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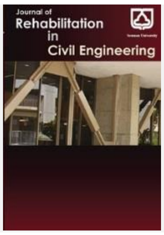

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Physical, Mechanical, Durability and Microstructure Properties of Lightweight Concrete Containing Nanomaterials: A comprehensive Review

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ABSTRACT

In the construction industry, lightweight concrete (LWC) is a common structural and masonry element. Its low density and significant thermal and acoustic insulation properties are why it is popular. Recent studies have examined the potential benefits of adding different types of nanomaterials (NMs) to LWC to improve its characteristics. Recent decades have seen a notable increase in interest in the growing field of nanotechnology because of its innovative research and practical applications. The main objective of this review is the application of NMs to enhance both the fresh and hardened properties of LWC. The effects of NMs on the physical (thermal conductivity), mechanical (Compressive, Flexural, Splitting tensile strength), Microstructural, and Durability properties of LWC were examined. This study found that NMs improved the performance of LWC depending on the type and dosage of NMs. It showed better mechanical, microstructural, and durability properties than the samples without NMs. The addition of nanomaterials to concrete increases the pozzolanic content and surface energy of the cement composite, resulting in the durability enhancement of the cement composite. This article explored that incorporating nanoparticles into concrete enhances its strength by (12 to 58) %, (and 16 to 90) %, (16 to 55) % on the 28th day for the compressive, Flexural, and splitting tensile strength respectively, but it reduces the workability of the cement composite. However, the excessive concentration of nanoparticles causes particle agglomeration, which decreases the strength and durability of the cement composite. Thus, the review concluded that using nanomaterials in concrete is more favorable concerning the strength and durability advancement of the composite, as it improves their qualities and accelerates the hydration process. The knowledge gained from this review and the created database could be helpful to researchers and industry experts to facilitate the adoption of NMs to enhance the performance of LWC.

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1. Introduction

Concrete produced with an oven-dry density of less than 2000 kg/m^3 is often referred to as "lightweight concrete"[1]. Lightweight concrete (LWC) has been utilized in concrete buildings for a long time. LWC's key advantages include reducing structural weight, cutting transportation costs, improving the strength-to-weight ratio, offering strong tensile strain capabilities as well as providing superior fire and noise isolation [2]. By using LWC, structures' dead loads are decreased and their seismic resistance is increased, making it possible to design structural elements that are lighter and more compact. Precast, lighter and smaller concrete pieces are also preferable since they are more buoyant, easier to pull, and necessitate less costly methods of processing and transporting. Consequently, floating structures that make use of LWC have progressively increased in frequency [3,4].

LWC is used in precast items fabrication such as slabs, panels, and blocks because of its low density. Additionally, it can be applied with on-site additives in ready-mixture treatments. One of the most well-known vertical structures to use lightweight concrete (LWC) is the Marian Tower in Chicago, which serves as an example of a modern structure constructed with LWC [5]. Following the early 20th-century emergence of lightweight industrial aggregate, the focus shifted to building plants to manufacture LWC for use in critical infrastructure [6]. Numerous bridges in the United States and Canada were constructed using light concrete technology. Although there was a surge in interest in this kind of concrete in the mid-1900s, engineers were only able to utilize it in certain locations due to concerns about its poor compressive strength [7,8]. As shown in Figure 1 [8], there are three varieties of lightweight concrete, each having unique characteristics. The first variety of concrete is called colloidal or cellular concrete. It is created by forcing air bubbles into the mixture to create spaces that aid in weight loss. Sandless concrete is the second variety of concrete. concrete in the second variety combines water, aggregate, and cement as a binder instead of sand. Concrete containing lightweight aggregate is the third kind. This type is produced by replacing traditional aggregate with lightweight aggregates such as perlite, pumice [9], vermiculite [10], expanded clay [10], thermo cole beads [10], coke breeze [11], artificial cinders [12], shale [13], slate [14], Cement Clinker aggregate [15], fly ash aggregate [16,17], and scoria.

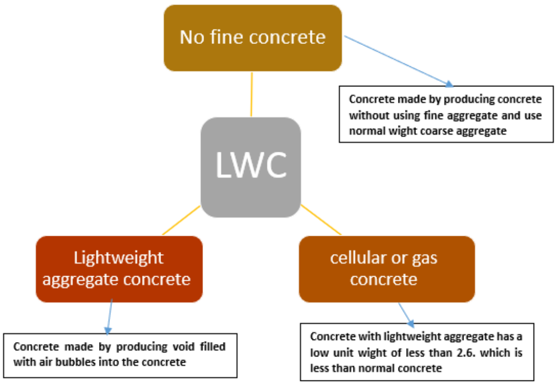


Fig. 1. Types of LWC.

Despite the material benefits of LWC, the biggest obstacle to the widespread use of LWC infields is the conflict between density and strength, stiffness, and toughness. This is caused by the poor strength and stiffness of the lightweight concrete in addition to the brittle cement paste-to-aggregate bond. Furthermore, it was discovered that the variables governing the stiffness of the lightweight concrete included aggregate kinds, specimen size and geometry, and stress type. Before field applications, basic concerns including bleeding, segregation, and addition to strength, the interfacial transition zone's (ITZ) effect needs to be considered. Thus, a range of methods was used to enhance the properties of lightweight concrete, including fiber and fine particle reinforcing [18].

The most often used method to increase the strength of LWC is to use a variety of fiber kinds as reinforcing elements. Compared to typical concrete, which fractures at the matrix-aggregate contact, LWC is less resistant to flexural and fracture loads due to aggregate rupture. After matrix cracking, the fibers can boost LWC's energy absorption capacity and slow the cracks' initiation, improving the material's fatigue strength [19]. The results showed fibers addition greatly improved the material's tensile strength, flexural toughness, and impact resistance [20]. Moreover, the addition of steel fibers increased the load-carrying ability of LWC by 28% and the ductility ratio by around 85% when compared to plain LWC [20]. While adding fibers improves the mechanical properties, adding different types of fibers was also found to reduce workability, increase water absorption, and increase the void index of LWC. These disadvantages affecting the packing of LWC mixtures severely restricted the wide range of applications for LWC [19].

This study aims to identify the effects of various nanomaterials, such as graphene, silica, nano metakaolin, alumina, carbon nanotubes, or nano-silica on the mechanical performance of lightweight concrete. In addition, it aims to present a thorough review of the body of research on the mechanical properties of lightweight concrete incorporating nanomaterials. Also, to assess how the number of nanomaterials used, their dispersion methods, and their mixing processes affect the mechanical characteristics of lightweight concrete. Additionally, to investigate the synergistic effects of combining multiple nanomaterials in lightweight concrete and their impact on mechanical behaviour. Furthermore, to assess the long-term durability and sustainability aspects of lightweight concrete containing nanomaterials. Finally, to identify potential challenges, limitations, and gaps in the current understanding of nanomaterials in lightweight concrete and propose future research directions.

This study provides a comprehensive and up-to-date review of research conducted on the mechanical properties of lightweight concrete with nanomaterials, consolidating information from various sources. It presents a detailed comparative analysis of the effects of different nanomaterials on the mechanical performance of lightweight concrete, highlighting their unique contributions and potential applications. Moreover, this study explores new insights into the optimization of nanomaterial dosage, dispersion, and mixing techniques to achieve enhanced mechanical properties in lightweight concrete. Also, it proposes innovative approaches for combining multiple nanomaterials to create synergistic effects and improve the overall mechanical behaviour of lightweight concrete. The review addresses gaps or limitations in the current knowledge base and suggests areas for further research and development in lightweight concrete containing nanomaterials field of study. Figure 2. shows the type of Nanoparticles

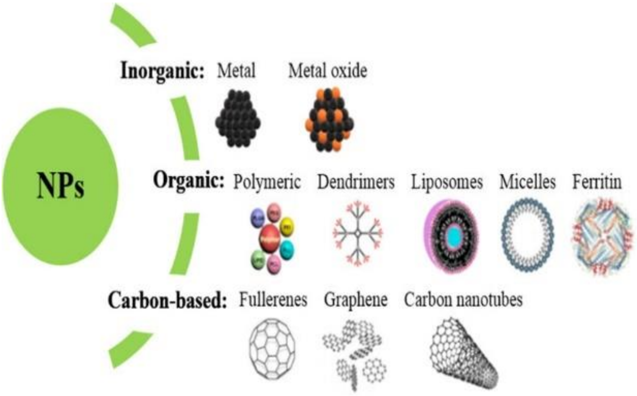


Fig. 2. Type of Nanoparticles[21].

2. Research significance

This study presents a discussion of the impact of nanomaterials on lightweight concrete. It emphasizes the potential advantages of utilizing nanoparticles in lightweight concrete, such as enhanced mechanical properties, durability, and microstructure, such as nano-silica, nano metakaolin, nano CaO_3, nano Al_2O_3, nano Fe_2O_3, nano ZnO_2, nano MgO, and CNTs [21-23]. Additionally, this paper discusses the difficulties in determining the appropriate dosage and effectiveness of nanomaterials and suggests future directions for study and development [24].

When compiling and analyzing the most recent research, scholars and practitioners in the construction sector will find this review article to be an important resource, to enhance the performance of lightweight concrete, a variety of fibers and their combinations with nanoparticles have been chosen and carefully explained. Moreover, adding nanoparticles can assist in reducing the environmental impact of concrete buildings by enhancing the durability properties of lightweight concrete.

3. Nanomaterials used in concrete

According to researchers, nanomaterials are among the best components when mixed with cement because they improve the composite's flexural strength, durability, and resistance to shear and compressive strength. Additionally, in the building and construction sectors, chemical activation procedures for concrete and its constituents have improved concrete with technical features that distinguish it from ordinary concrete and are environmentally benign. Additionally, it was noted that these materials offer solutions for several complex structural designs, indicating a promising future for the development of concrete with novel and highly desired specifications [24]. Furthermore, several studies demonstrated that nanoparticles enhance the strength, smoothness, and longevity of concrete [24]. Figure 3 demonstrates that nano silicate (SiO_2), which makes up 51% of the nanomaterials used most frequently to improve the qualities of concrete, is followed by 15% of TiO_2 and 6% of Al_2O_3.

The main goals of adding nanoparticles to concrete are to boost workability, increase mechanical strength, improve durability, and add new functions. Nanomaterials can significantly increase the compressive, flexural, and tensile strength of concrete by strengthening the cementitious matrix. Additionally, they can improve the concrete's density and refine its microstructure, which will lessen its permeability and raise its resistance to environmental elements including carbonation, moisture intrusion, and chemical attack.

Additionally, by inserting encapsulated healing agents that may self-heal damage-induced fissures, nanomaterials can enhance the self-healing characteristics of concrete. Because of its capacity for self-healing, structures may last longer between repairs and maintenance needs.

Incorporating nanoparticles into concrete not only enhances its functionality but may also have positive environmental effects. The building industry may become more sustainable by lowering the requirement for material renewal and the corresponding carbon emissions by extending the lifespan and durability of concrete structures.

Nevertheless, there are still issues in successfully integrating nanoparticles into concrete. Critical factors that need to be taken into consideration include achieving uniform dispersion of nanoparticles, optimizing dosage, guaranteeing compatibility with other concrete components, and addressing potential health and environmental problems.

