Scientific Research Publishing

World Journal of Engineering and Technology, 2025, 13(1), 12-38
https://www.scirp.org/journal/wjet
ISSN Online: 2331-4249
ISSN Print: 2331-4222

Use of Polymeric Materials in Construction to Improve Durability & Sustainability

Waseem Ahmad Khatri, Mohammed Al Mehthel, Oscar Salazar, Mirza Baig, Saleh Al Wohaibi

Consulting Services Department, Saudi Arabian Oil Company, Dhahran, Kingdom of Saudi Arabia
Email: Waseem.khatri@aramco.com

How to cite this paper: Khatri, W.A., Al Mehthel, M., Salazar, O., Baig, M. and Al Wohaibi, S. (2025) Use of Polymeric Materials in Construction to Improve Durability & Sustainability. *World Journal of Engineering and Technology*, **13**, 12-38.
https://doi.org/10.4236/wjet.2025.131002

Received: October 21, 2024
Accepted: January 6, 2025
Published: January 9, 2025

Abstract

Building and construction sector, including infrastructures, are facing many challenges which are scarcity of raw materials, CO_2 emissions, lower construction efficiency, and deterioration under corrosive environment that cost the world economy $2.5 trillion and this translates to 3.4% of world gross domestic product. This paper presents several examples that show how the use of the nonmetallic materials improved sustainability and life cycles in the built environment by removing the corrosion issue from its root and using durable NM polymers in construction. The paper details recently patented Aramco technology for the use of nonmetallic paving panels that could be used as an alternative to concrete and asphalt paving. Other case studies presented cover use of GFRP Poles for traffic signs and signal poles to replace traditional steel poles. Details of developments for specialist structural application in bridges, in architectural applications, polymers in soils, fibers in pavement manholes and bendable concrete are presented.

Keywords

Non-Metallic Materials, Corrosion, Durability, Non-Metallic Paving, Metals, Building and Construction, Paving Panels, Bridges, Architectural, Polymers, Glass Fiber Reinforced Polymers (GFRP)

1. Introduction

The global cost of corrosion is estimated to be US$2.5 trillion, which is equivalent to 3.4% of the global GDP (2013). By using available corrosion control practices, it is estimated that savings of between 15 and 35% of the cost of corrosion could be realized; *i.e.*, between US$375 and $875 billion annually on a global basis.

These costs do not include individual safety or environmental consequences which can occur due to near misses, incidents, forced shutdowns (outages), accidents, etc. Corrosion in particular in the built environment impacts the road & rail bridges, civil infrastructure like pavement, roads, transmission pipe lines, water bridges, power transmission lines and railroads etc.

As a result of increasing costs of corrosion and impact on the infrastructure and facilities its important that non-metallic materials are looked at to replace traditional materials to address the situation and improve the life cycle and durability of the infrastructure. Several industries have come to realize that lack of corrosion management can be very costly and that with a proper corrosion management, significant cost savings can be achieved over the lifetime of an asset. To achieve the full extent of these savings, corrosion management and its integration into an organization's management system must be accomplished by selecting appropriate material for construction and infrastructure [1] [2] (**Figure 1**, **Figure 2**).

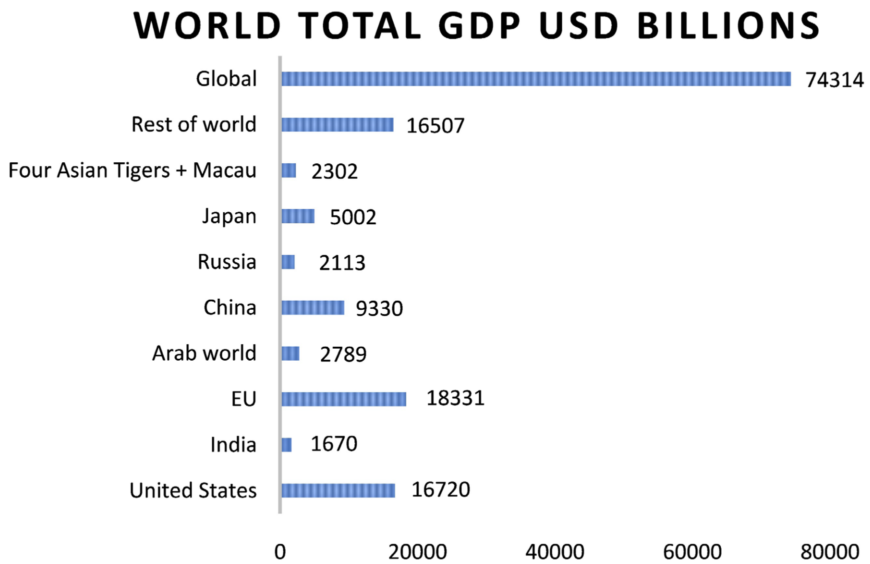

Figure 1. World GDP in Billion USD $ [1].

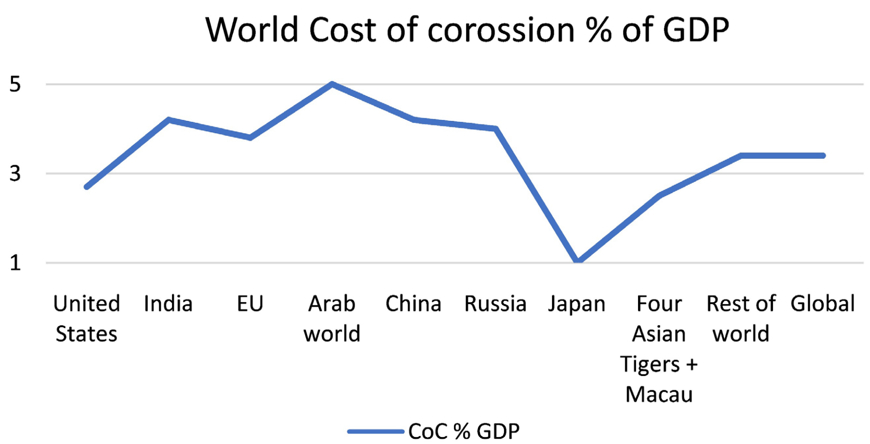

Figure 2. Cost of corrosion % of World GDP in Billion USD [1].

The building sector is one of the largest contributors to greenhouse gas emissions

(GHG), with occupied buildings being responsible for nearly 40%, of those total emissions, building operations are responsible for 27% annually, while building and infrastructure materials and construction (typically referred to as embodied carbon) are responsible for an additional 13% annually.

Three main construction materials—concrete, steel, and aluminum—are responsible for 23% of total global emissions; most of this is used in the built environment. There is an incredible opportunity for embodied carbon reduction in these high-impact materials through policy, design, material selection, and specification [3] (**Figure 3**).

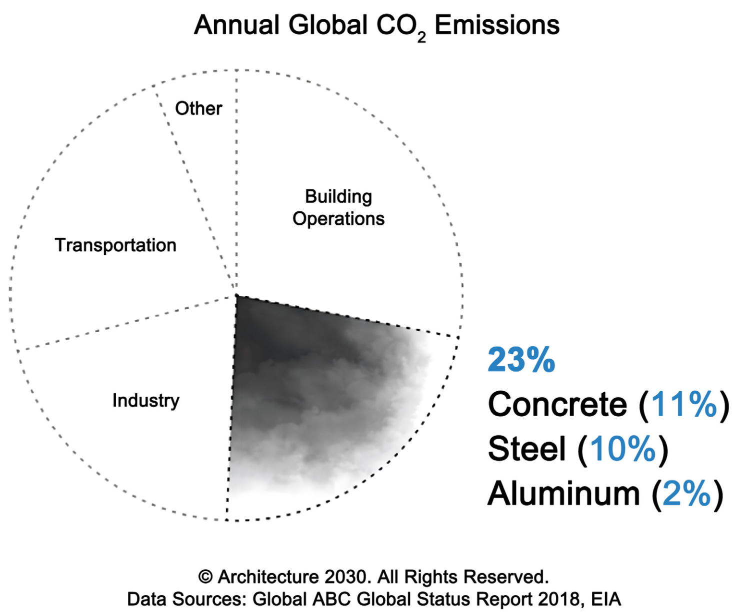

Figure 3. Concrete & steel and aluminum CO_2 emissions [3].

