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Mechanical properties and durability of high-strength concrete containing macro-polymeric and polypropylene fibers with nano-silica and silica fume

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HIGHLIGHTS

- Mechanical properties of HSC containing PP, MP and hybrid fibers with nano-silica and silica fume were studied.
- The optimum percentages of fibers and pozzolans were selected and employed in producing high-strength concrete.
- Introducing nano-silica and silica fume improved mechanical properties and durability of concrete.
- Substitution of MP with PP fibers reduced mechanical properties of concrete.
- High volume fractions of PP fiber brought about negative effects on mechanical properties of HSC.

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ABSTRACT

The current study investigates the effects of different amounts of polypropylene (PP) and macro-polymeric (MP) fibers on the mechanical properties and durability of high-strength concrete containing silica fume and nano-silica. In total, 280 concrete specimens were produced in 28 different test groups, for which the parameters of compressive strength, tensile strength, modulus of elasticity, water absorption, and porosity were evaluated. The macro-polymeric fibers in volume fractions of 0.25, 0.5, 0.75, 1.0, and 1.25%, and the polypropylene fibers in volume fractions of 0.1, 0.2, 0.3, 0.4, and 0.5% were used in this study. Furthermore, one set of specimens with the total fiber volume fraction of 1.0% of the concrete volume was tested in order to examine the effect of hybrid polypropylene-macro-polymeric fibers on the concrete properties. In addition, the nano-silica with the weight percentages of 1, 2, and 3%, and the silica fume with the weight percentages of 8, 10, and 12% were employed in the concrete mix design. In the current paper, first, the effects of macro-polymeric, polypropylene, and hybrid fibers on the physico-mechanical properties were comparatively examined, and then the influence of using nano-silica and silica fume in the high-strength concrete with no included fiber was investigated. Finally, the optimum percentages of fibers and pozzolans corresponding to the most significant increases in the tensile strength were chosen, which were subsequently used as the optimum combination of the high-strength concrete. The results of the experimental study suggest an improvement in the concrete mechanical properties and durability following the introduction of nano-silica and silica fume. In addition, incorporating macro-polymeric fibers in the concrete mixture given the volume content of fibers improves the mechanical properties of high-strength concrete. Moreover, high volume fractions of polypropylene fibers in the concrete mixture brought about negative effects on the physico-mechanical properties of the high-strength concrete.

1. Introduction

1.1. Fiber-reinforced concrete

Normal concrete is a composite material with low tensile strength and strain ranges [1,2]. Two main weaknesses of concrete, namely its brittle behavior and its weakness under

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tension, which lead to low ductility, have posed problems for the structural application of normal concrete. Generally, the addition of fibers to the concrete mixture can significantly improve the concrete mechanical properties [3–6]. The presence of abundant micro-cracks throughout the concrete body even before the beginning of tensile testing prevents the appropriate transfer of tensile stress during the test that leads to the crack widening. As a result, the application of fibers to compensate for the weakness in the tensile and ductile behavior and to obtain a concrete with less cracking seems evident, with the extent of behavioral improvement being strongly dependent on the type, shape, and percentage of fibers [7,8]. The appropriate types of fibers to produce fiber-reinforced concrete may include steel, glass, synthetic, and natural fibers, among which the synthetic fibers are divided into two groups considering their diameter, i.e. the fibers with the equivalent diameter more than and those with the equivalent diameter less than 0.3 mm referred to as macro-synthetic and micro-synthetic fibers, respectively [9]. Micro- and macro-synthetic fibers deal with micro- and macro-cracks, respectively, and some research has been performed to introduce macro-synthetic fibers as a steel fiber-replacement in shotcrete and other structural applications [10–12]. Depending on their shape and geometry, the fibers are capable of considerably enhancing the ductility, impact resistance, fracture energy, fire resistance, and durability of concrete [11,12]. Due to their low modulus of elasticity relative to that of steel fibers as well as their crimped shape, macro-synthetic (macro-polymeric) fibers demonstrate higher deformation at peak load, toughness, post-cracking load-carrying capacity, and reduced crack width [13]. Among various fibers, macro-polymeric and polypropylene fibers as synthetic fibers have been attracting increasing attention of researchers due to their lower cost and weight, resistance against corrosion and acids, excellent toughness, and enhanced shrinkage cracking resistance [14,15]. In general, reinforcing concrete with one type of fibers improves the concrete characteristics in a limited range. In contrast, hybrid fiber-reinforced concrete with two or more fiber types may be a better option for presenting enhanced properties. Since the cracks in concrete occur in various sizes and loading stages, employing various types of fibers with different lengths is an appropriate way to prevent macro- and micro-cracks propagation [16–19]. However, research on the macro-polymeric and hybrid polypropylene-macro-polymeric fibers is scarce in the literature.