In summary, incorporating nanoparticles into concrete is a viable strategy for transforming the building sector. Concrete can be made into a high-performing, long-lasting material with greater strength, increased durability, and extra functions by utilizing the special qualities of nanoparticles. The goal of this field's ongoing research and development is to advance the capabilities and useful application of nanotechnology in the concrete construction industry by investigating novel nanomaterials, manufacturing processes, and applications. Figure 3. Percentage of nanomaterials reported.

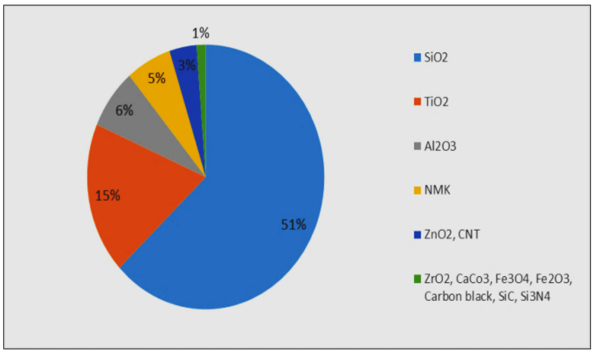


Fig. 3. Percentage of nanomaterials reported.

4. Nanomaterials effect on fresh properties of lightweight concrete containing nanomaterials

Improved mechanical performance requires a strong fresh-state performance. Workability testing is one of the most crucial assessments that must be carried out at this point [25]. The workability can be ascertained using the slump test Astm C143 [94] [28-29]. The test for flowability and the relationship between flow diameter, yield stress, plastic viscosity, and flow time. Based on prior studies, a higher slump slope indicates better workability, which in turn indicates how easily concrete will flow without separating [28]. Furthermore, workability and concrete strength are connected. Because concrete self-compacts, it needs to be sufficiently workable to get the maximum strength. The most important factors affecting the stage of fresh and hardened concrete are workability and slump flow.

Hong et al.,2022 [26] investigated how nano-graphene oxide affected the LWC slump test. The researchers separated their work into two sections: one has varying percentages of graphene oxide, and the other does not contain nano-graphene oxide. The lightweight concrete without nano-graphene oxide showed a slump height of 95 mm in the slump test, and the slump values fell to 50 mm over time. Comparing the greater dose of nano-graphene oxide to the reference combination, the workability decreased by 40%.

According to Xu et al., 2011 [29], adding nano-$CaCO_2$ to concrete increases its workability. According to the study, the slump measure rises with a progressive increase in nano $CaCO_3$, and it improves to 8.5% when it reaches 2%. The good dispersion of nano$CaCO_3$ in concrete; which successfully improved the classification of tiny particles and increased workability, was credited to this study. Sayman et al., 2019 [30] examined the impact of nano-silica on LWC performance. The findings showed that the slump considerably reduced as the nano-silica dose increased. According to researchers, as the amount of nano-silica in the concrete increased, the combinations required more water to become more workable.

In another investigation, the impact of nano clay on the workability of lightweight, self-compacting concrete was examined by Hamad and Sarhan, 2021 [31]. The outcomes were computed after adding various dosages of nano clay. According to the study, as the dose increased, nano clay enhanced stagnation flow, which improved workability. When the dosage was increased from (6–8%) nano clay, workability rose as much as 10%. The primary cause of this state is the infiltration of nano-clay particles, which fill in tiny gaps and enhance workability.

Joanna et al., 2019 [29] examined the effect of NS, micro-silica, and nano-carbon dioxide on the workability of LWC. The findings indicated that variations in the quantity of light aggregate caused variations in the slump's height., despite the equal proportion of nano-silica, nano-carbon dioxide, and macro-silica. The highest value was recorded when replacing 80% of light gravel. Figure 4. shows the slump values concerning the amount of certain NP types[

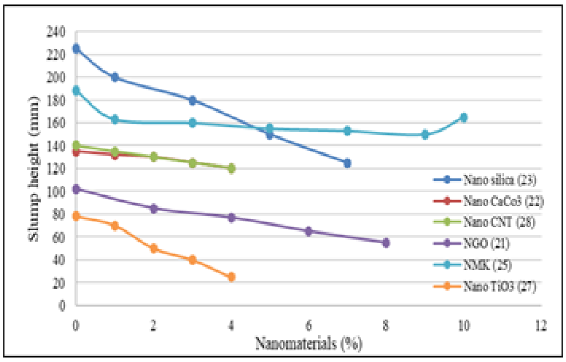


Fig. 4. Slump values concerning the amount of certain NP types[21-23][25][32,33].

Fig 4 illustrates how adding nanomaterials reduced the workability of LWC mixtures, and how this reduction rises with increasing nanomaterial concentration, irrespective of the kind. This decrease can be explained by the nanomaterial particles absorbing a portion of the mixed water. The particles' large specific surface area and strong reactivity draw in water molecules. Because of this, less free water is required to increase the mixture's fluidity.

Naniz and Mazloom, 2018 [2] proposed modifying the superplasticizer's dosage to get appropriate fluidity as a solution to this problem. The results demonstrated that, as seen in Figure 5, the addition of nanomaterials raised the dose of the superplasticizer (SP) when the water/binder ratio (w/b) remained constant. This increase was dependent upon the amount of nanoparticles that were replaced. where the number of nanomaterials grew along with the amount of superplasticizer (SP) needed to obtain the appropriate slump flow diameter. These results concluded that the addition of nanoparticles reduces the fluidity of LWC even at substantial doses of SP. The slump flow diameter and superplasticizer quantity are displayed in Fig 5.

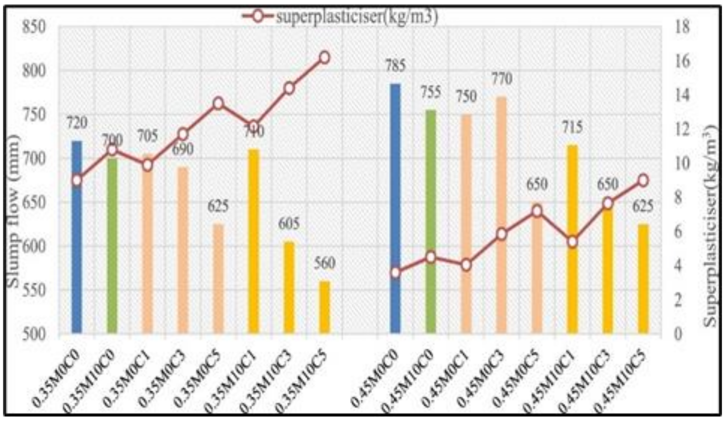


Fig. 5. Variation of flow diameter (mm) and superplasticizer additive quantity (kg/m³) at different w/b ratios [2].

Where the number before (M) refers to Water/binder ratio and (M) is micro-silica, (C) Colloidal nano-silica.

5. Nanomaterials effect on hardened properties of lightweight concrete containing nanomaterials

One of the newest techniques used in the building sector is nanoconcrete creation. Previous research demonstrated that mixing different nanoparticles produced nano concrete. The application of nanoparticles can modify lightweight concrete's mechanical properties in a variety of ways. Nanomaterials can interact with the concrete matrix in innovative ways due to their small size and huge surface area, which can improve several mechanical [34].

5.1. Compressive strength improvement

It has been found that adding graphene oxide (GO) or other nanoparticles to lightweight concrete, carbon nanotubes (CNT), and nano-silica (NS), improves its compressive strength. In the Lee et al. investigation, the compressive strength of high-strength lightweight concrete (HSLWC) was dramatically enhanced by adding a modest amount of GO [35]. Similarly, at 28 days, Narasimhan et al. discovered that adding 1% NS and 2% CNT produced a maximum compressive strength of 1072 MPa. [36]. After reviewing multiple investigations, Al-Luhybi and Altalabani concluded that adding NS material to lightweight concrete increases its compressive strength [24]. Furthermore, Wang et al. observed that adding 3% nano-silica to lightweight aggregate concrete increased its compressive strength considerably (LWAC) [37]. According to Sekhavati et al., adding nano-silica and nano-lime to lightweight concrete enhanced its compressive strength [38].

The impact of carbon nanotubes (CNTs) and nanoplates graphene (GON) on the properties of lightweight concrete was examined by Adhikary et al., 2021 [39]. Various combinations of graphene nanoplates and carbon nanotube concentrations were used to create a large number of lightweight concrete specimens. The findings showed that the addition of carbon nanotubes and graphene nanoplates somewhat boosted the compressive strength of lightweight concrete samples. The concrete specimen produced with the same concentration of graphene nanoplates and the composite specimen formed with carbon nanotubes exhibit a larger concentration of nanoplates when comparing the improvement in compressive strength. The composite samples with the highest (15%) increase in compressive strength were those created by combining (GO) nanoplates and CNTs.

Narasimhan et al., 2020 [38] looked into the effects of (CNT) and nano-silica (NS) as reinforcing fillers to increase the compressive strength of lightweight concrete built using expanded clayThe highest compressive strength was found in LWC samples containing 1% NS and 2% CNT, which was 39% greater than that of the control sample. Conversely, the addition of 3% CNT resulted in a significant 16% reduction in compressive strength after 28 days [34]. The addition of nano-silica + CNTs improves compressive strength, as shown in Figure 6.

Zhang et al., 2018 [18] studied how applying small amounts of nano-silica affected the compressive strength of LWC. The results demonstrated that adding nano-silica might alter the cement paste's hydration and enhance the interfacial area between the light aggregate and the cement paste. However, the addition of significant doses has a negative effect due to the size expansion at the interface between the cement paste and the aggregate. The investigation also demonstrated a 25% increase in compressive strength over the control mixture at low doses. Figure 7 illustrates how the addition of a small amount of nano-silica improves compressive strength.

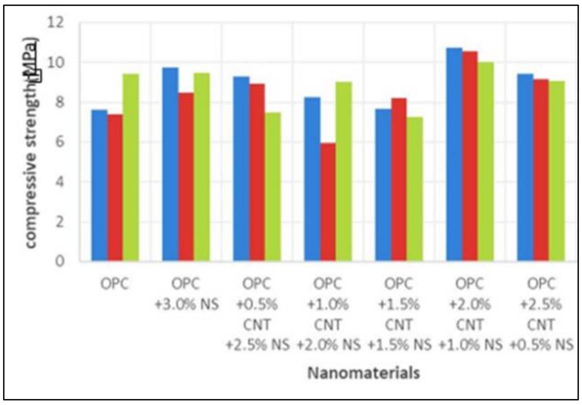


Fig. 6. Effect of NS, CNT on compressive strength.