Corrosion refers to any process involving the deterioration or degradation of metal components. The best-known case is that of the rusting of steel. Corrosion processes are usually electro-chemical in nature, having the essential features of a battery. Dissimilar metals in the presence of a conducting liquid, known as the electrolyte, develop an electrical potential that causes a current to flow whenever a suitable path is provided. Such electrical potentials may also be developed between two areas of a component made of a single metal as a result of small differences in composition or structure or of differences in the conditions to which the metal surface is exposed. That part of a metal component which becomes the corroding area is called the "anode"; that which acts as the other plate of the battery is called the "cathode" and does not corrode, but is an essential part of the system [4].

Like other natural hazards such as earthquakes or severe weather disturbances, corrosion can cause dangerous and expensive damage to everything from pipelines, bridges, and public buildings to vehicles, water and wastewater systems, hydrogen infrastructure, smart home and city appliances, electronics, batteries, sensors, and even nanotechnologies. Unlike weather-related disasters though, there are time-proven methods to prevent and control corrosion that can reduce or eliminate its impact on public safety, the economy, and the environment. However, investment in new technologies for biodegradability and programmable corrosion are still needed [5].

The construction industry must help to build a world that will improve the lives of future generations and use eco-friendly methods. Working sustainably involves meeting demands of the expanding population, as well as supporting the environment in the long-term. Sustainable construction means looking at materials which can provide better durability and resistance to degradation and improved life cycle costs (LCC). During construction projects, care must be taken to reduce waste and energy consumption where possible and protect the natural environment around the site. The end result of a sustainable construction project must be environmentally friendly building or environment [6].

Polymers have been established as a material resource of paramount importance in number of applications pertaining to almost all branches of engineering and applied sciences. The interdisciplinary scientific nature of Polymer Science emerging from Chemistry, but now encompassing physics, mathematics, biochemistry, thermo dynamics, energetics and multi-faceted engineering applications has made it a field of unmitigated importance [7].

Fiber-reinforced polymer (FRP) composites have been used in various civil engineering applications, buildings and bridges included, for over five decades. Their use in aerospace, marine and automotive industries even goes back to 1930s. FRPs also have their applications in sports and rail sector and wind turbines [8] [9]. For structural use, FRP composites are usually made by embedding fibers in a polymer matrix. The matrix consists of polyester, vinyl ester, or epoxy resins and fibers including glass, carbon, or aramid fibers. The resin binds the fibers together, while fibers provide strength and stiffness to the finished FRP product. The main aim is to produce a lightweight strong and stiff component [10].

FRP composites have desirable properties for use in structural engineering. Lightweight, chemical and corrosion resistance, low ecological footprint, fast deployment, electromagnetic transparency and thermal insulation of glass FRPs, and high strength-to-weight ratio, offsite fabrication and modular construction, superior durability and moldability are some of the main benefits of FRP for structural use. FRP composites are versatile and customizable. The ability to mold into complex shapes creates new aesthetic possibilities and provides geometrically efficient design solutions [11] [12].

FRP composites are suitable in structural applications where challenging environmental conditions exist and fast installation is needed. Due to their chemical, corrosion and environmental resistances, FRPs perform better in harsh environments compared with the traditional materials. Besides use in repair market, and as rebars in concrete members, full FRP profiles are used in chemical and food processing plants, wastewater treatment plants, cooling towers, foot and road bridges, bridges decks and edge elements, and railway platforms as primary structural elements. FRP elements are also used in secondary structures, such as insulated ladders, floor gratings, stairways with handrails, working platforms and walkways, and building façade panels [8] [13].

2. Corrosion and Durability Issues in the Built Environment

Facilities affected by corrosion include building structures, pipelines, fuel tanks, pavements, roofs, transformers, switchgear, electrical boxes, HVAC equipment, water towers, fire hydrants, motors, compressors, bridges, wharfs, piers, connectors, fencing, boilers, ladders, stairways, wash racks, fire sprinkler systems, airfield pavements, and water distribution lines. Facility vulnerability and the potential effects of corrosion need to be fully evaluated and understood as a requirement. It should be included in project planning, acquisition, design, construction, and sustainment phases and activities [14].

Corrosion is defined as the process that occurs naturally when the reinforced concrete structures within which the steel reinforced bars are embedded starts rusting. In other terms we can say that [2], corrosion of reinforced concrete is the damage of metal (*i.e.* steel reinforcement) by the chemical, electrochemical, and electrolytic reactions within the concrete surface environment. It forms as the concrete ages [15].

Corrosion is a major factor in the deterioration and degradation of civil intrastate and reduces structural durability considerably. In particular the corrosion of steel reinforcement is recognized as one of the most important degradation problems in reinforced concrete (RC) structures. **Photo 1** & **Photo 2** are showing the impact of corrosion to the structures. Huge amounts of financial resources are spent on the maintenance, repair, and rehabilitation of existing structures to ensure their structural integrity. Several research studies of corrosion indicate its negative effect on the mechanical properties of both steel and concrete, the degradation of the bond between them, and subsequently, the entire reduction of mechanical performance of corroded RC elements. Nowadays, a significant percentage of the existing built environment is or will be at the end of its useful lifespan; hence, the estimation of the bearing capacity of corroded RC elements has become a relevant engineering task [18].

Photo 1. Reinforced concrete beam corrosion [16].

Photo 2. Traffic light corrosion [17].

Non-metallic materials like Glass Fiber Reinforced Plastic (GFRP), carbon fibers, thermoset, thermoplastics are increasingly being deployed across multiple industries, including oil and gas, construction, maritime, automotive, packaging and renewables. They offer several advantages over metallic materials, such as corrosion-resistance, light weight, increased durability, lower cost, and improved environmental efficiency.

Non-metallics could bring about a paradigm shift in the way that industry deals with corrosion. There could be significant urge for industries to shift from corrosion control to corrosion prevention strategies. Developing sustainable non-metallic solutions may significantly reduce long-term corrosion costs for industries, benefitting one and all. Cross-industry collaboration has the potential to leverage on the expertise and champion generate solutions that will benefit multiple industries and sectors. Without cross collaboration, individual industry segments could face longer timeframes and higher costs for innovation.

Certain industries are already using non-metallics in coatings, components and structures to improve product performance in specific markets. For example, the automotive industry, are using higher volumes of plastics in cars to reduce weight and decrease CO_2 emissions. Likewise, the construction industry uses fibre-reinforced concrete to improve durability. Steel ships are often damaged by corrosion and repair is eventually no longer possible, which is not a problem when non-metallic materials are used. Using non-metallics materials such as fibre-reinforced plastic (FRP) instead of steel, for example, should reduce a ship's weight and lower fuel consumption [19].

3. Developments and Deployments of Non Metallics in Civil Infrastructure

3.1. Aramco Patented NM Paving Panels for Pavement and Walkway

Road infrastructure is key for any economy development and progression to move people and transport large amount of goods and logistics. New road construction and maintenance requires large amount of natural materials and funds and there is a need to look at more sustainable and more efficient way for road building. There has been development in producing plastic road in Europe using recycled plastic. The main targeted applications are to construct bike paths, footpaths, parking lots and squares [20].

To create innovative pavement which can offer ease of transportation, construction, recycling, ease of removal and relocation of road panels. Aramco patented a technology to produce walkway panels and paving for road construction. More details about this patent can be found at "Polymer Panels for walkways and Paving US 11,306,443 B2". These walkway panels are not only used for walkways but also can be used in road pavement construction.

The patent provides details of constructing walkway and road pavements with various options like with single layer panel, double layer (hollow), arrangement for rain water discharge and various fixing arrangements, different anchor designs for variable configuration and design.

To prove the concept there have been number of trials successfully completed within the factory setting and further large-scale deployment are planned for projects.

Following Photo 3(a) & Photo 3(b) showing the panels and the HS-20 truck load tests of the materials tested for the panels. The panel thickness tested was 50 mm using polymeric materials supported on supported on sand and aggregate base course layers. Further testing has revealed that there is an opportunity to further optimize the design due to higher than expected physical materials designed properties. The anchors used to keep the panels in position were also made out of polymeric materials [21].

