Review Article

Sani Haruna, Musa Adamu*, Yasser E. Ibrahim, Sadi I. Haruna, Hany M. Seif ElDin, Mukhtar Fatihu Hamza, and Marc Azab

Multifunctional engineered cementitious composites modified with nanomaterials and their applications: An overview

https://doi.org/10.1515/rams-2022-0309
received December 01, 2022; accepted April 01, 2023

Abstract: Due to their advantages such as high tensile strength, low cost of production, easy manufacturing methods, and ease of use, cementitious materials are extensively utilized in the construction industry. The applications of nanomaterials in cementitious materials have been found to enhance their properties. It allows molecular changes to improve the material behaviour and the performance of civil infrastructure structures, including buildings and highways. Owing to the high ductility of polyvinyl alcohol-engineered cementitious composites (ECCs), it was suggested to be used in steel-reinforced structural elements to enhance the strength and ductility of the components. The presence of hybrid fibres provided increased shattering resistance with decreased scabbing, spalling, destruction, and damage zone and better absorption of energy through distributed microcracking. The presence of nanomaterials in ECCs modifies its atomic macroscopic scales, enhancing its mechanical and microstructural properties. The versatile properties of nanomaterials offer immense potential to cementitious composite for structural applications.

Keywords: multifunctional, cementitious composite, nanomaterials

*** Corresponding author: Musa Adamu,** Engineering Management Department, College of Engineering, Prince Sultan University, 11586, Riyadh, Saudi Arabia, e-mail: madamu@psu.edu.sa
Sani Haruna, Sadi I. Haruna: Department of Civil Engineering, Faculty of Engineering, Bayero University Kano, Kano, Nigeria
Yasser E. Ibrahim: Engineering Management Department, College of Engineering, Prince Sultan University, 11586, Riyadh, Saudi Arabia
Hany M. Seif ElDin, Marc Azab: College of Engineering and Technology, American University of the Middle East, Egaila 54200, Kuwait
Mukhtar Fatihu Hamza: Department of Mechanical Engineering, College of Engineering, Prince Sattam Bin Abdulaziz University, Alkharj 16273, Saudi Arabia

1 Introduction

Cementitious composites are brittle materials with low tensile strength, poor deformation capability, and significant cracking capability. The occurrence of cracks tends to compromise the structures' integrity, load-bearing capability, safety, serviceability, and durability, thus, causing construction safety issues [1]. To address these concerns, fibres are added to cementitious materials to create engineered cementitious composites (ECCs). ECC is an ultra-high strength and high ductile concrete material with excellent mechanical and physical properties.

The ECC is regarded as a self-compacting composite, which can be compacted by its weight into any corner of the formwork due to its high workability [2,3]. The ECC was developed to enhance the concrete tensile strength by incorporating fibres [4]. Micro-mechanics aims to improve the ECC by keeping the fibre volume content low while achieving high tensile ductility and compressed microcrack width [5]. Studies showed that due to the high performance and longer fatigue life of the ECC, which is higher than those of the ordinary concrete, ECC is a good alternative to ordinary concrete in several engineering structures vulnerable to fatigue loading [6].

Due to the non-inclusion of coarse aggregates in ECCs, their modulus of elasticity is poor, hampering their structure use. Because of their low elasticity modulus values relative to their compressive strength, they are not ideal for standalone use in structures such as bridge piers, columns in tall buildings, *etc.* [7]. Basically, a repair material with high brittleness appears to create a repaired product with low longevity. ECCs show a high propensity for use as appropriate repair/retrofitting materials with high tensile ductility, micro crack, and multiple cracking activities. In addition, reasonable compatibility between the repair materials and the concrete substrate has been found to be important for the performance of the repaired products. When cracked and exposed to an aggressive environment, the repair systems appear to lose their durability.

In the last decade, numerous studies have been conducted on high-performance, multifunctional cementitious nanocomposite materials utilizing various types of nanoparticles [3]. Bahari *et al.* [8] carried out experimental program for the production of powder nanoscale silicon carbide (SiC) crystallite in cement mortar. The authors investigated the stress–strain of the mortar using atomic force microscopy, X-ray diffraction, X- powder, and Williamson Hall and Nanosurf techniques. The observed results indicate that the sample containing 10% SiC nanoparticles has a more stable structure. Ramezani *et al.* [9] investigated the influence of multi-walled carbon nanotubes (MWCNTs) on the workability of self-consolidating concrete pastes and mortars. The results indicated that the rheological properties of the cement paste were significantly modified due to the addition of MWCNTs. Sadeghi-Nik *et al.* [10] studied the effect of lanthanum oxide on the cement paste and concrete structures. The result revealed a good structure of the cementitious material due to the addition of lanthanum oxide, as demonstrated by scanning electron microscopy analysis result. Similarly, the properties of the cement paste were modified due to the incorporation of silicon carbide (SiC). The cement was synthesized through chemical wet techniques [11].

Discrete steel fibre was introduced into the cementitious composite to overcome the problem of the high brittleness property of the cementitious repair material [12]. Steel fibre enhances the fibre-reinforced concrete's ductility, energy absorption, resilience, and flexural capacity. However, when the amount of steel fibre is increased, there is a tendency for balling effect during mixing. In addition, it is difficult to achieve strain-hardening behaviour with steel fibre in the hardened state. The addition of steel fibre in cementitious composites tends to produce materials with high-performance properties, particularly for repair and maintenance applications. ECC reveals numerous cracks with a crack opening of less than 100 µm and uses polymer fibres with a 2% volume fraction [13]. It exhibits approximately 5% high tensile strain potential (300–500 times that of conventional concrete) [14,15].

