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FLEXURAL PERFORMANCE OF FIBER-REINFORCED CEMENTITIOUS MATRICES

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Abstract

Fiber reinforcement has been frequently employed in concrete structures. The various problems associated with handling and production methods prompted the search for new types of fibers. This paper presents the first results of a study to compare the flexural response of glass concrete specimens reinforced either with randomly distributed short fibers or with continuous fiber mesh, with equal fiber volume ratios. The single short fibers are distributed either throughout the volume of the test beam, over one half of the beam depth on the tension side, or within the most highly strained quarter depth of the beam. All specimens are tested according to ASTM C-1018, and toughness indices I_5, I_{10}, I_{20} are determined from the load-deformation curves of this closed-loop three-point bending test. Two different types of fiber material (polypropylene and AR-glass) and two fiber volume ratios are studied. The results indicate that fiber efficiency increases with their concentration near the tension face, and fiber mesh is considerably more efficient than randomly distributed fibers. Glass fiber reinforcement, because stronger and stiffer, is consistently more efficient than polypropylene fiber reinforcement.

1. Introduction

A major research project has been under way at Columbia University for the last several years to investigate the suitability of crushed waste glass as aggregate for concrete [1,2,3]. Many of the concrete products considered in these studies are reinforced with different types of fibers. Fiber reinforcement has been used in conventional concrete to improve tensile and flexural performance [4], to suppress shrinkage cracking [5], to increase impact and fatigue resistance [6,7] and to force preferred failure modes [8]. The question addressed here is whether it is more advantageous to reinforce the glass concrete with randomly distributed short fibers or with continuous fiber mesh, also referred to as textile reinforcement. The choice will depend on the performance characteristics for comparable fiber volumes, as well as on the suitability for commercial production of fiber-reinforced glass products.

Short random fibers have the advantages of simplicity and economy of concrete production, especially for lower fiber volume ratios. However, both polypropylene and AR-glass fibers (prime candidates for many glascrete products) are inherently hydrophobic. While this property is an advantage in mixing the cement matrices with short random fibers, the relatively poor bond between such fibers and the hardened cement matrix, combined with their random orientation in three dimensions, make their performance less than optimal, when used in applications such as thin sheets. Continuous fiber mesh, because of improved bond characteristics, appears to be preferable in those cases. Design and controlled manufacture of such continuous textile reinforcements allow for a wide range of possibilities. The target performance characteristics appear to be achieved more readily with continuous fiber mesh than with randomly distributed short fibers, when large volume ratios are called for. This advantage may prove critical in the case of thin sheet concrete products.

Research on the use of fabric meshes for thin cementitious sheet reinforcement commenced in the mid-1980's [9,10]. Subsequent research has shown that proper use of such meshes can not only lead to excellent flexural properties but also enables a wide range of applications [11,12]. Peled, Bentur and Yankelevsky [13,14,15] have studied systematically the effect of fabric geometry on the bond performance of cementitious composites and concluded that woven fabric provided considerably better bond to a cementitious matrix than straight fibers. The crimped geometry of the yarns produces an anchoring mechanism. As a result, the flexural toughness of the composite increased significantly, even if the fabric was made of low-modulus hydrophobic yarns.

The present paper compares the flexural performance of glascrete beams reinforced with short random fibers and with fabric mesh containing equal fiber volumes. The variables that were evaluated are: fiber type, volume ratio and spatial distribution. Flexural toughness tests according to ASTM-C1018 were conducted under closed-loop strain control. The load-deformation curves were analyzed. The conclusions were drawn as to the preferable method of incorporating fiber reinforcement.

2. Experimental program

The test specimens were beams of dimensions 25.4 x 25.4 x 152.4 mm, tested in three-point bending over an effective span of 101.6 mm. Two sets of specimens were prepared, one reinforced with short random fibers and one with fiber mesh.

For specimens reinforced with short random fibers, three cases were considered (Fig.1): 1) the fibers were distributed throughout the beam; 2) the fibers were distributed over half of the beam on the tension side; 3) the fibers were distributed within the most highly strained quarter depth of the beam. Two types of fibers were studied: polypropylene fibers with aspect ratio of 318 and tensile strength of 620 MPa, and AR-glass fibers with aspect ratio of 794 and tensile strength of 1800 MPa. Two fiber volumes were considered each for both types of fiber, designated as V_f and $2V_f$, corresponding to one and two layers of the fabric meshes. For polypropylene fibers, V_f=0.51%, while for glass fibers, V_f=0.19%. The specimens with fabric meshes contained one or two layers of mesh, positioned on the tension side of the beam with 2mm concrete cover. The polypropylene mesh had a 4.5 x 4.5mm square grid and the glass mesh a 5 x 5mm grid.

