Penerbit Akademia Baru

Journal of Advanced Research Design

Journal homepage:
https://akademiabaru.com/submit/index.php/ard
ISSN: 2289-7984

Developing Innovative Nano-Engineered Lightweight Foamed Concrete Incorporating Iron Oxide (II, III) with Enhanced Mechanical and Transport Properties

Afiya Abdul Sattar[1], Md Azree Othuman Mydin[1,*], Mohammad Shahadat[2]

[1] School of Housing, Building and Planning, Universiti Sains Malaysia, 11800, Penang, Malaysia
[2] Department of Textile and Fiber Engineering, Indian Institute of Technology, New Delhi 110016, India

ARTICLE INFO

Article history:
Received 2 October 2024
Received in revised form 4 November 2024
Accepted 20 November 2024
Available online 30 November 2024

Keywords:
Iron oxide; nanoparticles; lightweight foamed concrete; compressive strength; bending

ABSTRACT

Recently, scientists have focused substantial attention on the incorporation of nanoscale components in cement-based materials. Iron oxide (II, III) nanoparticles (IONPs) have garnered significant attention in nanoparticle research. This paper portrays preliminary discoveries of an investigation assessing the characteristics of foamed concrete (FC) with the presence of IONPs. A comprehensive assessment of characteristics was conducted, including its workability, axial compressive strength, bending strength, tensile strength, apparent porosity and water absorption capacity. Furthermore, scanning electron microscope examination was performed and evaluated. The results indicate a significant enhancement in the FC strength characteristics, with 28-day compressive, tensile, and bending strengths improving by up to 70, 76 and 52 %, respectively, with the inclusion of 3 % IONPs. Nonetheless, adding IONPs beyond 3 % did not yield significant improvements in mechanical properties. With a rise in IONPs from 1 to 5 %, the FC exhibited significant improvements in apparent porosity and water absorption. The decreasing pore size in FC containing IONPs was found to be the cause of the anomalies. A significant alteration in the arrangement of pore dimensions was noted in FC mixtures when the amounts of IONPs were modified. Results from this investigation emphasise the prospective benefits associated with integrating IONPs into FC that could boost its entire characteristics.

1. Introduction

Concrete is acknowledged as vital material of considerable significance in infrastructure and building projects, as well as new technological constructions worldwide. Concrete not only meets the requirements of high both tensile and compressive strength but also possesses advantageous qualities including simplicity of manufacture, resilience, resistance to fire and resilient permeability. Moreover, concrete's cost-effectiveness, accessibility of raw materials and versatility in shaping diverse structures constantly render it the preferred material for building professionals, despite its

* *Corresponding author.*
E-mail address: azree@usm.my

https://doi.org/10.37934/ard.122.1.826

detrimental ecological effects [1]. Each year, an astonishing 25 billion metric tons of concrete are produced worldwide. Consequently, environmental activists express alarm about the significant carbon dioxide emissions generated by cement manufacture for concrete, which constitutes roughly 10 % of global emissions. Nonetheless, it is crucial to recognize that concrete possesses certain disadvantages, such as fragility, a heterogeneous composition and possible volumetric instability. Recent decades have witnessed an increasing demand among scientists for the application of nanotechnology in cement-based products [2]. This is ascribed to the significant promise that nanotechnology possesses in this domain.

The integration of nanoparticles in concrete production presents numerous benefits. Refinement of concrete pores reduces chloride infiltration, so effectively preventing steel corrosion. Furthermore, studies have shown that nanoparticles can reduce the degree of carbonization in concrete. The boundary involving the matrix of cement and particles is subsequently fortified to ascertain the rigidity of concrete. The integration of nanoparticles into concrete leads to an increase in calcium hydroxide particle size and an enhanced tendency for tropism formation [3]. The methods aim to be low-pressure, cost-effective and environmentally friendly, thereby promoting environmentally friendly practices [3]. The increased surface area in relation to volume ratio associated with tiny particle size speeds up the progression of hydration of cement and, consequently, the pozzolanic process. Moreover, in addition to the positive environmental impacts associated with nanoparticles, their incorporation shows potential for enhancing the structural performance, durability and strength of cement-based substances [4].

Lightweight foamed concrete (LFC) is a type of concrete distinguished by its low density, generally between 200 to 1800 kg/m^3. For structural lightweight concrete, the unit weight ranges from 1400 to 2000 kg/m^3, in contrast to conventional weight concrete, which has a unit weight of 2400 kg/m^3. Minimizing the structure's weight facilitates the construction of structures with reduced cross-sectional parts, hence improving the effectiveness of functional spaces. The utilization of LFC has increasingly proliferated in recent infrastructure and building development projects. These advantages can be attributed to its advantageous qualities, including reduced self-weight, exceptional fire resistance and superior thermal insulating abilities. Nonetheless, the use of LFC is hindered by various limitations, including adverse strength characteristics, significant drying shrinkage and heightened susceptibility to splitting. These obstacles hinder the widespread deployment of LFC globally [5]. The incorporation of prefabricated foams in LWFC generates numerous air voids. Thus, including solid additives at nanoscale dimensions during the manufacturing of LFC can significantly improve its characteristics.

The impact of nanoparticles on cement-based materials has been the subject of numerous investigations [6-8]. Silicon dioxide nanoparticles may enhance the physical and mechanical features of concrete, claim Shah et al. [9]. The sample's durability against abrasive environment is enhanced when nanoparticles are present. Cement-silicone dioxide's resilience to water absorption has been enhanced. Both varieties of silicone dioxide nanoparticles improved the final strength of binary merged concrete, but they also reduced the workability of binary mixtures [10]. The porosity of concrete may be decreased by the nanoparticles, creating a denser intermediate transitioning region. Additionally, high-strength concrete structures that are more resilient can be made with nanoparticle-reinforced cement, which lowers the need for upkeep or rapid substitution [8]. Kawashima et al. [11] examined the microscopic properties of concrete containing nanoparticles. They found that further inner microscopic cracks emerge because the microstructure is robust due to the presence of nano silica fragments. According to Zhang et al. [12], incorporating nano-silica into slag and cement sped up hydrating process and reduced the inactive time. Cement-based composites can be mixed with nanomaterials like graphite, graphene dioxide, carbon nanotubes, graphene,

graphene oxide, silica, alumina, ferric oxide and titanium dioxide. By using these nanoparticles, concrete systems can survive more effectively and perform effectively [7]. The mechanical characteristics of concrete, such as its bending strength, tensile strength and axial compressive strength [9], as well as its durability against abrasion, water permeability, and pore makeup [10], can be greatly enhanced by nanomaterials because of their tiny particle size and greater surface area.

Iron oxide (II, III) nanoparticles (IONPs) exhibit a significant charge-to-size ratio among solid particles. As a result, these IONPs typically exhibit a predominance of deprotonated hydroxyl groups on their surface and are inclined to absorb positively charged surfactant ions. Conversely, alumina particles tend to be absorbed by wetting agent with carboxyl groups. Prior research indicates that an increase in LFC absorption capacity correlates with a reduction in the thickness of the interfacial transition zone. This results from the diminished buildup of water around the fine aggregate particles [13]. Additionally, LFC inherently offers internal curing advantages that may reduce shrinkage cracking and lower permeability, as indicated in reference. The adoption of IONPs may substantially improve the resistance of LFC to water and chloride ion ingress, as evidenced by prior studies. Figure 1 illustrates the enhancement of coercion resulting from decreasing size, reaching a peak at a certain dimension known as the crucial diameter, Ds. Under this circumstance, all IONPs spins align in the same orientation, enhancing the magnetic properties, and IONPs typically exhibit strong coercion, making them tough to demagnetize [14].

