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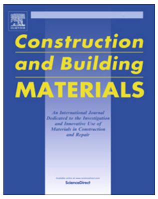

The effect of forta-ferro and steel fibers on mechanical properties of high-strength concrete with and without silica fume and nano-silica

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HIGHLIGHTS

- The effect of steel and forta-ferro fibers on the mechanical properties of high-strength concrete was investigated.
- The effect of silica fume and nano-silica on the mechanical properties of the fiber-reinforced concrete was studied.
- Equations for predicting the strength and the modulus of elasticity of fibrous concrete were proposed.

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ABSTRACT

This paper first addresses the effect of steel and forta-ferro fibers on the mechanical properties of high-strength concrete, and then, investigates the effect of silica fume and nano-silica on the mechanical properties of the fiber-reinforced concrete. In total, 230 concrete specimens were produced in two stages and subsequently tested; in the first stage of specimen production, hooked-end steel fibers with V_f of 0.5%, 0.75%, 1%, 1.25%, and 1.5%, and forta-ferro fibers with V_f of 0.2%, 0.35%, 0.5%, 0.65%, and 0.8% were added to concrete mixture, and in the second stage, silica fume with the weight percentage of 8%, 10%, and 12%, and nano-silica with that of 1%, 2%, and 3% were replaced the cement in mixtures with a fixed volume fraction of both fibers. The aim was to study the mechanical properties of the fiber-reinforced concrete including compressive strength, tensile strength, modulus of elasticity, water absorption, and density, and to propose equations for predicting the compressive and tensile strength and the modulus of elasticity of the fiber-reinforced concrete with no pozzolan.

1. Introduction

Normal concrete is being widely used because of the advantages it possesses such as low cost and ubiquitous availability; however, these aside, it has some deficiencies including brittle behavior, low tensile strength, and low strain capacity, as well as a weakness against crack opening and propagation [1–4]. Concrete failure occurs subsequent to and affected by crack formation; e.g., temperature and moisture changes result in the formation of microscopic cracks on the coarse aggregate surface, which then propagate throughout the concrete body by continuous loading [5].

With recent developments in the field of structural engineering, there have been growing demands for producing new concrete types with enhanced properties [6,7]. One example of such concretes is high-strength concrete (HSC) possessing higher strength and density compared to normal concrete [4]. In high-rise buildings, high-strength concrete prevents unacceptably thick columns in lower stories and increases the useable space of stories [8].

Since high-strength concretes are more brittle than normal concrete [9], researchers have been looking for ways to reinforce them and improve the behavior of these concrete types. One of the ways put forward was to use fibers as a concrete reinforcement. After the appearance of the first crack, the fibers bear the additional loads through bridging action, and via reducing the amount of stress concentration at the tip of crack, restraining and delaying its growth rate as well as redirecting its path, improve the strength and post-cracking behavior. Fibers also increase the tensile and bending strengths due to their resistance against the tensile stress occurring within the concrete microstructure [4,10]. Fibers increase the strain at peak stress and energy absorption capacity and reduce the negative effects of brittle materials through improving the post-peak behavior [11]. An increased energy absorption capacity of concrete leads to a reduced rupture risk in concrete structures especially under alternative and vibrating loads. A brittle matrix possesses a lower rupture strain relative to

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strong fibers; hence, by loading on a fiber-reinforced concrete, the cracks first appear in the matrix, and regarding the effect of fibers on the concrete and changes in the material behavior, given factors such as the type, geometry, and quantity of the used fibers as well as their orientation, three rupture modes may happen for the fiber-reinforced concrete [12]. If the fibers are added at low volume fractions, the fracture may occur immediately after the appearance of cracks in the matrix, which implies the insignificant effect of the fibers on the concrete behavior leading to a non-ductile concrete. In the case where fibers are used in concrete from low to medium quantities, the deformation may continue under lighter loads, and the strength may be provided until the fibers are pulled out from cracks. When the fibers are employed from medium to high quantities, the fiber-reinforced concrete may carry higher tensile stress and deformation following cracking. However, this condition occurs when the pull-out strength of fibers is greater than the load presented at the moment of first crack appearance, which is due to the sudden transfer of the entire load to fibers. In this case, the greatest ductility is obtained [12].

It can be said that fibers are generally of steel, glass, synthetic and natural types [13]. Steel fibers, depending on the characteristics of the type that is utilized, can increase the concrete compressive strength negligibly or by low quantities and even sometimes by 25% [14]. Steel fiber-reinforced concrete is employed in civil and industrial structures, airports, highway pavements, tunnels, bridges, hydraulic structures, etc. [14,15]. Moreover, high-strength concrete reinforced with steel fibers is also employed in retrofitting the existing buildings [16]. Polypropylene fibers as synthetic fibers can be used in concrete as monofilaments, fibrillated and twisted fibers. These fibers are chemically inert, and resistant to cracking due to plastic shrinkage [17,18]. Forta-ferro® fibers comprised of various synthetic materials are made of 100% virgin copolymer/polypropylene that is consisted of a twisted bundle of non-fibrillated monofilaments together with some fibrillated network fibers, which give a reinforced concrete system having very high efficiency and quality. These fibers reduce the shrinkage of fresh and hardened concrete; improve the impact resistance, fatigue resistance, and stiffness of concrete. Through integrating a coherent network of fibers, these fibers lead to long-term durability, improved structural characteristics, and controlled secondary or thermal cracks in concrete. Furthermore, forta-ferro fibers are noncorrosive and 100% resistant in an alkaline environment [19].

