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Performance of hybrid fiber-reinforced concrete for low-rise housing with thin walls

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HIGHLIGHTS

- Hybrid Fiber Reinforced Concrete is studied based on tests and a cost analysis.
- Variables of the experimental program were type of fibers and its volume content.
- Fiber volume content of 0.94% complied with residual strengths set by ACI-318-14.
- The cost of hybrid fibers is half of the steel fiber at the same performance level.

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ABSTRACT

Aimed at improving concrete behavior of thin walls used in low-cost and low-rise housing, an experimental program was carried out to investigate the mechanical properties of Fiber-Reinforced Concrete (FRC) and Hybrid Fiber-Reinforced Concrete (HyFRC). The combination of two types of fibers is experimentally investigated in this paper based on results of flexure tests and a cost-performance analysis. The experimental program included tests of 130 standard specimens; 67 small beams and 63 cylindrical specimens. Variables of the experimental program were the type of fibers and the fiber volume content. Two types of hooked-end steel fibers with aspect ratio of 80 and 65 and one type of macro-synthetic (polyethylene) fiber with aspect ratio of 84.5 were used for the mixtures. Volume content of fibers varied between 0.15% and 0.98% for steel fibers, and between 0.16% and 0.94% for polyethylene fibers. Test results of 14 mixtures showed that only mixtures with a fiber volume content of 0.83% and 0.98% for single-type of long steel fibers and 0.94% for hybrid fibers were compliant with the residual strengths prescribed by ACI-318-14. In addition, the ratio between fiber volume contents of polyethylene and steel fibers (PF/SF ratio) should roughly between 1.0 and 1.5, but the volume content of polyethylene fiber for hybrid mixtures should be limited to 0.60%. Finally, cost-performance analysis showed that the cost of hybrid fibers mixture is about half of the steel fiber mixtures at the same performance level.

1. Introduction

Fiber-reinforced concrete (FRC) is a composite material characterized by a cementitious matrix and discrete fiber reinforcement. The main advantage of FRC is the ability of developing residual tensile strength after first cracking [1]. In the post-cracking behavior, fibers contribute to sew the cracks and to increase the residual tensile strength due to the slip of fibers from the concrete matrix. This expected slippage mode of failure is ductile because it is controlled by the tensile rupture of fibers. In addition, this mode of failure provides energy dissipation by the appearance of multiple small cracks rather than a single wide crack. In terms of the volume content of fibers, strain hardening mechanism characterized by residual strength higher than the cracking strength of concrete is commonly observed when steel fiber volume content is higher than 1%. However, a slightly fragile behavior with residual strength lower than the cracking strength of concrete is expected when steel fiber volume content is lower than 1% [2,3]. On the other hand, high volume of contents of fibers could affect concrete mixed, placed and consolidated. Based on the previous aspects, it is reasonable that the fiber volume content should be chosen base

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not only on the type of structural element but also on its load demand level.

The state of the art of fiber-reinforced concrete recognized that steel and synthetic fibers are the main type of fibers used to reinforce concrete elements. Steel fibers have Young's modulus considerably higher than polyethylene fibers, thus steel fibers are expected to control cracks as well as to enhance the residual strength of concrete more efficiently. However, the use of steel fibers in FRC could lead to some drawbacks with respect to polyethylene fibers such as electrical conductivity, higher magnetic fields, corrosion and the increasing of the cost of FRC. In addition, polyethylene fibers are expected to enhance strain performance, control micro-cracking at early-age of concrete [4] and they are less expensive than steel fibers. Thus, a combination of steel and polyethylene fibers appears to be a practical and economical option for FRC structural elements. A hybrid fiber-reinforced concrete (HyFRC) is formed by a combination of different types of fibers having different material properties that are mixed together when added to concrete [5]. Dawood and Ramli [6] have demonstrated that the hybridization of two or three different types of fibers in a concrete matrix results in a composite with higher mechanical performance when compared to a single-type of fiber. The hybridization of fibers also provides improved specific characteristics not obtainable by any of the original fiber acting alone. Banthia and Grupta [7] argued that this advantage is a synergy of the fibers where one fiber is stronger and stiffer and provides strength, and the second fiber is more flexible and ductile and provides toughness and high strain capacity in the post-cracking branch.

For civil engineering applications, the use of FRC in structural elements subjected to seismic forces has been study in the past. It has been demonstrated the potential of FRC to increase shear resistance and serve as partial replacement of shear reinforcement [8]. Athanasopoulou and Parra-Montesinos [8] not only presented a summary of previous studies of FRC but also the authors evaluated the use of FRC in combination with conventional reinforcement steel in low-rise structural walls to simplify the required transverse reinforcement (reducing reinforcement steel). The authors proved that the use of FRC not only reduced web distributed reinforcement but also that walls with FRC can reached drifts capacities close to 3% without compromising its seismic performance. More recently and due to the popularity of the use of low-rise buildings with thin walls in Latin America and in Europe, Carrillo et al. [9] studied the use of FRC (steel fiber only) for low-rise walls in low-seismic region. The authors concluded that walls with volume content of steel fibers of 0.75% and 1.0% experimented a similar performance of walls reinforced with conventional steel. Considering the advantages of the HyFRC over FRC with steel fibers that were discussed above, it is interesting to explore the potential of the HyFRC in the application of low-rise walls. Regrettably and to the best knowledge of the authors, there is not any research about the behavior of HyFRC in low-rise housing with thin walls.

