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Deflection-hardening hybrid fiber reinforced concrete: The effect of aggregate content

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HIGHLIGHTS

- Deflection-hardening hybrid fiber reinforced HPFRC mixtures were developed.
- Coarse aggregates with MAS of 12 mm were used with maximal variations.
- Polyvinyl-alcohol, hooked-end steel and nylon fibers were used for hybridization.
- Matrix properties were optimized with different FA/PC and A/B ratios.
- Use of high amounts of coarse aggregates can contribute widespread usage of HPFRC.

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ABSTRACT

High Performance Fiber Reinforced Concretes (HPFRC) are emerging materials with superior mechanical properties accounting for crack occurrence and propagation under excessive tensile loads along with the many commonly encountered durability issues. One drawback of such materials is the restricted size and amount of coarse aggregates used in mixtures incorporating single or hybrid fibers (in most cases). This, therefore, increases the amount of binder resulting in higher cost, dimensional instability and cracking potential (especially at early ages). In this study, HPFRC mixtures with a maximum aggregate size of 12 mm were developed with maximal variation in coarse aggregate contents without compromising deflection-hardening behavior. Three different fibers were used at a maximum of 2% of volume in single or hybrid systems: polyvinyl-alcohol (P), hooked-end steel (S) and nylon (N) fibers. To function synergistically with different fiber types and high amounts of coarse aggregates, matrix properties were optimized by varying the proportions of fly ash to Portland cement (FA/PC ratios of 0.20, 0.45, and 0.70, by weight) and aggregate to binder (A/B ratios of 1.0, 1.5, and 2.0, by weight). Experimental results showed that a deflection-hardening response can be obtained from HPFRC mixtures with single or hybrid fiber systems regardless of the FA/PC ratio, A/B ratio, and initial curing age selected without endangering the compressive and flexural strength results. It is believed that production of hybrid fiber composite mixtures with high concentrations of coarse aggregates and industrial by-products can contribute to superior mechanical and durability performance, enhanced greenness, as well as the widespread usage of such materials in the field at a reasonable price compared to their counterparts.

1. Introduction

Concrete is a universal construction material with wide-spread suitability for relatively different applications, although it has one eye-catching drawback regarding versatility: low deflection capacity due to high brittleness. Luckily, it is possible to account for some of the issues related to brittle behavior and poor resistance to crack formation by utilizing randomly dispersed short fibers [1]. In this regard, High Performance Fiber Reinforced Concretes (HPFRC) with their superior performance and capability to arrest crack occurrence and propagation under tensile forces have come to the forefront lately. The crack bearing ability of HPFRC brings

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about not only preeminent mechanical features (e.g. strain and/or deflection hardening behavior) but also an increased resistance to different environmental conditions and several durability concerns causing further deterioration [2].

By embedding conventional reinforcements into concrete material, only cracks at certain structural sections and at a single scale can be arrested, although fracturing in concrete is multi-scale [3]. While it is possible to account for the randomly distributed crack zones through the use of fiber reinforcement, most of the HPFRCs incorporate one type of fiber, meaning that they are resistant to cracking in a single scale [4–6]. Given the multi-scale nature of fracturing in concrete, it is more logical to address cracking by the combination of fibers with different size, function and constitutive response for optimal behavior. In this sense, hybridization of fibers during the production of HPFRC can be promising [7,8]. Hybridization in HPFRC means the combination of two or more fibers with different properties in an appropriate manner to take full advantage of the resultant product. Based on the anticipated performance from the final composite material, the fiber properties to be considered are length, diameter, strength, elastic modulus, aspect ratio, specific gravity and so on. It can generally be stated that larger fibers are more effective in bridging macrocracks (providing toughness) while smaller fibers are effective in bridging microcracks, thus enhancing the behavior before and/or right after crack formation. With a proper combination of large and small fibers, individual benefits can be collected simultaneously in a single hybrid cementitious composite as seen in the studies listed above.

