BENDING AND PUNCHING SHEAR STRENGTH OF FIBER-REINFORCED GLASS CONCRETE SLABS

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An experimental study was carried out on fiber-reinforced glass aggregate concrete slabs under a central patch load. The slab specimens were reinforced either with randomly distributed short fibers or with continuous fiber mesh with equal fiber volume ratios. The influences of fiber type, form and volume ratio on the two-way bending behavior and punching shear capacity of the glass concrete slab were investigated.

Test results revealed that fiber mesh is decidedly more effective in bending than randomly distributed fibers, however randomly distributed fibers are somewhat more effective in punching shear. The shape and location of the critical punching shear perimeter is independent of fiber type, form and volume ratio. But crushed glass aggregate has some influence on both strength and failure mode of the slabs.

Keywords: concrete slabs; glass concrete; punching shear; two-way bending; fabric mesh; fiber-reinforced concrete.

INTRODUCTION

Thin-sheet concrete products have attracted considerable attention in recent years[1,2]. There are numerous potential applications, which previously were difficult or impossible to realize with conventional concrete materials. The introduction of non-ferrous reinforcement, either in the form of randomly distributed short fibers or continuous fiber mesh greatly reduces the cover requirements, thereby facilitating significant reductions of minimum thicknesses for such thin sheets. Their mechanical behavior differs considerably from that of conventional reinforced concrete panels, and so do the manufacturing processes. Thin-sheet products are often manufactured using extrusion and pultrusion processes.

If thin-sheet concrete panels are subjected to loads, conventional structural theory needs to be applied to assure that such loads can safely be resisted. Given their small thicknesses, punching shear performance may become important, especially if the reinforcement is dimensioned for flexural strength and the panels are subjected to large concentrated forces either by design or by accident.

Specific architectural surface treatments can open up an entire new category of applications such as claddings, veneers and face panels, which previously were mostly the domain of natural stone. Also the use of crushed glass particles as aggregate lends itself to a multitude of architectural treatments, including polished surfaces or exposed aggregate finishes[3,4]. The problem of alkali-silica reaction (ASR) needs to be considered, but technology exists to control the potentially damaging effects[5,6].

It was the objective of the study presented here to evaluate the bending and punching shear strength of fiber-reinforced concrete slabs with glass aggregate. The reinforcement consisted of either randomly distributed short fibers or continuous woven fiber mesh. Whereas short fibers have the advantage of simplicity and economy of production, performance specifications of thin-sheet products are more readily satisfied with continuous fiber mesh, especially if large fiber volume ratios are called for[7,8,9].

A considerable body of literature exists on the punching shear behavior of reinforced concrete slabs. When modeling such behavior for small-scale laboratory experiments it is important to accurately reproduce the boundary conditions that exist in real structures. Slabs are typically supported continuously along their edges and restrained by adjacent panels to various degrees. Such restraints typically affect the in-plane deformations of a representative slab panel subjected to a concentrated transverse load by forcing membrane or arch action. This can alter completely the load-carrying characteristics and failure mode[10-12], by greatly enhancing the punching shear capacity of such restrained slab panels.

The one-way bending behavior of fiber-reinforced concrete members with glass aggregate has been reported earlier[13]. This previous study showed that fiber mesh is clearly more effective than randomly distributed short fibers as reinforcement. However, the proper design of concrete slabs, whether used for thin-sheet products or more conventional structural slabs, depends on a thorough understanding of the two-way bending and punching shear behavior.

This paper reports on the experimental study of slab elements reinforced either with randomly distributed short fibers or continuous fiber mesh. The effect of the glass aggregate is assessed by also testing samples produced with regular river sand as aggregate. Three types of materials were studied for reinforcement: alkali-resistant glass (AR-glass), PVA, and polypropylene. In the punching shear test, only AR-glass fibers were studied.

RESEARCH SIGNIFICANCE

Fiber mesh reinforced thin-sheet concrete products with crushed glass aggregate lend themselves to numerous novel applications. If used for relatively large panels, their two-way bending and punching shear behavior needs to be known. A characterization of such behavior will facilitate the use of such panels for applications that until now was primarily the domain of natural stone. The research reported herein provides needed insights for their safe use.

MATERIALS AND TEST PROGRAM

Materials

A single concrete mix design was used throughout the test program. The water/binder ratio was 0.35. Crushed post-consumer glass was used as the aggregate, with maximum particle size #16. Strictly speaking, the material should therefore be referred to as mortar instead of concrete. The cement/aggregate ratio was 1:2. 15% of the Type III cement was replaced by metakaolin to suppress the potentially harmful effects of alkali-silica reaction[5]. Suitable admixtures were used to obtain the desired workability. The compressive strength of the mix, tested on 2-inch cubes after 28 days was 97.7 MPa.