A single glascrete mix design was used for all specimens. The water/binder ratio was 0.34. Crushed post-consumer glass was used as the aggregate with maximum particle size of #16. 15% of the type III cement was replaced by metakaolin to suppress the potential harmful effects of ASR [16]. In addition, a superplasticizer was used to obtain the desired workability. During casting, intensive vibration was applied to assure complete penetration of the cement matrix through the fabric openings. All specimens were demolded after one day and thereafter placed in a moisture room for 25 days before being tested. Each batch had three samples. The compressive strength of plain concrete was 97.7 MPa.

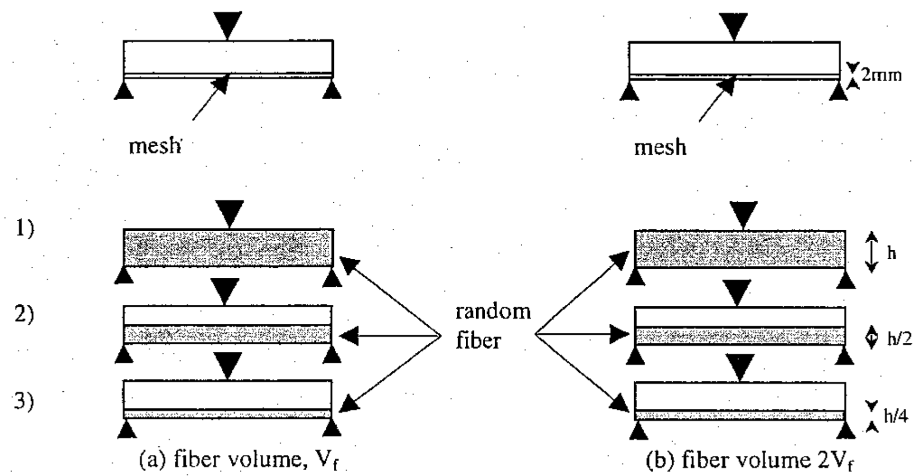
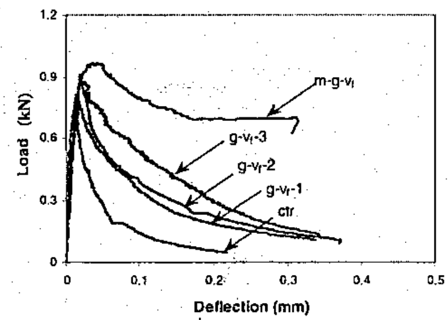


Fig.1 Fiber-reinforced beam specimens

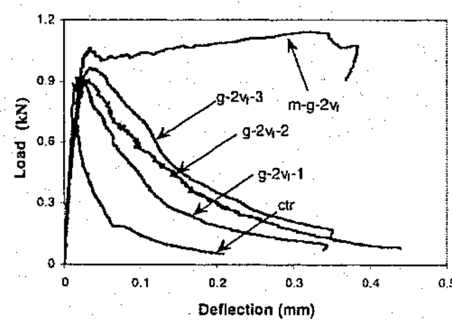
The closed-loop test was conducted in a 10kN MTS-458 machine with an external function generator. A displacement transducer monitored the crack mouth opening and supplied the feedback signal to the servo-controller. A LVDT was mounted at the specimen center to record the net deflections such that extraneous deflections resulting from the supports and loading fixtures were eliminated. The crack mouth opening displacement, applied load and net deflection histories for each beam were recorded through a data acquisition system.

3. Results and discussion

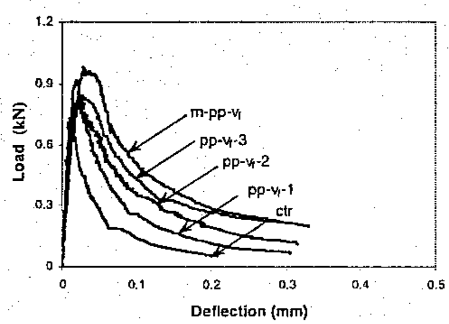
The load-displacement curves for beams with different fiber types and distributions are summarized in Fig.2. Figs.2a and 2b compare the mechanical behavior of samples with glass fiber mesh and equal amounts of short random fibers, V_f=0.19% and 0.38%, respectively. Figs.2c and 2d present the corresponding results for beams reinforced with polypropylene fiber mesh and short random fibers with V_f=0.51% and 1.02%, respectively. In Fig.2, "m" represents fiber mesh; "pp" signifies polypropylene and "g" AR-glass; "ctr" refers to the control specimen with no reinforcement. The numerical identifier refers to the three distributions of random fibers defined in Fig.1.