Although it is not a difficult task to hybridize the cementitious systems with fibers, utilization of aggregates with particle sizes larger than the average spacing of individual fibers causes inadequate dispersion/balling; the balling effect is more common in the case of increased maximum aggregate sizes (MAS) [9]. Generally, an increase in the size of aggregate particles causes more clumping and greater interaction of fibers [10]. It has also been hypothesized that increased aggregate amount and size increases matrix fracture toughness, thus lowering the overall ductility [11,12]. Additionally, the possibility of non-uniform fiber distribution in the presence of coarse aggregates is likely to increase when hybrid composite mixtures with two or more different fiber types are to be manufactured. Hence, in most of the instances, HPFRCs are produced with aggregates that are relatively small in size irrespective of the selected system of fibers (single or hybrid) [13,14]. Although the selection of relatively fine aggregates helps contribute to a more uniform fiber distribution in HPFRC mixtures, it also leads to higher amounts of Portland cement to be included in cementitious systems as the main binder, increasing the cost and chance for dimensional instability compared to counterpart systems incorporating coarse aggregates. To minimize this effect, industrial by-products such as fly ash (FA) and ground granulated blast furnace slag are commonly used in HPFRC mixtures due to both environmental and economical reasons. Reduced matrix fracture toughness, obtained with the use of industrial by-products as supplementation to ordinary Portland cement, can also potentially inhibit higher matrix fracture toughness values that are going to be obtained when a large amount of aggregate of a maximum possible size is used in cementitious systems [13]. Despite the importance of the subject, few studies targeting the development of strain and/or deflection-hardening HPFRC mixtures in the presence of coarse aggregates and hybrid fibers were encountered in the current literature, most probably due to abovementioned difficulties. In one such study, Blunt and Ostertag [15] produced deflection-hardening HPFRC mixtures with coarse aggregates having a maximum aggregate size (MAS) of 9.5 mm and utilizing three different fibers (two different types of steel fiber and one type of polyvinyl-alcohol fiber) at a volume of 1.5%. In a different paper by Hay and Ostertag [16], deflection-hardening HPFRC mixtures using fibers with almost similar types/volume and coarse aggregates with a MAS of 10 mm were produced by replacing cement with supplementary cementitious materials at a certain level to favor environmental issues. Rather than repeating these studies, this research paper focuses on the development of deflection-hardening hybrid fiber reinforced concrete mixtures with different aggregate amounts with MAS of 12 mm. To modify the fracture toughness of a matrix, which is crucial for its deflection-hardening behavior (and expected to improve with an increase in coarse aggregate content), various amounts of fly ash were added to HPFRC mixtures. To state briefly, the main purpose of this study is to develop hybrid fiber reinforced cementitious composites with deflection-hardening capability by proposing the incorporation of different fiber and matrix combinations with higher amounts of coarse aggregates. It is believed that the production of hybrid fiber reinforced cementitious composites based on a maximal amount of coarse aggregates and increased use of industrial by-products (without sacrificing the deflection-hardening behavior) can contribute to enhanced greenness and superior dimensional mechanical and durability performance as well as the widespread use of such materials in the field at a reasonable prices compared to that of HPFRC mixtures without coarse aggregate and industrial by-products.

2. Experimental program

2.1. Materials and mixture proportions

For the production of composite materials, CEM I 42.5R ordinary Portland cement (PC) which is similar to ASTM Type I cement, Class-F FA with a lime content of 9.78% and silica fume (SF) were used as the cementitious materials. The three different FA/PC ratios used throughout the present study were 0.20, 0.45 and 0.70. The total amount of SF used in the mixtures was kept constant at 7% of PC, by weight. Chemical and physical properties together with the particle size distributions of PC, FA and SF are shown in Table 1 and Fig. 1, respectively. Fine and coarse aggregates used were river sand with a fineness modulus of 2.67 and crushed stone with a maximum aggregate size (MAS) of 12 mm. As can also be seen in Fig. 1, fine and coarse aggregates were combined in order to obtain optimum gradation without sacrificing reasonable fresh concrete properties with the highest possible density. To find the well-graded aggregate combination, the 0.45 power chart method using the Fuller formula was adopted. As a result, a combined aggregate gradation was formulated using 57% of fine and 43% of coarse aggregates by weight. During the production of the mixtures, three different total aggregate (coarse + fine aggregates) to binder (PC + FA + SF) ratios (A/B) were selected, as 1.0, 1.5 and 2.0.

Table 1
Chemical composition and physical properties of PC, FA and SF.

	PC	FA	SF
Chemical composition, %			
SiO_2	20.77	57.01	91.96
Al_2O_3	5.55	20.97	1.20
Fe_2O_3	3.35	4.15	0.84
MgO	2.49	1.76	1.02
CaO	61.4	9.78	0.62
Na_2O	0.19	2.23	0.67
K_2O	0.77	1.53	1.16
Loss on ignition	2.2	1.25	1.86
Physical properties			
Specific gravity	3.06	2.02	0.60
Specific surface area (m^2/kg)	325	290	19080