2 Supplementary materials in cementitious composites

The omission of the coarse aggregate has led to a higher cement content in the composite matrix, resulting in high CO_2 emissions and economic disruption due to high cement costs. Due to its pozzolanic properties, fly ash is regarded as a good constituent for long-term performance production in concrete. The use of fly ash in ECCs is essential due to its low CO_2 emissions. Therefore, class F fly ash is commonly used in ECC production, as it is beneficial compared to Class C fly ash. The unreacted particles of fly ash act as inert aggregates in the ECC matrix; thus, the fly ash could be used as a strength adjuster in achieving high-strain hardening [16]. According to Yang *et al.* [17], long-term tensile ductility of about 2–3% can be maintained by adding high amounts of recycled fly ash. With an increase in the amount of fly ash, both the crack width and the free drying shrinkage are substantially decreased, which can help the long-term longevity of high-volume fly ash in ECC structures. They have further revealed that the micromechanics investigation suggests that the increased frictional bond of the fibre/matrix interface in HVFA ECCs contributed to the tight crack width. Conversely, the application of industrial waste stream material to replace cement by generating more saturated multiple cracking while minimizing environmental influences, HVFA ECCs showed a significant improvement. Although the use of fly ash in ECC decreases the strength of the interfacial chemical bonding between the matrix phase and fibres, its presence in the cementitious component helps achieve uniform fibres at the fresh state. Termkhajornkit *et al.* [18] reported that the self-healing ability of ECC can be improved with a high fly ash content. Similarly, according to Zhang *et al.* [19], high fly ash content in ECC tends to increase the material's deformation characteristics while decreasing its compressive strength. The crack does, however, get thinner and narrower, which is helpful for ECC to achieve saturation cracking behaviour. They further revealed that the high fly ash content resulted in a more porous ECC matrix, increasing its sorptivity. However, these studies have not disclosed the mitigation of the decrease in the strength of ECC due to the use of fly ash in the composite matrix.

Although there is limited literature on the application of slag in ECC, Özbay *et al.* [20] examined the efficacy of freezing–thawing and sulphate attack on high-volume slag in ECCs. They reported that adding slag to ECCs increased its ductility, hardened the air content, water absorption, porosity, and sorptivity, which slightly decreased its compressive and flexural strengths. Regardless of the slag amount and the applied freezing–thawing cycle, the ductility of ECC specimens drastically decreased. Furthermore, they found improved resistance to sulphate and chloride ion penetration by adding the slag. According to Zhou *et al.* [21], the slag particles provide a driving force for fibre dispersion.

2.1 Role of fibres in ECCs

The presence of fibres in cementitious composites restricts crack development and enhances the mechanical properties of the composite. The properties of the fibres, including the fibre type, aspect ratio, elastic modulus, tensile strength, surface properties, and fibre content, determine the performance of cementitious materials [22–24]. Fibres such as steel, polyvinyl alcohol (PVA), polypropylene (PP), and polyethylene (PE) fibres are the widely used fibres in the ECC production. In contrast, natural fibres such as banana, bagasse, coir, jute, and sisal fibre are also utilized to strengthen concretes [25]. According to Yang and Li [26], the ECC reinforced with PVA fibres demonstrates higher flexural strength and toughness and is cheaper than the PP-based ECC. For example, a normal PVA-ECC containing a 2% fibre volume fraction can improve a tensile strain strength of up to 4% and an ultimate strength of 4.5 MPa can be obtained [26]. Parameswaran [27] reported a significant decrease in the mechanical properties of PVA-ECC under autoclaving conditions. Because fibres cannot replace conventional steel reinforcement, they are used in the structural concrete to improve cracking resistance and bending resistance. As a result of high ductility in PVA-ECC, it was suggested to be utilized in steel-reinforced structural elements to increase the strength and ductility of the components [28]. Figure 1 presents the classification of different fibres according to their characteristics. Owing to the fact that PVA fibres are less stable than the cementitious matrix, it induces slip hardening in the composite. Slip hardening can be helpful if the fibre's tensile strength is not surpassed before slipping [29]. PVA fibres of 8–12 mm in length and 39 μm in diameter are commonly used in ECCs [26]. The ECC made with PVA fibres requires adequate mixing to spread the cement particles evenly throughout the fibres.

The application of organic fibres rather than synthetic fibres, which are agricultural by-products, is another creative technique to improve the sustainability of fibre-reinforced composites. These fibres are also less expensive, environmentally friendly, and affordable than synthetic ones. Organic fibres are fragile and easily break down, especially in alkaline media [25,31]. On the other hand, organic fibres have been shown to increase the long-term mechanical properties of cementitious materials through concise alteration. Bagasse fibres, a by-product of the sugarcane industry, were used to strengthen cementitious materials. Studies have indicated that bagasse fibres could modify the setting properties and enhance the essential concrete mechanical strength [32].

Steel fibres are produced either in cold or hot conditions. Steel's malleability allows it to be utilized for a wide range of steel fibres, including but not limited to crimped, hooked, button-ended, indented, and twisted fibres. The use of different shapes of steel fibres improves the mechanical behaviour of steel-reinforced concrete by providing the matrix with a mechanical joint. Won *et al.* [33] studied the bonding behaviour of the micro steel fibre ECC. Even though the hooked-type steel fibre reveals better interface strength and bond strength, they discovered that the amorphous micro-steel fibre had a tensile

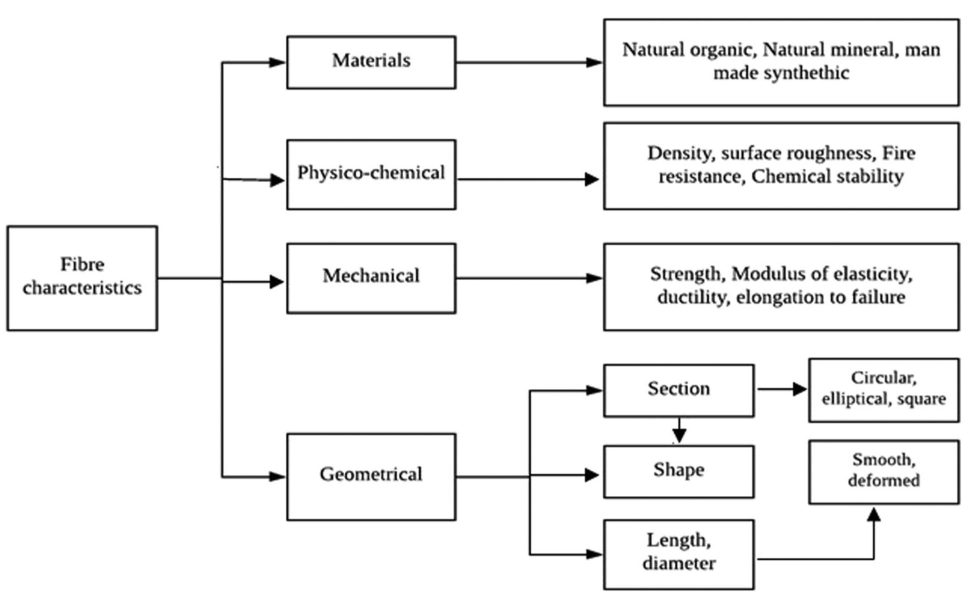

Figure 1: Flow chart of fibre characterization [30].

strength that was almost 30% greater than the hooked-type steel fibre. The use of steel fibres in high-strength cementitious components has been able to reduce the distribution of macro cracks [34]. A related study by Redon *et al.* [29] indicated that the inclusion of steel fibres was shown to improve the post-peak behaviour of UHPFRC, but had little effect on the strength and elastic modulus. Steel tyre wire fibres have been more influential in regulating growth.