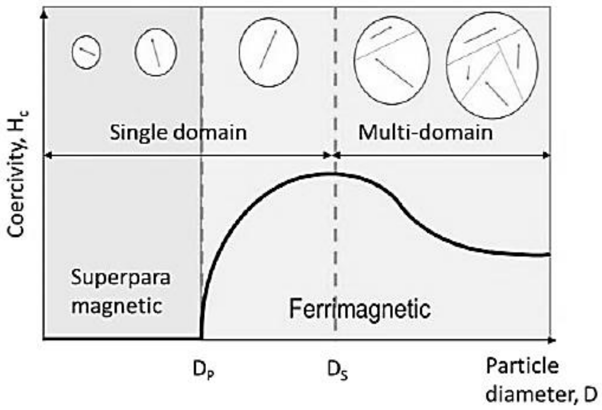


Fig. 1. Schematic diagram of the dependency of coercion on the IONPs diameter [14]

At this point, only limited study has been undertaken to investigate the possible use of nanoparticles in the manufacturing of LFC [15-18]. The majority of research conducted so far has focused on utilizing various nanoparticles to improve the characteristics of conventional concrete [19-22]. Among all the nanoparticles investigated, IONPs have been recognized as the most extensively utilized and researched [23]. IONPs have demonstrated their vital contributions to various disciplines, including medicine, physics, chemistry, biology, and allied domains, owing to their distinctive properties [24-26]. The primary factor contributing to these phenomena is the effective distribution of hydrophilic breakdown agents in aqueous solutions [27-31]. Figure 2 illustrates the superparamagnetic IONPs, which vary from ferrimagnetic ions as they lack coercion and hysteresis loops due to their single-domain magnetic forces, hence allowing magnetization just in the case of a magnetic field that is external.

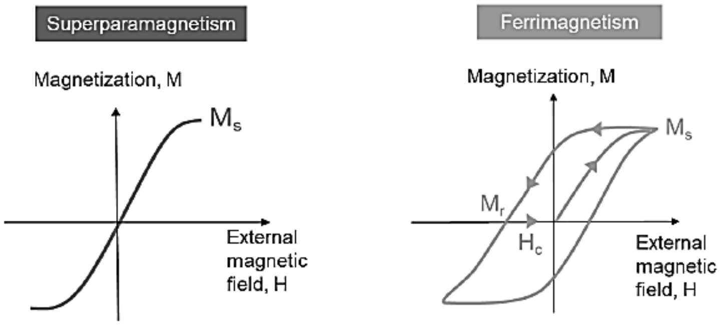


Fig. 2. Conceptual depiction of the superparamagnetic and ferrimagnetism hysteresis curve [14]

Shekari and Razzaghi [28] investigated the strength and resilience of concrete employing different nanoparticles. The researchers determined that incorporating nanoparticles into concrete at a concentration of 1.5 % by cement weight fractions significantly enhanced its strength and toughness, with aluminum dioxide identified as the best option [29]. Bragança et al. [30] investigated the influence of magnetite nano-oxide on the characteristics of concrete. Following a 300-day evaluation of concrete incorporating 1 % ferro-ferric oxide (Fe_3O_4) nanoparticles in a chloride and sulphur dioxide environment via impedance spectrometry, it was determined that the concrete exhibited durability. Figure 3 illustrates the configuration of the crystalline makeup of IONPs [31]. Figure 3a illustrates the crystal arrangement of IONPs, whereas Figure 3b depicts the octahedral and tetrahedral sublattice configurations of IONPs. The exceptional chemical and physical characteristics of IONPs are affected by several parameters, including microscopic structure, grain shape and particle size. Microstructural aspects encompass crystal structure, dimensions of crystal lattice variables, lattice imperfections, and crystal concentration, as well as the diverse phasing of the nanoparticles.

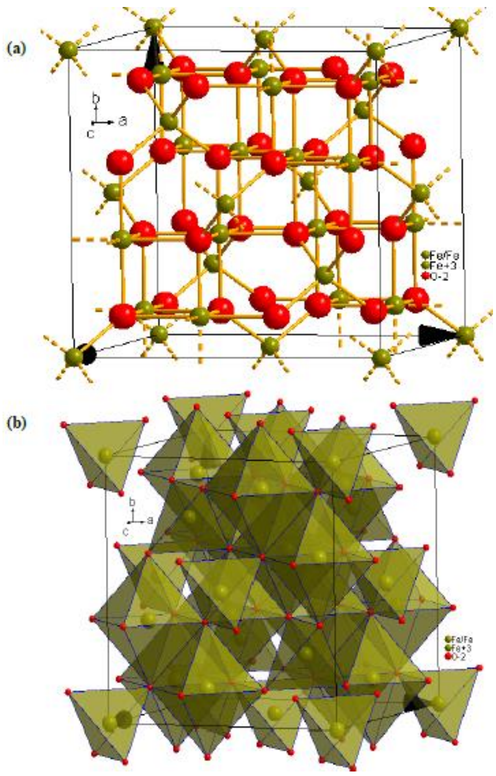


Fig. 3. Crystal arrangement of reverse spinel IONPs: (a) crystal configuration of IONPs and (b) hexagonal and rectangular sublattice arrangements

Given these characteristics, more examination of the application of IONPs in cementitious materials, such as LFC, is necessary. This study will significantly influence both sustainability and the improvement of mechanical properties. Prior studies have investigated multiple parameters associated with the integration of IONPs into ULFC in diverse amounts. As a result, microstructural improvements have demonstrated benefits in tensile and compressive strengths, along with durability characteristics.

The previous study clearly indicates that only a little investigation has been conducted on the potential application of nanoparticles in the production of LFC. The predominant study to far has concentrated on employing diverse nanoparticles to enhance the properties of traditional concrete. Among all the nanoparticles studied, IONPs have been identified as the most widely employed and examined. Hence, to fill the gaps of knowledge, this study seeks to evaluate the fresh, mechanical, transport and microstructural characteristics of LFC with the incorporation of IONPs.

2. Methodology

2.1 Materials

Five primary materials were necessary for the production of the FC specimens specifically cement, aggregate, water and a foaming agent. IONPs were utilized as an additive in LFC. The technique for this study is illustrated in Figure 4.

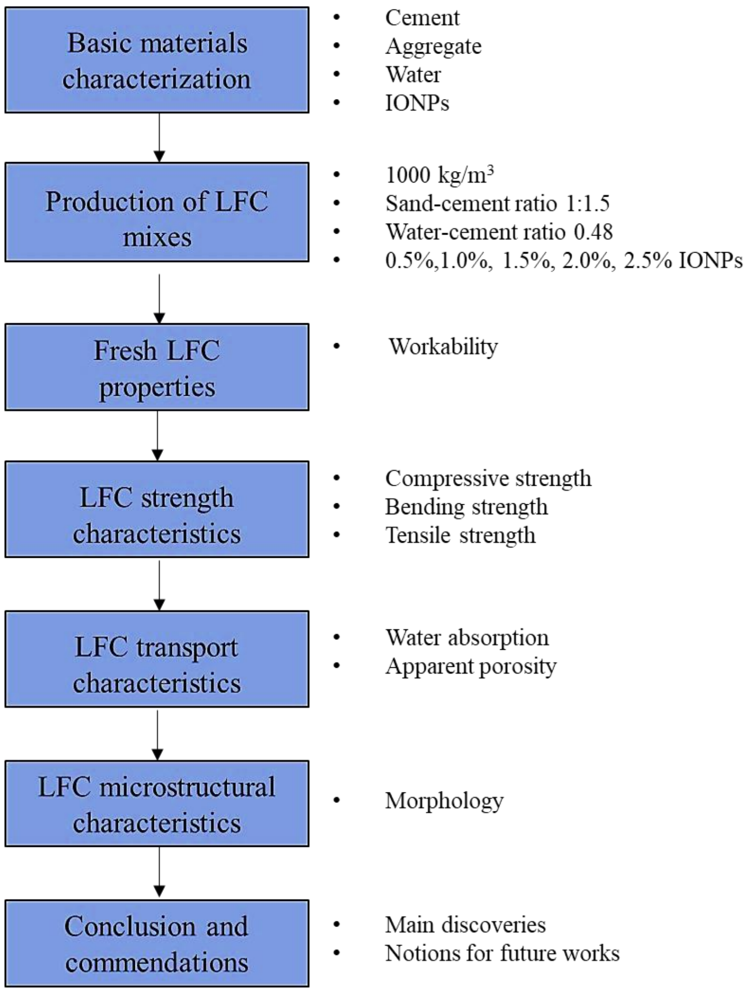


Fig. 4. Methodology for the present study

2.1.1 Portland cement

The LFC mixtures were augmented with IONPs as an additive to improve their efficacy. BS-EN 197-1 [32] indicates that OPC CEM-1 cement is appropriate for various purposes. The specific gravity of CEM1 is 3.16 fulfills BS12 [33] requirements. The compressive strength of CEM1 was measured at 45.2 MPa (day-28), as determined experimentally. Table 1 delineates the chemical constituents of the OPC.

