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The effect of polyamide fibers on the strength and toughness properties of structural lightweight aggregate concrete

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HIGHLIGHTS

- PA synthetic fibers with high fiber volume ratios (0.5% and upper) can be effectively used to enhance the strength and toughness capacities of SLWAC as an alternative to steel fibers.
- The use of PA fibers in the hybrid form in concrete mixes is more beneficial than the single forms of micro and macro PA fibers in terms of the strength and toughness capacities of SLWAC.
- Although the increase in the compressive strength of micro, macro and hybrid PA fiber-reinforced SLWAC was not notable (generally below 5%), the increase in the splitting tensile and flexural strength was very significant.
- Compared to pre-peak toughness, the compressive and flexural post-peak toughness values were too significantly higher, especially in macro and hybrid PA fiber-reinforced concrete specimens than in control specimens due to the bridging effect of PA fibers on the concrete matrix, which effectively prevents the spread of uncontrolled cracks after the peak load.
- JSCE SF-4 and the ASTM C1018 design codes have different weaknesses in evaluating the toughness of fiber reinforced concrete.
- Neither of these design codes is suitable for measuring the toughness capacity of reinforced concrete with low fiber content due to brittle behavior after the peak load.

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ABSTRACT

This study investigated the effects of single and hybrid use of micro and macro polyamide (PA) synthetic fibers on the workability, compressive, splitting tensile and flexural strength, as well as compressive and flexural toughness of structural lightweight aggregate concrete (SLWAC). The fibers were added into the concrete mixes as 0.25%, 0.5%, and 0.75% by the volume of concrete. Flexural toughness was evaluated in accordance with the JSCESF-4 and ASTM C1018-97 standards. The test results clearly show that while the increase in the splitting tensile and flexural strength of SLWAC was significant, the increase in compressive strength was not notable. Although the compressive and flexural toughness capacity of SLWAC with a low PA fiber content did not increase significantly, the increase in the toughness capacity of SLWAC with a high PA fiber content was remarkable. The JSCESF-4 and ASTM C1018 standards can only be applied to measure the toughness capacity of SLWAC that shows highly ductile behavior after the peak load. Furthermore, the use of PA synthetic fibers in the hybrid form was more effective in enhancing the strength and toughness properties of SLWAC compared to the single form.

1. Introduction

Conventional concrete produced using natural aggregates, such as sand and gravel have a high unit weight and good strength. The weight of reinforced concrete (RC) structures built using conventional concrete is considerably higher than that of masonry and steel structures. As known, earthquake load increases in direct proportion to the weight of a structure. Hence, RC buildings located in seismic zones are affected more severely by earthquake loads. In order to ensure that RC structures are safe and can withstand the force of earthquakes, the cross sections of columns, beams, shear-walls, and foundations are chosen to be larger in the projecting phase. This leads to aesthetically poor structures with higher construction cost and less architectural use [1–3]. To prevent these negative situations, rather than conventional concretes, structural lightweight aggregate concrete (SLWAC) with low density and thermal conductivity [4], high strength/weight ratio, better durability and fire resistance characteristics [5,6] is widely used in

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high-rise buildings, long-span bridges, wall panels and blocks, tunnel lining, roof floors, screed concrete of floors, bridge openings, and pre-stressed concrete units [7–13]. Some methods commonly utilized in SLWAC production include the use of natural lightweight aggregates, such as pumice, diatomite, and volcanic cinders, as well as artificial by-products; e.g., clay, slate, expanded shale, and perlite. ACI 213R-03 [14] defines SLWAC as a concrete with a minimum 28-day compressive strength of 17 MPa and equilibrium density between 1120 and 1920 kg/m^3. However, the brittleness of lightweight concrete is higher than that of normal weight concrete (NWC) for the same mix proportions and compressive strength [15–17]. Furthermore, the mechanical properties of lightweight concrete are generally lower compared to NWC [17–19]. As known, the most common way of increasing the strength and ductility of concrete is to add different types of fibers in the concrete mix. The most important properties of fibers that affect concrete strength and ductility are fiber volume, aspect ratio (l/d), elastic modulus, and tensile strength of fibers. Among all fiber types, steel fibers are most frequently used to enhance the mechanical properties of SLWAC [20–26]. However, adding steel fibers to SLWAC, especially at a volume of greater than 1% increases the density of SLWAC due to high specific gravity of steel fiber [17,27,28]. Furthermore, steel fibers have a low corrosion resistance and negatively affect long-term durability and performance of concrete [29,30]. Therefore, as an alternative to steel fibers, different types of synthetic fibers, such as carbon, aramid, polyester, polypropylene (PP), polyethylene (PE), and polyvinyl alcohol are now commonly utilized in either single or hybrid form in the concrete mix to enhance the strength and ductility of SLWAC [13,31–37]. Recently, with the developments in petrochemical and textile industries, the use of PA 6.6 (nylon) fibers in concrete has become widespread. PA fibers are a product of thermoplastics and have high strength, good electrical and chemical properties, a low friction coefficient, high resistance to abrasion, and the ability to maintain properties at high temperatures. PA micro and macro fibers are being produced from the raw materials PA 6.6 according to the EN 14889-2 Class I [38]. Micro and macro PA fibers are produced in the form of staple and filament fibers, respectively. Both fiber types are formed from polymers of long-chain polyamides. Although micro PA fibers provide superior results in terms of preventing early age shrinkage cracks, the macro PA fibers are highly effective to enhance especially the axial load capacity and post-peak behavior of the concretes. Easy mixing and applicability enables them use in a variety of construction applications including repair mortars, concrete port's slab on ground concrete, concrete pavements, screed, shotcrete, tunnel lining and precast concrete components. Micro and macro PA fibers provide long-term durability, resistance to corrosion effects, ease of application, pumping and spraying results in energy savings. Furthermore, PA fibers have higher tensile strength than polypropylene and polyethylene fibers [39,40]. Although a considerable amount of research has been undertaken on PA-reinforced conventional concrete [41–47], there are only a limited number of studies on PA synthetic fiber-reinforced SLWAC [48]. Therefore, this study aimed to investigate the effects of single and hybrid use of micro and macro PA synthetic fibers on the strength and toughness properties of SLWAC with the target compressive strength of 20 MPa. Pumice was used as fine and coarse aggregate material in the production of SLWAC. Compressive, splitting tensile and flexural strength, as well as compressive and flexural toughness (pre-peak and post-peak energy dissipation capacity) of SLWAC was investigated for different PA fiber volume ratios. The flexural toughness of the control and PA-reinforced SLWAC specimens were evaluated in accordance with two widely used standards; JSCE SF-4 [49] and ASTM C1018-97 [50]. The test results were also compared with those published earlier on SLWAC reinforced with different types of fiber.

