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Review Article

Application of Nano-Additives Reinforcement towards Concrete with Excellent Mechanical Properties: A Review

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Abstract

Until the last decade, extensive scientific research has been conducted on the different applications of nanoparticles in civil infrastructures. Nanoparticles are defined as ultrafine particles ranging in dimension below 100 nanometers. The addition of nanoparticles is a promising approach for increasing the concrete's strength and durability, hence enhancing the concrete's quality and promoting sustainability. In this literature study, the review focuses on commonly used nanoparticles in different categories, such as carbon nanotube (CNT), graphene (GNP), nano silica (NS), nano Al_2O_3, nano TiO_2, and nano clay. The review highlights the mixing method and the influence of nanoparticles on fresh and hardened concrete properties.

Keywords: High-performance concrete; Nanoparticle modification; Mechanical properties; Fresh and hardened properties

Introduction

Most nations base their economic growth on the infrastructure they have in place. Infrastructure includes things like buildings, bridges, and other infrastructures. When the economy increase, concrete is increasingly needed as infrastructure demand rises, especially high-performance concrete. The concrete mix contains cement, aggregates, sand, water, and any other additives required by design, and the current trend is to improve concrete performance by incorporating additives [1]. Currently, because of the unique physical and chemical characteristics of nanoparticles, nanotechnology presents prospective chances to develop better materials with increased qualities [2]. Nanoparticle-reinforced composites outperformed the ones with microparticles or larger-sized particles in many research fields, but the fabrication cost limited the large-scale application. Until recently, as the technology improved, the fabrication of nanoparticles became cheaper, creating a great opportunity to develop high-performance concrete by adding nanoparticles. Therefore, with growing demand to concrete with improved mechanical properties, nanoparticle reinforcement is an alternative with great potential.

Studies have shown that adding nanotechnology to the cementitious matrix can improve the properties of concrete. The term "nanoparticle" refers to particles that are 200 nm or smaller, and these substances are added to cementitious matrix either by dry mixing or by dispersing nanoparticles in water prior to wet mixing [3]. In comparison to cementitious composites without nanoparticles, cementitious composites with nanoparticles considerably enhanced microstructure and other mechanical properties. Adding various nanoparticles with proper concentrations to concrete can improve mechanical strength, chemical resistance, and lessen shrinkage while reducing bleeding and segregation. The dispersion of nanoparticles in cementitious composites, which can be accomplished by optimizing the mixing process, is one important component that affects performance [3]. In addition to dispersion, the amount of nanoparticles in the concrete mixture is also a critical factor affecting the performance. If nanomaterials are not dispersed uniformly, agglomerates of nanomaterials tend to develop, and the strength and durability of the concrete will diminish. Typically, less than 10% of nanomaterials are added in most of the studies. Also, the type of nanoparticles can significantly affect the performance of the concrete composite. To discover the optimal reinforcement, it is necessary to experiment with various types of nanomaterial with different concentrations [3]. Therefore, to develop high-performance concrete for the civil infrastructures, it is necessary to summarize the current research of nanoparticle reinforced concrete composites. To fulfill this need, this review incorporates contemporary research on the impact of nanomaterial incorporation on the mechanical strength, durability, and workability of cement-based composites. The discussion in this paper is focused on the commonly used nanoparticles and the effect of dosage on their reinforced properties.

Discussion

Commonly used nano-additives

This section focuses on nanoparticle categories and commonly used ones in the concrete mixture. The first way to classify nanoparticles is by dimensions; nanofillers can be classified as 0, 1, or 2-D materials when there are 0, 1, or 2 dimensions greater than 100 nm. Zero-dimensional nanoparticles have been suggested additives that can effectively act as filler, improving impermeability, and filling voids in the concrete mix, leading to an improved mechanical strength; some typically used 0-D nanoparticles are nano-silica and nano-alumina [4]. On the other hand, One-dimensional and two-dimensional particles can also contribute to compressive strength by decreasing porosity and redistributing pores, as well as frost resistance via the mechanism of crack bridging [4]. Materials can also classify the nanoparticle; first, there are carbon-based nanoparticles, which contain carbon atoms only. Then there are organic-based materials, consisting of organic matter; the other is mineral-based materials, such as metals and oxides. The typically used nanoparticles are presented in Table 1 (Table 1).