Table 1
OPC chemical compositions

Components	*Percentage*
Calcium oxide (CaO)	*59.95*
Silicon Dioxide (SiO_2)	*21.33*
Aluminium oxide (Al_2O_3)	*5.79*
Magnesium oxide (MgO)	*3.59*
Sulfur oxide (SO_3)	*2.95*
Iron oxide (Fe_2O_3)	*2.91*
Potassium oxide (K^2O)	*0.5*
Sodium oxide (Na_2O)	*0.19*
LOI	*2.79*

2.1.2 Aggregate

The formulation of the LFC, along with the grade of the sand employed, may influence the characteristics of the product. Fine sand functioned as a filler in FC mixes. The particle size distribution was assessed in line with ASTM C33-03 [34]. Figure 5 depicts the sand grading curve of the fine aggregate employed in this study. It can be seen that the aggregate sizes were within the upper and lower limit of ASTM C33. 2.71 % of the products had a maximum grain size of 5 mm (35-38].

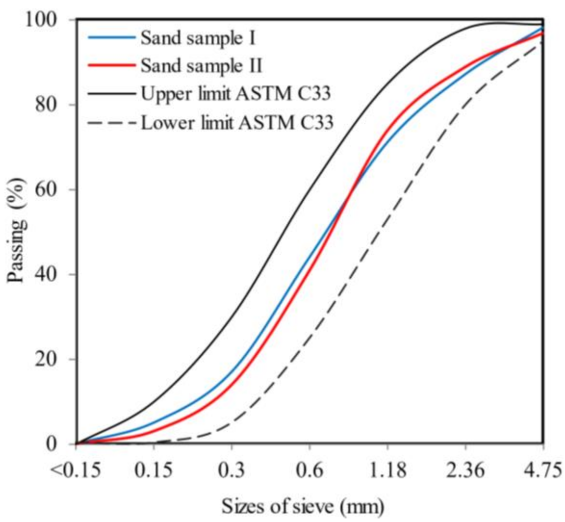


Fig. 5. Sand grading curve of fine aggregate

2.1.3 Water

Furthermore, the water utilized for combining the components was pristine and devoid of any contaminants or organic debris. This study employed a water-cement ratio of 0.45, as previous experiments indicated that this ratio ensured sufficient workability.

2.1.4 Iron oxide (II, III) nanoparticles

The IONPs were purchased from SBG Maju Trading. The IONP specimens were analysed employing X-ray diffraction (XRD) adopting a Rigaku X-Ray Diffractometer with Cu Kα radiation (λ = 1.540 Å), an angular resolution step size of 0.001°, and a θ–2θ range of 15–80°, under generator settings of 40 kV and 40 mA. The mean size of the IONPs was calculated using the full-width at half maxima (β) and the Bragg angle (θ) of the reflection. Figure 3 clarifies the XRD spectra of IONPs. Given the similarity of XRD patterns for maghemite and magnetite phases, it is essential to employ further characterization techniques to ascertain the oxidation state of iron and confirm whether containing Fe^{2+} and Fe^{3+} or just Fe^{2+}. Figure 6 illustrates the peak positions of the diffractogram associated with the phase classified under the cubic spatial group Fd-3m of magnetite. Figure 7 summarized the physical properties of IONPs.

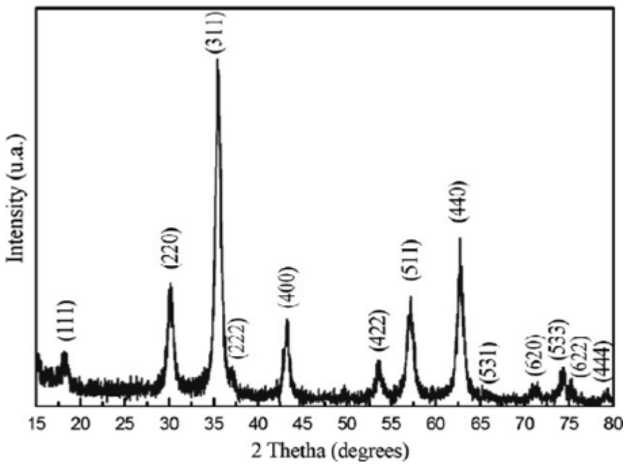


Fig. 6. XRD pattern of IONPs

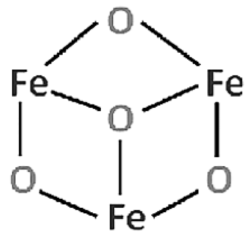
Parameters	Magnetite Nanoparticles
Chemical name	Magnetite/Iron Oxide
Chemical Structure	
Colour	Brownish-black
Form	Powder
Mean size	16.5 nm
Density	5 g/cc
Molecular weight	231.531 g/mol
Melting Point	1597 °C
Boiling point	2623 °C
Purity	99.1%

Fig. 7. IONPs physical properties

2.1.5 Foaming agent

The foam generator features an extendable foam tip that may emit a specified volume of foam at a predetermined rate of 3 to 10 ft^3/min, contingent upon the flow level. The foam density should be around 70 and 80 kg/m³. A mortar fluid slurry may be created if the density is verified to be inside of the permissible limit. Protein foaming compounds were employed to diminish the visible resistance of a solution and enhance the stiffness of the foam by lowering the solution's perceived resistance. The proportion of protein foaming agent to potable water utilized in the foam production was 1:25.

2.2 Mix Proportions

LFC with a density of 1000 kg/m³ was created in the present study. Table 2 illustrates that FC comprises different weight fractions of IONPs, aligned with the blended ratio of FC. The cement-aggregate ratio will be maintained at 1:1.5, and the water-cement ratio will be upheld at 0.48. Overall, six LFC blends were generated: A0 (control), A1, A2, A3, A4 and A5, representing weight fractions of FC additions ranging from 0 to 5 % in the finished mixture. Figure 8 illustrates the manufacture of the LFC mixture. Once the fresh LFC mixture was combined uniformly, it was put into steel moulds.

Table 2
LFC mix proportions containing varying proportions of IONPs

Mix	IONPs (%)	IONPs (kg/m^3)	Aggregate (kg/m^3)	Cement (kg/m^3)	Water (kg/m^3)	Stable Foam (kg/m^3)
A0	0	0.00	556	371	178	31
A1	1	11.05	556	371	178	31
A2	2	22.11	556	371	178	31
A3	3	33.16	556	371	178	31
A4	4	44.21	556	371	178	31
A5	5	55.27	556	371	178	31

(a) Adding foam in base mix (b) Homogenous LFC mix (c) Steel moulds

Fig. 8. Preparation of LFC mix

2.3 Methods

This part charts the assessment approaches devoted to evaluating the characteristics of LFC with various amounts of IONPs. The qualities examined included workability, water absorption, apparent porosity, bending strength, compressive strength and tensile strength. A flow table test was conducted in agreement with ASTM C230-97 [39] as shown in Figure 9(a). A vacuum saturation method was utilized to assess the apparent porosity of LFC [40] as demonstrated in Figure 9(b). A water absorption test, adhering to the BS-EN 1881-122 [41] (refer to Figure 9(c)). The bending strength test employed LFC prism, adhering to BS-EN 12390-5 [42] as shown in Figure 9(d). A tensile test was conducted in line with BS12390-6 [43] as indicated in Figure 9(e). The compression test (Figure 9(f)) was performed in agreement with the BS-EN 12390-3 [44].