Thus, the Research Center on Materials and Civil Infrastructure (CIMOC) of the Universidad de los Andes in Bogotá has conducted a research project exploring the applicability of HyFRC as web reinforcement of thin concrete walls. Computational results of this project shown that seismic demand for low-rise housing with thin walls (not more than three story buildings) in Colombia was low in terms of strength and strain demand, thus minimum reinforcement may be provided at walls [10]. Therefore, HyFRC could be a very interesting alternative to ease of fabrication and reduce the costs of structures such as low-rise housing. Therefore, a series of tests of HyFRC thin wall specimens were performed at the Large-Scale Structural Laboratory at the Universidad de Los Andes in Bogotá. Based on the experimental results, the HyFRC thin wall specimens shown outstanding performance even better than conventional reinforcement concrete thin walls [10]. This paper reported and discussed the mechanical properties of single-fiber and hybrid-fiber reinforced concrete mixtures that were used in the construction of the thin concrete walls specimens. Properties investigated for the FRC mixtures include the compressive strength and flexural performance of 63 cylindrical specimens and 67 small beams of concrete mixtures with different types of fibers and different fiber contents. Long and short hooked-end steel and polyethylene fibers were selected in the experimental program. The fiber volume content was varying between 0.15% and 1.25%. The goal of the research is to assess combinations of fibers that fulfill design requirements of FRC according to the ACI 318-14 Building Code [11] or *fib* 2010 Model Code [12] that satisfy requirements of strength and strain demands, as a proxy approach due to the lack of a more comprehensive provisions for FRC walls. A cost assessment in terms of performance of FRC is also presented and discussed in the paper.

2. Experimental program

Fiber-reinforced concrete beams with hooked-end or crimped steel fibers in dosages of 60 kg/m^3 have shown to resist shear stresses larger than $0.17\sqrt{f'_c}$ MPa [13]. This behavior is recognized in the section 9.6.3.1 of the current ACI 318-14 Building Code [11], which permit to use steel fibers instead of the minimum area of stirrup reinforcement in beams in which factored shear force varied between one half and the design shear strength provided by the concrete. ACI 318-14 [11] allows this alternative reinforcement if the following conditions are met: (1) steel discontinuous fiber reinforcement for concrete is deformed and have a length-to-diameter ratio (l_f/d_f) not smaller than 50 and not greater than 100; (2) FRC contains at least 60 kg/m^3; (3) the residual strengths in accordance with ASTM C-1609 standard [14] at midspan deflections of $L/300$ ($f_{L/300}$) and $L/150$ ($f_{L/150}$) are greater than or equal to 90% and 75% of the measured first-peak strength (f1), respectively; (4) the specified compressive strength (f'_c) does not exceed 40 MPa; (5) the height of the beam is not greater than 600 mm; (6) and the factored shear stress is not greater than $\phi\ 0.17\sqrt{f'_c}$ MPa. The complied of the concrete mixtures studied with ACI 318-14 [11] will be discussed later on Section 3 of this paper.

The experimental program was planned to characterize the compressive and the flexural performance of single-fiber and hybrid-fiber reinforced concrete. The experimental program included tests of 130 standard specimens: 67 small beams and 63 cylindrical specimens. The variables studied were the fiber material, the length-to-diameter ratios (l_f/d_f) of the fiber, and fiber volume content. Long (SF1) and short steel fibers (SF2), and a polyethylene fiber (PF) having three different length-to-diameter ratios (80, 63.6 and 84.6, respectively) were included in the study. The fiber volume content (V_f) is computed as the ratio between fiber dosage in kg/m^3 (D_f) and the unit weight of the fiber material (7850 kg/m^3 for steel fibers and 1270 kg/m^3 for polyethylene fibers, respectively). It is important to highlight that the minimum steel fiber dosage specified in ACI 318-14 [11] is $D_f = 60$ kg/m^3, which is equivalent to a $V_{f\text{-min}} = 0.76\%$. Fiber volume contents of single-steel fibers, single-polyethylene fibers and combination of both fibers (hybrid) varied between 0.15% and 0.98%, 0.16% and 0.94%, and 0.31% and 1.25%, respectively.

2.1. Materials properties

Normal-weight concrete with a specified nominal compressive strength (f'_c) of 21 MPa was selected as a commonly used concrete for casting thin concrete walls for low-rise housing. Maximum size of coarse aggregate for the ready-mixed concrete was 12.7 mm. An