Table 1: Commonly used nanoparticles in different categories.

Classification	Commonly used Nanoparticles
Carbon-based NP	CNT, GNP
Mineral-based NP	Al_2O_3, TiO_2, nanosilica, nanoclay
Organic-based NP	Nanocellulose

Mixing method for nanoparticle/concrete composite

Dispersion is one of the most critical factors affecting the performance of nanocomposite and achieving uniform dispersion of the nanoparticles in the composite matrix has been challenging for researchers. The nanoparticles' dispersion level significantly impacts the concrete's fresh and hardened properties. Generally, there are two approaches to disperse nanoparticle concrete mixtures: dry mixing with cement or dispersion in water [3]. In the dry mixing process, nanoparticles should be appropriately dispersed into cement powder by using stationary blades and a rotating drum. Then the mixed powder can be directly used to fabricate concrete composite with water, sand, aggregates, or other admixtures [3]. In the wet mixing process, the nanopowder were pre-dispersed in water using ultrasonication, with or without a chemical dispersant; in addition, more than one type of nanoparticles can be pre-dispersed in water.

Suggested amount of nanoparticles

Researchers point out that the amount of nanoparticles should be controlled within 0.1–10% of cement weight, increasing mechanical properties in concrete composites [5]. With increasing nanoparticle dosage, the likelihood of agglomeration increased, resulting in a dramatic decrease in the performance of the concrete. Researchers pointed out that the agglomerate could reach to millimeter level in the mixture with a high concentration of nanoparticles [5]. Many studies have pointed out that optimum reinforcement can be achieved by 2% or nanoparticles, which avoid aggregation that negatively affects the mechanical properties [3].

Workability of nanoparticle/concrete composite

The addition of nanoparticles could improve or decrease the workability, depending on the type of nanoparticles. Due to their high surface area, nanoparticles absorb a huge amounts of water in certain instances, causing the fresh concrete mixture less workable. However, this property can be beneficial for some specialized applications, and where the greater cohesiveness of nano-modified concrete could avoid segregation [5]. In some instances, the inclusion of nanoparticles may increase the air content of the concrete, which may improve its workability. Another benefit is increased resistance to damage from freezing and thawing cycles. However, the strength may decrease when the air content is high. If the effects of nanoparticles on air entrainment can be well understood and predicted, this property might be used to adjust the air content of concrete, depending on the application demand. Research found that the workability of concrete improves by adding nano Silica, and nano clay [5]. Mudasir et al. mentioned that CNTs caused a drastic decrease in workability, which the slump flow diameter reduced from100 mm to 65 mm [6].

Mechanical Properties of nanoparticle/concrete composite

Nanoparticles increase the strength of cement-based materials by 1) enhancing the hydration process of cement, 2) increasing binder force, 3) modifying the structure of cement paste, and 4) increasing the mixture's density [7]. The following discussion is the effect of nanoparticles on the strength of concrete composites.

Compressive strength: Compressive strength is one of the most critical properties of concrete, since it ensures the quality of concrete constructions. This section discusses the effect of adding properly dispersed nanoparticles on the concrete's compressive strength. The compressive strength of concrete mixtures is affected differently by varied types of nanoparticles, and it is possible to attain the optimal compressive strength of the concrete by modifying the nanoparticle concentration [7]. In general, in most instances, the greatest strength was achieved at a lower nanoparticle level, with 1% or 2% nanoparticle content. In addition, numerous studies indicate that compressive strength might improve by above 20% at the age of 28 days [5]. In Table 2, selected studies on the compressive strength of nanoparticle/concrete are presented (Table 2).

Table 2: Influence of nanoparticles on compressive strength.

Type of Nanoparticles	Improvement (%)	Weight Content (%)	Ref.
CNT	39%	0.25 wt.%	[8]
GNP	8%	0.25 wt.%	[9]
NS	45%	2%	[10]
TiO_2	10%	3%	[11]
Al_2O_3	17%	0.50%	[12]
Nanoclay	50%	7.50%	[13]

Splitting Tensile strength: The improved split tensile strength can also be achieved by the incorporation of nanoparticles, as well as compressive strength. Similar to the compressive strength, the tensile strength will grow as the concentration of nanoparticles increases; however, once the weight content of nanoparticles exceeds a specific value, the tensile strength will be degraded. The inclusion of nanoparticles has been demonstrated to boost tensile strength by as much as 80 percent, according to the findings of numerous studies [14,15]. Furthermore, investigations on the splitting tensile strength are presented in Table 3 (Table 3).