(a) Workability (b) Apparent porosity (c) Water absorption

(d) Bending (e) Tensile (f) Compression

Fig. 9. Types of tests conducted

4. Results and discussion

4.1 Workability

Under optimal conditions, a premium LFC should have workability ranging from around 220 to 250 mm. A slump is necessary to acquire adequate strength. In general, a larger measured slump flow indicates improved workability of the LFC. This often signifies that the LFC flows effortlessly yet remains entirely unsegregated. Due to the self-compacting nature of the FC, it is essential for the LFC to possess an adequate level of workability to attain its optimal strength. The slump flow of LFC mixtures diminished with an increase in IONPs concentration, as illustrated in Figure 10. The 1 % IONPS LFC exhibited the maximum slump flow diameter of 248 mm, while the lowest slump of 234 mm was measured for LFC containing 5 % IONPs. In contrast to the control LFC, which exhibits a slump flow of 250 mm, the FC including IONPs demonstrates a reduced slump flow. Numerous investigations have demonstrated that IONPs exhibit a comparable influence on workability [45]. As

IONPs weight fractions rise, fluidity diminishes. There is a clear disparity in the workability of the LFC with 1 % IONPs compared to the control LFC. An increase in IONPs leads to a heightened requirement for water in the LFC mix. This modification has been implemented primarily because the IONPs medium slurry disperses uniformly, which may significantly enhance particle size dispersion due to its rapid spreading capability [46]. The incorporation of IONPs promotes cement hydration while also accelerating the setting process of cement. The water requirement in LFC escalates as the fraction of IONPs rises [47].

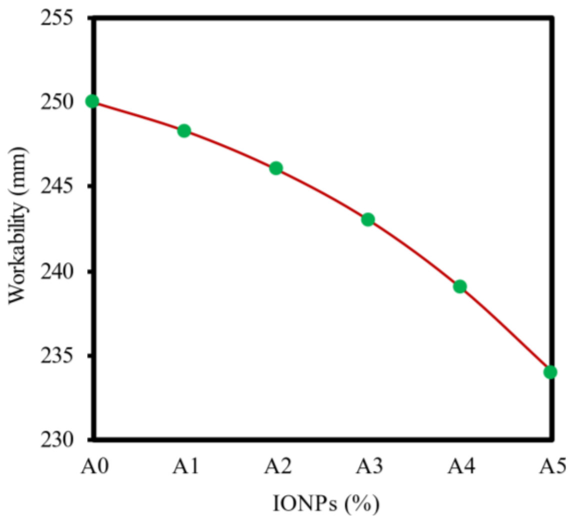


Fig. 10. Workability of LFC mixes containing different weight fractions of IONPs

4.2 Apparent Porosity

The capacity to delineate the properties of water movement in permeable media *via* capillary networks is contingent upon the porosity of LFC. Figure 11 illustrates the porosity of LFC with differing weight fractions of IONPs. The increased weight fractions of IONPs in the LFC combinations significantly diminished porosity. In comparison to the control LFC, the porosity enhanced by 8.6, 7.1, 6.2, 5.1 and 3.9 %, respectively, with the incorporation of 5 to 1 % of IONPs alongside the control LFC. The presence of IONPs in the interstices between the binder paste and the filler contact reduced capillary pore activity. The pores were saturated with IONPs. The observed trend in porosity values is due to a modification of the microstructure caused by IONPs, as previously mentioned. The integration of IONPs results in a reduction of these pore structures. Moreover, the incorporation of IONPs improved the densification of the mortar's microstructure and reduced its porosity, particularly the interconnectivity of pores within the matrix [49]. Multiple capillary networks are present within LFCs, facilitating the passage of deleterious ions into the matrix. Uniformly distributed IONPs can function as crystallization and nucleation sites for hydration processes following introduction. This enhances the crystallization and development of hydration products. The reactivity of IONPs resulted in the creation of several supplementary C-S-H and other gels. The gels improved the pores and created a discontinuous pore structure by the interconnection of hydration products.

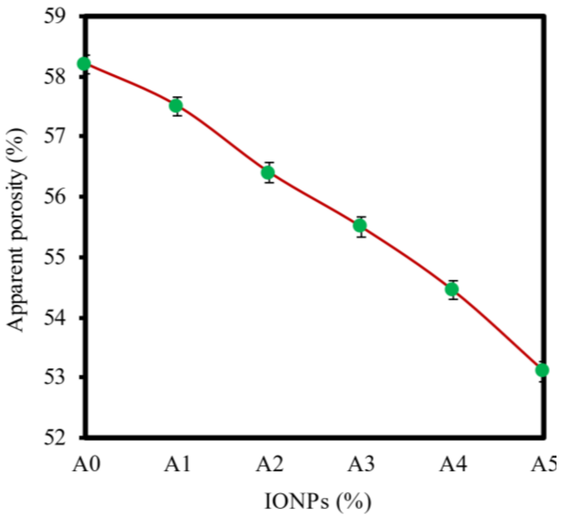


Fig. 11. Apparent porosity of LFC mixes containing different weight fractions of IONPs

4.3 Water Absorption

The amount of water that LFC can absorb was used to figure out how porous it seems. This standard was used to measure how permeable LFC was to water. The total amount of water that LFC absorbs is affected by how porous and dense it seems. Higher rates of water absorption in LFC could shorten the life of destructive particles and solutes that enter over the holes and move through the cementitious matrix with the water. Figure 12 shows the test results for how much water LFCs can absorb at different IONP weight fractions. Figure 12 shows that adding IONPs to this study slowed down the rate at which water was absorbed. The sample of LFC with 5 % IONPs (A5) had the slowest water uptake rate, 10.9 % less than the control sample (A0). The presence of IONPs results in a reduction of water absorption in LFC, as indicated by the findings, due to its superior microstructure observed in the morphological study. The reduced particle size of the IONPs in the LFC mixture facilitates the formation of a seal linking the gel pores contained by the composition [47]. The presence of IONPs reduced the size and number of pores, enhancing the LFC microstructure. Furthermore, it enriched the adhesion connecting the cement base and the sand, resulting in a stronger LFC. Furthermore, the incorporation of IONPs in LFC led to the formation of filled pore arrays, resulting in a reduction in space diameters.

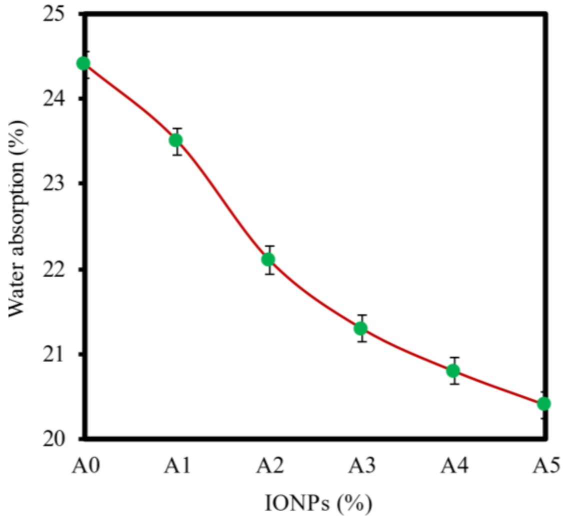


Fig. 12. Water absorption of LFC mixes containing different weight fractions of IONPs

4.4 Bending Strength

Figure 13 indicates that the bending strength measurements are 0.57, 0.61, 0.69, 0.90, 0.73 and 0.70 MPa after 7 days of testing for specimen A0 to A5 respectively. Extending the curing period to 28 days results in bending strength values of 0.67, 0.72, 0.82, 1.06, 0.87 and 0.83 MPa for IONPs dosages of 0 to 5 % in LFC, respectively. Extending the curing period to 56 days results in an enhancement of bending strength to 0.74, 0.82, 0.93, 1.21, 0.99 and 0.93 MPa for IONPs dosages of 0, 1, 2, 3, 4 and 5 %, in that order. The A3 mix exhibited enhancements in bending strength of approximately 58, 58 and 64 % compared to the A0 mix at 7, 28 and 56 days, respectively. The IONPs exhibits a robust adhesion to the cement matrix owing to its superlattice structure and elevated van der Waals forces at the interface. IONPs also create a compact arrangement of hydration products, enhancing particle size distribution during hydration and reducing pore size and connectivity, hence increasing bending strength during hydration. Particles that are unevenly distributed may aggregate, resulting in reduced bending strength with the addition of 3 % IONPs to LFC [50].

