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Experimental and mechanical performance of shotcrete made with nanomaterials and fiber reinforcement

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HIGHLIGHTS

- Nano-SiO_2 prevent the diffusion of external destructive factors into the concrete and improve the durability.
- Nano-Al_2O_3 acts as filler for improving the pozzolanic reaction in the concrete.
- Limit the durability impact and cracking due to shrinkage effects, sprayable the modified shotcrete.
- The effect of glass fiber has been done to prevent cracking, in the shotcrete.
- The increase in the flexibility properties of shotcrete due to glass fiber is an important consideration.

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ABSTRACT

Studying the application of nanomaterial in cement matrixes is a new subject which has attracted the attention of researchers. Development of engineered cementitious composite has produced a solution to numerous shotcrete application challenges. In this study, mechanical tests were conducted to evaluate the strength of the concrete modified by fibers and nanomaterials in terms of comparison with conventional concrete and shotcrete.

It is included in the application of Nano-Al_2O_3 and Nano-SiO_2, which are some of the cement constituent. With proper homogenization, Nano-Al_2O_3 acts as filler for improving the pozzolanic reaction in the concrete. Nano-SiO_2 particles also prevent the diffusion of external destructive factors into the concrete, thus improving the durability and stability of concrete. On the other hand, application of Alkali Resistant (AR) glass fibers improves the tensile and compressive strengths as well as concrete continuity and also resolves the changes created in mechanical properties of the fibers caused by alkaline concrete environment. Test results revealed that the maximum increase in compression and flexural strengths of modified concrete were 20.6 and 52%, respectively of its optimum compounds for 0.7% glass fiber with 1% Nano-Al_2O_3 and 1.5% Nano-SiO_2, while in the modified shotcrete, these values were increased by 22.9 and 75%, respectively. In addition, application of the mentioned materials led to decrease of penetration depth and water absorption of the modified concrete by 46.78 and 2.5%, respectively, in relation to the conventional concrete. Also, addition of fibers and nanomaterials in shotcrete reduced the effect of cracking due to shrinkage and the modified shotcrete material rebound.

1. Introduction

Application of shotcrete in the lining of tunnels is known as one of the highly efficient strategies all around the world. Deterioration and failure of concrete are highly dependent on the formation of cracks and micro cracks. By increasing the load, micro cracks have been attached and form the main cracks, which finally extend in the concrete. Tunnel linings required to resist ground stresses and to deformation associated with seismicity, should be designed with a possible loss of ductility exhibited by fiber reinforced shotcrete [1].

High performance concrete (HPC) is a specialized series of concrete prepared to provide excellent mechanical properties. For preparation of HPC some admixture (mineral, mechanical, fiber) can be added [2–4]. Fibers in the concrete lead to improved tensile and compressive strengths, energy absorption capability, abrasion resistance, ductility, softness and durability, uniformity and proper continuity [5,6]. They also lead to decreased permeability of

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concrete surface and as a result, preventing the entrance of corrosive materials. The shotcrete reinforced by the fibers was also designed similar to the concrete, based on the experimental obtained data [7,8]. When a new type of fiber has been applied in cement matrixes, in order to introduce a proper mixing plan, it is essential to conduct some experiments on the modified concrete samples to use it for construction of shotcrete samples [9]. Glass fibers have a privilege place in strengthening of concrete. The major values of compressive stresses have been taken from the concrete, while the glass fibers, highly tolerate the tensile, flexural and shear stresses [10].

In most of the studies conducted on the concrete materials reinforced by conventional glass fibers, it was observed that due to high silicon content in the alkaline environment of the concrete, the strength of the concrete was reduced after a relatively short time [11]. Based on the researches, use of ER-glass fiber is the best method for reducing the damages caused by alkaline concrete environment [12].

Research conducted by Chandramouli et al. (2010) showed that applying 1.5% dosage glass fibers, leads to increasing the Modulus of rupture and toughness about 20% and 50%, respectively. By increasing the toughness, the glass fibers prevent the development of more cracks in the concrete [13].

Yoo and et al. (2016) experimentally verified that the use glass fiber in FRP bar-reinforced concrete beams considerably improve the stiffness and decrease the crack widths, they also noted that the compost of steel and glass fiber to concrete did not improved any structural performance in ultra-high performance concrete [14]. Yu et al. showed that adding nano-silica and hybrid fibers to Ultra-High Performance Fibre Reinforced Concrete can effectively restrict and minimize the cracks, which causes that the mechanical properties of concretem is significantly improved [15].