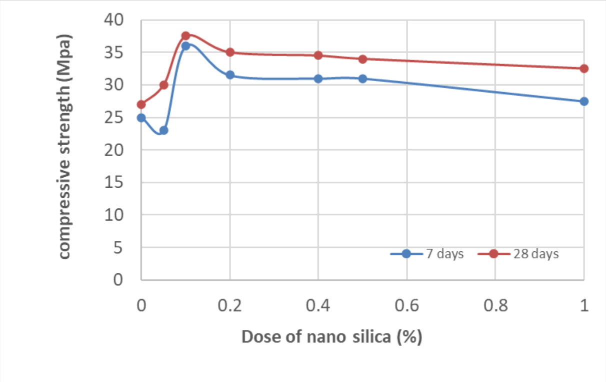
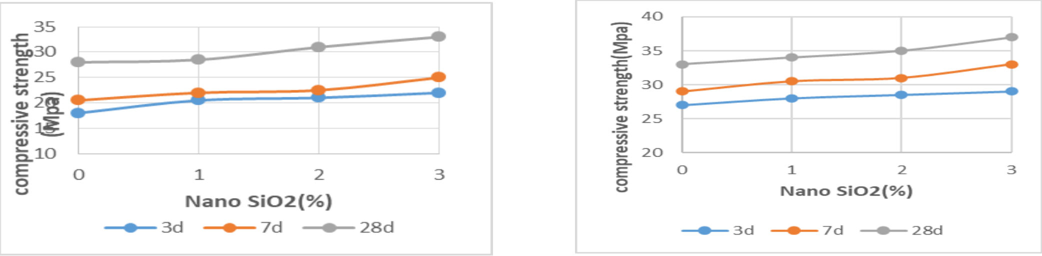


Fig. 7. Effect of a low dose of NS.

The impact of NS at doses of 1,2,3% on the compressive strength of light concrete was investigated by Wang et al., 2018 [37]. The investigators employed a pair of lightweight aggregate varieties. The outcomes demonstrated that adding nano-silica greatly increases compressive strength. Long-term deflation was not significantly affected, according to the study. A 52% improvement in compressive strength was observed, with the maximum strength being attained at a 3% dose. Figure 8 illustrates how adding nano-silica in varying nanosizes improves compressive strength.



(A) (B)

Fig. 8. Impact of NS on concrete compressive strength. (A) Lightweight concrete with Ceramsite lightweight aggregate, (B) With lightweight aggregate.

To demonstrate how nano-silica impacts the pore properties, strength, and thermal insulation of concrete with light aggregate, Abdel Rahman et al., 2019 conducted an experimental analysis. The scientists employed three concentrations of nano-silica (1,2,4%). The results of the investigation demonstrated a notable impact of nanotechnology on compressive strength, as well as a notable improvement. The softness of the nanomaterial that absorbs the mixture's water also causes a decline in the workability of concrete, according to the authors. Densifying the microstructure and matrix of the concrete required the use of nano-silica. Figure 9 illustrates how adding nano-silica improves compressive strength [40].

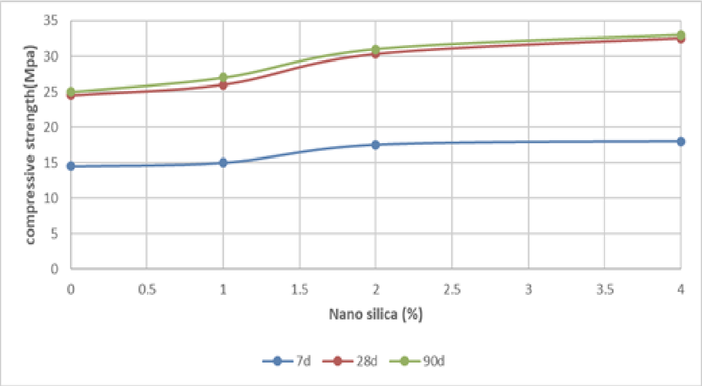


Fig. 9. Effect of nano-silica on compressive strength.

Nano-silica and nano-lime were utilized by Sikavita et al., 2019 to examine their impact on the durability and compressive strength of lightweight concrete subjected to an acidic environment. The researchers discovered that using 5% nano-silica and 5% nano-lime increased compressive strength by 53%. Furthermore, this ratio represented the concrete's maximum strength [38]. Figure 10 shows how nano-silica affects compressive strength.

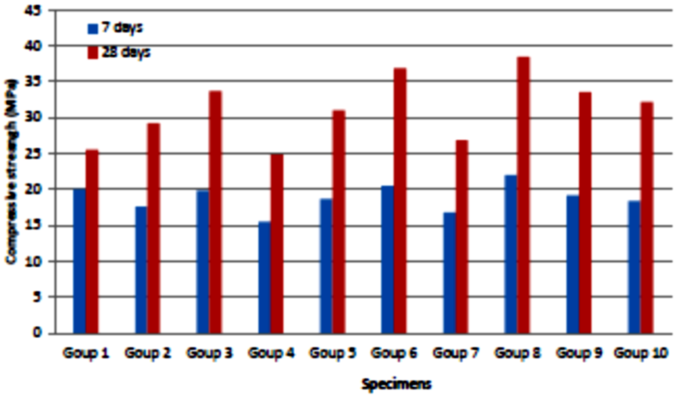


Fig. 10. effect of nano-SiO2 on compressive strength.

Sikavita et al.,2019 used nano-silica and nano-lime to investigate their effects on the durability and compressive strength of lightweight concrete exposed to an acidic environment. The researchers discovered that adding 5% nano-silica and 5% nano-lime increased the compressive strength by 53 percent. Moreover, this ratio indicated the maximum strength of the concrete [41]. The impact of nano-silica on compressive strength is demonstrated in Figure 11.

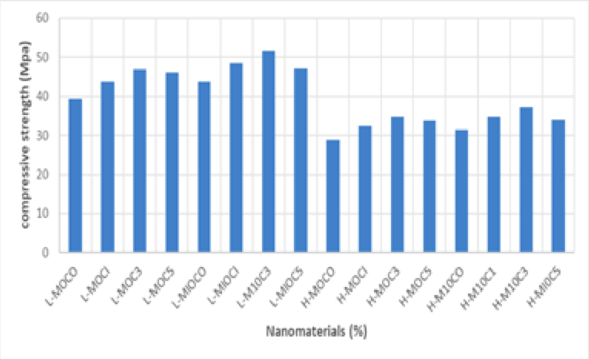


Fig. 11. Effect of nano-silica and micro-silica on concrete compressive strength.

Sugumaran et al. conducted research in 2021 to determine the effect of nano-metakaolin on the compressive strength of lightweight self-compacting concrete. The results showed that concrete mixtures containing nano-metakaolin provided good compressive strength results. This means that these mixtures can be employed when applying an external treatment is difficult. The outcomes also showed that the lightweight compacted concrete satisfies technical requirements and has good workability that is comparable to the properties of the reference concrete because of the dispersion of nanoparticles [42]. Figure 12 shows how nanometakaolin affects compressive strength.

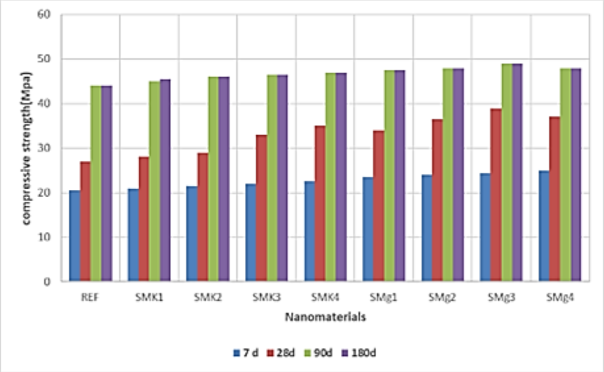


Fig. 12. Effect of NMK on concrete compressive strength.

Different percentages of nano-metakaolin (5, 10, 15, and 20%) were utilized by Keleştemur et al., 2015 to demonstrate how it impacted the concrete's mechanical characteristics, especially compressive strength. tests were conducted on samples between the ages of 7 and 90 days. The research demonstrated that as the dose of nano-metakaolin was raised, the compressive strength rose until it reached the optimal value of 15%, at which point it recorded a rate that was 26.0% greater than the reference mixture. The researchers attributed this improvement to the packing effect between the cement paste and aggregate interface, which raised the concrete's density. Furthermore, the pozzolanic interaction between calcium hydroxide and nano-metakaolin produced the C-S-H gel, which is responsible for the concrete's strength [43].

Shoukry et al.'s 2016 study [46] combined white Portland cement and vermiculite with nano-metakaolin (2, 4, 6, 8, 10) %. There were six types of lightweight concrete mixtures created. The first mixture is a nano-metakaolin-free control mixture. As previously indicated, the other five mixes have different proportions. After 28 days, the samples' compressive strength was assessed to determine the impact of nano-metakaolin. When 10% nano-metakaolin was substituted, the compressive strength rose by 58% compared to the control combination. 10% provided the highest compressive strength, according to the study. Ultimately, the findings demonstrated that the lightweight concrete mixture's improved microstructure was the cause of the improvement that produced the highest compressive strength [44].

Karahan et al., 2012 [45] made shale-and-lightweight concrete mixtures to investigate the effects of nano-metakaolin on the concrete's compressive strength. Four mixes were created by the researchers. Nano-metakaolin (5, 10, and 15%) was added to three mixes instead of some of the cement. The mixture that was in control was the fourth one. The concrete's density was less than 2000 kg/m3, according to the researchers, when enlarged shale aggregates (SCLC) were used. The results showed that when 10% of nano-metakaolin was added, the compressive strength increased by a significant percentage (1%), and the resistance then equalled that of the control combination. The impact of nanometakaolin on compressive strength is depicted in Figure 13.

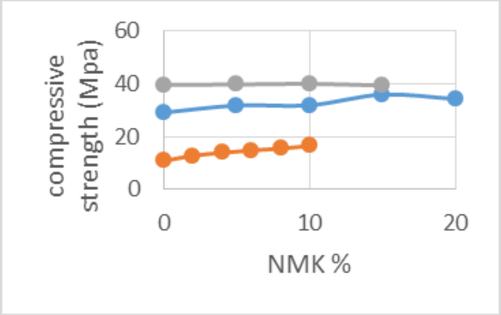


Fig. 13. Effect of nano metakaolin on compressive strength.

The effects of adding CNT and nano-silica on the compressive strength of lightweight concrete were investigated by Du Ying et al., 2013. CNTs and nano-silica dosages of 20, 60, and 100% were applied at cement weight percentages of 0.05, 0.15, and 0.45. Twelve combinations not including the reference mixture were created. At 28 days of age, compressive strength tests were performed. The results showed that the compressive strength increased when both nanomaterials were used together. When combined, they enhanced the hydration reaction and the microscopic structure. With an increased rate of 16%, the addition of 0.05% CNT resulted in the maximum compressive strength [46]. Figure 14 shows the impact of nano CNTs on the compressive strength of lightweight concrete.

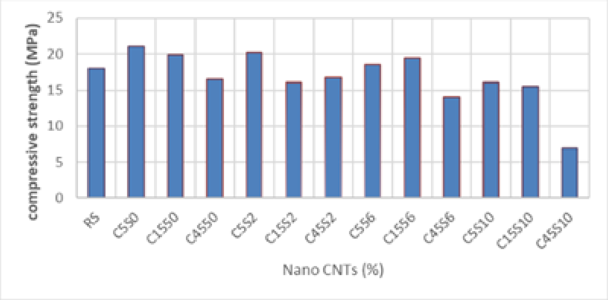


Fig. 14. Nano CNTs impacts on compressive strength.

