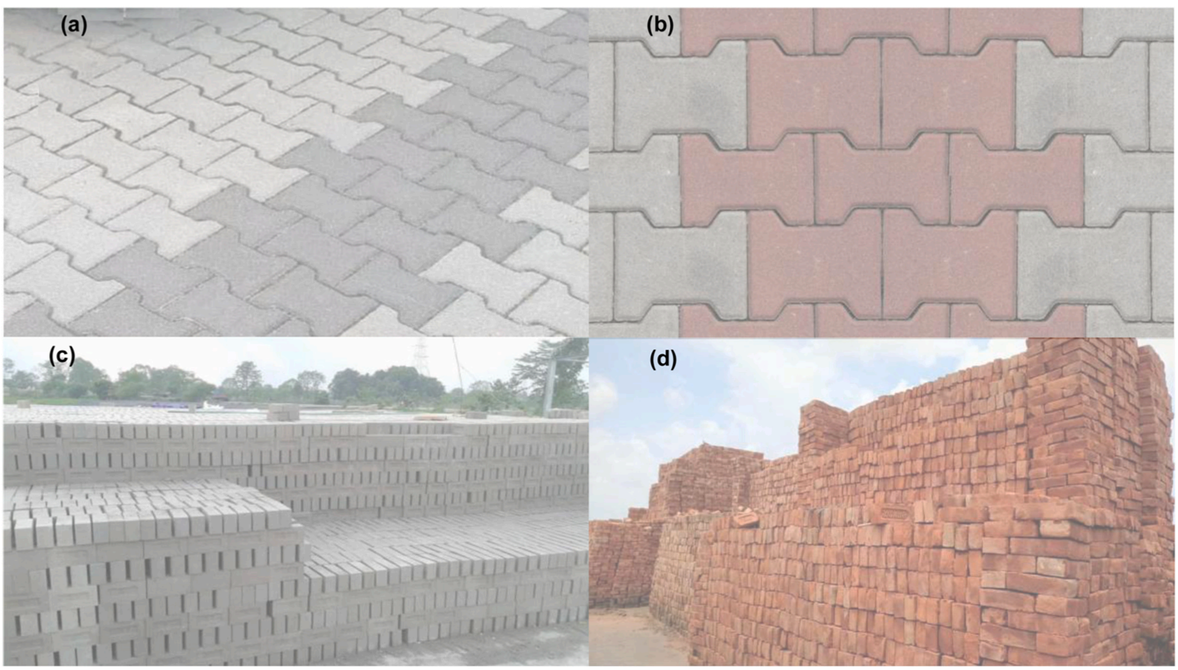

Fig. 14. Composites are seen in different sustainable construction materials such as (a) interlocking tiles with different materials with light and dark colour pigments, (b) interlocking tiles produced with reclaimed bricks and concrete materials, (c) fly ash bricks and (d) burnt bricks with red clay.

are excellent choices for utilization as sustainable structures in the form of modular, portable, prefabricated, and civil engineering structures.

This research also shows that feasibility studies on composites for sustainability have resulted in successful deployments using cutting-edge methodologies and developments. Importantly, this study agrees that the composite market is growing and that the manufacturers of composite materials have also made the development of composite materials to be helpful in delivering sustainable structures. They enable builders and construction managers to be able to meet the demand of their clients with the promise of low-cost carbon fibre, by developing unique designs as sustainable structures with a shift from glass to less dense, and stiffer carbon fibre. This study has also presented various properties of composites, their classifications, their advantages, the cost implications, novel composites, the research trends, and case studies. This study has shown that more building materials are been developed using composites and sustainable structures have been developed using these composites. However, there are advantages of lightness in structures like doors, windows, panelling, road barriers, and home/office furniture, but there are still challenges with the fire-resistance and toughness for security/defence structures like security doors. Hence, developing more composite materials that are sustainable is a priority in this sector.

Architectural designs have been enhanced by the use of composite materials and additive manufacturing in the construction industry, though it is a developing technology. In addition, there are sustainable composites for external claddings, wall panel materials and acoustic materials that mimic masonry or stone. Cladding, laminated walls and roofing sheet materials that are translucent are available in a variety of colours and profiles to meet user needs either residential or commercial users. Though various construction materials can also be used to improve the condition of sustainable buildings, this review has also presented various material properties of highlighted construction materials like cementitious composites, concrete, OSB and MFB. This study also demonstrates the efforts put forth in the creation of different applications, but these composites have been adapted in heavy duty materials like bridge decks and engineered fibre mats for roads. Furthermore, there are a variety of industrial design codes and publications which demonstrate that composites work well in the construction industry. However, the authors recommend further study on the machine learning of composite materials for construction purposes and elaborating applicable standards. Moreso, further study should include an annotated bibliography and a bibliometric review covering

Fig. 15. Composites are utilised in developing various sustainable constructions including (a) the Shard, London, UK, (b) Aberdeen Harbour Marine Operations Centre, (c) Taiwan's Taoyuan Airport Terminal 3, (d) Biomes created for the Eden Project, UK, (e) Solar Decathlon House in King Abdullah University of Science and Technology (KAUST), Saudi Arabia, and (f) "The Red Pavilion" is situated in a plaza outside a new office building and adjacent to the Emily Carr University of Art & Design campus in Vancouver, BC, Canada (Photo copyright: Robert Stefanowicz, courtesy of 3A Composites USA).

Fig. 16. Typical offshore platform showing different materials that include composites and steel.

composites for sustainable construction. In conclusion, it is evident that composites research has progressed with various standards on composites despite the lack of any unified composites Data Book. Further work should include developing more design rules on composites for sustainable construction. Finally, this research demonstrates the technological and economic benefits of composites in the sustainable

Table 7
The literature list reflecting the research trends on composite materials for sustainable structures.

S/N	Research Trend	References
1	Manufacturing Techniques	[126,127,191]
2	Systematic Review, Scientometric Review	[7,11,12,27,28,30,31]
3	Recycled Construction Waste Composites; Plastic Wastes	[43,47,48,81]
4	Sustainable Composite Materials	[11,12,18,22,255]
5	Engineered Fibre Mats, Cement-Matric Composites	[14,57–59]
6	Sustainable Construction	[14–17];
7	Composite Materials	[9–12,23,46,47,67,129,152,181]
8	Smart Building	[13,189]
9	Geopolymers, Fly Ash, Slag, Bauxite Residue, Red Mud	[28,81–84]
10	Kenaf Fibre-Reinforced Concrete, Basalt Fibre-Reinforced Concrete	[11,12,85–87]
11	Cementitious Composites	[19–21,46,92]
12	Offshore Composites, Marine Composites	[11,12,18,49,51,68,97,138–140,215–217,256]
13	Life Cycle Analysis (LCA)	[9,31,114,115]
14	Building Information Modelling (BIM)	[5,222]
15	COVID-19 Protocols	[3,5,222]
16	Ordinary Portland Cement (OPC)	[28,84]
17	Reinforced Concrete	[107,108]
18	Composite Microstructure	[60–62,64–66]
19	Single Lap Joint, Composite Bonded Joint	[178,179,253,254]
20	Composite Matrices, Polymer Composites	[18,44,55,56,144,200]
21	Sustainable Modular Integrated Construction, Prefabricated Composites	[37,38]
22	Bio-Fibrous Concrete Composites, Natural Composites, Geopolymers, Biocomposites, Cementitious Composites	[19–24,28,45,86–88,257,258];
23	Sustainability, Sustainable Development, Energy Efficiency, Green House Gas (GHG) Emissions	[25–29];
24	Built Environment	[3,9,10,13]
25	Construction and Demolition Waste (CDW), Solid Waste	[30,34,259,260]
26	Machine Learning	[28,61,179]
27	Circular Economy	[9,27,30,261]

development of materials, as its research trend predicts future directions for academics and industry.

Data availability statement

No data was used for the research described in the article. Data sharing not applicable to this article as all datasets generated and analysed during the current study have been shared within the text of this manuscript. The data supporting the reported results have been shared at this time, and the sources have been added for the publications used on this review.

Funding

The School of Engineering, Lancaster University, UK, and the EPSRC Doctoral Training Centre (DTC) are highly appreciated for conducting this study. In addition, the funding of NDDC Foreign Postgraduate Scholarship Award by Niger Delta Development Commission (NDDC), Nigeria is also appreciated, as well as the support of Standards Organisation of Nigeria (SON), F.C.T Abuja, Nigeria. The authors also acknowledge the funding support of Tertiary Education Trust Fund (TETFUND), Nigeria and Universiti Tenaga Nasional (UNITEN)'s BOLD25 Initaitive, Malaysia on this project. This work is part of both the doctoral research and postdoctoral research conducted at Lancaster University, UK.

CRediT authorship contribution statement

Chiemela Victor Amaechi: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Salmia Binti Beddu:** Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – review & editing. **Idris Ahmed Ja'e:** Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – review & editing. **Abiodun Kolawole Oyetunji:** Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – review & editing. **Raqib Abu Salia:** Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – review & editing. **Obafemi M. Oyewole:** Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – review & editing. **Olalekan O. Ojedokun:** Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – review & editing. **Bo Huang:** Funding acquisition, Investigation, Resources, Software, Validation, Visualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors acknowledge the technical support from Lancaster University School of Engineering. The support of the journal editors and reviewers are also well appreciated. Lastly, the permission received from the authors, firms and publishers to re-use their images in this paper is well appreciated.

Data availability

No data was used for the research described in the article.