(a) (b)

Photo 3. Roadway panels.

3.2. GFRP Poles for Traffic Signs and Signal Poles

Historically, manufacturers and end users have relied on wood, metal and concrete for all types of poles and post application due a perceived conventional material knowledge of strength in addition to other properties. In the past decade or so significant amount of progress has been made in the field of nonmetallic material like GFRP—Glass fiber Reinforced Polymer. GFRP material have demonstrated to have many benefits and advantages such as: lightweight, corrosion resistant, high reliability, excellent dielectric strength, and long service life. GFRP poles offers better safety in comparison to steel as it snaps when impacted due to lower shear strength. In comparison, steel with higher impact resistance increases chances of injuries occupants of the vehicle.

Successful trial has been conducted using GFRP poles for traffic signs and signal poles in the Eastern Province of Saudi Arabia. Traffic sign poles were manufactured using filament winding and signal pole using pultrusion process. AASHTO standard "Specifications for Structural Supports for Highway Signs, Luminaires and Traffic Signals" and ANSI 136.2. "Roadway and Area Lighting Equipment" was used as materials specification and design for the pole. The poles can be pultruded or filament winded with advanced UV protection in a matrix that offers superior toughness and strength. In addition, the poles exhibit excellent corrosion, moisture and fire resistance properties. **Photo 4(a)** & **Photo 4(b)** are showing the traffic signs at as side of a highway and **Photo 5** is showing a bespoke design traffic signal pole.

Pilots completed demonstrated that there is a need to develop a dedicated design and construction guidelines to standardize the construction process. Further study about the crash resistance of GFRP poles at different speeds needs to be investigated [22].

(a) (b)

Photo 4. Completed GFRP traffic signs [22].

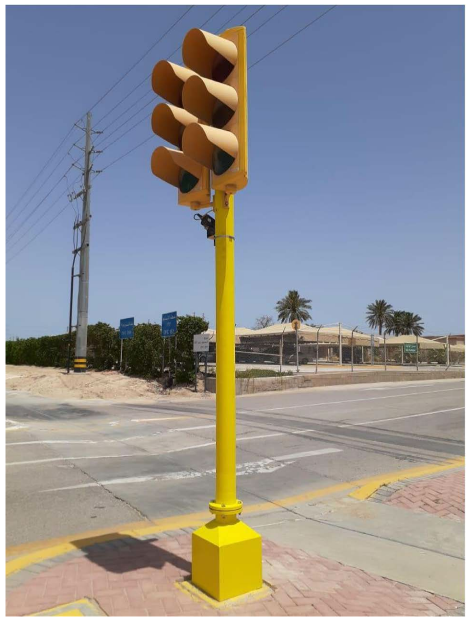

Photo 5. Completed GFRP traffic signal [22].

3.3. NM Architectural Structural Applications

Fiber composite materials such as glass fiber, carbon fiber, and aramid have been widely used in the structural applications for some time. Fiber composites offers advantages of being light weight, resistance to corrosion and ease of installation and improved life cycle costs in comparison to steel. One emerging material, carbon fiber, can be a robust next-generation construction material. They have a relatively lower weight compare to steel but can take significant loads. One example of construction is a Carbon Café built in Saudi Aramco Lab 7 location as shown in **Figure 4**. This structure demonstrates the advantage of carbon fiber composites in architectural structural applications. The 3500-square-foot Carbon Café consists of a black canopy, acting simultaneously as roof and walls of the building's main section. This canopy, measures 66 × 33 feet and is integrated with a polycarbonate skylight on its rear side as shown in **Photo 6(a)** & **Photo 6(b)**.

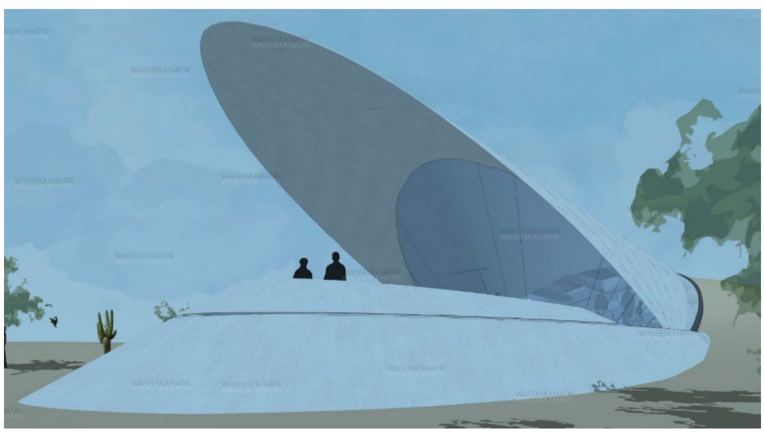

Figure 4. Carbon café architectural view.

(a) (b)

Photo 6. Installation/details of Carbon café structure.

On the inside it is made of a two-layer structure with insulation and sandwiched mechanical, electrical and plumbing (MEP). The design of the canopy was done by Finite Element Method (FEM), is able to withstand high wind, seismic and thermal loads, as well as loads from hanging soffits and the MEP equipment, with maximum allowed deflection of less than 20 millimeters at the tip.

Another example of the advantages of composites and the multiple possibilities of innovative architectural is the waving sun shade canopy that was produced for a community project using GFRP materials and supported on steel structures as shown in Photo 7(a) & Photo 7(b) below. The curved shaped structures canopies produced had steel connections which were connected to the main steel structures. The molding process allowed to produce unique waving design assumed by the architect and create the effect using the lighting attached to the canopies.

(a) (b)

Photo 7. Waiving sun-shades for community park area.

3.4. Composite Foot Bridges

Composite bridges are gaining popularity which are made of non-metallic materials. The Fiber Reinforced Polymer (FRP) is a composite material made of minimum two components. The basic ones are a reinforcement and a polymer matrix. The first one is a dispersed phase affecting the stiffness and strength of a composite. It is made of carbon, glass or aramid fibers, usually in the form of chopped stand mats or multilayer woven fabrics. The second one is a resin which gives shape (monolithic nature of the product), an appropriate arrangement of reinforcement and load distribution on a volume of a composite. It is made of a polymer, which is usually an epoxy, vinyl ester or polyester. The characteristics of a final product called "laminate" depends on the properties of materials used for each phase and on their content percentage. Composite structures are often combined in so-called sandwiches, in which the core is used as a light filler to create distance between two laminates (skins). Thus, a structure has much higher flexural stiffness. The major advantages of this material are low volume weight, relatively high stiffness and strength, good fatigue resistance, flexibility in shaping the geometry like curves etc., high material damping properties, high environmental and chemical resistance giving excellent long-term durability.

Following are two composite bridge studies:

1) Dragon's Bridge over Rhyl Harbour in North Wales, UK:

The lifting bridge over Rhyl Harbor in North Wales serves as an additional crossing for pedestrians and cyclists across the River Clwyd as shown below in **Photo 8**. The footbridge was constructed in 2013. Its each deck is 30 m long and weighs 8 tons. The structure is mainly the sandwich type. The laminates reinforcement is a mixture of glass and carbon fabrics.

Photo 8. Dragon's Bridge over Rhyl Harbour [23].

2) The Ooypoort pedestrian bridge connecting Nijmegen to Ooijpolder, Denmark:

The Ooypoort GFRP composite pedestrian bridge connecting Nijmegen to Ooijpolder in Denmark was officially opened in 2014 as shown in **Photo 9(a)** & **Photo 9(b)**. The structure has 56 m span length is among longest single-span composite bridges in the world at the time of opening. It was designed to accommodate house boats even in case of high-water levels. All composite parts of the structure were produced by vacuum infusion. Its dimensions forced production in three sections that were subsequently joined together [23].

(a)

(b)

Photo 9. Ooypoort pedestrian bridge [23].

3.5. Glass Fiber Reinforced Polymer (GFRP) Manholes

Manholes allow access to underground utility vaults for the making of connections or performing maintenance on underground public utility sewer systems. It fulfills several functions such as inspection and maintenance of drains or sewers, cleaning and flushing, maintenance of water meters and fittings, housing of pumping stations.