The effects of complimentary cementitious materials, nano-alumina, and nano-rice husk ash, on the compressive strength of lightweight concrete were investigated by Mohseni et al., 2016. The addition of nano-alumina (NA) helped maintain compressive strength even with 20 or 30wt% rice husk ash (RHA), while polypropylene fibers significantly increased flexural strength Incorporating RHA and NA in polypropylene fiber-reinforced cement mortars resulted in increased flexural strength and reduced water absorption and drying shrinkage.

Fine particles like RHA segmented large pores, aiding in the nucleation of hydration products in cement paste, leading to reduced water absorption.

XRD analysis showed that RHA turned into amorphous silica when burned between 300 and 700°C, mainly composed of silica. The study found that although there were some differences in each material's compressive strength, combining the materials produced the strongest result. The greatest increase in compressive strength was observed when 10% nano rice husk was replaced with 3% nano alumina. The percentage indicated a 20.1% increase in compressive strength at 90 days, compared to an 18.2% rise at 28 days [47]. Figure 15 shows the effect of nano-alumina and nano-rice husk ash on compressive strength. Figure15. Shows the effect of nano-rice husk ash, and nano-alumina on compressive strength of lightweight concrete.

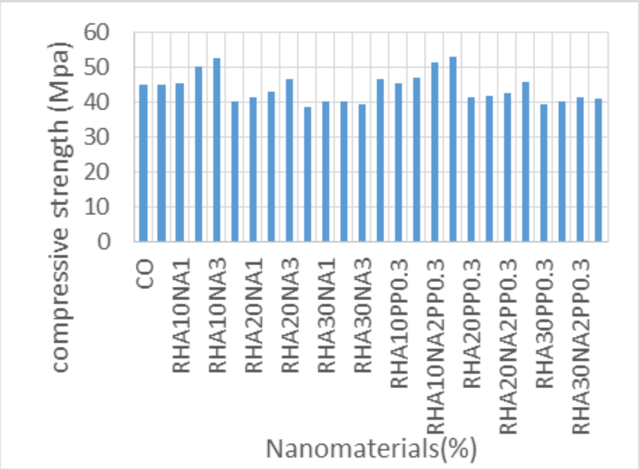


Fig. 15. Effect of nano-rice husk ash, and nano-alumina on compressive strength.

Table 1. Compressive strength improvement for lightweight concrete containing different nanomaterials.

NO.	Nanomaterial used	Replacement % of nanomaterials	Optimum nanomaterials %	% Of improvement	Reference
1	Nano Al2O3	1,2,3	2	23	[42]
2	Nano CNT	0.05,0.15,0.45	0.05	16	[41]
3	Nano CNT+NS	0.5,1,1.5,2,2.5,3	2+1	40	[31]
4	nano-metakaolin	2, 4, 6, 8, 10	10	58	[44]
		5,10,15,20	15	27	[38]
5	Nano metakaolin+ MGO	(5,10,15,20),(2.5,5,7.5,10)	20+10	12.5	[37]
6	Nano silica	1,2,3	3	52	[33]
		1,2,4	4	30	[34]
		0.05, 0.1, 0.2, 0.5	0.05	42	[32]
7	Nano lime+nano silica	5,10,15	5+5	53	[35]
8	Nano silica + microsilica	1,3,5NS + Ms10	3+10	31	[36]
9	TiO2	3,5	5	23	[48]
10	Fe2O3	3,5	5	47	[48]
11	ZnO2	0.5,1,1.5,2	2	25	[49]
12	Nano clay	2,4,6,8,10	10	48	[31]
13	Nano CaCO3	1,2,3	3	34	[50]

Fig. 16. and Table 1. Shows the effect of various nanomaterials on the compressive strength of lightweight concrete.

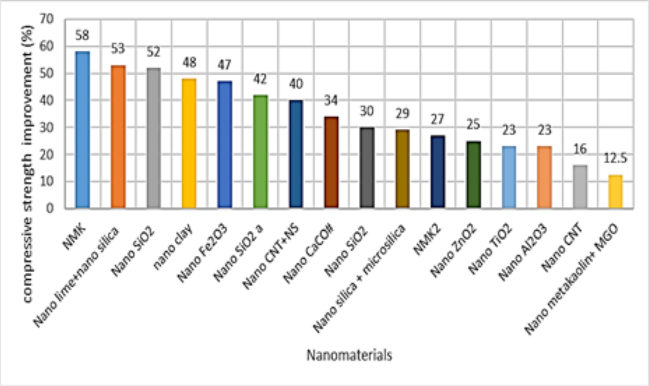


Fig. 16. Compressive strength improvement with different nano-composite types.

5.2. Flexural strength improvement

Improving the flexural strength of lightweight concrete involves various strategies and modifications to the mix design to ensure it can withstand bending and tensile forces while remaining lightweight. Many studies were conducted to enhance the flexural strength of lightweight concrete.

The effects of nano aluminium in the ratios of (1,2,3)% nano aluminium and (19,20,30)% rice husk ash and polypropylene fibers were investigated by Mohseni et al., 2016. To investigate how adding micro aluminium to other components affects bending resistance, the researchers created 25 different combinations. Models were assessed when they were 28 and 90 days old. The results of the investigation showed that the bending resistance increased as the model became older and that the addition of (3% nano aluminium, 10% rice husk ash, and 0.3% polypropylene fibers) produced the highest bending resistance. These percentages increased the bending strength to 41%, according to the study. The outcome has shown that the strength loss resulting from substituting polypropylene fibers and rice husk ash was offset by raising the dose of nano aluminium to 3% [47].

To determine the impact of nano aluminium on bending strength, Shabar et al.,2017 created four combinations, each having 0.25, 0.5, 0.75, or 1% of the material. Comparing the concrete mix with the reference mix, the researchers found that the addition of nano-aluminum lowers the bending resistance as its proportion rises. Up to the maximum dosage, the study revealed a steady, linear decrease in bending resistance. The high reactivity of nano aluminium, which reduced the rate at which calcium hydrate gel, which gives concrete its strength, was produced, was how the researchers explained these decreases [51].

Small quantities of nano-silica were added to lightweight concrete by Zhang et al.,2018 to examine the impact on flexural strength. Five combinations with nano silica contents of (0.05, 0.1, 0.2, 0.5, and 1)% were utilized. The models underwent 7 and 28 days of processing and assessment. while compared to the control combination, the researchers found that the flexural strength results at 7 days of age did not change while employing a dose of 0.05%; however, the flexural strength increased to 41% when the addition rate reached 0.1%. When the dose of nano-silica was raised by more than 2%, the flexural strength decreased. The flexural strength at 28 days increased by (46, 23, 45, 48, 70) % for all doses in the models compared to the flexural strength at 7 days. The results of the study indicated that flexural strength decreased when the dose was increased above 0.5% [18].

Different dosages of nano-silica were employed by Rahman et al., 2019 to assess how it affected the flexural strength of lightweight concrete. Doses of (2 and 4) % nano silica were applied to partially replace the cement's weight in lightweight concrete. After receiving treatment for 28 days, flexural strength was assessed. The findings demonstrated that adding 2% nano-silica enhanced the flexural strength by 16% while adding 4% nano-silica raised the flexural strength by 25%. The outcomes were unchanged when the models were 90 days, according to the researchers [40].

Ghanbari et al., 2020 [52] looked at the effect of nano-silica on the flexural strength of lightweight concrete. Three different doses of nano-silica (2,4,6%) were utilized and compared to the mixture that served as the standard. The research showed that all of the combinations improved flexural strength. The sample with 4% nano-silica had the highest recorded flexural strength at 28 days of age, which was 35% higher than the reference combination's flexural strength. The improvement can be attributed, according to the study, to the process of using nano-silica to fill the gaps, which strengthened the microstructure and enhanced its interconnectivity. Additionally, the pozzolanic action of the material improves the area of contact between the cement paste and aggregate by fortifying the adhesion of the contact areas.

Nano clay was employed by Hamad et al.,2021 to increase the flexural strength of lightweight concrete. Five distinct combinations were created using five different dosages of nano clay (2,4,6,8, and 10%). The models were assessed when they were 7, 28, and 56 days old. The outcomes demonstrated that the addition of nanoclay improved every mixture over time. When flexural strength was compared to the reference combination at 56 days of age, the researchers found that this improvement was the largest percentage at 16%. The study also revealed that the greatest improvement across all age groups was 10% nanoclay [31].

Nano-titanium was employed by Ali Nazri et al.,2022 to improve the flexural resistance of lightweight concrete. According to the study, flexural strength can be increased by hastening the synthesis of C-S-H by adding a dose of 4% nano-titanium. Furthermore, the outcomes demonstrated that the addition of nano titanium dosage improved the microstructure of the concrete mixture because of the well-packed big, medium, and fine pores [53].

To confirm their impact on the flexural strength of lightweight concrete, Du et al., 2023 investigated carbon nanotube at a dose of (0.05, 0.15, 0.45)% and nano-silica at a content of (0.2, 0.6, 1)% by weight of cement. The reference combination was used to compare the results of the tests. The study found that all combinations comprising the two nanomaterials increased flexural strength by 10% to 50%. With an improvement rate of 90% over the reference mixture, the dose of 0.15% carbon nanotube with 0.2% nano-silica was found to have the maximum flexural resistance. While the sample with the 10% nano-silica and 0.45% carbon nanotube demonstrated the least improvement in flexural strength, with an improvement of only 7.53% [46].

Researchers Othman et al.,2023 looked into how flexural strength was affected by nano-calcium carbonate. The investigators employed six nano-calcium carbonate dosages. A dose of (1,2,3,4,5,6) % Nano $CaCO_3$ was added, and the results showed that the flexural strength rose by (7.46, 22.39, 30.26, 58.75, 23.5, 7.2) %, correspondingly. When 4% nano $CaCO_3$ was added, the greatest improvement in flexural strength (64%) was observed. According to the study, the robust networked nature of nano-calcium carbonate which is typified by van der Waals forces that enhance molecular communication is the cause of this enhancement. Additionally, the compact arrangement of wetting products produced by Nano Calcium Carbonate results in smaller pores and larger particles, which in turn shortens the interfacial distance and boosts strength. Ultimately, a dose increase of more than 4% decreased the bending resistance because the cement paste's microstructure was damaged by particle aggregation or the introduction of calcium carbonate nanoparticles between the particles [54]. Figure 17. and Table 2. shows the effect of various nanomaterials on the flexural strength of lightweight concrete.

Table 2. Flexural Strength improvement for lightweight concrete containing different nanomaterials.

NO.	Nanomaterials Used	Replacement % of nanomaterials	Optimum nanomaterials %	% Of improvement	references
1	Nano clay	2,4,6,8,10	10	+16	[31]
2	Nano Al2O3	1,2,3	3	+41	[47]
		(0.25, 0.5, 0.75, 1)	none		[51]
3	Nano silica	(0.05, 0.1, 0.2, 0.5, 1)	0.1	+41	[18]
		2, 4	4	+25	[40]
		(2,4,6)	4	+35	[52]
4	Nano CuO	4	4	+16	[53]
5	CNTs +NS	(0.05, 0.15, 0.45 +(0.2, 0.6, 1)	0.15CNT+0.2NS	+90	[46]
6	Nano-calcium carbonate	(1,2,3,4,5,6)	4	+59	[54]

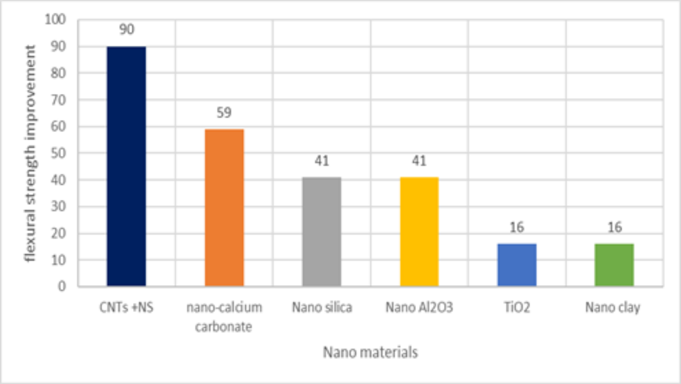


Fig. 17. Flexural strength improvement with different nano-composite types.