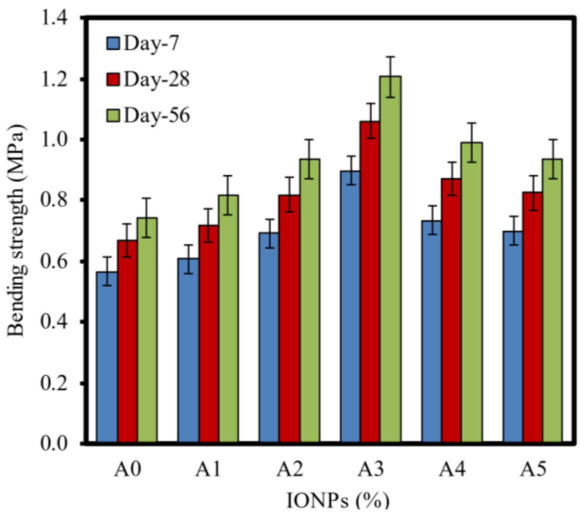


Fig. 13. Bending strength of LFC mixes containing different weight fractions of IONPs

4.5 Tensile Strength

The application of IONPs at concentrations of 1, 2, 3, 4 and 5 % yields increases in tensile strength of 17, 28, 75, 38 and 28 %, respectively, as contrasted with the control LFC (A0) after 28 days of cured. After 56 days, the improvements in tensile strength are 17, 32, 75, 42 and 31 %, respectively, in comparison to the control sample, as depicted in Figure 14. The incorporation of IONPs into the cement matrix results in the formation of H_2SiO_2, which then reacts with the existing calcium ions to yield further C-S-H. The resulting C-S-H molecules are suspended in water, with the interstitial gaps filled by the IONPs, leading to the creation of bulkier C-S-H products [90]. The LFC sample with 3 % IONPs shows tensile strengths of 0.47, 0.56 and 0.63 MPa, indicating peak strength at 7, 28 and 56 days, correspondingly. An increase in strength enhances the interaction across the concrete substrate and fragments [51]. The diameters of the IONPs markedly affect strength growth, as the fragments subsequently spread uniformly throughout the outermost layer, facilitating filling and succeeding reactive activities.

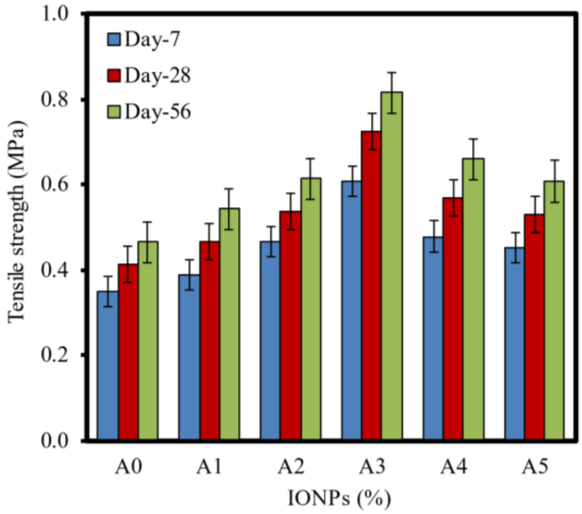


Fig. 14. Tensile strength of LFC mixes containing different weight fractions of IONPs

4.6 Compressive Strength

Figure 15 indicates that the addition of 3 % IONPs to LFC resulted in maximal compressive strength. The incorporation of 3 % IONPs yielded a compressive strength of 6.25 MPa after 56 days, compared to the control sample's strength of 3.63 MPa, reflecting a 72 % improvement. The compressive strength of LFC improved from 7 to 56 days with the incorporation of 3 % IONPS relative to the cement mass. The compressive strength of the A0 mix increased by approximately 36 %. The improvement in compressive strength may have arisen from the interaction of IONPs with calcium hydroxide granules in lime, leading to the formation of an extra layer of C-S-H gel. In the LFC matrices, these components work together to improve compressive strength. Furthermore, nanoparticles possessing a significant specific surface area are susceptible to further contact with the group [52]. Nonetheless, a concrete mixture lacking IONPs will be incapable of achieving even a small formation of C-S-H after hydration with cement. C-S-H is essential for strength augmentation. As a result, cementitious materials without IONPs exhibit reduced compressive strength due to their deficiency. A reaction involving calcium hydroxide molecules and IONPS generates an increased quantity of CSH gel. The complexity of IONPs stems from their nanoscale size, large contact area, and atomic structure. These atoms can rapidly move under outside pressure, accumulating energy along the procedure and preventing distortion at that moment [53]. Microcracks form within LFCs when subjected to force, leading to fractures that exhibit both tiny and major cracks as a consequence of the applied pressure. If internal fractures develop, enlarge and coalesce, the LFC matrix loses its load-bearing ability. In contrast, IONPs improve the breaking toughness and crack expansion of the LFC samples.

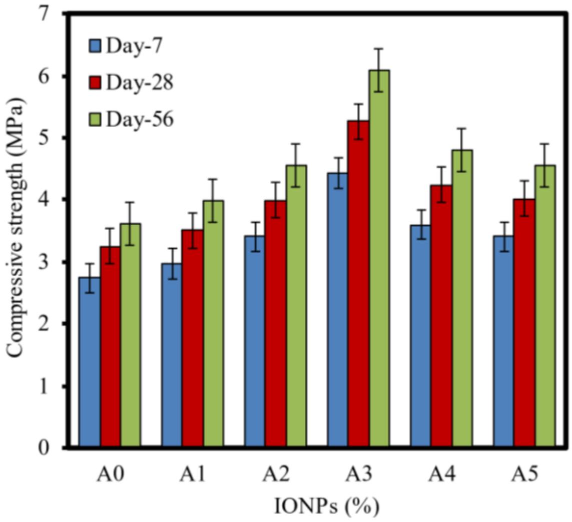
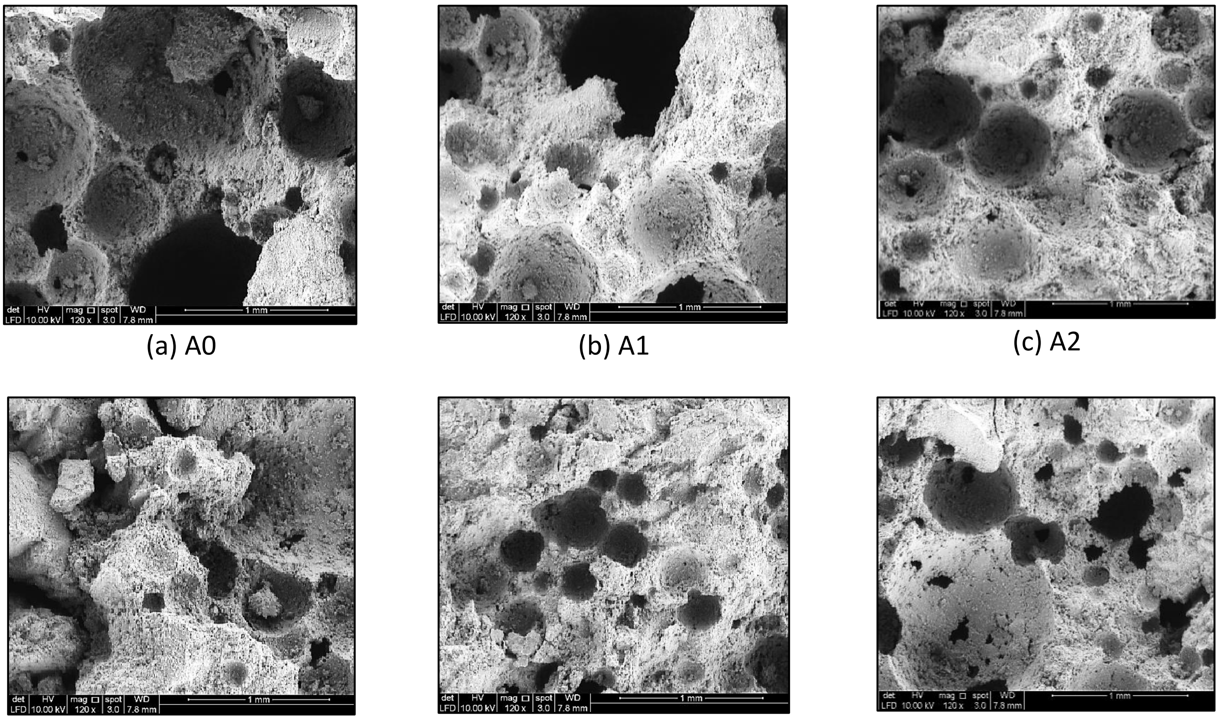