The typical manhole construction material is cement concrete, however they are highly vulnerable to microbially induced corrosion (MIC), mainly due to hydrogen sulfide (H_2S) generated by sulfur oxidizing microorganisms present inside the sanitary sewers systems.

Initially, concrete is usually immune to biological attack because of its high alkalinity (formation of calcium hydroxide, byproduct of the hydration of cement). However, after a time the erosive action of water generate roughness on the surface, facilitating the colonization of microbes on concrete surfaces. The sulfur-oxidizing bacteria on the surface oxidizes the H2S dissolved in the moisture from the sewer to produce sulfuric acid (H_2SO_4), commonly referred to as biogenic sulfuric acid, which is believed to be responsible for the gradual weakening and removal of concrete layers. This degradation process results in frequent maintenance/rehabilitation work to prevent failure. In many cases, this requires the closure of roads and generation of foul gas during maintenance, which affect the public safety as well [24].

Nonmetallic manholes in FRP and thermoplastic (HDPE) are gaining popularity due to their lower initial cost and longer lifecycle almost corrosion free as compared to concrete (**Photo 10(a)** & **Photo 10(b)**).

(a) (b)

Photo 10. Shows typical FRP manholes.

3.6. Polymers in Soils

Polymer application is very useful in strengthening and stabilizing loose soil and road subgrade. The application of chemical polymers to subgrade and sub-base layers of proposed road construction will lead to elimination and/or reduction in conventional pavement layer construction like aggregates and asphalt surfaces but these can still be included for heavy usage like haul road, highways and construction roads where thickness can be optimized to get economic benefits.

Polymer soil stabilization is the method of adding polymers to the soil in order to improve the overall physical property. Polymers are a chemical compound with molecules that bond together to create a repeating chain. In other words, the polymer is bonding the soil particles together, very similar to the function of glue. Polymers are traditionally sold in liquid form and are less diluted than other methods of soil stabilization, meaning that more product is required than other means of soil stabilization. Chemical polymers are typically used for unpaved surfaces such as dirt roads, paths, or temporary pond lining [25].

Two trials were conducted as detailed below for a haul road construction:

Method 1 (the first 200 m of trial section)—application of the chemical polymer, mixing, and compaction of the top 100 mm of the existing Marl road. The subgrade was compacted with standard 95% compaction.

Method 2 (final 150 m of trial section)—excavation of 200 mm top soil, and application of the chemical polymer, mixing and compaction of 100 mm of Marl underlying topsoil. The stabilized layer is then capped with 200 mm sub-base material mixed with polymer (Figure 5).

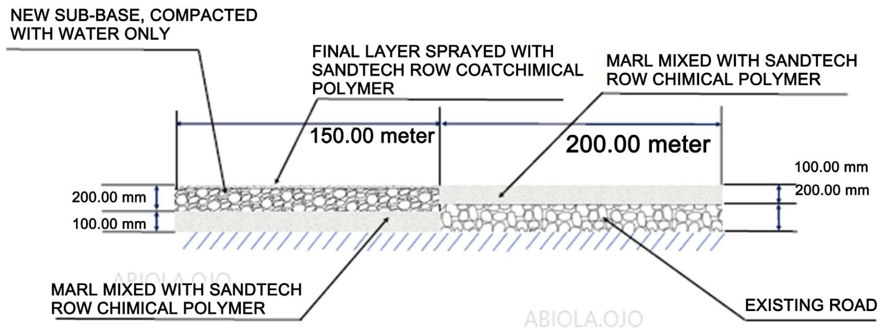

Figure 5. Schematic figure of trial section along existing haul road.

California Bearing Ratio (CBR) values were tested with bulk as (base case) and Cores (C1) & Cores (2). Table 1 shows the CBR values.

Table 1. Shows the CBR values.

Cores/section	CBR Ratio (%)
Base case (Base case)	19/22
C1-200 meters trial section	43.2
C2-200 meters trial section	58.7
C3-150 meters trial section	61.8
C4-150 meters trial section	60.4
C4-150 meters trial section	58.7

The final CBR test results show an increase in CBR value of road base material (final layer) from approx. 100% to 180% in comparison to the default haul road. The application of chemical polymers significantly increased the durability of the road construction, reduced the test trial time and cost of construction. Overall, chemical polymers can reduce the lift cycle costs for new projects and operating facilities. The haul road shows no sign of deterioration after one year in operation (Figure 6).

There are various types of polymers, but the main types are synthetic and biopolymers. Synthetic polymers are mineral-based and have many of the same binding properties as Portland cement. While not all synthetic polymers are known as environmentally friendly or toxic. It is known that synthetic polymers do tend to have more environmental concerns. Biopolymers are polymers that are a result of a biological process. Biopolymers tend to have less strength than

Synthetic polymers, but have more environmentally friendly qualities [26].

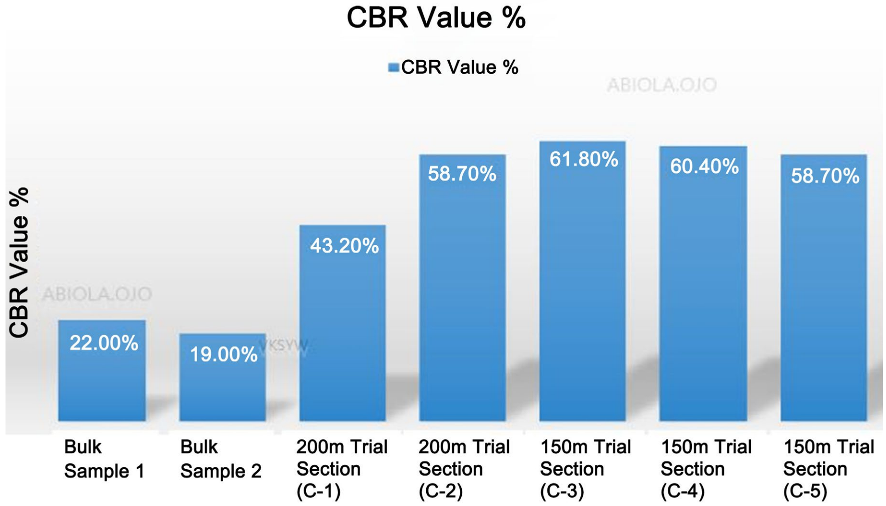

Figure 6. Summary of CBR test results.

Polymers work based on a long repeating molecule; meaning that the soil particles are bonding to the molecule. This makes polymers compatible with all types of soil, ranging from sandy soils to clay soils. The size of a polymer's molecule will affect the performance on any given soil, seeing that the soil particle will need to fit into the molecule. The polymer's molecule size is particularly important since a molecule that is too big may not allow a small clay particle to fit properly, or vice versa with a small molecule and large sand particle. While polymers are a versatile soil stabilizer, not all of them work well with fine soil types.

The lifespan and characteristics of polymers can vary depending on the polymer. However, traditional applications last 1 to 3 years with little maintenance. Most polymer applications create an impermeable surface for the life of the application. Although, just as the lifespan varies, the performance of pavement with water can vary as well [27].

Chemical polymer is a water-based liquid that can be mixed with soil to create a mixture which is well bonded and hardens as water evaporates from the matrix. The polymers are by-product of crude refining with a wide range of industry applications such as textile, automotive, aerospace, chemicals, agricultural and construction sectors etc. Application of chemical polymers in the road construction promotes circular economy, and its increasing utilization has encouraged several research projects and Intellectual property applications.

In general, chemical polymers mixed with soil for various civil engineering applications, have shown to increase water retention, reduce erosion, increase soil shear strength, and support soil structure. A wide range of liquid polymer products have been widely used to address problems ranging from the prevention of desertification, erosion protection of road slopes and berms to strength increase of subgrades that is used on light traffic roads, walkways, slopes for ponds & swales.

3.7. Fiber Reinforced Asphalt Concrete (FRAC)

Asphalt mixtures are classified as an essential material used word-wide for pavement construction as shown in Photo 11 due to their physical advantageous and chemical characteristics such as flexibility, durability and ease of maintenance. Nevertheless, asphalt mixtures are subjected to various type of distresses, such as cracking, rutting, and aging etc. as shown in Photo 12 that may impact the paved road performance and service life. These damages and failures are caused by various factors, such as load intensity, load frequency, environmental conditions, material properties and material interaction. To enhance and improve the properties of asphalt mixtures performance, several modifiers and additives can be used such as fibers, polymers, and rubbers. A part of these additives and modifiers synthetic fibers as shown in Photo 13 shave demonstrated good results in

Photo 11. Executing pavement construction activity.