2.2 Role of hybrid fibres in cementitious composites

Green cementitious composites are developed to produce user-friendly and sustainable construction materials. The concept behind hybrid fibres is that they could produce synergistic effects and perform well in cementitious composites [35]. Low- and high-modulus fibre hybridization in cementitious composites contributed to better strain capacity. Moreover, the ECC made of steel and PVA fibres of varying sizes contributed to the reduction of micro- and macro-cracks while also boosting dynamic resistance [35]. Soe *et al.* [36] studied the effect of the hybrid steel–PVA fibre in ECCs. They reported that the hybrid steel–PVA ECC panel outperformed in impact resistance, fibre bridging performance, and durability. According to Ali and Nehdi [37], the hybrid fibre consisting of PVA and shape memory alloy in ECCs enhanced the flexural strength by 97% and the tensile strength by 59%, while the workability decreased by up to 43% with the increase in SMA fibres. In another research, Tian *et al.* [25] used hybrid bagasse and steel fibres to produce ECCs. They have reported its decreased deformation properties, which is attributed to the high porosity of the fibres in the matrix. However, hybrid fibres comprising steel and PP fibres demonstrated exceptional seismic behaviour in terms of enhanced energy dissipation, stiffness, and load capacity [38]. Muhammad *et al.* [12] have investigated the influence of hybrid fibres in ECCs using response surface methodology. Their investigations revealed that the hybrid fraction of fibres had an unfavourable effect on flow ability and had a beneficial influence on the flexural strength and tensile strength. They have further reported an optimum proportion of the hybrid fibres with 0.5% tyre wire and 1.5% of PVA fibre.

Khan and Cao [39] have investigated the hybridization of four different fibre lengths in cement materials and achieved enhanced mechanical performance compared to simple and single-length fibre-reinforced mortar. The hybrid fibre coefficient also displayed remarkable stability concerning mechanical properties. In another investigation by Ali *et al.* [40], the incorporation of PVA and SMA fibres into the ECC matrix has been reported to have modified the failure mode of the ECC mixture under impact loads from brittle to ductile. Moreover, Maalej *et al.* [41] have concluded that the ECC's tensile strength dynamic increase factor is considerably higher than that for concretes, likely due to the microcracking mechanism distributed and the bridging effects of tough PE fibres. The presence of hybrid fibre increased the shattering resistance with decreased scabbing, spalling, fragmentation, and damage zone, and better absorption of energy through distributed microcracking. Hybrid steel fibre-reinforced ECC specimens show remarkable workability than those with short fibre types, which can be due to the resistance of long fibres to short fibre rotation and decreased resistance to fluid flow [42]. Ozkan and Demir [43] used three combinations of hybrid fibres at varying proportions of PVA/basalt fibre (75/25, 50/50, and 25/75) in producing ECC at a total fibre content of 2%. They have obtained an optimum hybrid fibre proportion of 75% PVA and 25% basalt fibre. This proportion produced the best result concerning the mechanical performance of the ECC. Fibre's hybridization will greatly reduce the environmental impact and produce user-friendly building materials with excellent properties. In addition, the cost of production of ECCs can be minimized by using low-cost hybrid fibres like basalt fibre in the ECC that can be used in the building industry.

3 Effect of nanomaterials in cementitious composites

Cementitious composites have become the recommended construction material for various rehabilitation and construction applications due to their strength, durability, and sustainability. The permeability of the composites, nevertheless, provides a pathway for the seepage of moisture along with harmful ions, which may pose potential challenges to its longevity. One of the most efficient methods to enhance the properties of these cementitious materials, which has recently gained attention, is using nanomaterials to densify the composite matrix. It is very interesting to consider how various nanomaterials influence the performance of cementitious composites. For instance, Ramezani *et al.* [44] investigated the reinforcing effect of CNT types on the expansion, mechanical, and microstructure of cement mortar under an alkali–silica reaction. The CNTs were incorporated into the mortar at 0.1 and 0.3 c wt%. The author prepared eight different compositions of the cement mortar mixture. The results showed that some mix proportion had remarkably mitigated the damage caused by the alkali–silica reaction in the cement mortar. The CNTs refine the pore structure of the mixture, reduce the alkalinity of the pore solution, and prevent crack propagation. Colston *et al.* [45] suggested that the addition of nanomaterials into cement composites contributes to the improvement of their microstructures. Similarly, their dispersion quality, especially CNTs, is essential to achieve better performance, as confirmed in the previous literature [46]. There are various nanomaterials used in cementitious composites. The most used nanomaterials are nano-silica [47–49], MWCNTs [46,50], nano graphene materials like graphene oxide (GO) and graphene nanoplatelets [51–53], and nano titanium oxide [54,55].

3.1 Effect of nano-silica

The incorporation of nano-silica into ECC composites has significantly contributed to its improved performance. Several studies [15,56,57] have shown that owing to the high pozzolanic properties of the nanomaterials, nano-silica has been reported to have improved the quality of the cement paste, resulting in refined hydrated phases (C–S–H) and densified the microstructure of the modified ECC with improved properties. The sluggish pozzolanic reaction of the fly ash causes the production of slow strength in cement/fly ash systems [58]. The integration of nano-silica is more effective and appropriate to resolve this obstacle. Incorporating nanoparticles into fly ash cement systems strengthens the bonding of hydration products that accelerate the pozzolanic reaction and compensate for the early decrease in strength. Nano-silica helps to hydrate the cement by serving as a cement nucleus. This behaviour improves the permeability of the cement due to its densified microstructure and the narrower ITZ [59]. Nano-silica could fill nano voids in cement composites without altering the packing position of cement particles while effectively improving the packing density.