5.3. Splitting tensile strength improvement

It is known that concrete of all types cannot bear tensile loads, but it is necessary to study this property to ensure control of cracks resulting from tensile forces. splitting tensile strength is very important, especially in applications for bridges, sidewalks, and precast members. Researchers conducted studies on improving breakaway tensile strength.

To investigate the effects of changing the amount of nano aluminium, Nazri et al., 2010 tested the effects on lightweight concrete. There were four different dosages of nanoaluminum (0.5, 1, 1.5, and 2) % used. To compare the effects of various nanoaluminum concentrations with a reference mixture that didn't contain any nanomaterial, five combinations were made. The models were evaluated at 7, 28, and 90 days of age. Tensile strength increased greater in all combinations than in the control mixture, according to the analysis. The addition of 1% nano aluminium increases the tensile strength. The researchers attributed the decline in the concrete's tensile strength to a rise in the quantity of nanoaluminum in the concrete mixture. Because of this increase, calcium hydroxide and nano aluminium particles did not mix [55].

Othman et al., 2022 [56] investigated the impact of Fe3O4 at the nanoscale to show how it affected tensile strength. Six combinations with varying nano-Fe_3O_4 (0.10, 0.15, 0.20, 0.25, and 0.30) % by weight of cement were created by the researchers. The models were assessed when they were 7, 28, and 56 days old. The combinations adding micro Fe_3O_4 all improved, but to varying degrees, the researchers found. At 56 days of age, adding 0.25% nano Fe_3O_4 and 51% yielded the maximum tensile strength. The results of the investigation demonstrated that the nanomaterial's ability to speed up the production of calcium hydrate, which gives concrete its strength, was the cause of the gain in tensile strength.

Ghanbari et al., 2020 [52] examined the joint effects of nano-silica (2,4,6%) and fibers (0.25,0.5,0.751,1.5%) on the tensile strength of lightweight concrete. Twenty-four different concrete mixtures containing different proportions of the two components were made and contrasted. The study found that at 28 days of age, the tensile strength of the 24 combinations increased from (3-55) % when compared to the control mixture. This was ascribed to the combined effect of NS and fibers. The study's findings showed that while using each material separately improved tensile strength, the improvement was not as significant as when the two materials were combined. The best tensile strength was obtained by adding 1.5% fiber and 4% nano-silica, according to the study. The findings demonstrated that the pozzolanic activity of nano-silica, which interacts with the components of the concrete to increase connections between the aggregate and cement paste, is primarily responsible for the improvement in the tensile strength of lightweight concrete. As the paste's strength increases, the lightweight aggregate's restricted hardness increases as well since it keeps the aggregate from shattering. The study found that adding nano-silica to lightweight concrete yielded better results than including fibers.

Saad et al., 2021 [57] investigated how lightweight concrete's tensile strength was affected by nano-silica. Three doses of nano-silica (0.75, 1.5, and 2) % were utilized by the researchers. Models were assessed when they were 28 days old. The findings demonstrated that the tensile strength of every mixture rose and that the tensile strength increased with each additional dose beyond 2%. When 2% was added, the tensile strength increased to the greatest point, showing a 45% improvement over the control combination.

Asil et al., 2022 [58] demonstrated how basalt fibers and geopolymer-containing lightweight concrete's tensile strength was affected by nano-CNTs. The binders utilized by the researchers were a combination of nano-CNTs and blast furnace slag. According to the study, adding bar fibers and CNTs could result in a 32% improvement in tensile strength. The concrete's constituent parts interacted with the nano-CNTs to fill up the spaces, create a hydrogel, and create a dense structure that improved the material's tensile strength. Additionally, as cracks typically start in the light aggregate, the presence of basalt fibers fortifies the link between the cement paste and aggregate. According to the study, adding CNTs at a rate of 0.15% and basalt fibers at a rate of 0.6% produced the highest tensile strength.

Hong et al., 2023 [35] utilized various dosages of nano-graphene oxide (NGO) to illustrate how it affects lightweight concrete's tensile strength. Five mixes with NGO were created; the percentage of cement in each combination was (0.02, 0.04, 0.05, 0.06, and 0.08) by weight. The researchers combined NGO-containing mixes with rice husk ash. Tensile strength was increased by all five mixes, according to the study. When more than 0.05% NGO was added, the researchers saw a drop in tensile strength. By adding 0.05% NGO, the tensile strength was the highest (24%) as compared to the reference combination. When NGO was used in the right proportion, it was completely consumed and a substantial amount of calcium hydrate was produced, which improved the tensile strength. The NGO particles, on the other hand, multiplied and interacted with the concrete particles without interacting with them, weakening the connection and decreasing the strength of the joint when the dosage was increased over the optimal limit.

Ali et al., 2023 [59] investigated how lightweight concrete's tensile strength was affected by nano-silica. Lightweight concrete is made with expanded clay aggregate, which is lightweight. Three combinations were made, depending on the % of nano-silica in the mixture (0.5, 0.75, and 1%). At the ages of 7, 28, and 90 days, the models underwent testing and examination. The results showed that at the age of 28 days, the mixtures containing nano-silica had an increase in tensile strength (3, 10, 16) % as compared to the reference combination. All age groups showed the highest tensile strength when 1% nano-silica was applied. The results showed that the tensile strength of all mixes grew linearly and progressively. The interaction of calcium hydroxide and nano-silica The researchers attributed this rise to the cement paste-aggregate interfacial zone (ITZ), which improved the mixture's microstructure. As shown in Table 3. and Figure 18, the splitting tensile strength of lightweight concrete is affected by nanomaterials when combined with them.

Table 3. Splitting tensile strength improvement.

NO.	Nanomaterials Used	Replacement % of nanomaterials	Optimum % of nanomaterials	% Of improvement	references
1	Nano silica	2,4,6	4	+55	[52]
2	Nano Aluminum	0.5, 1, 1.5, 2	1	+35	[55]
3	Nano Fe2O3	0.10, 0.15, 0.20, 0.25, 0.30	0.25	+51	[56]
4	Nano silica	0.75, 1.5, 2	2	+45	[57]
5	Nano-CNTs	0.05,0.1,0.15,0.2	0.15	+20	[58]
6	NGO	0.02, 0.04, 0.05, 0.06, 0.08	0.05	+24	[35]
7	Nano-silica	0.5, 0.75, 1	1	+16	[59]

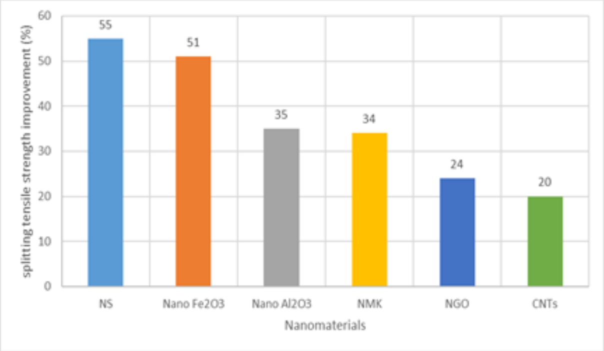


Fig. 18. Split tensile strength improvement with different nano-composite types.

5.4. Water absorption

Atmaca et al., 2017 [60] investigated the permeation of gases into the concrete mixture when adding nano-silica. The researchers used 3% nano-silica on different mixtures of lightweight aggregates (0, 10, 20, 30, 40) %. The results demonstrated that by improving the microstructure of lightweight concrete, the addition of nano-silica decreased water absorption and permeability to gases and chlorides.

Narasimhan et al., 2020 [36] studied the effect of nano-silica and nano-CNTs on the absorption coefficient of lightweight concrete. The study showed that the lowest sample absorption was in the control mixture and increased after adding nanomaterials. The researchers explained this increase in the water absorption process to the high surface area of the nanomaterial particles, which increases hydration reactions and thus increases water absorption. The study showed that the highest absorption rate was when adding 1:2 nano-silica/nano-CNTs, as well as when using a dose of 1:2 nano-silica/nano-CNTs. In addition, researches showed that the voids in lightweight aggregates have a role similar to that of nanomaterials in increasing water absorption.

Heidarzad et al., 2021 [61] used nano aluminium oxide and studied its effect on concrete. The addition of nano aluminium oxide led to a reduction in water absorption from (10-46) %, depending on the dose used when compared with the reference mixture. The results showed that the lowest water absorption was when a 3% dose was added, and the highest absorption was when a 1.5% dose was added. It forms a hydrous silicate gel, which in turn reduces the pores and thus reduces water absorption. Reducing water absorption increases the durability of concrete and harmful environmental factors.

Asil et al., 2022 [58] studied the effect of (CNTs) on the absorption property of lightweight concrete. Researchers note Concrete quality is classified into three categories; medium and good based on the results of water absorption tests. Concrete (LWGC) specimens' water absorption decreases as the number of carbon nanotubes (CNTs) combined with ground granulated blast furnace slag (GGBFS) increases. The presence of CNTs alone reduces water absorption by 23.6% to 31% while their combined use with blast furnaces (BFs) reduces it even further ranging from 16.8% to 37.4%. The inclusion of CNTs significantly decreases water absorption. Enhances the compaction and filling of channels and pores. By combining CNTs with GGBFS the issue of water absorption, in aggregates is effectively addressed, resulting in durability.

The finding was supported by Rahman et al., who discovered that increasing the dose of nano-silica in lightweight concrete decreased the amount of effective water porosity and decreased water absorption [62]. Table 4. shows the amount of improvement in reducing water absorption and the ideal percentage of nanomaterial added to concrete.

Table 4. Effect of nanomaterials on water absorption of lightweight concrete.

Nano type	Nano-material replacement %	Ideal mix %	Major findings	% of reduction	Refe.
Nano-silica	3	3	Reduce the water absorption	73	[63]
	1,2,3	3	Reduce the water absorption	27	[60]
Nano-silica and nano-CNTs	0.5,1,1.5,2,2.5,3 NS+CNT	1+2	Increase the water absorption	44	[36]
nano Aluminum oxide	0.5,1,1.5,2,3	3	Reduce the water absorption	47	[61]
CNTs+ BFs	0.5,1,1.5,2,3CNT+0.3,0.6,0.9BFs	0.15+0.6	Reduce the water absorption	37	[58]

6. Microstructure properties of lightweight concrete containing nanomaterials

In lightweight concrete, in particular, the microstructure of the mixture is crucial. It identifies gaps, clusters, and areas of strong interconnectedness for some of its constituent parts. Numerous tests are carried out, such as SEM, FESEM, XRD, and numerous others, to determine the intricate structure of the concrete mixture. The tests that were carried out in earlier research to determine the degree to which nanoparticles affect the microstructure of lightweight concrete will be covered in this study.