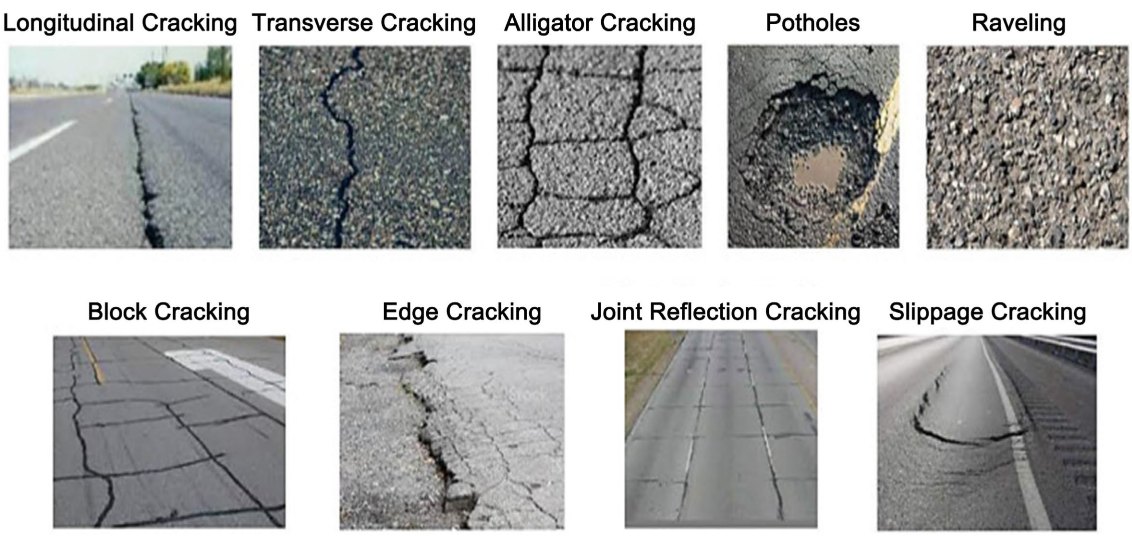

Photo 12. Type of pavement distresses and failure.

Photo 13. Synthetic fibers.

enhancing and improving the mechanical properties of the asphalt mixture [28] [29]. Fiber reinforcement is a well-known technique for enhancing the performance of asphalt concrete pavements for heavy trafficked roads and airfields and infrastructure projects because of improved durability.

Fiber reinforcement of concrete has gained popularity and a method to increase the strength and cracking resistance of the material. Conceptually, fiber acts as a supplementary reinforcing material that provides additional tensile strength in the resulting composite, when it gets mixed with asphalt material [30]. Fiber can provide a three-dimensional reinforcement network that can increase tensile strength, reduce permanent deformation, bridge cracks, and improve fatigue resistance. In addition, it can adjust the asphalt mixtures binder by increasing its stability, elasticity, and viscosity. Inclusion of fibers in paving materials serves to reinforce the material by adding additional tensile strength to the material that results from interconnection between aggregates. This interconnection may allow the material to withstand additional strain energy before cracking or fracture occurs. The following re illustrate a case study where the fiber reinforced asphalt mixtures (FRAC) were used in one of Saudi Aramco facility North Jeddah Bulk Plant Expansion project [31].

The following report illustrate a case study where the fiber reinforced asphalt mixtures (FRAC) were used in one of Saudi Aramco facility North Jeddah Bulk Plant Expansion project.

FRAC was piloted in one of Saudi Aramco facility. The pilot execution methodology of fiber reinforced asphalt mixture was as per The Fiber Reinforced Asphalt Concrete (FRAC) Guide Specification for Highway Construction [4]. The pilot consisted of constructing 70 mm thick surface course layer for a truck lane for a Bulk plant facility for an ongoing project in North Jeddah Bulk Plant with a surface area of 180 square meters. A total of 30 tons of fiber asphalt mix design as shown in **Photo 14** and 15 kilograms of synthetic fibers materials as shown in **Photo 15** was used. Fibers used is blend of Polyolefin and aramid fibers and mixed with asphalt concrete during the batching process at a rate of 1-pound (0.5 Kg) fiber per metric ton of asphalt mix batch. Addition of the fibers in the batch plant is shown **Photo 16**. The objective of this pilot is to demonstrate the use of synthetic fiber materials in pavement construction which are derived from petroleum products. As path forward the pilot will be monitored for its performance for a period of one year and compared to conventional asphalt within the project [32].

Photo 14. FRAC 70 mm thick surface course layer.

Photo 15. Used FRAC mix (**Appendix A**).

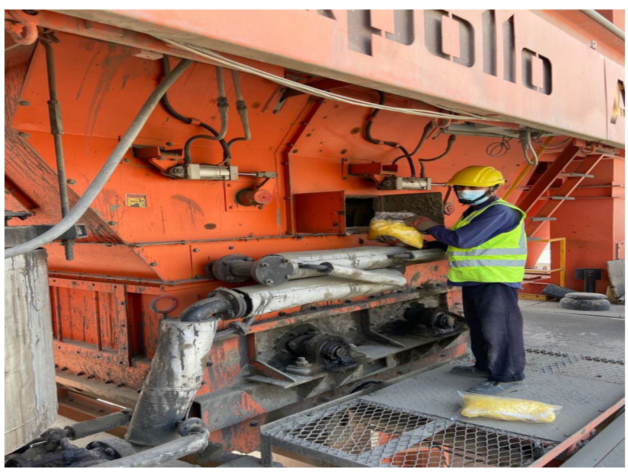

Photo 16. Introducing the synthetic fibers to the mix.

3.8. Bendable Concrete/Engineering Cementitious Composites (ECC) Mix (Photo 17)

Bendable concrete is also known as Engineered Cementitious Composite (ECC) [33] or Strain Hardening Cementitious Composite (SHCC) [34], belonging to the broad class of fiber reinforced concrete (FRC) [35] since it contains fibers in a cementitious matrix. However, under tensile loading, traditional FRCs exhibit a tension-softening behavior after the appearance of a crack that continues to widen as the load bearing capacity decreases. The elastic limit for both normal concrete and FRC is reached at about 0.01%. The low elastic limit reveals that FRC is brittle in tension. Ultra-High-Performance Concrete (UHPC), as a relatively newer class of FRC with optimized gradation of granular constituents, emphasizes high compressive strength and can sustain post-cracking tensile strength. In general, UHPC has tensile strain capacity of 0.2% or less [34].

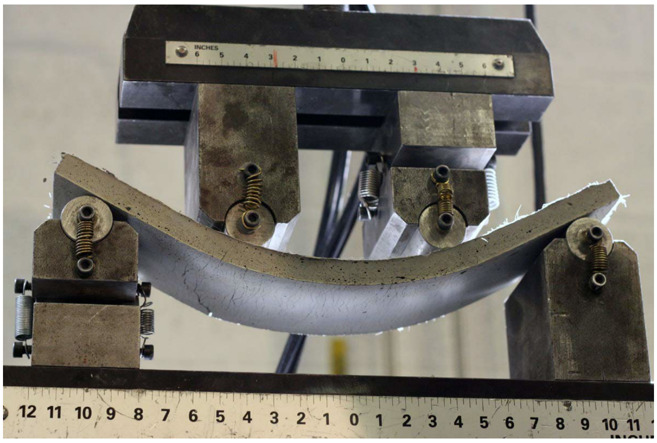

Photo 17. ECC bendable concrete in flexural test machine.