The broad usage of nano-silica has been attributed to its high pozzolanic reaction, ability to enhance cement hydration, and its capacity to bridge the micropores in cementitious composites, thereby providing efficient packing density. Zhang *et al.* [60] reported that the inclusion of as little as 1% NS in high-volume fly ash has increased the hydration and decreased the inactive period. The smaller the nano-size, the higher the early strength growth of the high-volume fly ash concrete. When nano-silica is embedded into fly ash cement systems, both the fly ash and the nano-silica use the CH created during cement hydration to improve the hardened strength. This is due to the high reactivity and the high surface area of the nano-silica [61]. Nevertheless, nano-silica has a greater share because it responds quicker than fly ash, which does not respond until after 7 days as reported by Shaikh *et al.* [62]. This implies that defining the quantity of nano-silica needed in the cementitious systems for a given quantity of fly ash is essential. According to Rong *et al.* [63], incorporating nano-silica particles has modified the hydration mechanism of ultra-high-performance concrete. During acceleration and deceleration cycles, cement hydration was improved by an increase in the nano-silica content. They further revealed that specimens with nano-silica particles had a lower $Ca(OH)_2$ content relative to the control samples. However, the addition of the nano-silica content of about 5% can reduce the mechanical and microstructural characterization of the cementitious materials. As a result of the agglomeration of nano-silica particles, the threshold for nano-silica in the fly ash–cement system becomes critical to avoid the unreacted fly ash in the cement material system that affects the performance of the hardened matrix.

Snehal *et al.* [64] have reported 3% of nano-silica as the optimum amount in nano-silica-blended cementitious composites. The involvement of nano-silica in the cementitious matrix has accelerated the hydration and pozzolanic activity, consequently densifying the nanoscale microstructure. Yeşilmen *et al.* [65] compared the experimental outcomes of ECCs with different nanomaterials after 24 h, as shown in Figure 2. In terms of early age, ECC modified with nana-$CaCO_3$ (ECC-NC) exhibited the most attractive mechanical behaviour. As a result, the nano-$CaCO_3$ activation mechanism seemed to be more active in the first 24 h. However, after 28 days, the mechanical properties of the nano-silica-modified ECC outperformed those of ECC-NC. This behaviour is explained by the high reactivity of the nano-silica related to pozzolanic reactions and has the benefit of a much finer particle structure although the activation mechanisms are different for nano-$CaCO_3$.

3.2 Effects of MWCNTs in cementitious composites

CNTs are carbon allotropes with a hollow cylindrical nanostructure. They typically have a diameter of a few nanometres and a length of a few microns. CNTs are divided into two groups based on the number of concentric tubes

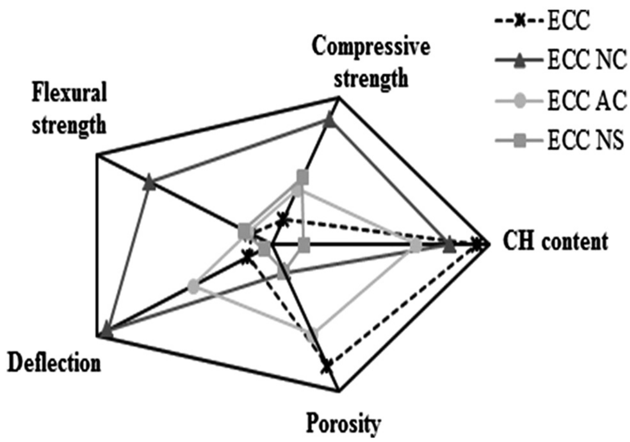

Figure 2: Properties of ECCs after 24 h of casting [65].

they have: single-walled carbon nanotubes (SCNTs) and MWCNTs [66]. The descriptive images of the SCNTs and MWCNTs are presented in Figure 3. CNTs exhibited high strength and elasticity modulus due to their excellent carbon bonds [66]. Different types of surfactants, like Arabic gum, polycarboxylate-based superplasticizer, sodium dodecylbenzene sulphonate, *etc*., are reported to have been used in the dispersion of CNTs in cementitious materials [67]. The surfactant content has a high influence on the CNT dispersion [68]. Moreover, one aspect that must be considered is the type of the surfactant. Luo *et al.* [69] confirmed that anionic sodium dodecyl benzenesulfonate demonstrates the best distribution of MWCNTs. This is due to the strong bond between the surfactant and CNTs caused by the long alkyl chain, tiny headgroup, *etc.* [70]. In contrast, cationic cetyltrimethylammonium bromide (CTAB) revealed the worst dispersion ability. This behaviour is attributed to the positive charge head group of CTAB that might have neutralized the repulsion force between negatively charged MWCNTs in water [52]

Several studies [72–74] on the manufacture and characterization of cementitious materials containing CNT have been performed systematically by experts. CNTs are recognized to be more efficient than other conventional reinforcement materials owing to their enhanced strength and chemical stability [75]. The amount of CNTs/MWCNTs and aspect ratios are variables that influence the enhancement of the properties of the modified CNT/MWCNT cementitious composites. The effect of varying lengths and doses of MWCNTs on the strength of the cement paste at different curing ages has been studied by Konsta-Gdoutos *et al.* [76]. They have reported that the degree of reinforcement of cementitious-based composites increased with the concentration of MWCNTs. In addition, Ramezani [77] evaluated the influence of the CNT length, diameter, and concentration on the porosity of cementitious composites. The porosity in the cement composite would depend on the length and diameter of CNTs incorporated in specimens with a high concentration of CNTs. The cement composites containing short and small-diameter CNTs at high concentrations can refine the pore structure of the cement composite by filling its big pores with a smaller one. However, the cement composite incorporated with a high concentration of CNTs of either long or bigger diameter form CNT agglomerates and yield larger pore sizes, as confirmed by Ramezani *et al.* [46] and Wang *et al.* [78] and is also shown in Figure 4.

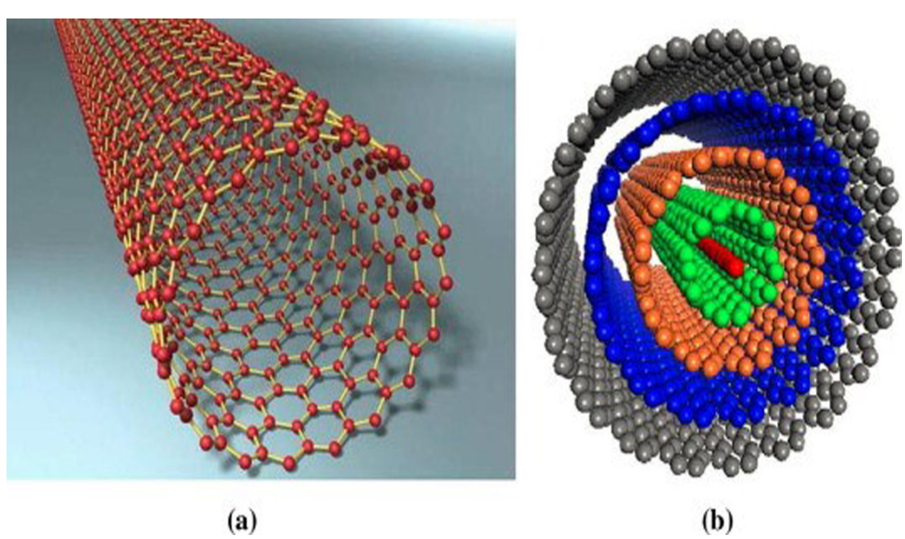

Figure 3: Insightful images of (a) SCNTs and (b) MWCNTs [71].