In their study, Kun-Yew et al. [20] added different types of polypropylene fibers in the concrete volume, and enhanced the mechanical properties such as tensile and flexural strength, and modulus of elasticity. Moreover, the use of 0.5% volume fraction of polypropylene fibers resulted in 95.8% reduction in the slump. The effects of fiber hybridization on the tensile behavior of ultra-high performance hybrid fiber-reinforced concrete were investigated in the work of Park et al. [21], in which four types of macro-steel fibers with different shapes and geometries as well as one type of micro-steel fibers were utilized. Their results revealed that using different types of fibers in the concrete prevented micro-crack and macro-crack propagation, and compensated for the concrete weakness in tension. Afroughsabet and Ozbakkaloglu [22] studied the effect of hybrid fibers on the mechanical properties and durability of high-strength concrete. In their study, the hybridization of steel and polypropylene fibers with the total fiber volume fraction of 1% by volume of the concrete was investigated, and the results suggested better mechanical properties and durability of concrete for the hybrid fiber-containing specimen compared to the plain concrete. In addition, replacing steel fibers by polypropylene fibers resulted in a decrease in the strength.

1.2. Nano-silica and silica fume

Modern developments in the field of civil engineering construction have created an urgent demand for new types of concrete with improved qualities such as high strength, toughness, and durability [23,24]. Consistent with the fast progress of the concrete technology and use of pozzolans as supplementary cementitious materials, the capability of producing high-strength concrete (HSC) and high-performance concrete (HPC) has risen accordingly [25,26]. Furthermore, considering that the high-strength concrete technology is a new development in the concrete construction industry, in order to improve concrete behavior as well as the microstructure of cementitious materials at the micro and nano levels, nano-silica and silica fume pozzolans can be used as a weight percentage of cement. Generally, the cement-replacing pozzolan in the concrete produces calcium silicate hydrate (C-S-H) gel during the pozzolanic reaction with the calcium hydroxide formed by cement hydration, which in turn results in higher strength and lower concrete porosity [27,28]. Today, researchers and engineers in the field of concrete technology are considering nano-silica as a new additive material of interest, since as one of the nanotechnology products, it possesses a very high amorphous silica percentage, a very large specific surface area, and very smaller dimensions in relation to silica fume. The compressive strength at the initial aging stages for the concrete containing nano-silica as opposed to silica fume is greater because of a faster and more active pozzolanic reaction as well as reduced initial hardening time. Li et al. [29] investigated and compared different percentages of nano-silica and silica fume particles by the weight of cement, and showed that adding 10% nano-silica increased the concrete compressive strength by 26% while adding the same amount of silica fume enhanced the compressive strength by 15%. Amin and Abu el-Hassan [30] investigated the effects of using various types of nanomaterials on the mechanical properties of high-strength concrete. The obtained results indicate that 3% nano-silica by the weight of cement as the optimum percentage improves the concrete mechanical properties considerably.

In the present study, the effects of using different amounts of polypropylene and macro-polymeric fibers on the mechanical properties and durability of high-strength concrete containing nano-silica and silica fume are investigated. Altogether, 28 mix designs containing different percentages of polypropylene (PP), macro-polymeric (MP), and hybrid PP-MP fibers along with different amounts of nano-silica and silica fume were prepared and used for producing concrete specimens. First, 16 mixtures were prepared and tested in order to examine the effects of PP, MP, and hybrid PP-MP fibers as well as to determine their optimum percentage. Next, in order to investigate and compare the effects of using nano-silica and silica fume on the mechanical properties and durability of high-strength concrete and to determine their optimum percentage, 6 mix designs were prepared and tested. Finally, 6 mix designs possessing the optimum percentages of fibers and pozzolans (corresponding to the most significant increases in the tensile strength) were selected and subsequently employed in producing high-strength concrete. This work investigated the physico-mechanical properties of the concrete specimens including compressive strength, splitting tensile strength, modulus of elasticity, water absorption, and porosity.

2. Experimental program

2.1. Materials and specimens

In this study, ordinary Portland cement type I (CEM-I 42.5 N) in compliance with ASTM C150 [31] was used, for which the chemical