Fig. 15. Compressive strength of LFC mixes containing different weight fractions of IONPs

4.7 Microstructural Properties

Figure 16 presents scanning electron microscopy pictures of LFC containing various weight fractions of IONPs. The SEM of mix A0 indicates that hydrated products are adhered to and interconnected with the C-S-H gel. Prominent air pores and fused air spaces are distinctly observable (Figure 16a). Moreover, the microstructure of the LFC including A1 to A5 revealed the formation of compact and dense hydration products, accompanied by a reduction in calcium hydroxide (C-H) crystals (Figure 16a–f). The small particles of IONPs, in contrast to the C-S-H gel, lead to a decrease in the size of air voids, as illustrated in Figure 16(b) and 16(c). IONPs grains possess a diameter of approximately 50 nm, rendering them appropriate for functioning as a nucleus due to their favorable size. This will yield thick, hydrated products with an enhanced interfacial transition zone (ITZ). A C-S-H gel is generated through the pozzolanic reaction of IONPs with lime, which diminishes porosity and enhances density and mechanical characteristics, as illustrated in Figure 16(d). A particle of IONPs is roughly 120 times finer than a grain of cement and possesses the capability to occupy voids in the cement matrix, hence producing a denser matrix [54-56]. Consequently, IONPs are an important material for improving the robustness of cement substances by declining calcium leaching. The IONPs nucleation process enhanced the LFC porosity structure. The integration of IONPs into the hardened pastes significantly altered the hydration behavior and microstructure of the paste. Figures 16(e) and 16(f) indicate the creation of pores with a greater diameter than those observed at a 3 % dosage of IONPs.



(a) A0 (b) A1 (c) A2

(d) A3 (e) A4 (f) A5

Fig. 16. Morphology of LFC mixes containing different weight fractions of IONPs

4.8 Environmental Benefits

Currently, building supplies developed through nanotechnology as well as nanoscience are driving technological and financial growth while ensuring an environmentally friendly future. It is established that nanomaterial-based concretes offer significant benefits for future ecological sustainability, including energy conservation and preservation, renewable power generation, enhanced durability and toughness, better resilience to acid harm, and eco-friendliness for self-cleaning and self-healing applications [57]. Hamers [58] emphasizes the necessity of comprehending the design fundamentals of various nanomaterials based on the physicochemical processes at the microscopic level. Moreover, the expertise and principles of chemistry should be employed to guarantee that diverse nanomaterial-activated items and developments in the building sector provide enhanced environmental responsibility along with financial advantages relative to conventional cement-based supplies. In summary, nanoparticles are promising due to their superior strength and exceptional endurance, contributing to sustainable development.

The adverse effects of IONPs may also be associated with their expense. Assessment indicates that the overall expense of substances, when evaluated alongside their harmful effects, reveals that IONPs with affordable prices as well as low toxicity possess considerable usefulness and potential for broader dissemination. The employment of IONPs characterized by elevated cost and cytotoxicity warrants reevaluation [59]. Despite the uncertainties regarding the harmful effects of IONPs, nanomaterials can serve as a viable method for ecological remediation [60]. IONPs can degrade, remove, or neutralize deleterious chemicals in polluted environments [61]. Moreover, IONPs can be engineered to minimize their contact with the outermost layer of cells, for instance, by incorporating a surface charge that is negative (electrostatic stabilization of IONPs) or utilizing inhibitors that diminish protein adsorption. Less harmful substances may be utilized in IONPs that incorporate shell substances, thereby diminishing their relationship to the core material or the environment, or by introducing a chelating agent that mitigates the damaging effect of nanostructured substances metals, or *via* molecules of antioxidants that inhibit the decomposition of IONPs [62].

5. Conclusions

This work demonstrates that the integration of IONPs into LFC substantially improves the overall properties of LFC. The study produces the subsequent outcomes.

1. An increase in IONPs dosage led to a reduction in workability of LFC mixes. An increase in IONPs leads to a heightened requirement for water in the LFC mix. This modification has been implemented primarily because the IONPs medium slurry disperses uniformly, which may significantly enhance particle size dispersion due to its rapid spreading capability.
2. The addition of 3 % IONPs to the material resulted in a 56-day compressive strength of 6.25 MPa, in contrast to the control specimen's strength of 3.63 MPa, indicating a 72 % enhancement. In the LFC cementitious matrix, IONPs cooperate to enhance compressive strength.
3. The A3 mix exhibited enhancements in bending strength of approximately 58, 58 and 64 % compared to the A0 mix at 7, 28 and 56 days, respectively. The IONPs exhibits a robust adhesion to the cement matrix owing to its superlattice structure and elevated van der Waals forces at the interface. IONPs also create a compact arrangement of hydration products, enhancing particle size distribution during hydration and reducing pore size and connectivity, hence increasing bending strength during hydration.
4. The rise in IONPs concentration from 1 to 5 % guided to a substantial augmentation of apparent porosity and water absorption of the LFC. In cement matrix-filler interfaces, IONPs diminish the transport characteristics of LFC by enhancing the density of the ITZ due to its elevated reactivity.
5. The optimal weight fraction of IONPs to be included into LFC is 3 %. IONPs enhance the mechanical characteristics of LFC by augmenting the packing intensity of hydration effects and diminishing the pores dimension and interconnectivity. The particles in LFC- IONPs composites are unevenly distributed, resulting in agglomeration that diminishes mechanical characteristics.
6. This study provides evidence that nanoparticles may serve as a viable replacement to non-renewable sources.

Acknowledgement
The authors are thankful to the Ministry of Higher Education, Malaysia for their financial support of this research, which was provided via the Fundamental Research Grant Scheme; Grant Ref. No. FRGS/1/2022/TK01/USM/02/3.