Kizilkanat et al. (2015) studied the effect of basalt and glass fiber on the properties of reinforced concrete. The results indicated that fibers decreased workability and increase compressive strength. But no considerable change was observed in modulus of elasticity, flexural and tensile strength [16].

Said et al. (2012) performed an experimental study about the effect of Nano-SiO2 on concrete. The results showed that adding Nano-SiO2 lead to significant improvement in strength properties and also change in reactivity, pore structure and transition area [17].

Silva et al. (2016) studied the effect of Nano-SiO_2 and Nano-Al_2O_3 on modified concrete. The results revealed that the dosage of cement is determinative parameter. For specimens prepared with low dosages of cement, adding Nano-SiO_2 decrease shear and flexural strength capacity, whereas an increase in the shear strength observed in specimens with higher dosages of cement. However, these have almost no effect on the bending strength [18].

Ardalan et al. (2017) studied the effects of Nano-SiO_2 particles on concrete permeability by employing the technique of spraying nanosilicon and treatment in the water-diluted Nano-SiO_2 oxide. According to their results, permeation resistance of specimens is improved considerably by curing of concrete panels in the Nano-SiO_2 environment. The optimum value of permeability was obtained in mixture with 0.48 w/c cured in 12% Nano-SiO_2 solution, as well as samples sprayed with 50% nanosilicon at time 2 [19].

In the present study, in order to resolve the defects which existed in shotcrete, we aim to study the mechanical properties of modified concrete with different dosages of Nano-SiO_2 and Nano-Al_2O_3 so as to find the optimum composition in shotcrete. Also, regarding the increase of the created compressive and tensile strengths, it is possible to use this type of modified shotcrete instead of increasing the thickness of shotcrete in the walls and roof of the tunnel, which could be considered as a substituent of tunnels' lining methods. Therefore, the effect of fibers and nanoparticles would be investigated in the case of strengthening view by uniaxial compression, flexural and Brazilian tensile test. On the contrary, the effect of application of Nano-SiO_2 and Nano-Al_2O_3 on the durability of shotcrete at sensitive parts of the tunnel wall are also studied. Specimens were first prepared to specify the effect of Nano-SiO_2 and Nano-Al_2O_3 and AR-glass fiber for compressive, flexural and tensile strength of concrete. Then the specimens was prepared to determine the effect of the addition on mechanical properties of shotcrete.

Table 1
Gradation of the aggregates used in the study.

Sieve size	Percent by weight passing individual sieves	The used Percent in this research
3/4 in. (19 mm)	–	–
1/2 in. (12 mm)	100	100
3/8 in. (10 mm)	90–100	100
No. 4 (4.75 mm)	70–85	86.8
No. 8 (2.4 mm)	50–70	68.1
No. 16 (1.2 mm)	35–55	51.6
No. 30 (600 μm)	20–35	37.4
No. 50 (300 μm)	8–20	13.8
No. 100 (150 μm)	2–10	5

Table 2
Chemical and physical properties of the cement.

Chemical compound	Percent (wt%)
CaO	63.0
SiO_2	20.4
Al_2O_3	4.9
Fe_2O_3	3.9
MgO	1.7
SO_3	2.0
$Na_2O + K_2O$	0.9
Loss on ignition (LOI)	1.5
Physical properties	
Specific gravity	3.12
Blaine fineness (m^2/kg)	295
Average particle size (μm)	26

2. Materials and laboratory test

2.1. Aggregates

The graded materials used in this study, according Table 1, have been set based on mountain rubble by complying with the ACI 506R-16 standard, provided from South Tehran mines [20].

2.2. Cement

In this study, Ordinary Portland Cement complying with the ASTM C150/C150 [21] was used. The properties of the cement are presented in Table 2.

2.3. Nanomaterials

The Nano-alumina (Al_2O_3) and Nano-silica (SiO_2) with the physical and chemical properties presented in Tables 3 and 4 have been used in this study. Fig. 1 shows the appearance of nanomaterials image by scanning microscope.

2.4. Alkali Resistant (AR) glass fiber

The used AR-glass fibers as shown in Fig. 2 have been selected in the range of length 10 mm regarding the maximum size of the aggregates.

The physical properties of AR-glass fibers are given in Table 5.

2.5. Mix design and test methods

To achieve uniform distribution of nanomaterial in cement matrix, first Nano powder (Nano-Al_2O_3 + Nano-SIO_2) was mixed with water as shown in Fig. 3, then Portland cement was added gradually at 20 °C for 15 min.