References

[1] S. Ullah, D. Xiaopeng, D.R. Anbar, C.V. Amaechi, A.K. Oyetunji, M.W. Ashraf, M. Siddiq, Risk identification techniques for international contracting projects by construction professionals using factor analysis, Ain Shams Eng. J. 15 (4) (2024) 102655, https://doi.org/10.1016/j.asej.2024.102655.
[2] H. Sarvari, D.J. Edwards, I. Rillie, J.J. Posillico, Building a safer future: analysis of studies on safety I and safety II in the construction industry, Saf. Sci. 178 (2024) 106621, https://doi.org/10.1016/j.ssci.2024.106621.
[3] C.V. Amaechi, E.C. Amaechi, S.C. Amechi, A.K. Oyetunji, I.M. Kgosiemang, O. J. Mgbeoji, A.S. Ojo, A.M. Abelenda, M. Milad, I. Adelusi, A. Coker, Management of biohazards and pandemics: COVID-19 and its implications in the construction sector, Comput. Water Energy Environ. Eng. 11 (2022) 34–63, https://doi.org/10.4236/cweee.2022.111003.
[4] L. Berglund, J. Johansson, M. Johansson, M. Nygren, M. Stenberg, Safety culture development in the construction industry: the case of a safety park in Sweden, Heliyon 9 (9) (2023) e18679, https://doi.org/10.1016/j.heliyon.2023.e18679.
[5] M.A. Olukolajo, A.K. Oyetunji, I.B. Oluyeye, Covid-19 protocols: assessing construction site workers compliance, J. Eng. Des. Technol. 20 (1) (2021) 115–131, https://doi.org/10.1108/JEDT-03-2021-0131.
[6] C.V. Amaechi, Health, Safety and Biohazards in Construction, first ed., LAP Publishers, Germany, 2016, 978-3-659-96922-5. Available at: https://www.researchgate.net/publication/316940525_Health_Safety_and_Biohazards_in_Construction. (Accessed 30 March 2025).
[7] A. Sotayo, D. Bradley, M. Bather, P. Sareh, M. Oudjene, I. El-Houjeyri, A. M. Harte, S. Mehra, C. O'Ceallaigh, P. Haller, S. Namari, Review of state of the art of dowel laminated timber members and densified wood materials as sustainable engineered wood products for construction and building applications, Dev. Built Environ. 1 (2020) 100004, https://doi.org/10.1016/j.dibe.2019.100004.
[8] R. Vagtholm, A. Matteo, B. Vand, L. Tupenaite, Evolution and Current state of building materials, construction methods, and building regulations in the U.K.:

implications for sustainable building practices, Buildings 13 (2023) 1480, https://doi.org/10.3390/buildings13061480.
[9] M. Norouzi, M. Chàfer, L.F. Cabeza, L. Jiménez, D. Boer, Circular economy in the building and construction sector: a scientific evolution analysis, J. Build. Eng. 44 (2021) 102704, https://doi.org/10.1016/j.jobe.2021.102704.
[10] R.R. Nagavally, Composite materials-history, types, fabrication techniques, advantages, and applications, in: Proceedings of 29th IRF International Conference, 24th July, 2016, Bengaluru, India, 2016, pp. 25–30, 978-93-86083-69-2, https://www.digitalxplore.org/up_proc/pdf/240-146959633425-30.pdf.
[11] C.V. Amaechi, A. Reda, S.B. Beddu, D.B. Mohamed, A. Syamsir, I.A. Ja'e, B. Huang, C. Wang, X. Ju, J. Cassavela, A.K. Oyetunji, Knowledge maps from scientometric review on composite marine risers, Sustainable Marine Structures 7 (1) (2025) 1–20, https://doi.org/10.36956/sms.v7i1.1067.
[12] C.V. Amaechi, A. Reda, S.B. Beddu, I.A. Ja'e, B. Huang, J. Cassavela, C. Wang, A. K. Oyetunji, Bibliometric review and meta-analysis for research trends on composite marine risers, Structures 73 (2025) 108208, https://doi.org/10.1016/j.istruc.2025.108208. Elsevier.
[13] E.O. Alohan, A.K. Oyetunji, C.V. Amaechi, E.C. Dike, P. Chima, An agreement analysis on the perception of property stakeholders for the acceptability of smart buildings in the Nigerian built environment, Buildings 13 (2023) 1620, https://doi.org/10.3390/buildings13071620.
[14] X. Li, L. Li, N. Li, M. Bao, Y. Bao, Z. Wu, J. Wang, F. Rao, Y. Chen, Sustainable production of engineered bamboo scrimber composites for construction and flooring applications, Constr. Build. Mater. 347 (2022) 128615, https://doi.org/10.1016/j.conbuildmat.2022.128615.
[15] D.R. Palubiski, M.L. Longana, J.M. Dulieu-Barton, I. Hamerton, D.S. Ivanov, Multi-matrix continuously-reinforced composites: a novel route to sustainable repair of composite structures, Mater. Des. 235 (2023) 112446, https://doi.org/10.1016/j.matdes.2023.112446.
[16] S. Bhalla, A. Singh, D. Bhagat, et al., Achieving sustainable built-environment using bamboo composite frame system with cow-dung masonry infills, Urban Lifeline 1 (2023) 7, https://doi.org/10.1007/s44285-023-00008-7.
[17] M.A. Hubbe, Sustainable composites: a review with critical questions to guide future initiatives, Sustainability 15 (2023) 11088, https://doi.org/10.3390/su151411088.
[18] C.V. Amaechi, A. Reda, M.A. Shahin, I.A. Sultan, S.B. Beddu, I.A. Ja'e, State-of-the-art review of composite marine risers for floating and fixed platforms in deep seas, Appl. Ocean Res. 138 (2023) 103624, https://doi.org/10.1016/j.apor.2023.103624.
[19] P.S. Mangat, O.O. Ojedokun, Influence of curing on pore properties and strength of alkali activated mortars, Constr. Build. Mater. 188 (2018) 337–348, https://doi.org/10.1016/j.conbuildmat.2018.07.180.
[20] P.S. Mangat, O.O. Ojedokun, Bound chloride ingress in alkali activated concrete, Constr. Build. Mater. 212 (2019) 375–387, https://doi.org/10.1016/j.conbuildmat.2019.03.302.
[21] H. Hasan, B. Huang, M.B.S. Saafi, J. Sun, Y. Chi, Whale Eric, D. Hepworth, J. Ye, Novel engineered high performance sugar beetroot 2D nanoplatelet-cementitious composites, Constr. Build. Mater. 202 (2019) 546–562, https://doi.org/10.1016/j.conbuildmat.2019.01.019.
[22] B. Huang, Y. Chi, T. Almotlaq, J. Wang, M. Saafi, J. Ye, J. Sun, Y. Wang, J. Ye, Influence of sugar beetroot microsheets on the hydration kinetics of cementitious composites: electrochemical characterization, Cement Concr. Compos. 144 (2023) 105314, https://doi.org/10.1016/j.cemconcomp.2023.105314.
[23] B. Huang, Y. Chi, J. Wang, G. Wang, J. Ye, E. Whale, D. Hepworth, J. Ye, M. Saafi, Mechanical and fracture properties of sugar beetroot-based nanosheets (SNS) doped cementitious composites, Constr. Build. Mater. 409 (2023) 133926, https://doi.org/10.1016/j.conbuildmat.2023.133926.
[24] B. Huang, J. Wang, G. Piukovics, N. Zabihi, J. Ye, M. Saafi, J. Ye, Hybrid cement composite-based sensor for in-situ chloride monitoring in concrete structures, Sensor. Actuator. B Chem. 385 (2023) 133638, https://doi.org/10.1016/j.snb.2023.133638.
[25] D.K. Kalla, P.S. Dhanasekaran, B. Zhang, R. Asmatulu, Sustainability of fiber reinforced composites: status and vision for future, in: Proceedings of the ASME 2011 International Mechanical Engineering Congress and Exposition. Volume 3: Design and Manufacturing. Denver, Colorado, USA. November 11–17, ASME, 2011, pp. 167–173, https://doi.org/10.1115/IMECE2011-62498.
[26] F.G. Montoya, M.G. Montoya, J. Gómez, F. Manzano-Agugliaro, E. Alameda-Hernández, The research on energy in Spain: a scientometric approach, Renew. Sustain. Energy Rev. 29 (2014) 173–183, https://doi.org/10.1016/j.rser.2013.08.094. January 2014.