ECC is described using mechanical strengths, deformation characteristics, time-dependent volume changes, and durability. The crack control ability and ductility distinguish ECC from other types of concrete. When a crack is generated, the dispersed fibers within ECC inhibit crack propagation via a bridging mechanism, resulting in crack widths typically between 0.002 - 0.004 inch. With the crack control ability, ECC gains self-healing ability since the fine cracks promote the filling of cracks by secondary hydration reactions of un-hydrated cementitious materials within ECC. The combination of crack control and self-healing abilities makes ECC gain low permeability, which is an important factor for durability. Moreover, the incorporation of synthetic fibers significantly enhances fire resistance. When exposed to elevated temperatures, the fibers melt and create interconnected channels to alleviate the buildup of internal vapor pressure, which is the main driving force for the thermal spalling of concrete.

3.8.1. Since the Invention of ECC, Various Versions of ECC Have Been Developed as Listed Below

High-strength high-ductility ECC: The compressive strength and tensile ductility at 28 days achieved 21.8 ksi and 3% or higher, respectively, making the mechanical strengths of ECC comparable with UHPC.

Lightweight ECC: The density at 28 days was 111 lb/ft3 or lower, while the compressive strength at 28 days was retained at 5.8 ksi, making the material promising for many structural applications that desire lightweight materials [35];

Sprayable ECC: It has been successfully created by integrating micromechanical and rheological designs. This ECC achieved optimal fresh properties through controlled interactions among cement particles and suitable admixtures, while uniaxial tensile testing demonstrates its strain-hardening behavior [36];

Carbon-sequestering ECC: The CO_2-sequestered ECC showed strengths of 4.7 ksi (compressive) and 0.5 ksi (tensile) at 28 days, with a strain capacity of 2.9%. It absorbed 6.1 lb/ft3 CO_2 (4.7% of mixture weight) and exhibited a 42% reduction in cradle-to-gate emission compared with equivalent-strength conventional concrete [37] [38];

3.8.5 3D-printable ECC (3DP-ECC) It has similar microcracking and strain-hardening behavior as other ECC. In uniaxial tension, the 3DP-ECC displayed a 3% strain capacity [39] [40];

Smart ECC This ECC variant offers multifunctionality, including a self-sensing capability for structural health monitoring, self-healing attributes for crack repair in both early and mature specimens, and temperature regulation potential via using phase change additives [41]-[47];

In essence, ECC constitutes a family of sustainable, resilient, durable, and smart materials, adaptable to achieve high mechanical strengths and various properties for diverse applications.

3.8.2. Section of Materials

The primary ingredients of ECC include binders, aggregates, fibers, and chemical admixtures [48]. The synergy of these constituents endows ECC with exceptional performance characteristics. The selection of each type of ingredient is presented in the following subsections.

1) Binders: The binders include cement and SCMs [49] [50]. For cement, Portland cement (Type I/II) is the most popular one to utilize due to the economic benefits and wide availability, but other types of cement, such as white cement [51], quick-setting cement [52] [53], and limestone calcined clay cement [54], also have been used to prepare ECC. Their choice depends on job requirements such as architectural coloring and early pavement reopening to traffic, and on carbon footprint consideration.

2) Typically, ECC mixtures use fine aggregates and do not use coarse aggregates [55]. The use of fine aggregates offers many advantages such as the improvement of fresh properties and the refinement of microstructures via reducing porosity, increasing mechanical strengths and durability. Fine aggregates also help reduce material cost and mitigate shrinkage [56]. The type and size of aggregates significantly affect the mechanical properties of ECC.

3) Chopped fibers are essential ingredients in ECC as they offer the bridging

effect that restrains cracks. The types of fiber include polymeric (synthetic) fibers, glass fibers, carbon fiber, steel fibers, and natural fibers [57] [58]. The chopped fibers play critical roles in the tensile properties, crack resistance, and durability of ECC. Polymeric fibers are most popular due to their offering a range of strength and relatively small diameter at attractive cost.

The popular synthetic fibers used in ECC include polyvinyl alcohol (PVA) [23], polyethylene (PE) [59], and polypropylene (PP) fibers [60]. Among them, PVA fibers are mostly used due to their advantages such as economic benefits and high tensile strength. PVA fibers can be oiled to turn the hydrophilic surface into hydrophobic surfaces which reduce the chemical bond between fiber and matrix, improving the ductility and toughness of ECC. The tensile strength and ultimate strain of ECC with PVA fibers are often about 580 - 870 psi and 3% - 6%, respectively. The crack width is often finer than 0.004 in.

PE fibers are used primarily aiming at achieving higher tensile strength of ECC due to the higher tensile strength of PE fibers. When PE fibers are used along with a high-strength matrix, the tensile strength and ultimate strain of ECC with PE fibers can achieve 1160 - 2900 psi and 5% - 12%, respectively [61]. A drawback of PE fibers is the lower performance in controlling crack width, compared with PVA fibers. The crack width can be 0.004 in or wider [62].

The use of ECC has been steadily increasing worldwide. The experiences gained from current ECC applications are incredibly valuable since they offer valuable insights into the appropriate use and adoption of ECC. The decision to use ECC over normal concrete is often driven by the desire for improved structural resilience and durability [63], along with the need for overcoming existing construction challenges.

Potential applications for ECC include bridge decks, bridge girders, retaining walls and beam and columns in building dams, water channels, tunnels and basements.

3.9. Sustainability of Polymers

Polymer sustainability is about meeting the needs of the present without compromising on the needs of future generations, as per Brundtland report [64]. In the past, good structural design used materials and resources efficiently with focus on performance and economy. The sustainable design approach is based on material that considers environmental, economic and social factors, energy and resource consumption in addition to performance criteria.

The evaluation of sustainability of materials involves life cycle assessment from cradle to grave including raw material procurement, fabrication and processing, construction, maintenance, recycling and disposal. An ideal sustainable material would have a closed life cycle loop that utilizes renewable resources, energy and zero waste with low impact on environment, people and society [65].

Due to lightweight and ease in transportation, polymer materials are generally less energy-intensive to produce. They also have minimal ecological and carbon footprint compared to the traditional materials. FRPs have no corrosion with superior performance in chemically aggressive environments. FRP composites resist creep and fatigue loads better than other materials. This leads to low maintenance for structures that use FRP materials, the expected durability of structures is enhanced by using FRPs. Sustainability of FRPs can be better understood by evaluating various stages of their lifespan and their impact on environment including the economics and impact on the facility. In this way, better insights can be gained into the life cycle assessment of FRPs.

A study led by Mackenzie, has shown that plastic solutions provided lower Green House Gas (GHG) emissions in 13 of the 14 applications where plastic was compared with alternative materials. The study was based on a life cycle approach to assess GHG emissions of plastics versus alternative materials in sectors like packaging, consumer goods, automotive, textiles and building & construction. In the building & construction sector, of interest for this paper, the products were: municipal sewer pipe and municipal water pipe. The materials of comparison were PVC and reinforced concrete for gravity pipes, and PVC and ductile iron in force main pipes [66].

4. Discussions

Use of NM in civil infrastructure offers a game changer to improve, reduce the cost of maintenance, increase the service life and offer a sustainable option to adopt in comparison to steel and concrete. The paper discussed various application which demonstrated to replace reinforced concrete to polymer panels, traffic signs and signal steel poles to GFRP poles. NM bridge and other structure of architectural significance produce curved and other shapes which are difficult to produce in traditional steel or concrete construction. Manhole made of GFRP were also presented which address deterioration issues faced by concrete in harsh environmental conditions like in sewers.

Initial cost of polymeric materials can be higher, but they offer corrosion resistance and have a longer service life than traditional building materials. This means that they can be reused instead of being disposed of, avoiding the generation of end-of-life waste. Furthermore, GFRP can be considered a promising material in the energy transition, as it requires reduced energy consumption and CO_2 emissions compared to those required by steel [67] [68].

5. Conclusion

Polymer base materials account for the highest growth area in construction materials. Nonmetallic materials offer tangible benefits in reducing the structure life cycle costs, environmental CO_2 footprint, improving energy efficiency and less maintenance costs while improving aesthetics. The Middle East region has an extraordinary potential to reduce production costs of oil-based polymers and become a key producer of polymers from petrochemicals in the years ahead. Based on this Aramco has developed a sound nonmetallic deployment strategy in

Building and Construction sector. The development of NM in various applications highlighted in this paper like paving, structures, bridges, specialist applications is expected to grow in the coming future.