However, Manzur *et al.* [79] concluded that the smaller the diameters of MWCNTs, the more effective they are for filling nanopore spaces in cementitious composite systems. Luo *et al.* [80] reported that incorporating MWCNTs significantly improves the flexural strength and the stress-intensity factor of the nanocomposites with dispersed MWCNTs, with the overall magnification amplitude being between 45 and 80% with respect to the control specimens. The optimum amount of CNT contents to boost the strength properties of cement composites was in the range from 0.01 to 0.15% by weight of the cement [81]. They have recommended additional research on the durability and functional stability of the composites based on their understanding of cement chemistry. Wang *et al.* [78] found that the median volume pore diameter reduced by 26% while the total porosity increased by 1.5% compared to the control cement paste when incorporating 0.15 c wt% of short CNTs.

The microstructural properties of CNT-modified cementitious composites were studied by Parveen *et al.* [67], as depicted in Figure 5. The authors reported that the appearance of CNTs along the crack surface (Figure 5b and c) was detected, suggesting their homogeneous distribution inside the cement paste matrix. As shown in Figure 5(d), the CNT was also witnessed to have been injected densely in the cement hydration products (C–S–H phases), which was attributed to the fact that CNTs served as a nucleating means for the C–S–H gel and later formed a coating along the CNT bundles. The presence of CNTs has improved the hardened properties of cementitious materials due to their pore-filling ability and enhanced chemical reaction.

3.3 Effects of nano-GO in cementitious composites

Since its discovery in 2004 [82], GO has received huge interest and has reopened an exciting new area for nanotechnology applications in cement-based materials. Graphene is considered the perfect nanofiller for modifying cementitious-based materials; however, it is hard to synthesize and very costly [83]. Multilayer graphene nanoplatelets (MGNPs) are commonly used in practical applications, as GNP can be produced conveniently from graphite or GO. GO has recently become a common nanofiller for cement-based materials. MGNPs and GO are both derived from graphene even though they have their own pros and cons. Hydrophilic functional groups unintentionally reduce GO's ability to disperse composites better than MGNPs [84].

According to Zheng *et al.* [83], nano-graphene (NGO) can modify and strengthen cementitious composites from atomic to macroscopic scales, giving them excellent mechanical properties, resilience, and multi-functionality. As shown in Figure 6, the compressive strength of GO-based cementitious materials increases with the increasing dose of GO, which implies a remarkable performance in strength. Figure 6(b) also indicates that GO can help to improve the flexural

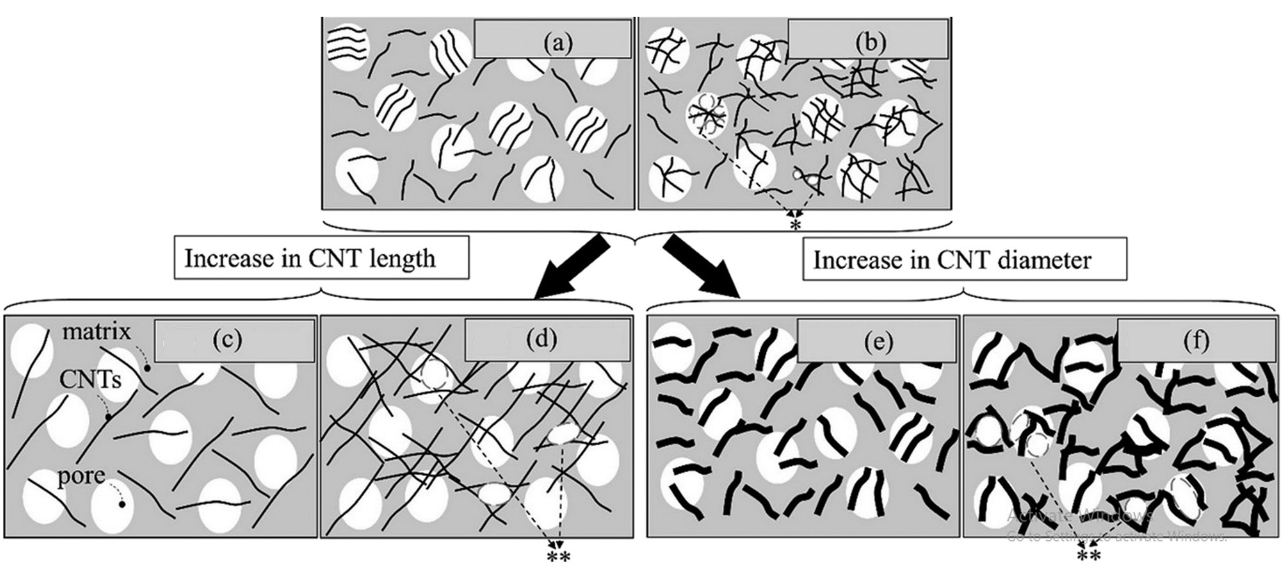

Figure 4: Schematic illustration of the effect of reinforcing cementitious composites with different CNT concentrations, lengths, and diameters on the pore size distribution. (a) L-SL/SD; (b) H-SL/SD; (c) L-LL/SD; (d) H-LL/SD; (e) L-SL/LD; (f) H-SL/LD. *H, high concentration; S, short; L, length and D, diameter [46].