Table 3: Influence of nanoparticles on splitting tensile strength.

Type of Nanoparticles	Improvement (%)	Weight Content (%)	RRef.
CNT	36%	0.50%	[[16]
GNP	64%	5%	[[17]
NS	20%	2%	[[18]
TiO_2	22%	5%	[[19]
Al_2O_3	18%	3%	[[20]
Nanoclay	28%	7.5	[[13]

Flexural Strength: Researchers have found that the at the flexural strength of concrete can also be significantly improved by incorporating nanoparticles, and a maximum improvement of around 60% was found in Yehia's work [21]. On the other hand, the flexural strength improved by 40-50% were commonly achieved by other studies [7,15], and some other studies are presented in Table 4 (Table 4).

Table 4: Influence of nanoparticles on flexural strength.

Type of Nanoparticles	Improvement (%)	Weight Content (%)	Ref.
CNT	27%	0.25%	[8]
GNP	16%	0.25%	[9]
NS	52%	10%	[7]
TiO_2	27%	3%	[11]
Al_2O_3	17%	3%	[20]
Nanoclay	35%	7.50%	[13]

Shrinkage of nanoparticle/concrete composite

Concrete shrinks when exposed to relative humidity levels below 100 percent and consequently loses water, leading to cracks developed at the early age of service [22]. It is clear that varied nanomaterials affect the mixture's drying shrinkage. The development of shrinkage in cement paste is proportional to the number of pores with a diameter of less than 20 nm in the matrix at early ages; thus, a greater number of small pores in a cementitious system results in more significant autogenous shrinkage at early ages. The inclusion of nanoparticles reduces the pores' size, reducing the capillary strains and autogenous shrinkage [15]. In this case, researchers have found the largest reduction in early age shrinkage can reach above 50% with the addition of nanoparticles [23]. Many researchers found that the addition of nanoparticles can increase the shrinkage of the concrete, for example, Chen et al. found that the shrinkage strain increased 32% compared to the reference [24]. In addition, increased shrinkage also found in the concrete composite with CNT, TiO_2, Al_2O_3, and nanosilica. However, studies pointed out that shrinkage in nanoparticle/concrete may vary with different sample mix, one investigation indicates that the addition of CNT also reduce the shrinkage of the concrete of 15.0%, and similar finds were obtained is nanosilica/concrete composites [23].

Summary

This work reviews the effect of nanoscale additives on the workability and mechanical performance of concrete. The influence of nanoparticle types and concentration on the performance of concrete mixture was discussed, and the summaries are presented below:

1. Depending on the type of nanoparticles, the incorporation of nanoparticles could either increase or decrease the workability. Due to their large surface area, nanoparticles can absorb large quantities of water, making the fresh concrete mixture less workable. In some situations, the incorporation of nanoparticles may increase the concrete's air content, so enhancing its workability.
2. Nanoparticles increase the strength of cement-based materials by several ways: i) enhancing the hydration process of cement, ii) increasing binder force, iii) modifying the structure of cement paste, and iv) increasing the mixture's density. Based on the literature, significantly improved compressive strength was observed in NS, CNT, TiO2 samples, and CNT, TiO2, and nanoclay have strong reinforcement on flexural strength; at last, GNP, TiO2, Al2O3, nanoclay, NS can be very beneficial to increase the splitting tensile strength. Most of the nanoparticles will increase the strength and start to decrease when the concentration of nanoparticles is too high and forming agglomeration.
3. Despite the excellent improvement in strength, the incorporation of nanoparticles could lead to increased shrinkage, which makes concrete more vulnerable to tensile cracking. However, with proper design, the addition of CNT, NS, nanoclay, Al2O3 can reduce the shrinkage of the concrete.

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Conflict of Interest

No conflict of interest.

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