[27] Timothy O. Olawumi, Daniel W.M. Chan, A scientometric review of global research on sustainability and sustainable development, J. Clean. Prod. 183 (10 May 2018) (2018) 231–250, https://doi.org/10.1016/j.jclepro.2018.02.162.
[28] H.A.T. Nguyen, D.H. Pham, Y. Ahn, B.L. Oo, B.T.H. Lim, Machine learning and sustainable geopolymer materials: a systematic review, Mater. Today Sustain. (2025) 101095, https://doi.org/10.1016/j.mtsust.2025.101095.
[29] A. Almusaed, I. Yitmen, J.A. Myhren, A. Almssad, Assessing the impact of recycled building materials on environmental sustainability and energy efficiency: a comprehensive framework for reducing greenhouse gas emissions, Buildings 14 (2024) 1566, https://doi.org/10.3390/buildings14061566.
[30] I. Onungwe, D.V.L. Hunt, I. Jefferson, Transition and implementation of circular economy in municipal solid waste management system in Nigeria: a systematic review of the literature, Sustainability 15 (2023) 12602, https://doi.org/10.3390/su151612602.
[31] C. Illankoon, S.C. Vithanage, Closing the loop in the construction industry: a systematic literature review on the development of circular economy, J. Build. Eng. 76 (2023) 107362, https://doi.org/10.1016/j.jobe.2023.107362.
[32] F.S. Hafez, B. Sa'di, M. Safa-Gamal, Y.H. Taufiq-Yap, M. Alrifaey, M. Seyedmahmoudian, A. Stojcevski, B. Horan, S. Mekhilef, Energy efficiency in sustainable buildings: a systematic review with taxonomy, challenges, motivations, methodological aspects, recommendations, and pathways for future research, Energy Strategy Rev. 45 (2023) 101013, https://doi.org/10.1016/j.esr.2022.101013.
[33] J. Ayarkwa, D.G.J. Opoku, P. Antwi-Afari, R.Y.M. Li, Sustainable building processes' challenges and strategies: the relative important index approach, Cleaner Engineering and Technology 7 (2022) 100455, https://doi.org/10.1016/j.clet.2022.100455.
[34] C. Onyekwere, Erception of key actors on the drivers and barriers to construction and demolition waste (CDW) management in Nigeria: a roadmap for the recognition of the informal sector. P, 2023. PhD Thesis, Cardiff, https://orca.cardiff.ac.uk/id/eprint/170145/.
[35] A. Asthana, R. Srinivas, S.S. Chauhan, D. Bandhu, S.P. Dwivedi, K.K. Saxena, K. Kaur, I. Alnaser, Development and mechanical properties evaluation of environmentally sustainable composite material using various reinforcements with epoxy, Case Stud. Constr. Mater. 21 (2024) e03624, https://doi.org/10.1016/j.cscm.2024.e03624.
[36] Z. Han, J. Jang, J.B.R. Souppez, H.S. Seo, D. Oh, Comparison of structural design and future trends in composite hulls: a regulatory review, Int. J. Nav. Archit. Ocean Eng. 15 (2023) 100558, https://doi.org/10.1016/j.ijnaoe.2023.100558.
[37] M. Hussein, A.E. Eltoukhy, A. Karam, I.A. Shaban, T. Zayed, Modelling in off-site construction supply chain management: a review and future directions for sustainable modular integrated construction, J. Clean. Prod. 310 (2021) 127503, https://doi.org/10.1016/j.jclepro.2021.127503.
[38] A.O. Sojobi, K.M. Liew, Multi-objective optimization of high performance bio-inspired prefabricated composites for sustainable and resilient construction, Compos. Struct. 279 (2022) 114732, https://doi.org/10.1016/j.compstruct.2021.114732.
[39] P. Kosky, R. Balmer, W. Keat, G. Wise, Exploring Engineering: an Introduction to Engineering and Design, Elsevier Publisher, Imprint: Academic Press, London, UK, 2013, https://doi.org/10.1016/C2011-0-04445-9.
[40] D.S. Matawal, G.N. Omange, O.D. Akinmade, C.V. Amaechi, Challenges of Road Pavement Failure in Nigeria – Proceeding for National Conference on Road Pavement Failure in Nigeria, NBRRI, Publisher: NBRRI (Nigerian Building and Road Research Institute), Abuja, Nigeria, 2013.
[41] J. Fan, J. Njuguna, An introduction to lightweight composite materials and their use in transport structures, in: Book: *Lightweight Composite Structures in Transport: Design, Manufacturing, Analysis and Performance*. 2016, Elsevier BV, 2016, pp. 3–34, https://doi.org/10.1016/B978-1-78242-325-6.00001-3.
[42] N. Onwuannyi, A.K. Oyetunji, An insight of systemic constraints to effective maintenance of Nigeria's road infrastructure, Int. J. Soc. Sci. 13 (2) (2019) 53–71. Available at: https://www.researchgate.net/publication/340315594_An_Insight_of_Systemic_Constraints_to_Effective_Maintenance_of_Nigeria's_Road_Infrastructure. (Accessed 11 March 2024).
[43] T. Mohan Harish, Karingamanna Jayanarayanan, K.M. Mini, Recent trends in utilization of plastics waste composites as construction materials, Constr. Build. Mater. 271 (2021) (2021) 121520, https://doi.org/10.1016/j.conbuildmat.2020.121520.
[44] Nur Syafiqaz Nor Arman, Ruey Shan Chen, Sahrim Ahmad, Review of state-of-the-art studies on the water absorption capacity of agricultural fiber-reinforced polymer composites for sustainable construction, Constr. Build. Mater. 302 (2021) (2021) 124174, https://doi.org/10.1016/j.conbuildmat.2021.124174.
[45] O.G. Aluko, J.M. Yatim, M.A.A. Kadir, K. Yahya, A review of properties of bio-fibrous concrete exposed to elevated temperatures, Constr. Build. Mater. 260 (2020) (2020) 119671, https://doi.org/10.1016/j.conbuildmat.2020.119671.
[46] S. Divya, S. Praveenkumar, B.A. Tayeh, Performance of modified nano carbon blended with supplementary materials in cement composite – an interpretive review, Constr. Build. Mater. 346 (2022) (2022) 128452, https://doi.org/10.1016/j.conbuildmat.2022.128452.
[47] P. Yao, D. Yang, C. Wang, Z. Ma, Upcycling of construction waste powder for sustainable ultra-high performance engineered cementitious composites: effects of waste powder source and content, Constr. Build. Mater. 349 (2022) (2022) 128789, https://doi.org/10.1016/j.conbuildmat.2022.128789.
[48] Jaroslav Pokorný, Radek Ševčík, Jiří Šál, Lucie Zárybnická, Lightweight blended building waste in the production of innovative cement-based composites for sustainable construction, Constr. Build. Mater. 299 (2021) (2021) 123933, https://doi.org/10.1016/j.conbuildmat.2021.123933.
[49] F. Rubino, A. Nisticò, F. Tucci, P. Carlone, Marine application of fiber reinforced composites: a review, J. Mar. Sci. Eng. 8 (2020) 26, https://doi.org/10.3390/jmse8010026.
[50] O. El Hawary, L. Boccarusso, M.P. Ansell, M. Durante, F. Pinto, An overview of natural fiber composites for marine applications, J. Mar. Sci. Eng. 11 (2023) 1076, https://doi.org/10.3390/jmse11051076.
[51] J.G. Williams, Offshore oil composites: designing in cost savings, Composites World (2) (2009). Available at: https://www.compositesworld.com/articles/offshore-oil-composites-designing-in-cost-savings. (Accessed 11 March 2024).
[52] O.O. Ochoa, M.M. Salama, Offshore composites: transition barriers to an enabling technology, Compos. Sci. Technol. 65 (2005) (2005) 2588–2596, https://doi.org/10.1016/j.compscitech.2005.05.019.
[53] H. Acuña-Pizano, M.E. González-Trevizo, A. Luna-León, K.E. Martínez-Torres, F. Fernández-Melchor, Plastic composites as sustainable building materials: a