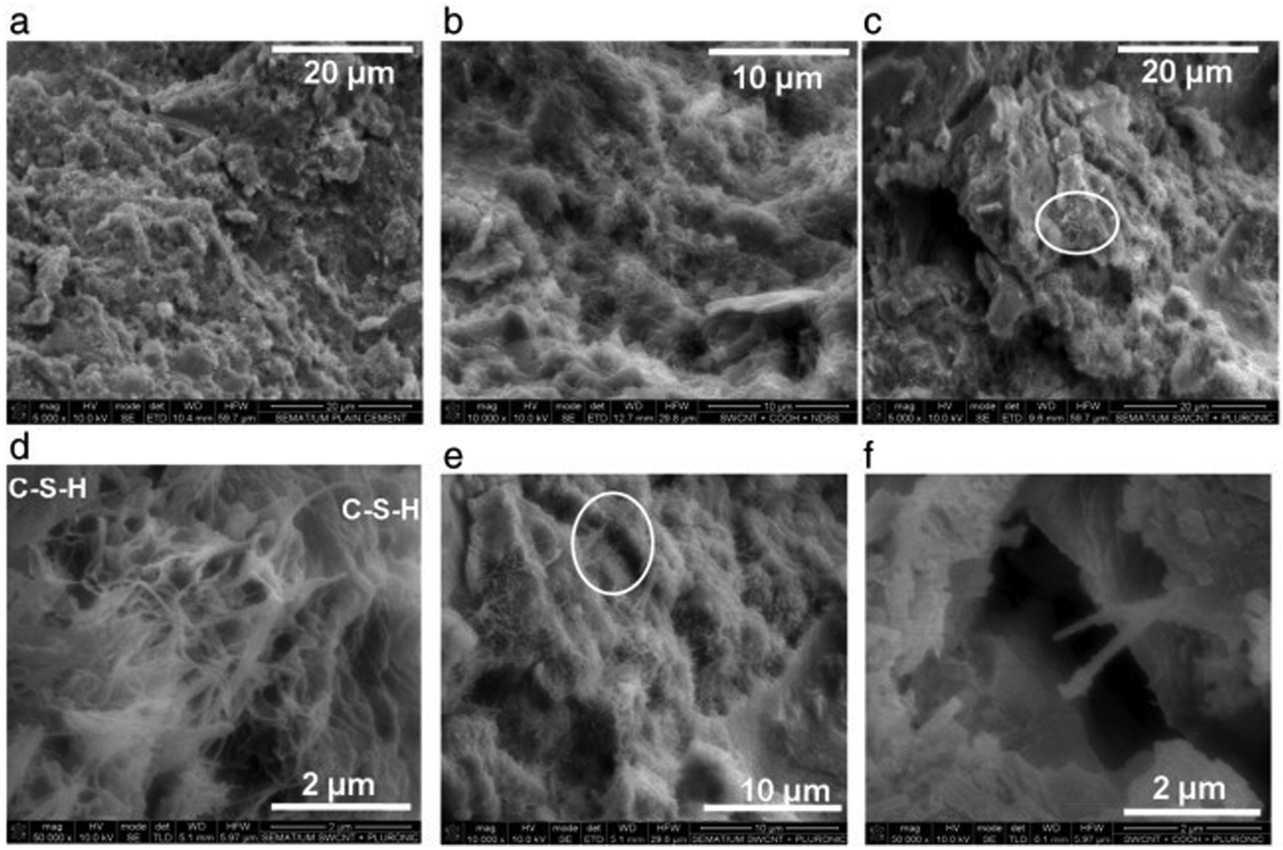

Figure 5: SEM micrographs: (a) control specimen and (b–f) CNT/mortar samples at different magnifications [67].

strength of the modified ECCs when blended with other nano-carbon materials such as CNTs, and that the enhancement effect is better than the control mixture. However, a higher GO dosage will decrease the mechanical properties of the cementitious composites [83,85]. Due to enhanced hydration, nano-filling, and crack-bridging effects, the addition of 0.16 wt% GO to the cement paste will increase the flexural strength by 11.62%. As a result of poor dispersibility in

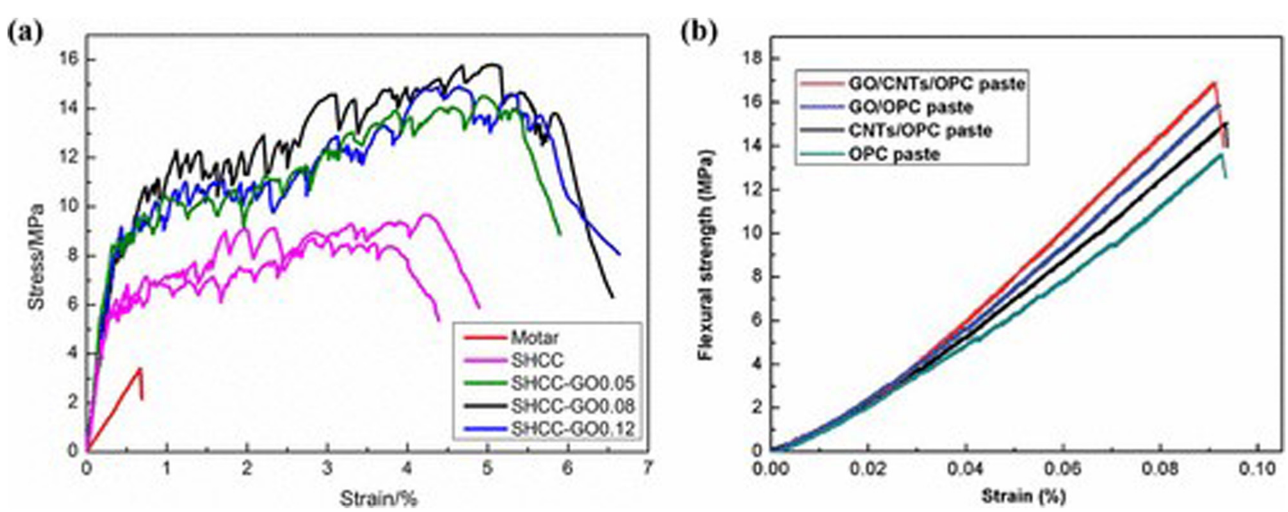

Figure 6: (a) Stress–strain curve of GO-modified ECCs at different dosages of GO and (b) flexural-strain curve of CNT/GO-filled cementitious composites [83].

alkaline settings, graphene, on the other hand, restricts the hydration and mechanical performance of the cement paste [86]. Moreover, Hou *et al.* [87] reported that 0.16 wt% of GNP reduces the compressive strength and flexural strength of the cement paste by 3.36 and 10.59%, respectively, compared with the reference specimen. Similar results were obtained in other studies [88,89]. The main cause of the decreasing effect is due to the agglomeration of nanoparticles [90]. The hydration products, like Ca $(OH)_2$, appear to expand all over the graphene sheets due to the nucleation effect, as illustrated in Figure 7. However, the involvement of graphene layers also reduces product space exploration, making the products narrower and thereby densifying the modified ECCs.