In order to strengthen the fiber-reinforced concrete, the matrix-fibers bonds should be improved. After the appearance of the first crack in concrete, the fibers come to play and create a bridge among cracks. As the load increases, the fibers transfer the additional stresses to the matrix, and in the case this transfer does not take place, the concrete will fail and there will be no ductile behavior. Hence, developing a strong link and bond between the fibers and the matrix leads to reaching the highest ductility level in the concrete reinforced with fibers [12]. The boundary area between the cement mortar and aggregate or fiber surface is referred to as contact area, which plays an essential role in permeability, durability, and strength of concrete. One of the factors capable of affecting the thickness of contact area is pozzolanic materials [12]. Pozzolan is a name given to siliceous or aluminous siliceous materials that possess low or no cementitious value per se, but in the form of dispersed fine particles in the presence of moisture reacts with calcium hydroxide at the ambient temperature as compounds possessing cementitious properties [20]. Employing pozzolans as cement replacement or supplement is very useful in order to produce high-strength concrete, and can reduce the concrete porosity particularly in long-term [1]. Silica fume is a type of pozzolan that improves the bond strength between cement paste and aggregate grains. Silica fume combines with calcium hydroxide leading to weak cement hydration process, which in return results in additional cementation and a considerable reduction in permeability [20].

Today, use of nano-particles as materials produced with high technology and in very fine sizes is expanding due to their desired effects on different materials [21]. Since very tiny structures and mass transfer in nanoscale specify the mechanical strength and lifetime of concrete structures, these particles can enhance the concrete nano-structure [22]. Among these materials, nano-silica can be mentioned, being capable of increasing the compressive strength of hardened cement paste, especially in early ages. In addition, nano-silica fills the concrete pores and improves the cement paste-aggregate bond, which results in concrete strength increase. Research has shown that the pozzolanic activity of nano-silica is much higher than that of silica fume [23,24]. With its very fine particle size, nano-silica is uniformly dispersed throughout the cement paste and accelerates the cement hydration process due to its high activity [21].

Here, 230 cylindrical specimens with 23 different mix designs were produced in two different stages with the aim of investigating the effect of steel and forta-ferro fibers on the physical and mechanical properties of the high-strength concrete. In the first stage, no pozzolan was utilized in the fiber-reinforced concrete mixture, while in the second stage, silica fume and nano-silica were used as a cement-replacement, and their influence on the compressive and tensile strength, modulus of elasticity, water absorption, and density of concrete was examined. In the first stage, five different volume fractions were used for each fiber type including 0.5%, 0.75%, 1%, 1.25%, and 1.5% for steel fibers, and 0.2%, 0.35%, 0.5%, 0.65%, and 0.8% for forta-ferro fibers. The second stage involved replacing three different weight percentages of the cement by each pozzolan type including 8%, 10%, and 12% for silica fume, and 1%, 2%, and 3% for nano-silica to the concrete mixtures each containing a fixed volume fraction of either fiber types.

2. Experimental program

2.1. Materials and specimens

In this study, ordinary Portland cement, CEM I 42.5R, silica fume and nano-silica with purity of 95% and 98.8%, respectively, were utilized. The physicochemical properties of the cement, silica fume, and nano-silica are listed in Table 1. The coarse aggregate with the maximum size, specific gravity, and water absorption of 12.5 mm, 2.68, and 0.47%, respectively, and the fine aggregate with the specific gravity, fineness modulus, and water absorption of 2.58, 2.6, and 1.73%, respectively, were used. Fig. 1 illustrates the grading curves of the aggregates. Using chemical admixtures may control loss of slump as well as hardening rate, leading to an improved workability, extended batching time for placing, accelerated strength acquisition, and enhanced durability [20]. Therefore, to reach an appropriate workability for the concrete mix, the SPC10 superplasticizer based on polycarboxylate with the solid content of 48% was added. Hooked-end steel fibers have a greater effect on the tensile strength relative to corrugated fibers [25]. Moreover, fibers having the aspect ratios greater than 100 may give rise to balling phenomenon where separating the fibers just by vibration is very difficult; on the other hand, fibers with the aspect ratios less than 50 do not tend to clump in the form of balls, which makes it easier to scatter them by vibration [13], but they have a smaller influence on the strength. Since the aspect ratios less than 60 are suitable for mixing, and given that the aspect ratio of 100 gives the desired strength [26], and considering that the use of steel fibers with the aspect ratios ranging from 50 to 70 is practical for concrete