thermal and mechanical exploration, Constr. Build. Mater. 344 (2022) 128083, https://doi.org/10.1016/j.conbuildmat.2022.128083.
[54] S. Dolmatov, P. Kolesnikov, A. Kamenchukov, S. Voinash, R. Zagidullin, I. Kiyamov, L. Sabitov, Composite building materials from agricultural waste for house-building in seismic hazardous areas, AIP Conf. Proc. 2969 (1) (2024), https://doi.org/10.1063/5.0181868. AIP Publishing.
[55] A. Hosoi, S. Sakuma, Y. Fujita, H. Kawada, Prediction of initiation of transverse cracks in cross-ply CFRP laminates under fatigue loading by fatigue properties of unidirectional CFRP in 90° direction, Compos. Part A Appl. Sci. Manuf. 68 (2015) 398–405, https://doi.org/10.1016/j.compositesa.2014.10.022.
[56] M. Quaresimin, P.A. Carraro, L. Maragoni, Early stage damage in off-axis plies under fatigue loading, Compos. Sci. Technol. 128 (2016) 147–154, https://doi.org/10.1016/j.compscitech.2016.03.015.
[57] J.H. Xie, Y.C. Guo, L.S. Liu, Z.H. Xie, Compressive and flexural behaviours of a new steel-fibre-reinforced recycled aggregate concrete with crumb rubber, Constr. Build. Mater. 79 (2015) 263–272, https://doi.org/10.1016/j.conbuildmat.2015.01.036.
[58] O. Youssf, M.A. ElGawady, J.E. Mills, X. Ma, An experimental investigation of crumb rubber concrete confined by fibre reinforced polymer tubes, Constr. Build. Mater. 53 (2014) 522–532, https://doi.org/10.1016/j.conbuildmat.2013.12.007.
[59] Chi-Yao Chen, Maw-Tien Lee, Application of Crumb Rubber in Cement-Matrix Composite, Materials 12 (3) (2019) 529, https://doi.org/10.3390/ma12030529. https://www.mdpi.com/1996-1944/12/3/529. (Accessed 10 February 2019).
[60] J. Chen, L. Wan, Y. Ismail, P. Hou, J. Ye, D. Yang, Micromechanical analysis of UD CFRP composite lamina under multiaxial loading with different loading paths, Compos. Struct. 269 (2021), https://doi.org/10.1016/j.compstruct.2021.114024.
[61] J. Chen, L. Wan, Y. Ismail, A micromechanics and machine learning coupled approach for failure prediction of unidirectional CFRP composites under triaxial loading: a preliminary study, Compos. Struct. 267 (2021) (2021), https://doi.org/10.1016/j.compstruct.2021.113876.
[62] J. Ye, H. Cai, L. Liu, Z. Zhai, C.V. Amaechi, Y. Wang, L. Wan, D. Yang, X. Chen, J. Ye, Microscale intrinsic properties of hybrid unidirectional/woven composite laminates: part I: experimental tests, Compos. Struct. 262 (113369) (2021) 1–11, https://doi.org/10.1016/j.compstruct.2020.113369.
[63] M.B.S. Saafi, A. Gullane, B. Huang, H. Sadeghi, J. Ye, F. Sadeghi, Inherently multifunctional geopolymeric cementitious composite as electrical energy storage and self-sensing structural material, Compos. Struct. 201 (2018) 766–778, https://doi.org/10.1016/j.compstruct.2018.06.101.
[64] Y. Chi, B. Huang, M. Saafi, J. Ye, C. Lambert, Carrot-based covalently bonded saccharides as a new 2D material for healing defective calcium-silicate-hydrate in cement: integrating atomistic computational simulation with experimental studies, Compos. B Eng. 199 (2020) 108235, https://doi.org/10.1016/j.compositesb.2020.108235.
[65] Y. Chi, B. Huang, M. Saafi, N. Fullwood, C. Lambert, E. Whale, D. Hepworth, J. Ye, 2D bio-based nanomaterial as a green route to amplify the formation of hydrate phases of cement composites: atomistic simulations and analytical characterization, Constr. Build. Mater. 299 (123867) (2021), https://doi.org/10.1016/j.conbuildmat.2021.123867.
[66] Z. Huang, T. Liang, B. Huang, Y. Zhou, J. Ye, Ultra-lightweight high ductility cement composite incorporated with low PE fiber and rubber powder, Constr. Build. Mater. 312 (125430) (2021), https://doi.org/10.1016/j.conbuildmat.2021.125430.
[67] E. Mangino, J. Carruthers, G. Pitarresi, The future use of structural composite materials in the automotive industry, Int. J. Veh. Des. 44 (3–4) (2017) 211–232, https://doi.org/10.1504/IJVD.2007.013640.
[68] C.V. Amaechi, C. Chesterton, H.O. Butler, N. Gillet, C. Wang, I.A. Ja'e, A. Reda, A. C. Odijie, Review of composite marine risers for deep-water applications: design, development and mechanics, J. Compos. Sci. 6 (3) (2022) 96, https://doi.org/10.3390/jcs6030096, 2022.
[69] C.V. Amaechi, N. Gillett, A.C. Odijie, X. Hou, J. Ye, Composite risers for deep waters using a numerical modelling approach, Compos. Struct. 210 (2019) 486–499, https://doi.org/10.1016/j.compstruct.2018.11.057.
[70] C.V. Amaechi, C. Chesterton, H.O. Butler, Z. Gu, A.C. Odijie, F. Wang, X. Hou, J. Ye, Finite element modelling on the mechanical behaviour of marine bonded composite hose (MBCH) under burst and collapse, J. Mar. Sci. Eng. 10 (2022) 151, https://doi.org/10.3390/jmse10020151, 2022.
[71] C.V. Amaechi, N. Gillet, I.A. Ja'e, C. Wang, Tailoring the local design of deep water composite risers to minimise structural weight, J. Compos. Sci. 6 (2022) 103, https://doi.org/10.3390/jcs6040103, 2022.
[72] A. Bedford, K.M. Liechti, Mechanics of Materials, Springer Nature, 2019.
[73] Matweb, Material property data. MatWeb LLC, MatWeb [Online]. Available at: https://matweb.com/search/QuickText.aspx, 2025. (Accessed 21 June 2025).
[74] M. Ashby, Material Property Data for Engineering Materials. Engineering Department and Granta Design, 27, fifth ed., ANSYS & Granta EduPack, 2016. Available at: https://www.ansys.com/content/dam/amp/2021/august/webpage-requests/education-resources-dam-upload-batch-2/material-property-data-for-eng-materials-BOKENGEN21.pdf. (Accessed 21 June 2025).
[75] Europe Composites, Europe Composites Market Brief 2020: U.S. Commercial Service, Department of Commerce, United States of America, 2020. Available at: https://www.trade.gov/sites/default/files/2021-03/European%20Composites%20Market%20Brief%202020_508%20Compliant.pdf. (Accessed 11 March 2024).
[76] Composite-Tech, Why FRP Rebar Is Replacing Steel in U.S. Infrastructure Projects. Published on 4th Nov 2025. Composite-Tech, Available at: https://composite-tech.com/2025/11/05/why-frp-rebar-is-replacing-steel-in-us-infrastructure-projects/, 2025. (Accessed 10 January 2025).
[77] Fibre-Tech, Is FRP Rebar the Best Steel Rebar Alternative? Published on 23 Oct 2025. Fibre-Tech, Available at: https://fibretech.org/blog/frp-rebar-best-steel-rebar-alternative/, 2025. (Accessed 10 January 2026).
[78] A. Ghosh, A. Hasan, Recent patterns and trends in sustainable concrete research in India: a five-year scientometric review, Mater. Today Proc. 32 (Part 4) (2020) 910–916, https://doi.org/10.1016/j.matpr.2020.04.744.
[79] Z. Wu, K. Yang, X. Lai, M.F. Antwi-Afari, A scientometric review of system dynamics applications in construction management research, Sustainability 12 (2020) 7474, https://doi.org/10.3390/su12187474.
[80] H. Jin, M. Chan, R. Morda, C.X. Lou, Z. Vrcelj, A scientometric review of sustainable infrastructure research: visualization and analysis, Int. J. Constr. Manag. (2021), https://doi.org/10.1080/15623599.2021.2017114.
[81] Georgy Lazorenko, Anton Kasprzhitskii, Elham H. Fini, Sustainable construction via novel geopolymer composites incorporating waste plastic of different sizes and shapes, Constr. Build. Mater. 324 (2022) (2022) 126697, https://doi.org/10.1016/j.conbuildmat.2022.126697.
[82] Shaker M.A. Qaidi, Bassam A. Tayeh, Hemn Unis Ahmed, Wael Emad, A review of the sustainable utilisation of red mud and fly ash for the production of geopolymer composites, Constr. Build. Mater. 350 (2022) 128892, https://doi.org/10.1016/j.conbuildmat.2022.128892.
[83] Z. Zhang, T. Su, L. Zhang, R. Zheng, K. Ma, L. Zhang, C.V. Amaechi, C. Wang, The influence of fly ash and slag on the mechanical properties of geopolymer concrete, Buildings 14 (2024) 2720, https://doi.org/10.3390/buildings14092720.
[84] A. Danish, T. Ozbakkaloglu, M.A. Mosaberpanah, M.U. Salim, M. Bayram, J. H. Yeon, K. Jafar, Sustainability benefits and commercialization challenges and strategies of geopolymer concrete: a review, J. Build. Eng. 58 (2022) 105005, https://doi.org/10.1016/j.jobe.2022.105005.
[85] I.A. Ja'e, A.R. Salih, A. Syamsir, T.H. Min, Z. Itam, C.V. Amaechi, V. Anggraini, J. Sridhar, Experimental and predictive evaluation of mechanical properties of kenaf-polypropylene fibre-reinforced concrete using response surface methodology, Dev. Built Environ. 16 (2023) 100262, https://doi.org/10.1016/j.dibe.2023.100262.
[86] I.A. Ja'e, Z.C. Muda, M. Amran, A. Syamsir, C.V. Amaechi, E.H.H. Al-Qadami, M. A.D. Huenchuan, S. Avudaiappan, Modelling and optimisation of the structural performance of lightweight polypropylene fibre-reinforced LECA concrete, Results Eng. 24 (2024) 103149, https://doi.org/10.1016/j.rineng.2024.103149.
[87] I.A. Ja'e, R.A.N. bin Raja Sazrin, A. Syamsir, N. Bheel, C.V. Amaechi, T.H. Min, V. Anggraini, Optimisation of mechanical properties and impact resistance of basalt fibre reinforced concrete containing silica fume: experimental and response surface assessment, Dev. Built Environ. 17 (2024) 100368, https://doi.org/10.1016/j.dibe.2024.100368.
[88] I.A. Jae, Z.C. Muda, C.V. Amaechi, H. Almujibah, A. Syamsir, T.H. Min, A. E. Elshekh, M.O. Bashir, Assessment of thermo-mechanical performance of lightweight fibre-reinforced LECA concrete for enhanced energy efficiency, Case Stud. Therm. Eng. (2025) 106189, https://doi.org/10.1016/j.csite.2025.106189.
[89] H.B. Birgin, A. D'Alessandro, A. Meoni, F. Ubertini, Self-sensing eco-earth composite with carbon microfibers for sustainable smart buildings, J. Compos. Sci. 7 (2023) 63, https://doi.org/10.3390/jcs7020063.
[90] J. Watts, Concrete: the most destructive material on Earth, Guardian (2019) [Online] Available at: https://www.theguardian.com/cities/2019/feb/25/concrete-the-most-destructive-material-on-earth. (Accessed 11 March 2024).
[91] ACI, Report on the Role of Materials in Sustainable Concrete Construction (ACI 130R-19), American Concrete Institute (ACI), 2019. Available at: https://www.concrete.org/store/productdetail.aspx?ItemID=13019. (Accessed 30 March 2025).
[92] H.U. Ahmed, L.J. Mahmood, M.A. Muhammad, R.H. Faraj, S.M. Qaidi, N.H. Sor, A.S. Mohammed, A.A. Mohammed, Geopolymer concrete as a cleaner construction material: an overview on materials and structural performances, Clean. Mater. 5 (2022) 100111, https://doi.org/10.1016/j.clema.2022.100111.
[93] R.W. Poston, News Detail- Concrete: the Most Destructive Material on Earth? American Concrete Institute (ACI), 2019. Available at: https://www.concrete.org/news/newsdetail.aspx?f=51716973. (Accessed 5 May 2024).
[94] D.V. Val, S.I. Malami, B. Suryanto, I.B. Muhit, Reliability-based durability requirements for RC structures made of low-carbon concretes in climate change conditions, Civ. Eng. Environ. Syst. (2025) 1–26, https://doi.org/10.1080/10286608.2025.2478008.
[95] Jun Liu, Guang Liu, Weizhuo Zhang, Zhenlin Li, Feng Xing, Luping Tang, Application potential analysis of biochar as a carbon capture material in cementitious composites: a review, Constr. Build. Mater. 350 (2022) (2022) 128715, https://doi.org/10.1016/j.conbuildmat.2022.128715.
[96] J.G. Williams, Composite material offshore corrosion solutions, in: Proceedings of International Workshop on Corrosion Control of Marine Structures and Pipelines. Galveston, Texas, February 9-11, 1999, 1999. Available at: https://www.bsee.gov/sites/bsee.gov/files/tap-technical-assessment-program//392aa.pdf. (Accessed 11 March 2024).
[97] S. Black, The offshore industry is still utilising composites, Composites World (4) (2003). Available at: https://www.compositesworld.com/articles/offshore-applications-the-future-is-now. (Accessed 11 March 2024).
[98] M. Razavi Setvati, Z. Mustaffa, N. Shafiq, Z.I. Syed, A review on composite materials for offshore structures, in: Proceedings of the ASME 2014 33rd International Conference on Ocean, Offshore and Arctic Engineering, 5, Materials Technology; Petroleum Technology, San Francisco, California, USA, 2014, https://doi.org/10.1115/OMAE2014-23542. June 8–13, 2014. V005T03A016. ASME.