3.4 Applications

The applications of the cementitious composite are found to be beneficial for various infrastructures such as tunnels, highways, and other building utilities. Notably, in designing these types of buildings, the use of ECCs has increased. Nanomaterials have been discovered to offer useful enhancement in the cementitious matrix mechanical properties of the cement matrix and newly developed properties, such as temperature autosensing and self-cleaning capabilities. However, it is a fact that experimental work at the microscopic scale is expensive, and cement and construction firms typically work with small budgets. Nanomaterials also help in reducing the

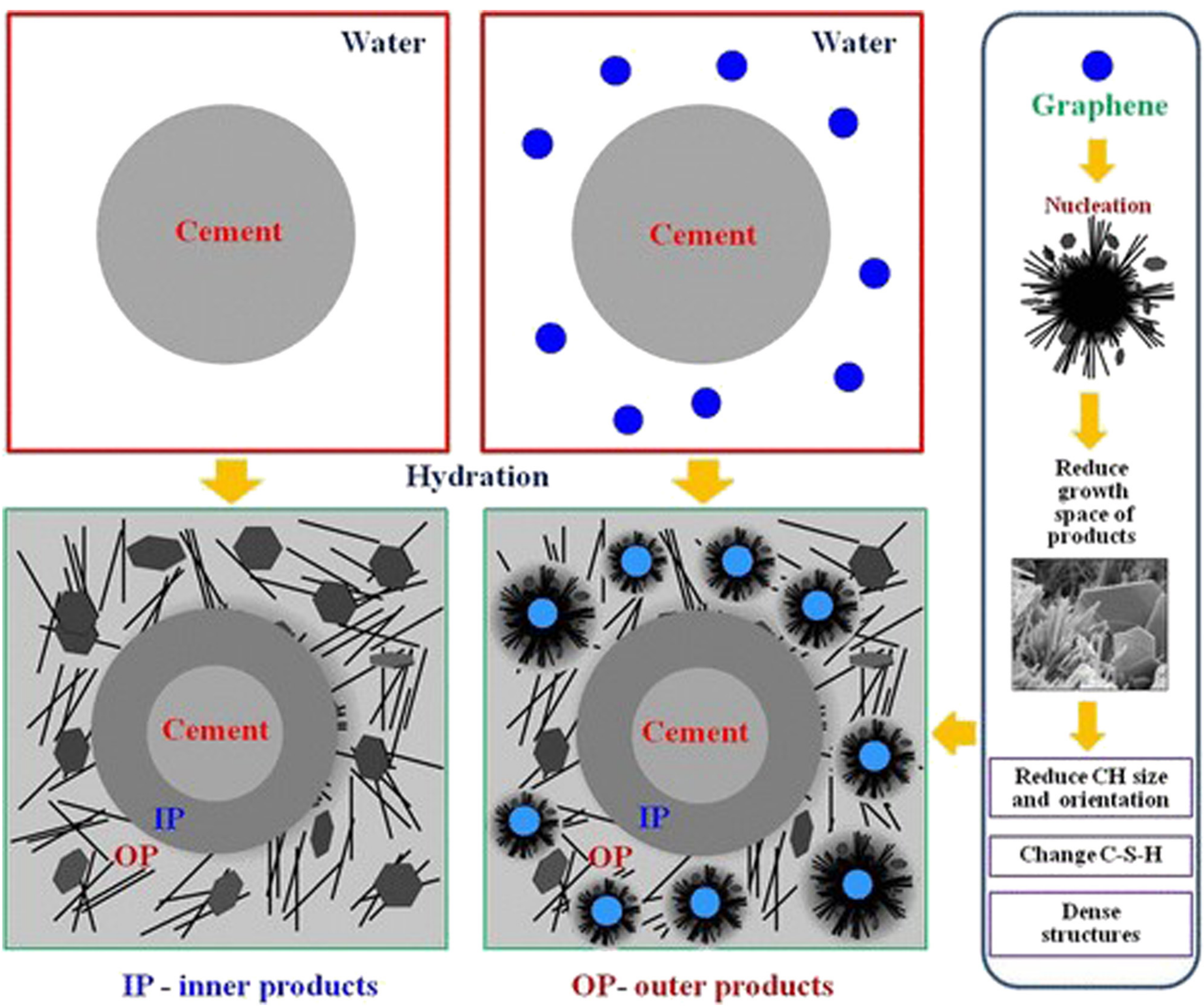

Figure 7: The influence of graphene on the initiation of cement hydration all over the cement grains [83].

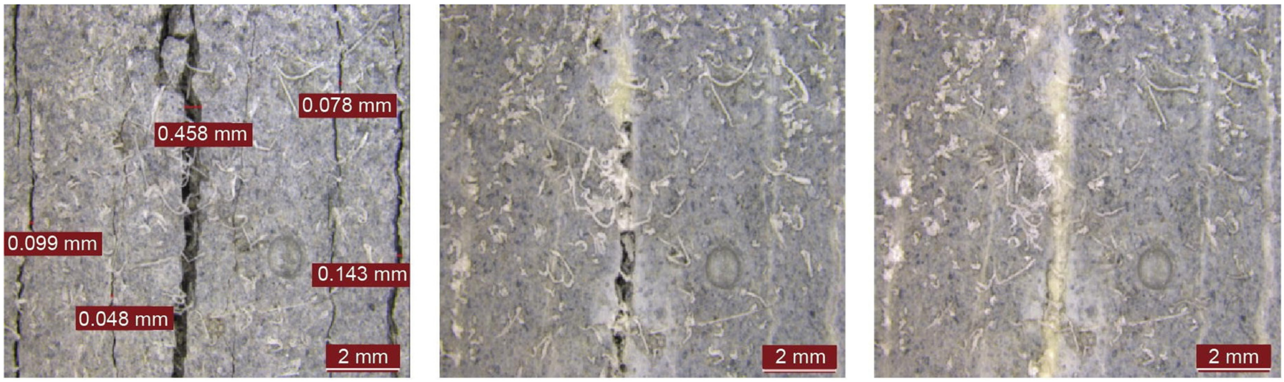

Figure 8: Aged ECC specimens after 1 year exposure [96].

environmental impacts of building projects. By minimizing cement consumption, the reinforcement offered by nano-products will reduce the environmental impact of the cement matrix. The versatile properties of nanomaterials give cementitious composites immense potential for structural use. As reported by Paul *et al.* [91], the optimum dosage of nanomaterials for various applications is also important, as arbitrary applications cannot fulfil or improve their usage in cementitious materials. For instance, Singh *et al.* [92] developed GO–ferrofluid–cement composite materials for electromagnetic coating and achieved substantial coating efficiency. Different nanomaterials tend to have different chemical compositions. Therefore, various chemical reactions can occur with binders. It is, therefore, important to identify the applications of their uses based on the nanomaterial types and binders. Nanomaterials have also been used by Zhang [93] to eliminate heavy metal ions. He has applied the absorption properties of nano graphene platelets to cementitious composites, purifying the sewage and safeguarding the ecosystem.