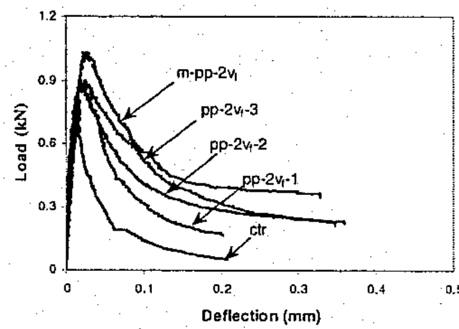
(a) glass fiber, V_f=0.19%



(b) glass fiber, $2V_f$=0.38%



(c) polypropylene fiber, V_f=0.51%

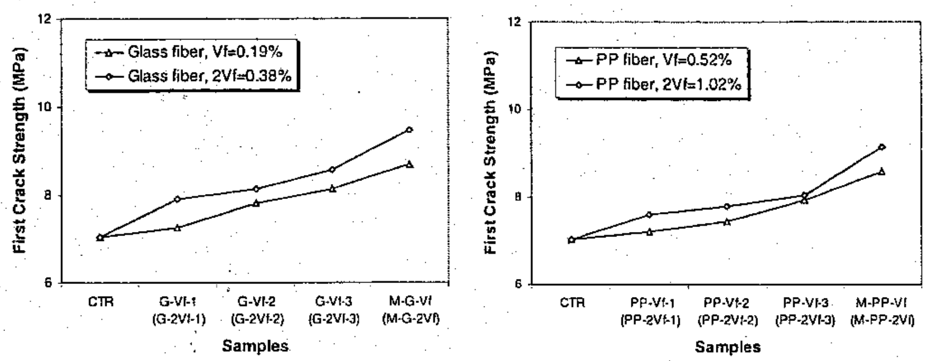


(d) polypropylene fiber, $2V_f$=1.02%

Fig.2 Load-deflection curves

3.1 First crack strength

The first crack strengths recorded for all specimens are presented in Fig.3. Randomly distributed fibers are seen to be consistently the more effective the closer they are concentrated near the tension face. Yet, in no case do they match the continuous fiber mesh. Short random fibers are known to be effective in arresting initial microcracks in the matrix and to slow the formation of the microcrack band during the strain localization stage. This increases the peak load, i.e. the first crack strength of the material. Ramakrishnan et. al. [17] found out that the flexural strength of concrete containing 0.1-0.3 percent of short polypropylene fibers increased by about 20 percent after 28 days compared with plain concrete. According to Figs.3a and 3b, continuous fiber mesh is clearly more effective in increasing the first crack strength than short random fibers. One possible explanation is the interfacial bond between the fibers and matrix, which in the case of fiber mesh benefits from the yarn curvature in the warp direction. Furthermore, the yarns in the filling direction have a restraining effect on the yarns in the warp direction and can also resist the sliding of loaded yarns in the matrix.



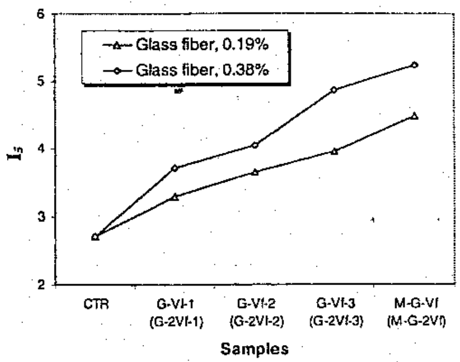
(a) samples with glass fibers (b) samples with polypropylene fibers

Fig.3 First crack strengths

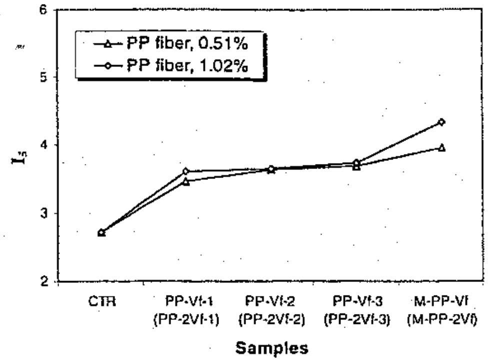
By comparing Fig.3a with Fig.3b, it can be seen that glass fiber reinforcement is slightly more effective in increasing first crack strength than polypropylene, both in the case of short random fibers and fabric meshes. This could be explained with the fact that the aspect ratio (794), tensile strength (1860 MPa) and elastic modulus (70 GP) of glass fibers are much higher than those of polypropylene fibers (318, 620 MPa and 3.5 GPa, respectively). At the small crack opening, the much stiffer glass material is more efficient.