6.1. SEM, fesem

One powerful analytical instrument is field emission scanning electron microscopy (FESEM). With the use of these instruments, materials' morphology and microstructure can be examined at extremely high resolutions. FESEM testing is essential to comprehending and characterizing the properties of lightweight concrete that contains nanoparticles. The microstructure of lightweight concrete can be accurately analyzed by the use of FESEM investigation. This test is one of the best ways to find the distribution and dispersion of nanoparticles and provide a clear image of the concrete matrix both before and after adding the nanomaterial since the microstructure changes when nanomaterials are coupled with their components. Ismail et al., 2018 [64] concluded that the presence of fewer voids in the concrete mixture containing nano-silica than in the control mixture was shown by the use of SEM inspection. Additionally, compared to combinations containing (1.5,2) % NS, this study helped confirm that the mixture containing (0.75) % nano silica was free of cracks. Fahmy et al., 2022 [65] verified the microstructure of lightweight self-compacting concrete by SEM analysis with the addition of Nano Waste Class and Nano Waste Ceramic. When the two nanomaterials were added, it was found that the texture grew more compact, small holes decreased, and massive crystals formed, but at a slow rate. Al-FESEM was utilized by Samadi et al., 2020 to analyze their materials After adding the nanomaterial to the geopolymer refuge, the researchers observed a discernible improvement in the microstructure. The aforementioned analysis also revealed to the researchers that a high concentration of non-interacting particles reduced the microstructure's density[66]. Behfarnia et al.,2017 [67] examined the microstructure of nano- and micro-silica-containing geopolymer concrete using SEM. The application of nano-silica, according to the researchers, enhanced the microstructure of geopolymer concrete. The creation of CSH gel, which gives concrete its extra strength, was used by the researchers to explain this improvement. As the pozzolanic interaction of nano-silica with the components of concrete filled the spaces, this gel formed. Ibrahim et al., 2018 [68] conducted research on the impact of nano-silica on the microstructure and strength of concrete. In comparison to the control mixture, the researchers observed that the addition of nano-silica enhanced the microstructure of concrete. The results of the SEM examination, which provided an accurate image of the microscopic structure, were interpreted by the researchers. Additionally, a clear picture of the Si and Al compounds in charge of the polymerization process was provided by the examination[69][70]. Sastry et al., 2021 [70-71] revealed that adding nano-titanium to fly ash-containing geopolymer concrete enhances its microstructure. The scientists deduced that this improvement stemmed from the quick production of wet goods and nano-packing, which shrank the pores, through SEM analysis. Additionally, it was noted that the addition of nanoparticles enhanced the microstructure of geopolymer mortars. Ng et al., 2018 [72-73] examined the microscopic alterations brought about by adding nanoparticles to concrete using a scanning electron microscope (SEM). Researchers have shown that adding nanoparticles to concrete alters its characteristics in several basic ways, including compressive, flexural strength, split tensile, abrasion resistance, water permeability, and pore structure. Li et al., 2004 [69] displayed the concrete's microstructure, which contained nano-silica and nano- Fe_3O_4. The type of cement paste, the dispersion of the nanomaterial, and the interface region between the cement paste and the aggregate were all visible in the photos that were produced. These images provide a comprehensive description of the concrete mixture's increased strength. Muhammad et al.,[70], and DU et al., [63] released a study on the impact of nano-metakaolin on concrete's microstructure. The dispersion of nanoparticles and the connections between C-S-H crystals and the nanomaterial were depicted in the study. The investigation shed light on the increase in water content and strength.

Although dose and efficiency concerns still need to be resolved, the use of nanomaterials, particularly nano-SiO_2, in lightweight concrete (LWC) has demonstrated potential for increasing strength and durability [22]. Increases in cement concrete's workability and compressive strength have been observed when nanomaterials, such as NS, Al_2O_3 nanoparticles, NGO, CNTs, nano-TiO_2, nano Fe_3O_4, nano-clay/metakaolin, and nano-$CaCO_3$, are incorporated as supplemental cementitious materials [73]. Concrete's mechanical strength may be increased by using nanomaterials like nano-silica, multi-walled carbon nanotubes (MWCNT), and nano-titanium dioxide (n-TiO_2) [74]. Additionally, It has been discovered that adding nanomaterials as partial replacements for cement, such as nano-cement (NC), nano-silica-fume (NS), nano-fly-ash (NF), and nano-metakaolin (NM), improves the properties of concrete that harden [75]. Figure 19. shows images of the microstructure of lightweight concrete with nanomaterials incorporated. It showed that the amount of C-S-H produced was greater after adding doses of nanomaterials.

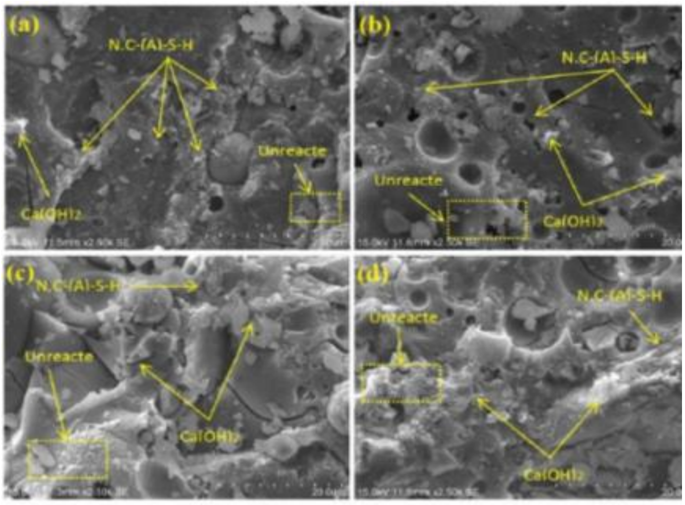


Fig. 19. FESEM pictures of AAMs with varying amounts of BGWNP [66].

6.2. X-ray

Researchers have utilized X-ray diffraction studies extensively, particularly in compounds that incorporate nanomaterials. This analysis is used in the construction industry to identify and assess the mineral content of raw materials, identify the composition of concrete at the microscopic level, and resolve challenging issues when integrating nanomaterials [76].

Zhang et al., 2018 [18] noticed that when tiny amounts of nano-silica were added to lightweight concrete, the composition of the concrete matrix was altered. The compounds took the shape of fibers, which filled in the fissures in the cement paste. The concrete's strength increased and its permeability decreased as a result of this microstructure change. The investigation also revealed that the X-ray examination revealed the fibers' chemical makeup.

Rahman et al., 2019 [40] investigated how the microstructure of lightweight concrete was affected by nano-silica. Utilizing X-ray analysis, the researchers ascertained the modifications brought about by adding nano-silica (NS) to the blend. The analysis provided precise data regarding the shrinkage of void diameters in the microstructure as a result of the packing induced by nano-silica. The analysis also assisted in determining that a higher dosage of nano-silica causes particle agglomeration, which compromises the microstructure and, consequently, the strength of the concrete.

Al-Saadi et al., 2020 [77] demonstrated the use of X-ray technology to confirm the presence of nano-calcium carbonate in geopolymer concrete samples. The analysis demonstrated the formation of the amorphous geopolymer linkages that give strength and certain mineral phases like hematite, and quartz. The analysis also demonstrated the impact of filler nanoparticles, which increased density and enhanced the microstructure.

6.3. XRD

Fahmy et al., 2022 [65] used XRD examination to investigate the microstructure of lightweight concrete. Through examination, the stages formed by lightweight concrete were observed. In addition, the highest CH peaks and lowest peaks were revealed, as well as how CSH was formed as a result of the pozzolanic reaction between nanoparticles and calcium hydroxide. The examination revealed valuable information about the improved mechanical properties and durability of lightweight concrete.

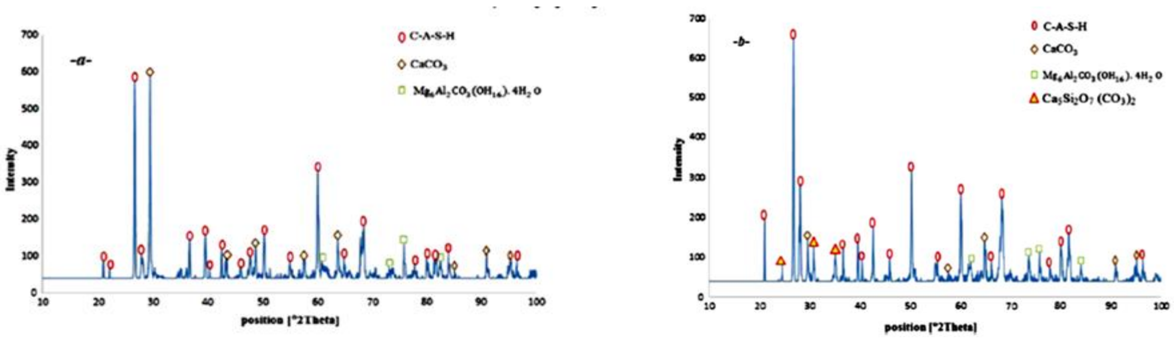
Al-Saadi et al., 2016 [78] used XRD examination to verify samples containing nano-silica, flax fibers, and fly ash. The examination gave an image of the diffraction of nano-silica, flax fibers, and fly ash. The examination also showed the main crystalline phases, the peaks of the reacting compounds, and an image of the non-reacting molecules.

Al-Saadi et al., 2016 [79] examined their concrete samples containing nano clay, geopolymer, and fly ash to verify the microstructure after mixing the materials. The examination showed the presence of three stages of nano clay horseshoes. The results showed the main diffraction phase and secondary phases by analyzing the results using XRD examination.

Adak et al., 2017 [80] studied the performance of structural geotextile concrete modified with the addition of fly ash. The researchers used XRD examination to verify the components of concrete after adding nano-silica and fly ash. Tests showed that the density of mullite, quartz, and hematite samples is more significant in geopolymer nanoconcrete when compared with the reference mixture. Through the examination, peaks of some compounds, such as silica, were observed, and the formation of new phases of quartz, albite, kaolinite, and calcium hydroxide.

In the same way, Behvarnia et al., 2017 [67] studied the effect of partial nano-silica on the permeability of concrete. Through XRD examination, the researchers concluded that three main phases were produced; calcite, C-A-S-H gel, magnesium, aluminium, and carbonate-hydroxide-hydrate. This examination facilitated obtaining a clear picture of the reactions and formation of compounds occurring within the concrete mixture.

Al-Saadi et al., 2019 [81] used XRD examination to determine the crystalline stages of nano-silica interaction with concrete components. Examination showed that all samples contained two crystalline phases. The XRD examination also gave an image of the presence of some compounds such as mullite and quartz in all samples. Figure 20. XRD analysis of (a): control specimens; (b): a 1% addition of NS.



(a) (b)

Fig. 20. XRD analysis of (a): control specimens; (b): a 1% addition of NS [76].