4 Applications of multifunctional ECCs

4.1 Self-healing of ECCs

In ECCs, self-healing integrates the sealing and blocking functions of the crack faces. The binding function restores the mechanical properties such as tensile strength, stiffness, and ductility, while the self-sealing function restores

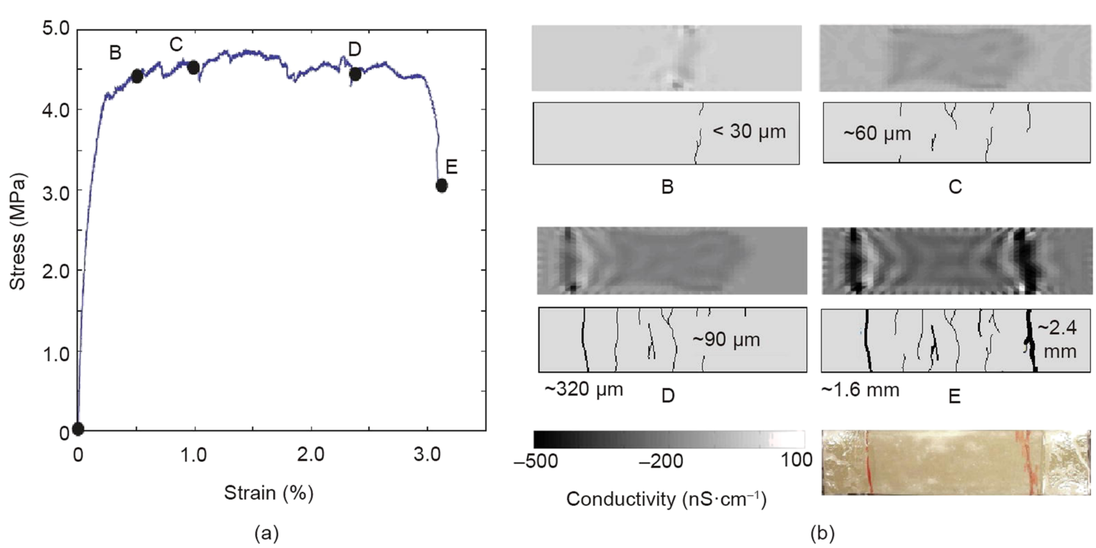

Figure 9: (a) A tensile stress–strain curve indicating the strain levels (b–e). (b) Conductivity maps were made using EIT [97].

the transport properties such as water permeation and chloride diffusion [94]. It was revealed that the self-healing capability of ECCs is more efficient when the crack width is less than 50 μm [95]. Once unhydrated cement grains and pozzolans come into contact with water, the mechanism of self-healing blends continued hydration and pozzolanic reactions. The subsequent calcium silicate hydrates (CSHs) fill the microcrack and bind the crack faces. Utilizing ECC components in areas with high CO_2 concentrations in the air can help to reduce CO_2 concentrations while also significantly contributing to infrastructure sustainability through improved self-healing capability. The autogenous self-healing performance of 1-year-old (aged) ECC mixtures with various compositions was investigated by Yıldırım *et al.* [96]. They have reported that various ECCs had different self-healing performances based on their compositions. Figure 8 demonstrates the effective self-healing ability of the ECC within a year of the aged ECC specimens after being exposed to carbonated water.

4.2 Self-sensing ECC

Self-sensing ECC was invented to detect and report damage instantly [97]. This feature is driven by the fact that ECC is a semi-conducting material with electrical resistivity that is susceptible to changes in the material microstructure induced by loading. This concept makes it possible to map the crack damage in ECCs using electrical impedance tomography (EIT). EIT works by applying regulated sinusoidal alternating current (AC) to a specimen and measuring the amplitude and phase of the voltage, out of which impedance as a function of AC frequency can be calculated. Figure 9 depicts the self-sensing principle of ECC. The self-sensing performance of the ECC can be employed to self-report the structural condition following a major loading event. These data could be beneficial in making decisions about whether to continue operating, repair, or replace structures in a major load event, with greater efficiency and less risk to first respondent. While significant progress has been made in high-performance multifunctional concrete over the last decade, more research is required to significantly green such materials, preferably steering them to become carbon neutral. The use of CO_2 as a resource for this purpose should be seriously regarded. There are additionally possibilities to incorporate material development with construction techniques, such as modern methods like architectural-scale 3D printing.

5 Conclusions

The excellent properties of carbon nanotubes (CNTs) have significantly contributed to the development of high-performance, multi-functional, and smart cementitious composites. However, some of their drawbacks, such as dispersion and weak bond strength between the GO particles and cement matrix, have limited the wide application of CNTs in construction industries. The following conclusions were summarized:

- In general, the inclusion of nanomaterials will influence the nanostructures of the hydration product. They also help in reducing the environmental impacts of building projects.
- The higher surface area of nano-silica creates more silica networks on the surface, which, in turn, can increase the responsiveness of the silica and make up a large amount of C–S–H.
- Because of their pore-filling ability and enhanced chemical reaction, nanomaterials have improved the mechanical properties of multi-layered ECCs.
- In general, the concentration, surfactant type, and dosage, ultrasonication energy/intensity, CNT physical features (*i.e.* length, diameter, aspect ratio, and surface condition), and surfactant type and dosage are critical aspects to obtaining a uniform dispersion of CNTs in the aqueous solution.
- The presence of hybrid fibres in multilayered ECC increased shattering resistance with decreasing scabbing, spalling, fragmentation, and damage zone and better absorption of energy through distributed microcracking.

Acknowledgments: The authors wish to acknowledge the support of the Structures and Materials Laboratory (S&M Lab) of the College of Engineering, Prince Sultan University, Riyadh, Saudi Arabia, for their vital support. The authors wish to also acknowledge the support of Prince sattam bin Abdulaziz University *via* project number (PSAU/2023/R/1444).

Funding information: The support of the Structures and Materials Laboratory (S&M Lab) of the College of Engineering, Prince Sultan University, Riyadh, Saudi Arabia and the support of Prince sattam bin Abdulaziz University *via* project number (PSAU/2023/R/1444).

Author contributions: Sani Haruna, Musa Adamu: conceptualization, writing – original draft, methodology, formal analysis; Sadi I Haruna, Mukhtar Fatihu Hamza: writing – original draft, data curation; Yasser E. Ibrahim, Marc Azab, Hany M. Seif ElDin: writing – review and editing, resources. All authors have accepted responsibility for the entire content of this manuscript and approved its submission.

Conflict of interest: The authors state no conflict of interest.

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