[99] O. Gunes, Failure modes in structural applications of fiber-reinforced polymer (FRP) composites and their prevention, in: 'Developments in Fiber-Reinforced Polymer (FRP) Composites for Civil Engineering'; A Volume in Woodhead Publishing Series in Civil and Structural Engineering, Woodhead Publishing Limited, London, UK, 2013. Nasim Uddin.
[100] M. Jawaid, M. Thariq, N. Saba, *Durability and life prediction in biocomposites, fibre-reinforced composites and hybrid composites*; A, in: Woodhead Publishing Series in Composites Science and Engineering. Imprint: Woodhead Publishing Limited, Publisher, Elsevier Ltd., London, UK, 2019, https://doi.org/10.1016/C2016-0-04449-2.
[101] A.T. Echtermeyer, H. Osnes, K.O. Ronold, E.T. Moe, Recommended practice for composite risers, in: Proceedings of the Offshore Technology Conference, Houston, Texas, USA. May 6–9, 2002, 2002, https://doi.org/10.4043/14022-MS.
[102] A.G. Gibson, J.L. Cantrill, S.J. Groves, Engineering standards for reinforced thermoplastic pipe, in: Paper No: OTC 14063. Proceedings of the Offshore Technology Conference, Houston, Texas, USA, , May 6–9, 2002, 2002, pp. 1–10, https://doi.org/10.4043/14063-MS.
[103] A.T. Echtermeyer, B. Steuten, Thermoplastic composite riser guidance note, OTC 24095, in: Proceedings of the Offshore Technology Conference, Houston, Texas, USA, May 6–9, 2013, 2013, pp. 1–10, https://doi.org/10.4043/24095-MS.
[104] Y. Bai, Q. Bai, Subsea Pipeline and Risers, Elsevier Publishers, Oxford, UK, 2005, https://doi.org/10.1016/B978-0-08-044566-3.X5000-3.
[105] B. Guo, S. Song, A. Ghalambor, T.R. Lin, J. Chacko, Offshore Pipelines, Elsevier Publishers, Oxford, UK, 2005.
[106] S. Kyriakides, E. Corona, Mechanics of Offshore Pipelines: Volume 1: Buckling and Collapse, Elsevier Publishers, Oxford, UK, 2007.
[107] I.M. Ahmed, K.D. Tsavdaridis, The evolution of composite flooring systems: applications, testing, modelling and eurocode design approaches, Journal of Constructional Steel Research 155 (2019) 286–300, https://doi.org/10.1016/j.jcsr.2019.01.007.
[108] V.O. Oyenuga, Simplified Reinforced Concrete Design: Consultants' Approach to Eurocode 2, third ed., Vasons concept consultants Ltd., Lagos, Nigeria, 2018, 9789789698936.
[109] F. Biondi, C. Malanga, Synthetic aperture radar doppler tomography reveals details of undiscovered high-resolution internal structure of the great pyramid of Giza, Remote Sens. 14 (2022) 5231, https://doi.org/10.3390/rs14205231.
[110] J. Davidovits, Ancient and modern concretes: what is the real difference? Concr. Int. 9 (12) (1987) 23–28. Available at: https://www.researchgate.net/publication/284676426.
[111] J. Davidovits, M. Morris, Why the Pharaohs Built the Pyramids with Fake Stones, Institut Géopolymère, 2009. Available at: http://www.geopolymer.org/wp-content/uploads/pyramid_chapt1.pdf.
[112] J. Mascarenhas-Mateus, A. Paula Pires, History of Construction Cultures Volume 1: Proceedings of the 7th International Congress on Construction History (7ICCH 2021), July 12-16, 2021, Lisbon, Portugal, Taylor & Francis, 2021, p. 812. Available at: https://library.oapen.org/bitstream/handle/20.500.12657/52779/9781000468755.pdf.
[113] M. Lehner, The Complete Pyramids. Solving the Ancient Mysteries, Thames & Hudson Ltd, London, 1997.
[114] D.S. Vijayan, A. Sivasuriyan, P. Devarajan, A. Stefańska, Ł. Wodzyński, E. Koda, Carbon fibre-reinforced polymer (CFRP) composites in civil engineering application—A comprehensive review, Buildings 13 (2023) 1509, https://doi.org/10.3390/buildings13061509.
[115] F. Ascione, G. Maselli, A. Nesticò, Sustainable materials selection in industrial construction: a life-cycle based approach to compare the economic and structural performances of glass fibre reinforced polymer (GFRP) and steel, J. Clean. Prod. 475 (2024) 143641, https://doi.org/10.1016/j.jclepro.2024.143641.
[116] M. Shakiba, M. Bazli, M. Karamloo, S. Mohammad, R. Mortazavia, Bond-slip performance of GFRP and steel reinforced beams under wet-dry and freeze-thaw cycles: the effect of concrete type, Constr. Build. Mater. 342 (Part B) (2022) 127916, https://doi.org/10.1016/j.conbuildmat.2022.127916, 1 August 2022.
[117] D. McGeorge, N. Sodahl, R. Moslemian, T. Horte, Hybrid and composite risers for deep waters and aggressive reservoirs, in: Proceedings of the 14th Offshore Mediterranean Conference (OMC) and Exhibition, Ravenna, Italy, 2019.
[118] J.D. Ortiz, S.S. Khedmatgozar Dolati, P. Malla, A. Nanni, A. Mehrabi, FRP-Reinforced/Strengthened concrete: state-of-the-Art review on durability and mechanical effects, Materials 16 (2023) 1990, https://doi.org/10.3390/ma16051990.
[119] H. Chen, M. Miao, X. Ding, Influence of moisture absorption on the interfacial strength of bamboo/vinyl ester composites, Compos. Appl. Sci. Manuf. 40 (12) (2009) 2013–2019, https://doi.org/10.1016/j.compositesa.2009.09.003.
[120] N.W. Burningham, W.F. Rumpel, Properties of boron fibers and composites, Polym. Eng. Sci. 7 (2) (1967) 124–127.
[121] L. Yan, H. Xu, Lightweight composite materials in automotive engineering: state-of-the-art and future trends, Alex. Eng. J. 118 (2025) 1–10, https://doi.org/10.1016/j.aej.2024.12.002.
[122] M. Bhaskar, M. Kumar, A. Patnaik, Mechanical and Tribological overview of ceramic particulates reinforced aluminium alloy composites, Rev. Adv. Mater. Sci. 58 (2019) 280–294, https://doi.org/10.1515/rams-2019-0033.
[123] J.R. Correia, Pultrusion of advanced fibre-reinforced polymer (FRP) composites, in: Advanced Fibre-Reinforced Polymer (FRP) Composites for Structural Applications, Woodhead Publishing, 2013, pp. 207–251, https://doi.org/10.1533/9780857098641.2.207.
[124] X. Bi, R. Huang, 3D printing of natural fiber and composites: a state-of-the-art review, Mater. Des. 222 (2022) 111065, https://doi.org/10.1016/j.matdes.2022.111065.
[125] J.Y. Jung, S. Yu, H. Kim, E. Cha, G.S. Shin, S.B. Eo, S.Y. Moon, M.W. Lee, M. Kucher, R. Böhm, J.Y. Hwang, Process-structure–property study of 3D-printed continuous fiber reinforced composites, Compos. Appl. Sci. Manuf. 188 (2025) 108538, https://doi.org/10.1016/j.compositesa.2024.108538.
[126] C.V. Amaechi, C.O. Agbomerie, A. Sotayo, F. Wang, X. Hou, J. Ye, Recycling of renewable composite materials in the offshore industry, Encyclopedia of Renewable and Sustainable Materials 2 (2020) (2020) 583–613, https://doi.org/10.1016/B978-0-12-803581-8.11445-6.
[127] C.V. Amaechi, C.O. Agbomerie, E.O. Orok, J. Ye, Economic aspects of fiber reinforced polymer composite recycling, Encyclopedia of Renewable and Sustainable Materials 2 (2020) (2020) 377–397, https://doi.org/10.1016/B978-0-12-803581-8.10738-6.
[128] R. Phiri, S.M. Rangappa, S. Siengchin, O.P. Oladijo, T. Ozbakkaloglu, Advances in lightweight composite structures and manufacturing technologies: a comprehensive review, Heliyon 10 (21) (2024) e39661, https://doi.org/10.1016/j.heliyon.2024.e39661, 15 November 2024.
[129] J. Zhang, G. Lin, U. Vaidya, H. Wang, Past, present and future prospective of global carbon fibre composite developments and applications, Compos. B Eng. 250 (2023) 110463, https://doi.org/10.1016/j.compositesb.2022.110463.
[130] A.P. Duarte, E. Vanooteghem, J.R. Correia, M.G. Gomes, Thermal response of pultruded glass fibre-reinforced polymer profiles subjected to outdoor environmental conditions, Constr. Build. Mater. 463 (2025) 139971, https://doi.org/10.1016/j.conbuildmat.2025.139971.
[131] S. Olcun, Y. Ibrahim, C. Isaacs, M. Karam, A. Elkholy, R. Kempers, Thermal conductivity of 3D-printed continuous pitch carbon fiber composites, Additive Manufacturing Letters 4 (2023) 100106, https://doi.org/10.1016/j.addlet.2022.100106.
[132] X. Liao, J. Denk, T. Tran, N. Miyajima, L. Benker, S. Rosenfeldt, S. Schafföner, M. Retsch, A. Greiner, G. Motz, S. Agarwal, Extremely low thermal conductivity and high electrical conductivity of sustainable carbonceramic electrospun nonwoven materials, Sci. Adv. 9 (13) (2023) eade6066, https://doi.org/10.1126/sciadv.ade6066.
[133] B. Krause, P. Rzeczkowski, P. Pötschke, Thermal conductivity and electrical resistivity of melt-mixed polypropylene composites containing mixtures of carbon-based fillers, Polymers 11 (2019) 1073, https://doi.org/10.3390/polym11061073.
[134] Myers, Composite mats. Signaure systems – a myers industries company, USA, Available at: https://www.signature-systems.com/composite-mats, 2024. (Accessed 5 May 2024).
[135] N. Spens, How to: composite furniture that's ahead of the curve, EpoxyCraft (2022). Available at: https://epoxycraft.com/top-tips-best-ways-to-use-epoxy/composite-furniture-thats-ahead-of-the-curve/.
[136] PohlCon, Modern construction with glass fiber composite material, Available at: https://pohlcon.com/en/company/news-and-press/details/modern-construction-with-glass-fiber-composite-material, 2024. (Accessed 24 April 2025).
[137] D. Hanonge, A. Luppi, Challenges of flexible riser systems in shallow waters, in: Proceedings of the Offshore Technology Conference, May 3–6, 2010, Houston, Texas, USA, 2010, pp. 1–10, https://doi.org/10.4043/20578-MS. Paper No:OTC 20578.
[138] C. Wang, K. Shankar, E. Morozov, Global design and analysis of deep sea FRP composite risers under combined environ-mental loads, Adv. Compos. Mater. 26 (2017) 79–98, https://doi.org/10.1080/09243046.2015.1052187.
[139] C. Wang, M. Sun, K. Shankar, S. Xing, L. Zhang, CFD simulation of vortex induced vibration for FRP composite riser with different modeling methods, Appl. Sci. 8 (2018) 8–9, https://doi.org/10.3390/app8050684.
[140] Y. Zhang, W.W. Gao, S.X. Xu, M. Duan, The research about the strength of composite riser pipes based on finite element method, Key Eng. Mater. KEM 665 (2015) 177–180, https://doi.org/10.4028/www.scientific.net/KEM.665.177.
[141] J. Qureshi, A review of fibre reinforced polymer structures, Fibers 10 (2022) 27, https://doi.org/10.3390/fib10030027.
[142] T.S. Balakrishnan, M.T.H. Sultan, F.S. Shahar, S.Y. Nayak, A.U.M. Shah, T. A. Sebaey, A.A. Basri, Plant fiber reinforcements as alternatives in pultruded FRP composites manufacturing: a review, J. Nat. Fibers 21 (1) (2024) 2298396, https://doi.org/10.1080/15440478.2023.2298396.
[143] D.K. Rajak, D.D. Pagar, P.L. Menezes, E. Linul, Fiber-reinforced polymer composites: manufacturing, properties, and applications, Polymers 11 (2019) 1667, https://doi.org/10.3390/polym11101667.
[144] H.T. Ali, R. Akrami, S. Fotouhi, M. Bodaghi, M. Saeedifar, M. Yusuf, M. Fotouhi, Fiber reinforced polymer composites in bridge industry, Structures 30 (2021, April) 774–785, https://doi.org/10.1016/j.istruc.2020.12.092. Elsevier.
[145] P.G. Kossakowski, W. Wciślik, Fiber-reinforced polymer composites in the construction of bridges: opportunities, problems and challenges, Fibers 10 (4) (2022) 37, https://doi.org/10.3390/fib10040037.
[146] A.K. Sharma, R. Bhandari, A. Aherwar, R. Rimašauskiene, Matrix materials used in composites: a comprehensive study, Mater. Today Proc. 21 (2020) (2020) 1559–1562, https://doi.org/10.1016/j.matpr.2019.11.086.
[147] J. Ye, Laminated Composite Plates and Shells: 3D Modelling, Springer-Verlag, London, UK, 2003, https://doi.org/10.1007/978-1-4471-0095-9.
[148] Saad, P.; Salama, M.M.; Jahnsen, O. Application of composites to deepwater top tensioned riser systems. In *Proceedings of the ASME 2002, 21st International Conference on Offshore Mechanics and Arctic Engineering*, Oslo, Norway, 23–28 June 2002; Volume 3, pp. 255–261 https://doi.org/10.1115/OMAE2002-28325.
[149] T. Cheldi, P. Cavassi, M. Serricchio, C.M. Spenelli, G. Vietina, S. Ballabio, Use of spoolable reinforced thermoplastic pipes for oil and water transportation, in: Proceedings of the 14th Offshore Mediterranean Conference (OMC) and Exhibition, Revenna, Italy. March 27-29, 2019, 2019.