Acknowledgements

The authors would like to thank Consulting Services Department Management (CSD) for their support in publishing this paper.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] NACE International (2016) International Measures of Prevention, Application, and Economics of Corrosion Technology Study.

[2] Angst, U.M. (2018) Challenges and Opportunities in Corrosion of Steel in Concrete. *Materials and Structures*, **51**, Article No. 4. https://doi.org/10.1617/s11527-017-1131-6

[3] Unknown (2021) "Why the Built Environment?", Architecture 2030.

[4] Sereda, P.J. (1961) "CBD-20. Corrosion in Buildings", National Research Council Canada.

[5] Bender, R.M., *et al.* (2022) Corrosion Challenges towards a Sustainable Society. *Materials and Corrosion*, **73**, 1730-1751.

[6] Unknown (2022) 3 Areas Sustainable Construction Can Help Build Greener Future. World Economic Forum. https://weforum.org

[7] Bhattacharjee James, M. (2019) Polymers in Civil Engineering: Review of Alternative Materials for Superior Performance. *Journal of Applied Science and Computations*, **6**, 1770-1773.

[8] Correia, J.R. (2014) Fibre-Reinforced Polymer (FRP) Composites. In: Goncalves, M.C. and Margarido, F., Eds., *Materials for Construction and Civil Engineering*, Springer International Publishing, 501-556. https://doi.org/10.1007/978-3-319-08236-3_11

[9] Bank, L.C. (2006) Composites for Construction: Structural Design with FRP Materials. Wiley. https://doi.org/10.1002/9780470121429

[10] Masuelli, M.A. (2013) Introduction of Fibre-Reinforced Polymers-Polymers and Composites: Concepts, Properties and Processes. In: Masuelli, M.A., Ed., *Fiber Reinforced Polymers the Technology Applied for Concrete Repair*, IntechOpen, 3-38.

[11] Kendall, D. (2007) Building the Future with FRP Composites. *Reinforced Plastics*, **51**, 26-33. https://doi.org/10.1016/s0034-3617(08)70131-0

[12] Enduro Composites (2021) FRP versus Traditional Materials. https://www.enduro-composites.com/about-enduro/news/frp-vs-traditional-materials

[13] Qureshi, J. (2022) A Review of Fibre Reinforced Polymer Structures. *Fibers*, **10**, Article No. 27. https://doi.org/10.3390/fib10030027

[14] Dean, J. (2021) Corrosion Prevention & Control (CPC) Design & Construction Issues. Whole Building Design Guide.

[15] Ottawa-Based Company (2019) Understanding the Process of Corrosion in Reinforced Concrete. https://www.giatecscientific.com/author/giatec/

[16] Namita (2018) Effects of Corrosion in Reinforcement.

[17] Unknown (2017) Corrosion Eating away at Traffic Light Poles. WPXI News.

[18] Apostolopoulos, C. and Koulouris, K. (2021) Corrosion Effects on Durability of RC Structures. *Metals*, **11**, Article No. 1812. https://doi.org/10.3390/met11111812

[19] Raghothamarao, V. (2021) Why Non-Metallics Can Be a Game Changer for Oil and Gas. https://Consultancy-me.com

[20] Unknown (2023) PlasticRoad Becomes CirculinQ. Plastic Road, PlasticRoad: Circular, Climate-Adaptive, and Lightweight.

[21] Al Mehthel, *et al.* (2022) Polymer Panels for Walkways and Paving. 11,306.443 B2.

[22] Khatri, W.A., Mehthel, M.A., Baig, M.M. and Baker, T.A. (2022) GFRP Poles for Traffic Signs and Signal Poles: A Case Study in Saudi Arabia. *Open Journal of Civil Engineering*, **12**, 476-491. https://doi.org/10.4236/ojce.2022.124027

[23] Pyrzowski, Ł. and Miskiewicz, M. (2017) Modern GFRP Composite Footbridges. *Proceedings of* 10*th International Conference* "*Environmental Engineering*", Vilnius, 27-28 April 2017, 1-8. https://doi.org/10.3846/enviro.2017.143

[24] Wei, S., Jiang, Z., Liu, H., Zhou, D. and Sanchez-Silva, M. (2013) Microbiologically Induced Deterioration of Concrete: A Review. *Brazilian Journal of Microbiology*, **44**, 1001-1007. https://doi.org/10.1590/s1517-83822014005000006

[25] Phanikumar, B.R. and Ramanjaneya Raju, E. (2020) Compaction and Strength Characteristics of an Expansive Clay Stabilised with Lime Sludge and Cement. *Soils and Foundations*, **60**, 129-138. https://doi.org/10.1016/j.sandf.2020.01.007

[26] Hu, W., Nie, Q., Huang, B., Su, A., Du, Y., Shu, X., *et al.* (2018) Mechanical Property and Microstructure Characteristics of Geopolymer Stabilized Aggregate Base. *Construction and Building Materials*, **191**, 1120-1127. https://doi.org/10.1016/j.conbuildmat.2018.10.081

[27] Adhikari, B. (2017) Mechanical and Durability Characteristics of Fly Ash Based Soil-Geopolymer Mixtures for Road Base and Subbase Layers. University of Louisiana.

[28] Kaloush, K., Zeiada, W., Biligiri, K., Rodezno, M. and Reed, J. (2010) Evaluation of Fiber-Reinforced Asphalt Mixtures Using Advanced Material Characterization Tests. *Journal of Testing and Evaluation*, **38**, 400-411.

[29] Gao, H., Zhang, L., Zhang, D., Ji, T. and Song, J. (2021) Mechanical Properties of Fiber-Reinforced Asphalt Concrete: Finite Element Simulation and Experimental Study. *e-Polymers*, **21**, 533-548. https://doi.org/10.1515/epoly-2021-0057

[30] Mahdi Abtahi, S., Sheikhzadeh, M. and Mahdi Hejazi, S. (2010) Fiber-Reinforced Asphalt-Concrete—A Review. *Construction and Building Materials*, **24**, 871-877.

[31] Rahaman, M.S.A., Ismail, A.F. and Mustafa, A. (2007) A Review of Heat Treatment on Polyacrylonitrile Fiber. *Polymer Degradation and Stability*, **92**, 1421-1432. https://doi.org/10.1016/j.polymdegradstab.2007.03.023

[32] Badeli, S., Carter, A., Doré, G. and Saliani, S. (2018) Evaluation of the Durability and the Performance of an Asphalt Mix Involving Aramid Pulp Fiber (APF): Complex Modulus before and after Freeze-Thaw Cycles, Fatigue, and TSRST Tests. *Construction and Building Materials*, **174**, 60-71. https://doi.org/10.1016/j.conbuildmat.2018.04.103

[33] Brundtland, G.H. (1987) Our Common Future-World Commission on Environment and Development. Oxford University Press.

[34] Lee, L.S. and Jain, R. (2009) The Role of FRP Composites in a Sustainable World. *Clean Technologies and Environmental Policy*, **11**, 247-249.

https://doi.org/10.1007/s10098-009-0253-0

[35] Feber, D., Helmcke, S., Hundertmark, T., Musso, C., Ong, W.J., Oxgaard, J. and Wallach, J. (2022) Climate Impact of Plastics. Mackinsey & Company Report.

[36] Kojima, S., Sakata, N., Kanda, T. and Hiraishi, T. (2004) Application of Direct Sprayed ECC for Retrofitting Dam Structure Surface-Application for Mitaka-Dam. *Concrete Journal*, **42**, 135-139.

[37] Guo, P., Meng, W., Du, J., Stevenson, L., Han, B. and Bao, Y. (2023) Lightweight Ultra-High-Performance Concrete (UHPC) with Expanded Glass Aggregate: Development, Characterization, and Life-Cycle Assessment. *Construction and Building Materials*, **371**, Article ID: 130441. https://doi.org/10.1016/j.conbuildmat.2023.130441

[38] Li, V.C. (2003) On Engineered Cementitious Composites (ECC): A Review of the Material and Its Applications. *Journal of Advanced Concrete Technology*, **1**, 215-230. https://doi.org/10.3151/jact.1.215

[39] Li, V.C. and Hashida, T. (1993) Engineering Ductile Fracture in Brittle-Matrix Composites. *Journal of Materials Science Letters*, **12**, 898-901. https://doi.org/10.1007/bf00455611

[40] Bentur, A. and Mindess, S. (2006) Fibre Reinforced Cementitious Composites. CRC Press.