References

[1] Singh, L. P., D. Ali, and U. Sharma. "Studies on optimization of silica nanoparticles dosage in cementitious system." *Cement and Concrete Composites* 70 (2016): 60-68. https://doi.org/10.1016/j.cemconcomp.2016.03.006
[2] Celik, Kemal, Cagla Meral, A. Petek Gursel, P. Kumar Mehta, Arpad Horvath, and Paulo JM Monteiro. "Mechanical properties, durability, and life-cycle assessment of self-consolidating concrete mixtures made with blended portland cements containing fly ash and limestone powder." *Cement and Concrete Composites* 56 (2015): 59-72. https://doi.org/10.1016/J.CEMCONCOMP.2014.11.003
[3] Björnström, Joakim, Anna Martinelli, Aleksandar Matic, Lars Börjesson, and Itai Panas. "Accelerating effects of colloidal nano-silica for beneficial calcium–silicate–hydrate formation in cement." *Chemical physics letters* 392, no. 1-3 (2004): 242-248. https://doi.org/10.1016/j.cplett.2004.05.071
[4] Li, Hui, Mao-hua Zhang, and Jin-ping Ou. "Abrasion resistance of concrete containing nano-particles for pavement." *Wear* 260, no. 11-12 (2006): 1262-1266. https://doi.org/10.1016/j.wear.2005.08.006

[5] Tattersall, G. H., and P. H. Baker. "An investigation on the effect of vibration on the workability of fresh concrete using a vertical pipe apparatus." *Magazine of Concrete Research* 41, no. 146 (1989): 3-9. https://doi.org/10.1680/macr.1989.41.146.3
[6] Nazari, Ali. "The effects of curing medium on flexural strength and water permeability of concrete incorporating TiO2 nanoparticles (Retraction of Vol 44, Pg 773, 2011)." (2021). https://doi.org/10.1617/s11527-010-9664-y
[7] Ghasemi, AM Raiess, Tayebeh Parhizkar, and A. A. Ramezanianpour. "Influence of colloidal nano-SiO2 addition as silica fume replacement material in properties of concrete." In *Proceeding, Second international conference on sustainable construction materials and technologies*, pp. 28-30. 2010.
[8] Chen, Jun, Shi-cong Kou, and Chi-sun Poon. "Hydration and properties of nano-TiO2 blended cement composites." *Cement and Concrete Composites* 34, no. 5 (2012): 642-649. https://doi.org/10.1016/j.cemconcomp.2012.02.009
[9] Shah, Surendra P., M. S. Konsta-Gdoutos, Z. S. Metaxa, and P. Mondal. "Nanoscale modification of cementitious materials." In *Nanotechnology in Construction 3: Proceedings of the NICOM3*, pp. 125-130. Berlin, Heidelberg: Springer Berlin Heidelberg, 2009.
[10] Khalaj, Gholamreza, and Ali Nazari. "Modeling split tensile strength of high strength self compacting concrete incorporating randomly oriented steel fibers and SiO2 nanoparticles." (2012): 1887-1892. https://doi.org/10.1016/j.compositesb.2012.01.068
[11] Kim, Jae Hong, Mark W. Beacraft, Seung Hee Kwon, and Surendra P. Shah. "Simple analytical model for formwork design of self-consolidating concrete." *ACI Materials Journal* 108, no. 1 (2011): 38. https://doi.org/10.14359/51664214
[12] Zhang, Min-Hong, and Jahidul Islam. "Use of nano-silica to reduce setting time and increase early strength of concretes with high volumes of fly ash or slag." *Construction and Building Materials* 29 (2012): 573-580. https://doi.org/10.1016/j.conbuildmat.2011.11.013
[13] Chen, Weifeng, Guo Lv, Weimin Hu, Dejiang Li, Shaona Chen, and Zhongxu Dai. "Synthesis and applications of graphene quantum dots: a review." *Nanotechnology Reviews* 7, no. 2 (2018): 157-185. https://doi.org/10.1515/ntrev-2017-0199 .
[14] Scepka, Tomas. "Noninvasive control of magnetic state in ferromagnetic nanodots by Hall probe magnetometry." *Doctoral Degree), Slovak University of Technology* (2016).
[15] Kazemi, Mosstafa, Massoud Ghobadi, and Ali Mirzaie. "Cobalt ferrite nanoparticles (CoFe2O4 MNPs) as catalyst and support: magnetically recoverable nanocatalysts in organic synthesis." *Nanotechnology reviews* 7, no. 1 (2018): 43-68. https://doi.org/10.1515/ntrev-2017-0138
[16] Li, Gengying. "Properties of high-volume fly ash concrete incorporating nano-SiO2." *Cement and Concrete research* 34, no. 6 (2004): 1043-1049. https://doi.org/10.1016/j.cemconres.2003.11.013
[17] Li, Hui, Hui-gang Xiao, Jie Yuan, and Jinping Ou. "Microstructure of cement mortar with nano-particles." *Composites part B: engineering* 35, no. 2 (2004): 185-189. http://dx.doi.org/10.1016/S1359-8368(03)00052-0
[18] Givi, Alireza Naji, Suraya Abdul Rashid, Farah Nora A. Aziz, and Mohamad Amran Mohd Salleh. "The effects of lime solution on the properties of SiO2 nanoparticles binary blended concrete." *Composites Part B: Engineering* 42, no. 3 (2011): 562-569. https://doi.org/10.1016/j.compositesb.2010.10.002
[19] Sureshkumar, M. P., M. Visakan, and P. G. Student. "Experimental investigation on applications of nanomaterials in concrete." *Int. J. Struct. Civ. Eng. Res* 3, no. 2 (2017): 1-9. https://www.ijirset.com
[20] Ying, Jingwei, Bin Zhou, and Jianzhuang Xiao. "Pore structure and chloride diffusivity of recycled aggregate concrete with nano-SiO2 and nano-TiO2." *Construction and Building Materials* 150 (2017): 49-55. https://doi.org/10.1016/j.conbuildmat.2017.05.168
[21] He, Kang, Yu Chen, and Wentao Xie. "Test on axial compression performance of nano-silica concrete-filled angle steel reinforced GFRP tubular column." *Nanotechnology Reviews* 8, no. 1 (2019): 523-538. https://doi.org/10.1515/ntrev-2019-0047
[22] Tadayon, Mostafa Khanzadi Mohsen, Hamed Sepehri, and Mohammad Sepehri. "Influence of nano-silica particles on mechanical properties and permeability of concrete." In *The 2nd International Conference on Sustainable Construction Materials and Technologies*, pp. 1-7. 2010.
[23] Ma, Qinyong, and Ying Zhu. "Experimental research on the microstructure and compressive and tensile properties of nano-SiO2 concrete containing basalt fibers." *Underground Space* 2, no. 3 (2017): 175-181. https://doi.org/10.1016/j.undsp.2017.07.001
[24] Makarova, Natalya Valentinovna, Vadim V. Potapov, Andrey V. Kozin, Evgeniy Anatolievich Chusovitin, Andrey V. Amosov, and A. V. Nepomnyaschiy. "Influence of hydrothermal nanosilica on mechanical properties of plain concrete." *Key Engineering Materials* 744 (2017): 126-130. https://doi.org/10.4028/www.scientific.net/KEM.744.126