7. Durability properties of lightweight concrete containing nanomaterials

Nanomaterials can enhance the durability of lightweight concrete by reducing permeability. This helps prevent the ingress of aggressive substances, such as chloride ions and sulfates, leading to better resistance against corrosion and chemical attack.

7.1. Rapid sulfate and chloride permeability test

Du et al., 2015 [63] studied the effect of adding nano-silica to lightweight concrete at different rates (1,2,3%). The researchers focused their study on the depth of penetration of materials (permeability). The researchers noticed a decrease in the penetration depth of the material. The particular reason for this circumstance is the decrease in concrete porosity due to the effect of nano-silica filling. The addition of nano-silica resulted in a decrease in the amount of water absorption due to the decrease in permeability. Adding nano-silica to lightweight concrete reduces the diffusion of chlorides inside it, and as the dose increases, the penetration of chlorides decreases.
Vargas et al.,2018 [82]examined the behaviour of lightweight concrete when nano-silica was added to it under the influence of sulfate attack. The researchers used different doses of nano-silica (0-10) % by weight of cement. Adding 10% nano-silica significantly reduced the attack of magnesium sulfate when compared to other mixtures that contained less nano-silica. The results showed a decrease in pore size in light concrete. The researchers explained that the reaction of nano-silica with calcium hydroxide formed a C-S-H gel that further improved the microstructure and thus reduced permeability and increased durability.

Sun et al., 2020 [50] studied the effect of nano-calcium carbonate, its penetrability to chlorides, and its resistance to frost and carbonization. After testing and calculating the chloride ion diffusion coefficient, the results showed a decrease in the chloride diffusion coefficient due to nano-calcium carbonate filling the pores, thus improving the microstructure, which enhanced the concrete's resistance to chlorides, sulfates, and harmful liquids. The results showed that the best percentage to prevent chlorides from penetrating concrete is 1% $CaCO_3$ and 20 fly ash.

.Hong et al., 2023 [35] studied the effect of Nanographene oxide on lightweight concrete. The study showed that adding graphene oxide reduces the penetration of chlorides into concrete. The results showed that adding a dose of 0.05% graphene oxide significantly reduced the migration of chloride ions, and this in turn increased the concrete's resistance to harmful chlorides. The researchers observed that the nanoparticles improved the microstructure, created harmless pores, and reduced or interrupted the transport of chlorides. High penetration of chlorides when increasing the dose leads to weak concrete, and this happens when the graphene oxide content increases and its particles agglomerate.

Garg et al.,2023 [62] found that using nano-metakaolin with lightweight concrete had a clear effect on the durability of concrete. All samples containing nano-metakaolin were not affected when exposed to attack by NaCl and $MgSO_4$, and the resistance increased as age increased. The study found that adding a 10% dosage produced the best compressive strength. Fly Ash and 7.5% nano metakaolin. It was also noted that the microstructure improved when adding nano-metakaolin, which enhanced durability. Table 5. shows the ideal percentage of nanomaterials that gave the best improvement to concrete against the effects of chlorides.

Table 5. Effect of various nanomaterials in preventing chlorides in lightweight concrete.

Nano type	Nano-material replacement %	Ideal mix %	Major findings	Refe.
Nano-silica	0-10	10	Prevent chlorides from penetrating concrete	[61]
	1,2	2	Prevent chlorides from penetrating concrete	[63]
	(0-10)	10	reduced the attack of magnesium sulfate	[82]
Nano-calcium carbonate + fly ash	1,2,3 +15,20,25	3+ 20	Prevent chlorides from penetrating concrete	[50]
Nanographene oxide	0.02,0.04,0.05, 0.06,0.08	0.05	Prevent chlorides from penetrating concrete	[35]
Nano-metakaolin + fly ash	2.5,5,7.5.10+ 5,10,15,20	10+7.5	Prevent chlorides from penetrating concrete	[62]
Nanographene oxide	0.02,0.04,0.05 0.06,0.08	0.05	Chloride Penetration Resistance	[35]
10 Nano metakaolin+20 fly ash	2.5,5,7.5,10 NMK+5,10,15,20FA	7.5+15	Chloride Penetration Resistance	[62]

7.2. Shrinkage

Federowicz et al., 2021 [22] studied the impact of lightweight aggregate (LWA) on the overall shrinkage of concrete has been thoroughly examined, and LWA's internal curing effect contributes to the reduction of total shrinkage. There isn't much research on shrinkage in lightweight concrete with nano-SiO_2 (NS). As demonstrated by Wang et al., NS might not have a significant impact on overall shrinkage. The shrinkage curves for concrete with and without NS during the first seven days were nearly the same. After ninety days, the differences in shrinkage values were apparent; for LWAC with ceramsite from Nantong with 1 weight percent, 2 weight percent, and 3 weight percent NS addition, respectively, the average total shrinkage increased by 2.2%, 3.9%, and 5.4%. While NS has little effect on overall shrinkage, it does reduce surface cracking. In comparison to reference samples, the addition of 3% NS resulted in a significant 25% reduction in fracture length and overall cracking area.

Mansour et al., 2021 [83] studied the effect of nano-metakaolin on the shrinkage property of lightweight concrete. The results indicated that shrinkage values increased when nano-metakaolin was incorporated. The researchers noted that the ageing of the models increased the shrinkage of the concrete. The use of expansive materials reduced shrinkage by reducing evaporation, which in turn improved the strength of lightweight concrete without water curing.

Ahmed et al., 2022 [1] showed the effect of nano-ceramics on the shrinkage property of lightweight concrete. The findings demonstrated that as curing age increases, concrete shrinkage increases. Also, the study showed that the use of 2% nano-ceramic improved concrete shrinkage.

He et al., 2023 [84] studied the effect of nano-metakaolin on the shrinkage property. the study showed that the drying shrinkage of HVMC is reduced by 39.6% relative to plain concrete when 20% LMK is applied. The drying shrinkage of HVMC decreases as the sample size increases. Table 6 shows the effect of nanomaterials on the shrinkage of lightweight concrete and the ideal percentage of nanomaterials added to it.

Table 6. Effect of nanomaterials in shrinkage of lightweight concrete.

Nano type	Nano-material replacement %	Ideal mix %	Major findings	% of reduction	Refe.
Nano silica	1, 2, 3	3	Increase the shrinkage	5.4	[37]
	1, 2, 3	3	Reduce the shrinkage	25	[22]
Nano-montmorillonite	1, 2, 3	3	Reduce the shrinkage	57.4	[85]
Carbon nanotubes	0.1,0.2, 0.3	0.3	Reduce the shrinkage	19.4	[85]
Nano-calcium carbonate	1, 2, 3	2	Reduce the shrinkage	17.1	[85]
CNTs	0.05–0.5%	0.1	Reduce the shrinkage	15.4	[86]
Naon Rise husk ash	10,20,30	30	Reduce the shrinkage	12	[87]

7.3. freeze-thaw

Concrete's ability to withstand freeze-thaw cycles can be significantly impacted by the use of nanoparticles. A crucial quality for concrete exposed to extreme weather is its capacity to withstand freeze-thaw cycles, especially in areas where these cycles occur frequently. By addressing several causes of deterioration, nanomaterials can effectively increase the resistance of concrete against the damaging effects of freezing and thawing.

Concrete can have its microstructure fine-tuned at the nanoscale level with the use of nanomaterials like nano-silica or nano-alumina. They produce a denser and more compact structure by filling the gaps and pores in the cementitious matrix. By limiting the amount of water and harmful compounds that can seep into the concrete during freeze-thaw cycles, this reduction in pore size and permeability lowers the risk of damage. Also, Freeze-thaw damage can affect the Interstice Zone (ITZ), which is the area between aggregates and the cementitious matrix. By strengthening the link between aggregates and the matrix, nanomaterials can produce an ITZ that is more resilient and long-lasting. Because of this enhanced interfacial binding, there is less water infiltration and the ITZ is shielded from cracking and voiding during freeze-thaw cycles. In addition to that, the mechanical qualities of concrete, such as its strength and toughness, can be enhanced using nanomaterials. Nanomaterials strengthen the cementitious matrix, making concrete more resilient to freeze-thaw damage and cracking. A more robust and resilient concrete that can tolerate the strains brought on by freezing and thawing is the result of improved strength and toughness.

It is crucial to remember that different elements, including the kind, dosage, and dispersion of the nanomaterials, the composition of the concrete mixture, and the surrounding environment, might affect how successful the nanomaterials are at enhancing the freeze-thaw resistance of concrete. To achieve the desired increases in freeze-thaw durability, it is imperative to conduct comprehensive experimental investigations and long-term performance evaluations to evaluate and optimize the particular nanomaterials and their dose.

Trangini et al., 2022 [95] showed in their study that adding nano-silica to the concrete mixture increased the concrete’s resistance against freezing and thawing cycles by 70%. The researchers showed that this improvement is due to the improvement of the microstructure, which led to weight reduction during freezing and thawing cycles and enhanced compressive strength.

Liu et al., 2022 [88] studied the effect of nanomaterials on the resistance of concrete to freeze-thaw cycles and it was found that Nano-modified silicone emulsion improved the durability of concrete by increasing the concrete's resistance against the number of freezing and thawing cycles and forming a hydrophobic layer.

Overall, the incorporation of nanomaterials in concrete offers potential benefits for enhancing the freeze-thaw resistance of the material. By improving the microstructure, reducing permeability, strengthening interfacial bonding, and providing self-healing capabilities, nanomaterials contribute to a more durable and resilient concrete that can withstand the detrimental effects of freeze-thaw cycles.

8. Effect of nanomaterials on thermal properties of lightweight concrete

The thermal properties of ordinary concrete are one of the biggest problems in hot and cold countries. high heat transfer causes pollution in the environment through harmful gases emitted, as well as the lack of a comfortable environment for the residents of these buildings. therefore, researchers resorted to finding radical solutions to this harmful characteristic. One of the most important of these solutions is the use of lightweight concrete, as it is characterized by low thermal conductivity due to the presence of air gaps inside it. Research has indicated that lightweight concrete has half the thermal conductivity of regular concrete due to a significant relationship between density and thermal conductivity [89]. Through studies conducted, researchers noted that adding nanomaterials such as nano-silica, nano-metakaolin, nanographene oxide, carbon nano tube, nano alumina, and nano-iron oxides can affect the thermal conductivity of light concrete through the production of cement compounds that are resistant to heat transfer [40][90].

Saleh et al., 2021 [91] have shown that the addition of nano-silica material to concrete enhanced its thermal insulation ability by comparing the measured thermal conductivity of normal concrete of (1.22 to 2.05) W/m.C to the concrete mixed with 3% nano-silica of the weight of cement that achieved 0.5 to 0.92 W/m.c. The concrete with nano-silica showed a decrease in the thermal conductivity coefficient when converted to thermal diffusion, it showed a decrease of 41% which indicates the effect of nano-silica. The researchers found that the main reason behind the low coefficient of thermal conductivity is the presence of a small air space within the microstructure of the concrete that hinders heat transfer, and this in turn increases the heat storage capacity in the concrete. Therefore, adding nano-silica to lightweight concrete will lead to significant environmental benefits by reducing global warming resulting from the heat emission of ordinary concrete.