3.2 Toughness indices

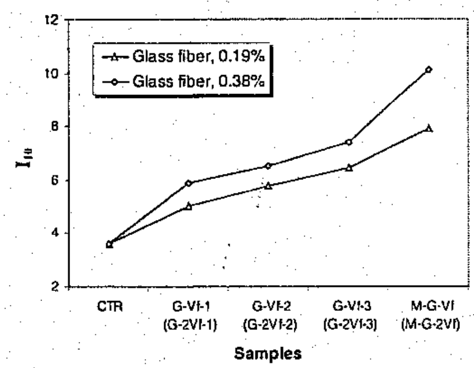
The toughness indices, I_5, I_{10}, I_{20} of ASTM C-1018 are employed to evaluate the flexural behavior of the fiber-reinforced specimens. Recently, the ASTM C1018 test has been criticized [18], because it depends overly on the first-crack definition, the load-deflection curve may have a region of instability, and because the toughness indices are not very effective in characterizing fracture behavior of fiber-reinforced concrete. In spite of such criticism, this method is still the most widely used approach to quantify the toughness of FRC. Especially, if a closed-loop controlled system is employed, reliable results can be obtained [19,20].



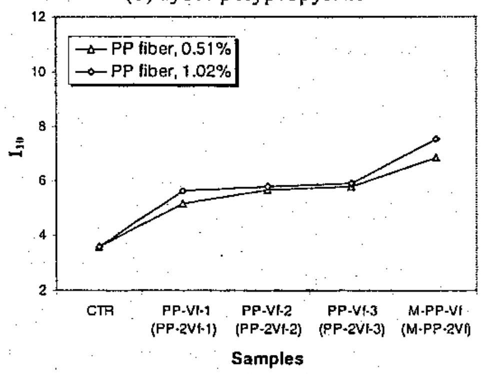
(a) I_5 for glass



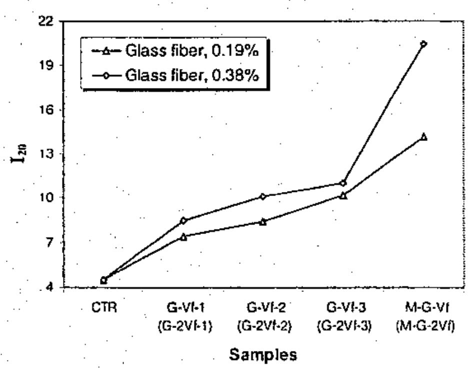
(b) I_5 for polypropylene



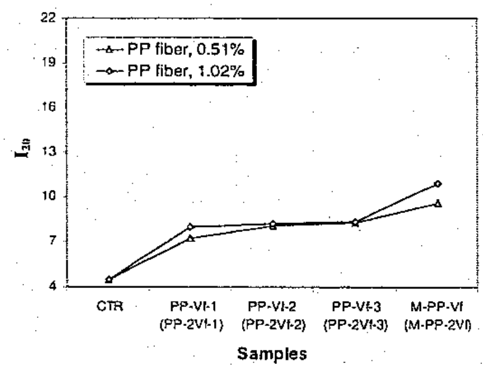
(c) I_{10} for glass



(d) I_{10} for polypropylene



(e) I_{20} for glass



(f) I_{20} for polypropylene

Fig.4 Toughness indices

The toughness indices of all the samples are shown in Fig.4. It can be seen that compared with plain concrete, the toughness indices of all fiber-reinforced specimens are increased, i.e. post-crack behavior is improved and fracture energy is increased considerably. For glass fiber-reinforced samples doubling the fiber volume clearly improves all indices. These indices also increase with the concentration of fibers near the tension face. For polypropylene fiber-reinforced samples, this is not at all the case. Doubling the fiber volume has barely an effect on those indices, and neither does the concentration of random fibers near the tension face. All toughness indices of specimens reinforced with randomly distributed fibers are approximately 50% higher than those of the unreinforced specimens. However, this observation does not imply there is no improvement. In fact, these toughness indices are relative values. From Fig.2, we can see the first crack toughness is increased with the increase of V_f and spatial distributions of the fibers. Therefore, even though the indices themselves remain constant, the post-cracking toughness is still enhanced with the higher V_f.

4. Conclusions

The use of high-performance polymeric fiber mesh has gained increased attention in structural engineering applications since the mid-1980's. Advantages of these fabric reinforcements include high strength, low unit weight and ease of coiling and handling. The fabric meshes are especially suitable for automated fabrication processes for thin sheet products such as pultrusion or extrusion, as well as for repair or strengthening of existing structures. Such thin sheet reinforcements can provide a complete integrated armature system to enhance the bending and shear resistance of beams. From the present study, it can be concluded that fabrics are very efficient in reinforcing glass concrete, which without any reinforcement is very brittle. Even at the very low volume ratio of 0.38% fiber glass mesh, strain hardening response can be achieved (Fig 2b). At the same fiber volume ratio, the reinforcing effect of the fiber mesh is superior to that of randomly distributed short fibers, due to its good interfacial bond between the matrix and the yarns and its placement near the tension face. Also, the stiffer and stronger AR-glass fiber mesh was found to clearly outperform polypropylene mesh.

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