[150] R.M. Jones, Mechanics of Composite Materials, second ed., CRC press, Boca Raton, 2018 https://doi.org/10.1201/9781498711067.
[151] Toughening mechanisms in composite materials, in: Q. Qin, J. Ye (Eds.), Woodhead Publishing Series in Composites Science and Engineering), Imprint: Woodhead Publishing; Elsevier, London, UK, 2015, https://doi.org/10.1016/C2013-0-16514-2.
[152] P.D. Mangalgiri, Composite materials for aerospace applications, Bull. Mater. Sci. 22 (1999) 657–664, https://doi.org/10.1007/BF02749982.
[153] M.V. Kulkarni, S.B. Boppana, Composites overview, in: S.B. Boppana, C. G. Ramachandra, K.P. Kumar, S. Ramesh (Eds.), Structural Composite Materials: Fabrication, Properties, Applications and Challenges, Composites Science and Technology Series. Springer, Springer Nature Singapore, Singapore. Singapore, 2023, pp. 3–21, https://doi.org/10.1007/978-981-99-5982-2_1.
[154] F. Khan, N. Hossain, J.J. Mim, S.M. Rahman, M.J. Iqbal, M. Billah, M. A. Chowdhury, Advances of composite materials in automobile applications–A review, Journal of Engineering Research (2024), https://doi.org/10.1016/j.jer.2024.02.017. Ahead-of print version.
[155] Shubham, B.C. Ray, Introduction to composite materials, in: Fiber Reinforced Polymer (FRP) Composites in Ballistic Protection. Engineering Materials, Springer, Singapore, 2024, https://doi.org/10.1007/978-981-99-9746-6_1.
[156] ISO, ISO 12439:2010 Mixing Water for Concrete, International Standardisation Organisation, Geneva, 2010.
[157] ISO, ISO 10406-1:2015 fibre-reinforced Polymer (FRP) Reinforcement of Concrete — Test Methods — Part 1: FRP Bars and Grids, International Standardisation Organisation, Geneva, 2015.
[158] ISO, ISO 10406-2:2015 fibre-reinforced Polymer (FRP) Reinforcement of Concrete — Test Methods — Part 2: FRP Sheets, International Standardisation Organisation, Geneva, 2015.
[159] ISO, ISO 14484:2020 Performance Guidelines for Design of Concrete Structures Using fibre-reinforced Polymer (FRP) Materials, International Standardisation Organisation, Geneva, 2020.
[160] ASTM D5117, Standard Test Method for Dye Penetration of Solid Fiberglass Reinforced Pultruded, ASTM International, West Conshohocken, PA, USA, 2017.
[161] ASTM D7957/D7957M, Standard Specification for Solid Round Glass Fiber Reinforced Polymer Bars for Concrete Reinforcement, ASTM International, West Conshohocken, PA, USA, 2022.
[162] W. Zhang, J. Xu, Advanced lightweight materials for automobiles: a review, Mater. Des. 221 (2022) 110994, https://doi.org/10.1016/j.matdes.2022.110994.
[163] M.L.P. Tonatto, M.M.C. Forte, V. Tita, et al., Progressive damage modeling of spiral and ring composite structures for offloading hoses, Mater. Des. 108 (2016) 374–382, https://doi.org/10.1016/j.matdes.2016.06.124.
[164] Q. Gao, P. Zhang, M. Duan, X. Yang, W. Shi, C. An, Z. Li, Investigation on structural behavior of ring-stiffened composite offshore rubber hose under internal pressure, Appl. Ocean Res. (2018), https://doi.org/10.1016/j.apor.2018.07.007.
[165] S.D. Bankar, P.N. Kulkarni, V.V. Kulkarni, N.K. Patil, Tension-tension fatigue life estimation of CFRP composites by modal testing, Mater. Today Proc. 46 (Part 1) (2021), https://doi.org/10.1016/j.matpr.2020.07.436, 2021, Pages 217-222.
[166] Y. Feng, Y. He, C. Gao, T-T fatigue behaviors of composite T800/MTM46 cross-ply laminate and reliability analysis on fatigue life, Adv. Mech. Eng. (2017), https://doi.org/10.1177/1687814017704829.
[167] M.A.A. Patil, I. Rit, M.M. Mirza, Circular and non-circular shaped composite component of fiber reinforce epoxy resin material under loading condition, International Journal of Engineering Applied Sciences and Technology 5 (5) (2020) 223–228. Available at: https://www.ijeast.com/papers/223-228,Tesma505,IJEAST.pdf.
[168] M. Kawai, S. Yajima, A. Hachinohe, T. Takano, Off-axis fatigue behavior of unidirectional carbon fiber-reinforced composites at room and high temperatures, J. Compos. Mater. 35 (2001) 545–576, https://doi.org/10.1177/002199801772662073.
[169] L. Maragoni, P.A. Carraro, M. Quaresimin, Effect of voids on the crack formation in [45/−45/0]s laminate under cyclic axial tension, Compos. Part A Appl. Sci. Manuf. 92 (2016) 493–500, https://doi.org/10.1016/j.compositesa.2016.02.018.
[170] A. Hosoi, H. Kawada, Fatigue life prediction for transverse crack initiation of CFRP cross-ply and quasi-isotropic laminates, Materials 11 (7) (2018) 1182, https://doi.org/10.3390/ma11071182.
[171] F. Ellyin, H. El-Kadi, A fatigue failure criterion for fiber reinforced composite laminae, Compos. Struct. 15 (1990) 61–74, https://doi.org/10.1016/0263-8223(90)90081-O.
[172] N. Gathercole, H. Reiter, T. Adam, B. Harris, Life prediction for fatigue of T800/5245 carbon-fibre composites: I. Constant-amplitude loading, Int. J. Fatigue. 16 (1994) 523–532, https://doi.org/10.1016/0142-1123(94)90478-2.
[173] M.M.A. Mostafa, T. Wu, X. Liu, Bond-slip behaviors of composite steel-reinforced high strength lightweight aggregate concrete columns with innovative X-shaped steel sections, Constr. Build. Mater. 341 (25 July 2022) (2022) 127838, https://doi.org/10.1016/j.conbuildmat.2022.127838.
[174] S. Adafer, Y. Si Youcef, S. Amziane, Cyclic behaviour of CFRP confined concrete under axial compression, Constr. Build. Mater. 341 (25 July 2022) (2022) 127838, https://doi.org/10.1016/j.conbuildmat.2022.127793.
[175] Seco, Composite materials: flying high! published 2nd April 2020, Available at: https://www.secotools.com/article/111877?language=en, 2020. (Accessed 5 June 2025).
[176] K. Karthick, D. Bharathidhasan, R. Ashok Kumar, Jaffarsha F. Mohamed, M. Sreeraam, K. Surya Prakash, Investigation on mechanical properties of aluminum metal matrix composites – a review, in: Proceedings of IOP Conference Series: Materials Science and Engineering, 923, 2020, https://doi.org/10.1088/1757-899x/923/1/012058.
[177] M. Meignanamoorthy, M. Ravichandran, Synthesis of metal matrix composites via powder metallurgy route: a review, Mechanics and Mechanical Engineering 22 (2018) 65–76, https://doi.org/10.2478/mme-2018-0007.
[178] R. Jairaja, G. Narayana Naik, Single and dual adhesive bond strength analysis of single lap joint between dissimilar adherends, Int. J. Adhesion Adhes. 92 (2019) 142–153, https://doi.org/10.1016/j.ijadhadh.2019.04.016. July 2019.
[179] Z. Gu, Y. Liu, D.J. Hughes, J. Ye, X. Hou, A parametric study of adhesive bonded joints with composite material using black-box and grey-box machine learning methods: deep neuron networks and genetic programming, Compos. B Eng. 217 (2021) 108894, https://doi.org/10.1016/j.compositesb.2021.108894.
[180] K. Ogi, S. Yashiro, Fatigue fracture criteria for transverse cracking with the use of the probabilistic SCG model and energy release rate, J. Jpn. Soc. Compos. Mater. 35 (2009) 212–220, https://doi.org/10.6089/jscm.35.212 (In Japanese).
[181] M.I. Ahmad, R. Mallick, S. Chakraborty, A. Guin, A. Chakraborti, Composite materials: the present scenario, future trends & its applications focusing on earthquake resistant building constructions, Journal of Civil Engineering and Environmental Technology 2 (12) (2015) 65–69. https://www.researchgate.net/publication/318724099.
[182] Nature, Editorial. Concrete needs to lose its colossal carbon footprint, Nature 597 (7878) (2021) 593–594, https://doi.org/10.1038/d41586-021-02612-5.
[183] D. Qin, P. Gao, F. Aslam, M. Sufian, H. Alabduljabbar, A comprehensive review on fire damage assessment of reinforced concrete structures, Case Stud. Constr. Mater. 16 (2022) e00843, https://doi.org/10.1016/j.cscm.2021.e00843.
[184] J. Takagi, A. Wada, Recent earthquakes and the need for a new philosophy for earthquake-resistant design, Soil Dynam. Earthq. Eng. 119 (2019) 499–507, https://doi.org/10.1016/j.soildyn.2017.11.024.
[185] M.A.G.P. Perera, P.G. Ranjith, Eco-friendly cementitious composites for enhanced strength: emerging trends and innovations, J. Clean. Prod. 468 (2024) 142962, https://doi.org/10.1016/j.jclepro.2024.142962.
[186] S.A. Meftah, R. Yeghnem, A. Tounsi, E.A. Adda bedia, Seismic behavior of RC coupled shear walls repaired with CFRP laminates having variable fibers spacing, Constr. Build. Mater. 21 (2007) 1661–1671, https://doi.org/10.1016/j.conbuildmat.2006.05.011.
[187] J.G. Yu, S.Q. Zhu, X.T. Feng, Seismic behavior of CFRP-steel composite plate shear wall with edge reinforcement, J. Constr. Steel Res. 203 (2023) 107816, https://doi.org/10.1016/j.jcsr.2023.107816.
[188] S. Mostofizadeh, K.F. Tee, Review of next-generation earthquake-resistant geopolymer concrete, Discov. Mater. 4 (2024) 62, https://doi.org/10.1007/s43939-024-00132-3.
[189] M. Alhassan, A. Alkhawaldeh, N. Betoush, A. Sawalha, L. Amaireh, A. Onaizi, Harmonizing smart technologies with building resilience and sustainable built environment systems, Results Eng. 22 (2024) 102158, https://doi.org/10.1016/j.rineng.2024.102158.
[190] A.A. Firoozi, A.A. Firoozi, D.O. Oyejobi, S. Avudaiappan, E.S. Flores, Emerging trends in sustainable building materials: technological innovations, enhanced performance, and future directions, Results Eng. (2024) 103521, https://doi.org/10.1016/j.rineng.2024.103521.
[191] M. Dolz, X. Martinez, D. Sá, J. Silva, A. Jurado, Composite materials, technologies and manufacturing: current scenario of european union shipyards, Ships Offshore Struct. 19 (8) (2024) 1157–1172, https://doi.org/10.1080/17445302.2023.2229160.
[192] Q. Wang, T. Chen, X. Wang, Y. Zheng, J. Zheng, G. Song, S. Liu, Recent progress on moisture absorption aging of plant fiber reinforced polymer composites, Polymers 15 (2023) 4121, https://doi.org/10.3390/polym15204121.
[193] X. Wang, X. Liu, D. Liu, Z. Wang, Y. Zhu, K. Qian, D. Zhang, Influence of moisture absorption on mechanical properties and damage mechanisms of three-dimensional six-directional braided composites under hydrostatic pressure, Polym. Test. 114 (2022) 107693, https://doi.org/10.1016/j.polymertesting.2022.107693.
[194] F. Korkees, Moisture absorption behavior and diffusion characteristics of continuous carbon fiber reinforced epoxy composites: a review, Polymer-Plastics Technology and Materials 62 (14) (2023) 1789–1822, https://doi.org/10.1080/25740881.2023.2234461.
[195] S.I. Talabi, J. Tobin, B. Strom, I. Brownstein, V. Kunc, A.A. Hassen, Recent and future developments in pultrusion technology with consideration for curved geometries: a review, Compos. B Eng. (2024) 111678, https://doi.org/10.1016/j.compositesb.2024.111678.
[196] T.S. Balakrishnan, M.T.H. Sultan, F.S. Shahar, A.A. Basri, A.U.M. Shah, T. A. Sebaey, A. Łukaszewicz, J. Józwik, R. Grzejda, Fatigue and impact properties of Kenaf/Glass-Reinforced hybrid pultruded composites for structural applications, Materials 17 (2024) 302, https://doi.org/10.3390/ma17020302.
[197] M. Volk, O. Yuksel, I. Baran, J.H. Hattel, J. Spangenberg, M. Sandberg, Cost-efficient, automated, and sustainable composite profile manufacture: a review of the state of the art, innovations, and future of pultrusion technologies, Compos. B Eng. 246 (2022) 110135, https://doi.org/10.1016/j.compositesb.2022.110135.
[198] J. Qureshi, A review of recycling methods for fibre reinforced polymer composites, Sustainability 14 (2022) 16855, https://doi.org/10.3390/su142416855.
[199] Tencom, A Comparison of Wood, Steel, and Pultruded Fiberglass for Construction, Tencom Ltd., Ohio, 2025. Available at: https://www.tencom.com/blog/pultruded-fiberglass-for-construction. (Accessed 25 April 2025).
[200] M.M. Alzahrani, K.A. Alamry, M.A. Hussein, Recent advances of fiber-reinforced polymer composites for defense innovations, Results Chem. (2025) 102199, https://doi.org/10.1016/j.rechem.2025.102199.