Bulut et al., 2020 [92] used nano-silica and nano-clay to investigate their effect on the thermal conductivity coefficient of concrete. Ratios of (05, 1, 1.5, 2, 2.5, 3) % nano silica and (2, 4, 6, 8, 10) % nano clay were used. The study showed that adding 0.5% of the two materials slightly reduced the thermal conductivity, but after increasing the proportions to (3% NS, and 10% NC), the thermal conductivity coefficient decreased by (29, 33) %, respectively. Increasing the doses of the two nanomaterials caused a difference in the results of the thermal conductivity coefficient. The researchers attributed the reason for the higher conductivity coefficient of NS than that of NC to the chemical properties and bonding between the material and the epoxy resin of the nanoparticles, in addition to the effect of the weight content.

Wang et al., 2021 [93] used CNTs in lightweight foamed concrete to investigate the thermal properties of lightweight concrete reinforced with nano-CNTs were studied after heating, and its thermal conductivity coefficient was compared with the thermal conductivity coefficient of normal and lightweight aggregates concrete that no nanomaterial. Samples were heated from room temperature to 800°C. The results showed that the thermal conductivity coefficient of foamed concrete containing nano-CNTs was lower when compared with other types of concrete. Using the thermal conductivity coefficient measurement test (one-dimensional heat transfer test and numerical analysis), it was found that increasing the temperature from room temperature to 150°C increased the thermal conductivity coefficient by 33% for all mixtures. But after increasing it to 200 percent, it decreased by 55% when increased the temperature to 600 by 60% when compared with thermal conductivity of 200 degrees Celsius. The conductivity coefficient almost stabilized when the temperature was raised to 800°C. The researchers justified the low thermal conductivity because the foamed concrete contained air bubbles that hindered heat transfer.

Wang et al., 2021 [93] used carbon nanotubes to enhance the thermal properties of lightweight foam concrete, especially the specific heat. The results showed that adding a nanocarbon tube increased the specific heat by 66% when the temperature increased from 25 to 150 degrees Celsius for all mixtures. By increasing the temperature above 200 degrees, the specific heat decreased and stabilized at an increase of 6% when compared with the reference mixture.

Saleh et al., 2021 [91] studied the effect of nano-silica on the specific heat of concrete. The researchers used three models, each containing a specific dose of nano-silica (1,2,3%). The study showed that adding nano-silica increases the specific heat of concrete. The researchers observed that the specific heat capacity increases linearly with increasing nano-silica dosage. The 3% dose recorded the highest specific heat capacity, as the specific heat increased by 8% (830 to 895 J/kg. C).

It's essential to note that the specific heat of lightweight concrete is influenced by various factors, including the type of lightweight aggregates used, the density of the concrete, and the mixing ratios. When incorporating nanomaterials, it's crucial to conduct thorough testing and analysis to understand how they affect the specific heat properties of the concrete and to optimize the mixture for the desired performance characteristics. The specific heat of the resulting composite material will be a combination of the specific heat of its components.

9. What is the potential research to conduct on these materials?

Nanotechnology in construction improves mechanical properties, creates stronger and lighter composites, reduces thermal transfer, and enables construction-related nano-sensors. Nanomaterials can be used as protective treatments to enhance the durability and conservation properties of construction materials. The addition of nanomaterials to essential construction materials, like steel and cement, has shown improvements in strength and durability. Nanotechnology research and development have introduced next-generation nanomaterials with various applications in construction, electronics, water purification, medicine, and agriculture. Overall, nanomaterials offer the potential for enhancing construction materials and addressing environmental sustainability challenges in the industry.

10. Discussion

10.1. Fresh Properties

The incorporation of nanomaterials in lightweight concrete can have significant effects on the fresh properties of the mixture. The addition of nanomaterials, such as nano-silica or nano alumina, can modify the rheological behaviour, workability, and setting time of the concrete. The study has shown that nanomaterials can decrease flowability, but they can reduce segregation and bleeding tendencies in lightweight concrete. However, it is essential to optimize the dosage and dispersion of nanomaterials to avoid negative impacts on fresh properties, such as increased viscosity or decreased workability.

10.2. Mechanical properties

Nanomaterials have demonstrated the potential to enhance the mechanical properties of lightweight concrete. The nanoscale particles can fill in the voids between larger aggregate particles, resulting in improved packing density and increased interfacial bond strength. This leads to enhanced compressive strength, tensile strength, and flexural strength of lightweight concrete. The pozzolanic reactivity of certain nanomaterials also contributes to the formation of additional hydration products, resulting in densification and improved mechanical performance. It is important to note that the effectiveness of nanomaterials may vary depending on factors such as type, dosage, and dispersion techniques.

10.3. Durability

The durability of lightweight concrete is a critical aspect, and nanomaterials can play a significant role in enhancing durability properties. The addition of nanomaterials can refine the pore structure, reduce the size and connectivity of capillary pores, and improve the resistance to moisture ingress, chloride ion penetration, carbonation, and sulfate attack. The improved pore structure and reduced permeability contribute to increased durability and enhanced resistance to aggressive environmental conditions. However, the long-term durability performance of lightweight concrete containing nanomaterials requires further investigation and validation through extensive exposure tests and monitoring.

10.4. Microstructural properties

Microstructural analysis provides valuable insights into the influence of nanomaterials on the lightweight concrete matrix. Advanced characterization techniques, such as SEM, XRD, and MIP, have been used to evaluate the microstructure, hydration products, and pore characteristics. Nanomaterials can affect the nucleation and growth of hydration products, resulting in refined microstructures with reduced pore sizes and improved interfacial transition zones. These changes positively impact the mechanical and durability properties of lightweight concrete. However, the distribution and dispersion of nanomaterials within the concrete matrix should be carefully controlled to maximize their beneficial effects.

11. Challenges and future directions

While the incorporation of nanomaterials in lightweight concrete shows promising results, several challenges and future research directions should be considered. These include optimizing the dosage and dispersion techniques to achieve uniform distribution and prevent agglomeration of nanomaterials. Additionally, the long-term performance and sustainability aspects of lightweight concrete containing nanomaterials need further investigation. Standardization of testing methods and protocols is essential to ensure accurate and reliable comparison of results across different studies. Moreover, the cost-effectiveness and scalability of incorporating nanomaterials in lightweight concrete should be evaluated to enable practical implementation in the construction industry.

In summary, the use of nanomaterials in lightweight concrete offers opportunities to enhance the fresh, mechanical, durability, and microstructural properties of the material. However, further research is required to optimize the dosages, dispersion techniques, and long-term performance of lightweight concrete containing nanomaterials. The findings from such studies can contribute to the development of more resilient and sustainable lightweight concrete structures in the future.

12. Conclusion and recommendation

The incorporation of nanomaterials in lightweight concrete has shown great potential for improving its fresh, mechanical, durability, and microstructural properties. Through a comprehensive review of the existing literature, it is evident that nanomaterials can have a significant impact on the performance of lightweight concrete.

In terms of fresh properties, nanomaterials can affect the workability and rheological behaviour of lightweight concrete. By optimizing the dosage and dispersion techniques, nanomaterials can improve the flowability and reduce the segregation and bleeding tendencies in the mixture.

Regarding mechanical properties, the addition of nanomaterials can lead to enhanced compressive strength, tensile strength, and flexural strength of lightweight concrete. The nanoscale particles fill in the voids between larger aggregate particles, resulting in improved packing density and increased interfacial bond strength. Additionally, the pozzolanic reactivity of certain nanomaterials contributes to densification and improved mechanical performance.

Durability is crucial for lightweight concrete, and nanomaterials offer opportunities to enhance its resistance to moisture ingress, chloride ion penetration, carbonation, and sulfate attack. The addition of nanomaterials refines the pore structure, reduces pore sizes, and improves the overall durability performance of lightweight concrete.

Microstructural analysis provides valuable insights into the influence of nanomaterials on the lightweight concrete matrix. Advanced characterization techniques reveal the refinement of microstructures, improved hydration products, and optimized interfacial transition zones, contributing to the observed enhancements in mechanical and durability properties.

However, several challenges and future research directions should be addressed. Optimization of dosage and dispersion techniques, long-term performance evaluation, standardization of testing methods, and cost-effectiveness analysis are areas that require further investigation. By overcoming these challenges, the practical implementation of lightweight concrete containing nanomaterials can be realized, leading to more resilient and sustainable construction practices.

In conclusion, the comprehensive review of the literature highlights the significant potential of nanomaterials in enhancing the fresh, mechanical, durability, and microstructural properties of lightweight concrete. Continued research and development in this field will contribute to the advancement and widespread adoption of lightweight concrete technology, ultimately leading to more efficient and durable structures in the construction industry.

Recommendations

Based on the comprehensive review, the following recommendations are proposed for future research:

1. Further exploration of Novel Nanomaterials: Investigate the effects of newly developed nanomaterials, such as graphene, carbon nanotubes, or nanostructured polymers, on the properties of lightweight concrete. Assess their compatibility, dispersion, and potential synergistic effects when combined with other nanomaterials.

2. Multi-Scale Investigations: Conduct multi-scale studies to understand the influence of nanomaterials on the microstructure of lightweight concrete. Utilize advanced characterization techniques, including electron microscopy, X-ray diffraction, and spectroscopy, to analyze the interfacial transition zone, pore structure, and hydration mechanisms at different length scales.
3. Long-Term Performance and Durability Studies: Conduct long-term monitoring and evaluation of lightweight concrete containing nanomaterials to assess their performance in real-world conditions. Investigate the durability properties, such as resistance to chemical attack, carbonation, and aging, over extended periods to ensure the sustained benefits of nanomaterial incorporation.
4. Life Cycle Assessment and Sustainability: Evaluate the environmental impact and sustainability aspects of lightweight concrete containing nanomaterials throughout its life cycle. Conduct life cycle assessments to compare the environmental performance of nanomaterial-enhanced lightweight concrete with conventional lightweight concrete, considering factors such as energy consumption, greenhouse gas emissions, and resource depletion.
5. Standardization and Guidelines: Develop standardized testing methods, guidelines, and specifications for the characterization and evaluation of lightweight concrete containing nanomaterials. This will ensure consistency in research outcomes and facilitate the practical implementation of these materials in construction projects.

By addressing these recommendations, future research can further advance the understanding of nanomaterial-enhanced lightweight concrete and enhance its potential in various construction applications. The continued exploration of nanomaterials in lightweight concrete will contribute to the development of sustainable, high-performance, and durable construction materials that meet the evolving needs of the industry.

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Authors contribution statement

Aziz, Farah: conceptualized the paper theme, designed the experimental methodology, and she led the project. She was instrumental in provided the primary supervision of the research team.

AlGhazali N. Abbas: contributed to co-wrote the sections of the manuscript that deal with mechanical testing and data interpretation.

Mohd Z. Mohamed: focused on the microstructural analysis. he contributed significantly to the interpretation of the results and co-authored the sections of the paper discussing microstructural properties.

Suraya A.Rashid: provided expert advice on the durability aspects of the research and assisted in refining the experimental design. She critically reviewed the manuscript and suggested substantial improvements.

Amer M. Ibrahim: candidate assisted in literature review, data collection, and preliminary data analysis. He also contributed to drafting the background and conclusion sections of the manuscript.

All authors discussed the results and implications and commented on the manuscript at all stages.

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