[25] Change, How Nanotechnology Can. "How Nanotechnology Can Change the Concrete World." *American Ceramic Society Bulletin* 84, no. 11 (2005): 17.
[26] Jagadesh, P., Karthik Prabhu, Moutassim Charai, Ibrahim Y. Hakeem, Emrah Madenci, and Yasin Onuralp Ozkilic. "A potential review on the influence of nanomaterials on the mechanical properties of high strength concrete." *Steel and composite structures* 48, no. 6 (2023): 649-666. https://doi.org/10.12989/scs.2023.48.6.649
[27] Kawashima, Shiho, Pengkun Hou, David J. Corr, and Surendra P. Shah. "Modification of cement-based materials with nanoparticles." *Cement and concrete composites* 36 (2013): 8-15. https://doi.org/10.1016/j.cemconcomp.2012.06.012
[28] Shekari, A. H., and M. Seyed Razzaghi. "Influence of nano particles on durability and mechanical properties of high performance concrete." *Procedia Engineering* 14 (2011): 3036-3041. https://doi.org/10.1016/j.proeng.2011.07.382
[29] Amin, Mohamed, and Khaled Abu el-Hassan. "Effect of using different types of nano materials on mechanical properties of high strength concrete." *Construction and building materials* 80 (2015): 116-124. https://doi.org/10.1016/j.conbuildmat.2014.12.075
[30] Bragança, Mariana OGP, Kleber F. Portella, Marcelle M. Bonato, Emerson Alberti, and Cláudia EB Marino. "Performance of Portland cement concretes with 1% nano-Fe3O4 addition: Electrochemical stability under chloride and sulfate environments." *Construction and Building Materials* 117 (2016): 152-162. https://doi.org/10.1016/j.conbuildmat.2016.05.033
[31] Montoro, V. I. N. C. E. N. Z. O. "Miscibilita fra gli ossidi salini di ferro e di manganese." *Gaz Chim Ital* 68 (1938): 728-733.
[32] EN, British Standard. "197-1, Cement-Part 1: Composition, specifications and conformity criteria for common cements." *London: European Committee For Standardisation* (2011).
[33] BS 12; Specification for Portland cement. British Standards Institute: London, UK, 1996.
[34] ASTM, C33. "Standard specification for concrete aggregates." *Philadelphia, PA: American Society for Testing and Materials* (2003).
[35] BS EN 3148; Water for Making Concrete (Including Notes on the Suitability of the Water). British Standards Institute: London, UK, 1980.
[36] BS 882; Specification for aggregate from natural resources for concrete. British Standards Institute: London, UK, 1992.
[37] EN, NF. "1097-6; Tests for Mechanical and Physical Properties of Aggregates—Part 6." *European Standards Organization: Brussels, Belgium* (2022).
[38] BS EN 1097-5: Tests for mechanical and physical properties of aggregates. Determination of the water content by drying in a ventilated oven. British Standards Institute: London, UK, 2008.
[39] ASTM C 230-97; Flow Table for Use in Tests of Hydraulic Cement. American Society for Testing and Materials: West Conshohocken, Pennsylvania, United States, 1997.
[40] Cabrera, J. G., and C. J. Lynsdale. "A new gas permeameter for measuring the permeability of mortar and concrete." *Magazine of concrete research* 40, no. 144 (1988): 177-182. https://doi.org/10.1680/macr.1988.40.144.177
[41] EN, BS. "BS EN1881-122: Testing concrete. Method for determination of water absorption." *British Standards Institution, UK* (2011).
[42] BS EN 12390-5; Testing Hardened Concrete. Flexural Strength of Test Specimens. British Standards Institute: London, UK, 2019
[43] En, B. S. "12390-6:(2009). Testing Hardened Concrete. Tensile Splitting Strength of Test Specimens." *British Standard Institution, London* (2009).
[44] En, B. S. "12390-3:(2009). Testing Hardened Concrete. Compressive Strength of Test Specimens." *British Standard Institution, London* 16 (2019)
[45] Khalaf, Mohammed A., Cheah Chee Ban, and Mahyuddin Ramli. "The constituents, properties and application of heavyweight concrete: A review." *Construction and building materials* 215 (2019): 73-89. http://dx.doi.org/10.1016/j.conbuildmat.2019.04.146
[46] Huang, Xinyun, Zhenfu Chen, Qiuwang Tao, Liping Xie, Dan Jin, and Dan Wu. "Effect of Magnetite Concrete on Splitting Tensile Strength and Gamma Ray Shielding Performance Exposed to Repeated Heating at High Temperature." *Materials* 16, no. 7 (2023): 2592. https://doi.org/10.3390/ma16072592
[47] Kong, Deyu, David J. Corr, Pengkun Hou, Yang Yang, and Surendra P. Shah. "Influence of colloidal silica sol on fresh properties of cement paste as compared to nano-silica powder with agglomerates in micron-scale." *Cement and Concrete Composites* 63 (2015): 30-41. https://doi.org/10.1016/j.cemconcomp.2015.08.002

[48] Martínez-García, Rebeca, MI Sánchez de Rojas, P. Jagadesh, Fernando López-Gayarre, Julia M. Morán-del-Pozo, and Andrés Juan-Valdes. "Effect of pores on the mechanical and durability properties on high strength recycled fine aggregate mortar." *case studies in construction materials* 16 (2022): e01050. https://doi.org/10.1016/j.cscm.2022.e01050

[49] Singh, L. P., D. Ali, and U. Sharma. "Studies on optimization of silica nanoparticles dosage in cementitious system." *Cement and Concrete Composites* 70 (2016): 60-68. https://doi.org/10.1016/j.cemconcomp.2016.03.006

[50] Del Bosque, IF Sáez, Wenzhong Zhu, Torsten Howind, A. Matías, MI Sánchez De Rojas, and C. Medina. "Properties of interfacial transition zones (ITZs) in concrete containing recycled mixed aggregate." *Cement and Concrete Composites* 81 (2017): 25-34. https://doi.org/10.1016/j.cemconcomp.2017.04.011

[51] Beigi, Morteza H., Javad Berenjian, Omid Lotfi Omran, Aref Sadeghi Nik, and Iman M. Nikbin. "An experimental survey on combined effects of fibers and nanosilica on the mechanical, rheological, and durability properties of self-compacting concrete." *Materials & Design* 50 (2013): 1019-1029. https://doi.org/10.1016/j.matdes.2013.03.046

[52] Amin, Mohamed, and Khaled Abu el-Hassan. "Effect of using different types of nano materials on mechanical properties of high strength concrete." *Construction and building materials* 80 (2015): 116-124. https://doi.org/10.1016/j.conbuildmat.2014.12.075

[53] Emamian, Seyed Ali, and Hamid Eskandari-Naddaf. "Effect of porosity on predicting compressive and flexural strength of cement mortar containing micro and nano-silica by ANN and GEP." *Construction and Building Materials* 218 (2019): 8-27. https://doi.org/10.1016/j.conbuildmat.2019.05.092

[54] Nensok, Mohammed Hassan, Md Azree Othuman Mydin, and Hanizam Awang. "Investigation of thermal, mechanical and transport properties of ultra lightweight foamed concrete (ULFC) strengthened with alkali treated banana fibre." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 86, no. 1 (2021): 123-139. http://dx.doi.org/10.37934/arfmts.86.1.123139

[55] Gajanan, K., and S. N. Tijare. "Applications of nanomaterials." *Materials Today: Proceedings* 5, no. 1 (2018): 1093-1096. https://10.1016/j.matpr.2017.11.187

[56] Hou, Li, Jun Li, Zhongyuan Lu, Yunhui Niu, Jun Jiang, and Taozhu Li. "Effect of nanoparticles on foaming agent and the foamed concrete." *Construction and Building Materials* 227 (2019): 116698. https://10.1016/j.conbuildmat.2019.116698

[57] Huseien, Ghasan Fahim, Kwok Wei Shah, and Abdul Rahman Mohd Sam. "Sustainability of nanomaterials based self-healing concrete: An all-inclusive insight." *Journal of Building Engineering* 23 (2019): 155-171. https://doi.org/10.1016/j.jobe.2019.01.032

[58] Hamers, Robert J. "Nanomaterials and global sustainability." *Accounts of Chemical Research* 50, no. 3 (2017): 633-637. https://doi.org/10.1021/acs.accounts.6b00634

[59] Gkika, D. A., N. Vordos, J. W. Nolan, A. C. Mitropoulos, E. F. Vansant, P. Cool, and J. Braet. "Price tag in nanomaterials?." *Journal of Nanoparticle Research* 19 (2017): 1-7. https://doi.org/10.1007/s11051-017-3875-x

[60] Arsenov, Danijela, Jelena Beljin, Danica Jović, Snežana Maletić, Milan Borišev, and Ivana Borišev. "Nanomaterials as endorsed environmental remediation tools for the next generation: Eco-safety and sustainability." *Journal of Geochemical Exploration* 253 (2023): 107283. https://doi.org/10.1016/j.gexplo.2023.107283

[61] Corsi, Ilaria, Iole Venditti, Francesco Trotta, and Carlo Punta. "Environmental safety of nanotechnologies: The eco-design of manufactured nanomaterials for environmental remediation." *Science of The Total Environment* 864 (2023): 161181. http://dx.doi.org/10.1016/j.scitotenv.2022.161181

[62] Buchman, Joseph T., Natalie V. Hudson-Smith, Kaitlin M. Landy, and Christy L. Haynes. "Understanding nanoparticle toxicity mechanisms to inform redesign strategies to reduce environmental impact." *Accounts of chemical research* 52, no. 6 (2019): 1632-1642. https://doi.org/10.1021/acs.accounts.9b00053