2. Experimental program

2.1. Materials

CEM I 42.5 R type cement, coarse and fine pumice aggregates, micro and macro PA fibers with the lengths of 12 and 54 mm, respectively and superplasticizers (SPs) were used in concrete mixtures. The cement used in all mixes was regular Portland cement CEM I 42.5 R in accordance with the EN 197-1 standard [51]. The chemical, physical and mechanical properties of the cement provided by the manufacturer are presented in Table 1. In all mixes, natural lightweight pumice of 0–4 mm and 4–8 mm was used as fine and coarse aggregates, respectively (Fig. 1). The sieve analysis of fine and coarse pumice aggregates was performed in accordance with EN 706 [52] and the results are shown in Fig. 2. The micro and macro PA fibers with the lengths of 12 and 54 mm, respectively were used in all mixes in the single and hybrid forms (Fig. 3). The tensile strength of PA fibers reported by the manufacturer were 900 MPa and the elongation rate ranged from 15 to 25%. The geometrical and mechanical properties of the PA fibers reported by the manufacturer are given in Table 2. A new generation polycarboxylate-based SP admixture was used to obtain good workability for the fresh concrete mixture.

2.2. Mixing

Mixing was performed using a pan mixer. There were a total of 10 mixes, one control mix and nine consisting of micro and macro PA synthetic fiber reinforced concrete. For each mixture, three 150 mm cube samples for compressive and splitting tensile tests and three 100 × 100 × 400 mm prisms for four point bending strength tests were prepared. A total of 90 specimens were tested to determine the compressive, splitting tensile and flexural strength of the concrete specimens. The procedure for mixing concrete was as follows: Pumice lightweight aggregates were placed in the curing pool with approximately 100 L of water and allowed to stand for 24 h to dry in laboratory conditions. Cement and pumice (fine and coarse aggregates) were first mixed in the dry state for approximately 2 min. Then, water and SP were added and the specimens were mixed for 3 min. This was followed by the addition of PA synthetic fibers in the single and hybrid forms and further mixing for 3 min. The total volume fractions of the PA synthetic fibers were kept at 0.25%, 0.5%, and 0.75%. The ratio of water/cement (w/c) used in all mixes was 0.45. SP, also known as a high-range water reducing admixture, was added to all mixes at 1% of the weight of cement. The mixture proportions are given in Table 3. Finally, the fresh concrete mixtures were cast into cubic and prismatic molds. All the fresh concrete specimens had similar flow properties before casting. They were remolded by air-curing at 20 ± 3 °C and at 60 ± 5% relative humidity for 1 day, and cured at 20 ± 3 °C in water for 28 days.

2.3. Testing procedures

For each mixture, three cube specimens of 150 mm in size were tested for compressive and splitting tensile strength tests and three beam specimens with 100 × 100 × 400 mm dimensions were used for the 4-point bending strength at 28 days, and the average values were obtained. Two linear variable differential transformers (LVDTs) were placed opposite to the cube specimens to obtain axial deformations of the control and PA-reinforced concrete. The axial deformation referred to in this paper is the average value of the two LVDTs. To obtain flexural load-deflection curves at the mid-point of the beams, an LVDT was mounted on the surface of the beam samples to record the mid-deflection. All the tests were performed under displacement control at a rate of 0.1 mm/min. The unit weight of the fresh concrete was measured in accordance with EN 12350-2 [53] and EN 12350-7 [54]. The compressive and splitting tensile tests were carried out on the 150 mm cube specimens

Table 1
Chemical, physical and mechanical properties of the cement.

Chemical properties	(%)	Physical and mechanical properties	
SO_3	2.64	Compressive strength	(MPa)
MgO	2.89	2 days	28.6
CaO	57.61	7 days	43.4
Al_2O_3	4.74	28 days	54.8
K_2O	0.72	Initial setting time (min)	182
SiO_2	18.03	Final setting time (min)	238
Na_2O	0.12	Specific gravity (g/cm^3)	3.04
Fe_2O_3	3.31	Specific surface (cm^2/g)	3719
Cl^-	0.014	Total volume exp. (mm)	1.87