[201] Tencom, Why Pultruded Profiles are Stronger and Last Longer, Tencom Ltd., Ohio, 2025. Available at: https://www.tencom.com/blog/why-pultruded-profiles-are-stronger-and-last-longer. (Accessed 25 April 2025).
[202] A. Sotayo, S. Green, G. Turvey, Experimental investigation and Finite Element (FE) analysis of the load-deformation response of PVC fencing structures, Structures 19 (2019) 424–435, https://doi.org/10.1016/j.istruc.2019.02.011.
[203] R.O. Loutfy, A. Richard, Cement-polymer composites from recycled polymers for construction applications. Final report on EPA contract number: EPD05051. Materials and electrochemical research (MER) corporation, Available at: https://cfpub.epa.gov/ncer_abstracts/index.cfm/fuseaction/display.highlight/abstract_id/7512/report/F, 2006. (Accessed 5 May 2024).
[204] L. Lijuan, R. Shenghua, L. Lan, Mechanical properties and constitutive equations of concrete containing a low volume of tire rubber particles, Constr. Build. Mater. 70 (2014) 291–308, https://doi.org/10.1016/j.conbuildmat.2014.07.105.
[205] A. Moustafa, M.A. ElGawady, Mechanical properties of high strength concrete with scrap tire rubber, Constr. Build. Mater. 93 (2015) 249–256, https://doi.org/10.1016/j.conbuildmat.2015.05.115.
[206] A.S. Mendis, S. Al-Deen, M. Ashraf, Behaviour of similar strength crumbed rubber concrete (CRC) mixes with different mix proportions, Constr. Build. Mater. 137 (2017) 354–366, https://doi.org/10.1016/j.conbuildmat.2017.01.125.
[207] H.M. Hamada, A. Al-Attar, F. Abed, S. Beddu, A.M. Humada, A. Majdi, S.T. Yousif, B.S. Thomas, Enhancing sustainability in concrete construction: a comprehensive review of plastic waste as an aggregate material, Sustain. Mater. Technol. 40 (2024) e00877, https://doi.org/10.1016/j.susmat.2024.e00877.
[208] S.N. Shah, S. Beddu, S.P. Yap, A. Putra, M.N. Othman, C.W. Yuen, K.H. Mo, Physical, strength and acoustic properties of lightweight cement composite with preplaced chemically-treated crumb rubber, Case Stud. Constr. Mater. 20 (2024) e02821, https://doi.org/10.1016/j.cscm.2023.e02821.
[209] Teckwood, How do composite materials work in construction?, Available at: https://teckwood.co.uk/how-do-composite-materials-work-in-construction/, 2020. (Accessed 5 May 2024).
[210] G. Nehls, Bedford reinforced plastics introduces FRP pedestrian and trial bridge line, Composites World (2021). Available at: https://www.compositesworld.com/news/bedford-reinforced-plastics-introduces-frp-pedestrian-and-trial-bridge-line. (Accessed 5 May 2024).
[211] G. Nehls, New Tennessee FRP bridge to promote composites use for rural infrastructure, Composites World (2021). Available at: https://www.compositesworld.com/news/new-tennessee-frp-bridge-to-promote-composites-usage-for-rural-infrastructure. (Accessed 5 May 2024).
[212] Rawji, FRP doors & frames. RAWJI, Available at: https://www.rawji.com/frp-doors.html, 2024. (Accessed 4 May 2024).
[213] C.M. Herr, Driving architectural design with material innovation: a design research approach. Sustainable Buildings and Structures, Leiden, CRC Press/Balkema, 2016.
[214] A. Reda, M.A. Shahin, I.A. Sultan, C.V. Amaechi, K.K. McKee, Necessity and suitability of in-line inspection for corrosion resistant alloy (CRA) clad pipelines, Ships Offshore Struct. 18 (9) (2023) 1360–1366, https://doi.org/10.1080/17445302.2022.2117928.
[215] Hanser, Composites in Offshore Oil: a Design and Application Guide, Hanser Pub Inc, 1999.
[216] PEP, Composites for the Offshore Oil and Gas Industry: Design and Application, PEP - Professional Engineering Publishers & Wiley, 2007.
[217] L. Gardner, Stability and design of stainless steel structures – review and outlook, Thin-Walled Struct. 141 (2019) 208–216, https://doi.org/10.1016/j.tws.2019.04.019.
[218] R. Sonnenschein, K. Gajdosova, I. Holly, FRP composites and their using in the construction of bridges, Procedia Eng. 161 (2016) 477–482, https://doi.org/10.1016/j.proeng.2016.08.665.
[219] IACMI, New Composite Bridge Showcases Sustainable Solution for Aging Infrastructure, Department of Civil and Environmental Engineering, The University of Tennessee, 2021. Available at: https://cee.utk.edu/new-composite-bridge-showcases-sustainable-solution-for-aging-infrastructure/. (Accessed 11 March 2024).
[220] Eden, Maps of the Eden Project, Eden Project, 2025. Available at: https://www.edenproject.com/visit/planning-your-visit/maps-of-the-eden-project.
[221] S.M. Sapuan, M.R. Mansor, Concurrent engineering approach in the development of composite products: a review, Mater. Des. 58 (2014) 161–167, https://doi.org/10.1016/j.matdes.2014.01.059.
[222] L.I. Obi, T. Omotayo, D. Ekundayo, A.K. Oyetunji, Enhancing BIM competencies of built environment undergraduates students using a problem-based learning and network analysis approach, Smart Sustain. Built Environ. 13 (1) (2024) 217–238, https://doi.org/10.1108/SASBE-05-2022-0085.
[223] ISO, ISO 10406-3:2019 fibre-reinforced Polymer (FRP) Reinforcement of Concrete — Test Methods — Part 3: CFRP Strips, International Standardisation Organisation, Geneva, 2019.
[224] Tencom, Increasing Demand for Pultruded Profiles in Four Sectors, Tencom Ltd., Ohio, 2025. Available at: https://www.tencom.com/blog/increasing-demand-for-pultruded-profiles-in-four-sectors. (Accessed 25 April 2025).
[225] L.C. Bank, M.G. Oliva, H.-U. Bae, J.W. Barker, S.-W. Yoo, Pultruded FRP plank as formwork and reinforcement for concrete members, Adv. Struct. Eng. 10 (5) (2007) 525–535, https://doi.org/10.1260/136943307782417681.
[226] ICC, International Building Code, International Code Council (ICC), USA, 1997. Available at: https://codes.iccsafe.org/content/IBC2021P2/preface.
[227] ICC, *ICC-ES AC-32*; Acceptance Criteria for Concrete with Synthetic Fibers, International Council of Codes Evaluation Services, Los Angeles, CA, USA, 2003, p. 2003.
[228] CSA, Design and Construction of Building Structures with Fibre-Reinforced Polymers (CSA S806-12 (R2017)), Canadian Standards Association, Mississauga, ON, Canada, 2012.
[229] CSA S807-19, Specification for Fibre-Reinforced Polymers (FRP) (CSA S807-19), Canadian Standards Association, Mississauga, ON, Canada, 2019, 9781488319396.
[230] ACI Committee 440, Code Requirements for Structural Concrete Reinforced with Glass FRP Bars (ACI 440.11-22), American Concrete Institute, Farmington Hills, MI, USA, 2022.
[231] ACI Committee 440, Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures (ACI 440.2R-17), American Concrete Institute, Farmington Hills, MI, USA, 2017, 9781945487590.
[232] AASHTO, Guide Specifications for the Design of Concrete Bridge Beams Prestressed with Carbon Fiber-Reinforced Polymer (CFRP) Systems, first ed., American Association of State Highway and Transportation Officials, Washington, DC, USA, 2018, 9781560517160.
[233] ACI Committee 440, Guide for the Design and Construction of Structural Concrete Reinforced with Fiber-Reinforced Polymer (FRP) Bars (ACI 440.1R-15), American Concrete Institute, Farmington Hills, MI, USA, 2015.
[234] ACI, ACI Building Code Requirements for Structural Concrete and Commentary (ACI 318-19), American Concrete Institute, Farmington Hills, MI, USA, 2019, 9781641950565.
[235] AASHTO, LRFD Bridge Design Specifications, ninth ed., American Association of State Highway and Transportation Officials, Washington, DC, USA, 2020, 9781560517382.
[236] AASHTO, Bridge Design Guide Specifications for GFRP-reinforced Concrete, second ed., American Association of State Highway and Transportation Officials, Washington, DC, USA, 2018, 2026245800.
[237] AASHTO, Guide Specifications for Design of Bonded FRP Systems for Repair and Strengthening of Concrete Bridge Elements, first ed., American Association of State Highway and Transportation Officials, Washington, DC, USA, 2012.
[238] AASHTO, (MBEI) Manual for Bridge Element Inspection, second ed., American Association of State Highway and Transportation Officials, Washington, DC, USA, 2019, 9781560515913.
[239] ACI 440.5-08, Specification for Construction with Fiber-Reinforced Polymer Reinforcing Bars, American Concrete Institute, Farmington Hills, MI, USA, 2008.
[240] JPCI, JPCI Recommendation for Design and Construction of Concrete Structures Using Fiber Reinforced Polymer, Japan Prestressed Concrete Institute, Tokyo, Japan, 2021.
[241] ISO, ISO 20290-5:2023. Aggregates for Concrete — Test Methods for Mechanical and Physical Properties — Part 5: Determination of Particle Size Distribution by Sieving Method, International Standardisation Organisation, Geneva, 2023.
[242] J.C. Prucz, S.N. Shoukry, G.W. William, M.S. Shoukry, Lightweight composite materials for heavy duty vehicles -Final Report, in: Report Contract No. DE-FC26-08NT02353, West Virginia University, USA, 2013, pp. 1–55. Available at: https://doi.org/10.2172/1116021 https://www.osti.gov/servlets/purl/1116021. (Accessed 11 March 2024).
[243] Henk de Boer, The dawn of the disruptive, deepwater TCP riser, J. Petrol. Technol. (2019). Published Nov. 3, 2019. Available at: https://jpt.spe.org/dawn-disruptive-deepwater-tcp-riser. (Accessed 11 March 2024).
[244] Y.-F. Li, W. Chen, T.-W. Cheng, The sustainable composite materials in civil and architectural engineering, Sustainability 14 (2022) 2134, https://doi.org/10.3390/su14042134.
[245] Marc André Meyers, Krishan Kumar Chawla, Mechanical Behavior of Materials, Cambridge university press, 2008.
[246] Damon Roberts, Stephen Anthony Hatton, Development and qualification of end fittings for composite riser pipe, in: Proceedings of the Offshore Technology Conference, Houston, Texas, USA, May 6-9, 2013, https://doi.org/10.4043/23977-MS.
[247] Mamdouh M. Salama, Gisle Stjern, Turid Storhaug, Brian Spencer, Andreas Echtermeyer, The first offshore field installation for a composite riser joint, in: Proceedings of the Offshore Technology Conference, Houston, Texas, May 6-9, 2002, 2002, https://doi.org/10.4043/14018-MS.
[248] A.G. Gibson, The cost effective use of fiber reinforced composites offshore, in: Research Report for the Health and Safety Executive (HSE), University of Newcastle, Upon Tyne, 2003. Available at: https://www.hse.gov.uk/Research/rrhtm/rr039.htm [Accessed on March, 2024].
[249] G.H. Loh, A. Sotayo, E. Pei, Development and testing of material extrusion additive manufactured polymer–textile composites, Fash Text 8 (2021) 2, https://doi.org/10.1186/s40691-020-00232-7.
[250] A. Sotayo, S. Green, G. Turvey, Development, characterisation and finite element modelling of novel waste carpet composites for structural applications, J. Clean. Prod. 183 (2018) 686–697, https://doi.org/10.1016/j.jclepro.2018.02.095.
[251] H. Cai, J. Ye, J. Shi, Y. Wang, Y. Shi, B. Huang, Y. Xu, M. Saafi, J. Ye, A new two-step modeling strategy for random micro-fiber reinforced composites with consideration of primary pores, Compos. Sci. Technol. 218 (2022), https://doi.org/10.1016/j.compscitech.2021.109122 [109122].
[252] H. Cai, J. Ye, Y. Wang, M. Saafi, B. Huang, D. Yang, J. Ye, An effective microscale approach for determining the anisotropy of polymer composites reinforced with randomly distributed short fibers, Compos. Struct. 240 (2020) 112087, https://doi.org/10.1016/j.compstruct.2020.112087.
[253] F. Ramezani, B.D. Simões, R.J.C. Carbas, E.A.S. Marques, L.F.M. da Silva, Developments in laminate modification of adhesively bonded composite joints, Materials 16 (2023) 568, https://doi.org/10.3390/ma16020568.
[254] F. Ramezani, P.D.P. Nunes, R.J.C. Carbas, E.A.S. Marques, L.F.M. da Silva, The joint strength of hybrid composite joints reinforced with different laminates