[41] O'Neil, E.F., Neeley, B.D. and Cargile, J.D. (1999) Tensile Properties of Very-High-Strength Concrete for Penetration-Resistant Structures. *Shock and Vibration*, **6**, 237-245. https://doi.org/10.1155/1999/415360

[42] O'Neil III, E.F. (2008) On Engineering the Microstructure of High-Performance Concretes to Improve Strength, Rheology, Toughness, and Frangibility. PhD Dissertation, Northwestern University.

[43] Chanvillard, G. and Rigaud, S. (2003) Complete Characterization of Tensile Properties of Ductal UHPFRC According to the French Recommendations. *Proceedings of the 4th International RILEM workshop High Performance Fiber Reinforced Cementitious Composites* (*HPFRCC4*), Ann Arbor, 16-18 June 2003, No. 33, 21-34.

[44] Li, V.C. (1993) From Micromechanics to Structural Engineering—The Design of Cementitious Composites for Civil Engineering Applications. *JSCE Journal of Structural Mechanics and Earthquake Engineering*, **10**, 37-48.

[45] Li, V.C., Wang, S. and Wu, C. (2001) Tensile Strain-Hardening Behavior of Polyvinyl Alcohol Engineered Cementitious Composite (PVA-ECC). *ACI Materials Journal*, **98**, 483-492.

[46] Xu, M., Yu, J., Zhou, J., Bao, Y. and Li, V.C. (2021) Effect of Curing Relative Humidity on Mechanical Properties of Engineered Cementitious Composites at Multiple Scales. *Construction and Building Materials*, **284**, Article ID: 122834. https://doi.org/10.1016/j.conbuildmat.2021.122834

[47] Alaloul, W.S., Musarat, M.A., A Tayeh, B., Sivalingam, S., Rosli, M.F.B., Haruna, S., *et al*. (2020) Mechanical and Deformation Properties of Rubberized Engineered Cementitious Composite (ECC). *Case Studies in Construction Materials*, **13**, e00385. https://doi.org/10.1016/j.cscm.2020.e00385

[48] Baetens, R., Jelle, B.P. and Gustavsen, A. (2010) Phase Change Materials for Building Applications: A State-of-the-Art Review. *Energy and Buildings*, **42**, 1361-1368. https://doi.org/10.1016/j.enbuild.2010.03.026

[49] Chandrasekhar, C. and R.N., G.D.R. (2023) Engineered Cementitious Composites (ECC) with Manufactured Sand (m-Sand) for Pavement Applications. *Composites Communications*, **41**, Article ID: 101657. https://doi.org/10.1016/j.coco.2023.101657

[50] Choi, J., Park, S., Kim, Y., Yang, K., Kim, Y.Y. and Lee, B.Y. (2022) Highly Ductile Behavior and Sustainability of Engineered Cementitious Composites Reinforced by PE Based Selvage Fibers. *Cement and Concrete Composites*, **134**, Article ID: 104729. https://doi.org/10.1016/j.cemconcomp.2022.104729

[51] Wang, S. and Li, V.C. (2006) High-Early-Strength Engineered Cementitious Composites. *ACI Materials Journal*, **103**, 97-105.

[52] Deng, H. and Li, H. (2018) Assessment of Self-Sensing Capability of Carbon Black Engineered Cementitious Composites. *Construction and Building Materials*, **173**, 1-9. https://doi.org/10.1016/j.conbuildmat.2018.04.031

[53] Cancio Díaz, Y., Sánchez Berriel, S., Heierli, U., Favier, A.R., Sánchez Machado, I.R., Scrivener, K.L., *et al.* (2017) Limestone Calcined Clay Cement as a Low-Carbon Solution to Meet Expanding Cement Demand in Emerging Economies. *Development Engineering*, **2**, 82-91. https://doi.org/10.1016/j.deveng.2017.06.001

[54] Dong, Z., Tan, H., Yu, J. and Liu, F. (2022) A Feasibility Study on Engineered Cementitious Composites Mixed with Coarse Aggregate. *Construction and Building Materials*, **350**, Article ID: 128587. https://doi.org/10.1016/j.conbuildmat.2022.128587

[55] Felekoglu, B., Tosun-Felekoglu, K., Ranade, R., Zhang, Q. and Li, V.C. (2014) Influence of Matrix Flowability, Fiber Mixing Procedure, and Curing Conditions on the Mechanical Performance of HTPP-ECC. *Composites Part B: Engineering*, **60**, 359-370. https://doi.org/10.1016/j.compositesb.2013.12.076

[56] Fu, C., Guo, R., Lin, Z., Xia, H., Yang, Y. and Ma, Q. (2021) Effect of Nanosilica and Silica Fume on the Mechanical Properties and Microstructure of Lightweight Engineered Cementitious Composites. *Construction and Building Materials*, **298**, Article ID: 123788. https://doi.org/10.1016/j.conbuildmat.2021.123788

[57] Gao, S., Wang, Z., Wang, W. and Qiu, H. (2018) Effect of Shrinkage-Reducing Admixture and Expansive Agent on Mechanical Properties and Drying Shrinkage of Engineered Cementitious Composite (ECC). *Construction and Building Materials*, **179**, 172-185. https://doi.org/10.1016/j.conbuildmat.2018.05.203

[58] Han, J., Cai, J., Pan, J. and Sun, Y. (2021) Study on the Conductivity of Carbon Fiber Self-Sensing High Ductility Cementitious Composite. *Journal of Building Engineering*, **43**, Article ID: 103125. https://doi.org/10.1016/j.jobe.2021.103125

[59] Hajj, E.Y., Sanders, D.H. and Weitzel, N.D. (2016) Development of Specifications for Engineered Cementitious Composites for Use in Bridge Deck Overlays.

[60] Halvaei, M., Jamshidi, M., Latifi, M. and Ejtemaei, M. (2020) Effects of Volume Fraction and Length of Carbon Short Fibers on Flexural Properties of Carbon Textile Reinforced Engineered Cementitious Composites (ECCs); an Experimental and Computational Study. *Construction and Building Materials*, **245**, Article ID: 118394. https://doi.org/10.1016/j.conbuildmat.2020.118394

[61] Aslani, F. and Wang, L. (2019) Fabrication and Characterization of an Engineered Cementitious Composite with Enhanced Fire Resistance Performance. *Journal of Cleaner Production*, **221**, 202-214. https://doi.org/10.1016/j.jclepro.2019.02.241

[62] Hou, M., Zhang, D. and Li, V.C. (2022) Crack Width Control and Mechanical Properties of Low Carbon Engineered Cementitious Composites (ECC). *Construction and Building Materials*, **348**, Article ID: 128692. https://doi.org/10.1016/j.conbuildmat.2022.128692

[63] Ali, M.A.E.M. and Nehdi, M.L. (2017) Innovative Crack-Healing Hybrid Fiber Reinforced Engineered Cementitious Composite. *Construction and Building Materials*, **150**, 689-702. https://doi.org/10.1016/j.conbuildmat.2017.06.023

[64] Brundtland, G. (1987) Report of the World Commission on Environment and Development: Our Common Future. United Nations General Assembly Document A/42/427.

[65] Schneiderman, D.K. and Hillmyer, M.A. (2017) 50th Anniversary Perspective: There Is a Great Future in Sustainable Polymers. *Macromolecules*, **50**, 3733-3749. https://doi.org/10.1021/acs.macromol.7b00293

[66] Climate Impact of Plastics, McKinsey, May 10, 2022, Version.

[67] Ascione, F., Maselli, G. and Nesticò, A. (2024) 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. *Journal of Cleaner Production*, **475**, Article ID: 143641. https://doi.org/10.1016/j.jclepro.2024.143641

[68] Sbahieh, S., Tahir, F. and Al-Ghamdi, S.G. (2022) Environmental and Mechanical Performance of Different Fiber Reinforced Polymers in Beams. *Materials Today*: *Proceedings*, **62**, 3548-3552. https://doi.org/10.1016/j.matpr.2022.04.398