materials, Journal of Advanced Joining Processes 5 (2022) 100103, https://doi.org/10.1016/j.jajp.2022.100103.
[255] Opeoluwa Akinradewo, Clinton Aigbavboa, Ayodeji Oke, David Edwards, A roadmap for present focus and future trends of blockchain technology in the built environment, African Journal of Science, Technology, Innovation and Development 15 (2) (2022) 153–165, https://doi.org/10.1080/20421338.2022.2046249. https://www.tandfonline.com/doi/full/10.1080/20421338.2022.2046249. (Accessed 30 March 2022).
[256] M.L.P. Tonatto, V. Tita, S.C. Amico, Composite spirals and rings under flexural loading: experimental and numerical analysis, J. Compos. Mater. 54 (20) (2020) 2697–2705, https://doi.org/10.1177/0021998320902504.
[257] I.A. Ja'e, Z.C. Muda, A. Syamsir, C.V. Amaechi, H. Almujibah, A.E. Elshekh, M.O. Bashir, A.H. Almaliki, Structural performance of lightweight fibre-reinforced oil palm shell concrete subjected to impact loadings under varying boundary conditions, Case Stud. Constr. Mater. 22 (2025) e04240, https://doi.org/10.1016/j.cscm.2025.e04240.
[258] I.A. Ja'e, Z.C. Muda, H. Almujibah, C.V. Amaechi, A. Syamsir, U.J. Alengaram, A.E. Elshekh, M.O. Bashir, Structural impact resilience of lightweight fiber-reinforced LECA concrete using ANN and RSM technique, Constr. Build. Mater. 471 (2025) 140699, https://doi.org/10.1016/j.conbuildmat.2025.140699.
[259] J. Soto-Paz, O. Arroyo, L.E. Torres-Guevara, B.A. Parra-Orobio, M. Casallas-Ojeda, The circular economy in the construction and demolition waste management: a comparative analysis in emerging and developed countries, J. Build. Eng. 78 (2023) 107724, https://doi.org/10.1016/j.jobe.2023.107724.
[260] R.A. Robayo-Salazar, W. Valencia-Saavedra, R. Mejía de Gutiérrez, Construction and demolition waste (CDW) recycling—As both binder and Aggregates—In alkali-activated materials: a novel Re-Use concept, Sustainability 12 (2020) 5775, https://doi.org/10.3390/su12145775.
[261] J. Dsilva, S. Zarmukhambetova, J. Locke, Assessment of building materials in the construction sector: a case study using life cycle assessment approach to achieve the circular economy, Heliyon 9 (10) (2023) e20404, https://doi.org/10.1016/j.heliyon.2023.e20404.