Two-way bending test

The test specimens were square plates of 152.4 mm length and 19 mm thickness, loaded at their center with a round steel pressure head of 12.7 mm diameter to simulate a concentrated load. The clear test span was 101.6 mm (Fig. 2). The load was applied by a 50 kN Instron test machine under displacement control at a rate of 1.0 mm/min. A LVDT was mounted to measure indirectly the center deflections such that extraneous influences from the supports and loading fixtures were eliminated (Fig. 2). Three data channels, representing applied load, displacement of load cell and center displacement of specimen, were connected to a PC and recorded by Labview software.

Two sets of specimens were prepared, one reinforced with short random fibers, distributed over half of the slab on the tension side, and one with fiber mesh. Three types of fibers were studied: AR-glass fibers with 12.7 mm long and tensile strength of 1800 MPa, PVA fibers with 6 mm long and tensile strength of 1400 MPa, and polypropylene fibers with 12.7 mm long and tensile strength of 620 MPa. Two fiber volumes were considered for each fiber type, designated as V_f and $2V_f$, corresponding to one and two layers of the fabric meshes. For polypropylene fibers, $V_f = 0.67\%$, while for glass fibers, $V_f = 0.25\%$ and for PVA fibers, $V_f = 0.44\%$. The mesh-reinforced specimens contained one or two layers of mesh, positioned on the tension side of the beam with 2mm concrete cover. Both the AR-glass and the PVA mesh had a 5 x 5mm grid, while the grid of the polypropylene mesh was 4.5 x 4.5mm. The former two were woven and the third one knitted (Fig. 1). All specimens were demolded one day after casting and placed in a moisture room for two months before being tested. Each batch consisted of three samples. Table 1 contains an overview of the test program.

Punching shear test

To eliminate warping of the slabs, circular specimens with a diameter of 127 mm and thickness of 19 mm were cast. The specimens were supported on a simple ring with a diameter of 101.6mm. The test setup, testing machine, and loading rate were similar as in the two-way bending tests and as shown in Fig. 2.

The specimens were reinforced with either short random AR-glass fibers distributed throughout the slabs or AR-glass fiber mesh. The mesh-reinforced specimens contained one or two layers of mesh ($V_f = 0.25\%$ or $2V_f = 0.50\%$), positioned either on the slab's tension side, compression side, or both, with 2mm concrete cover in each case. All specimens were demolded one day after casting and placed in a moisture room for seven days before being tested. Two control batches were cast, one with plain glass concrete and the other with plain normal concrete, using river sand as aggregate. To achieve the arch action, a plastic tube with a diameter of 127mm and thickness of 6.35mm was used to confine the specimens. The test program is summarized in Table 2.

TWO-WAY BENDING TEST RESULTS

The load-deflection curves for all 13 test specimens are shown in Fig. 3. Each of the three plots contains five curves: one for the control specimen without fiber (S-C), two for the specimens reinforced with randomly distributed short fibers (V_f and $2V_f$), and two for the specimens reinforced with one or two layers of fiber mesh (V_f and $2V_f$). Figs. 3a,b,c show the responses of specimens reinforced with AR-glass, PVA, and polypropylene fibers, respectively. The ultimate strengths are summarized in Table 1.

Regardless of what type of fiber is used, continuous fiber mesh is seen to be clearly more effective than randomly distributed fibers. A similar observation was made with one-way beam bending tests[13]. The reasons are as follows. First, the fiber mesh is placed in the optimum location and effectively bridges cracks in any direction. Secondly, the bond between the fiber mesh and matrix is better, benefiting from the yarn curvature in the warp direction. Third, the effective bridging length of the fiber mesh is greater. The difference between the slab and beam cases is that in two-way bending, yarns in both the warp (or weft) direction and fill direction are stressed. This leads to an interlocking effect at the intersection of orthogonal yarns, which greatly improves the anchorage of the fiber mesh. The larger the bending moment, the more effective the bridging yarns become. This may explain why the ultimate strengths of mesh-reinforced specimens are on average around 45% higher than those of short fiber-reinforced specimens in the two-way bending test, but only 12% higher for the one-way bending cases[13], Fig. 4. Furthermore, Table 2 shows that in two-way bending, randomly distributed short fibers (cases S-G1, S-A1, S-P1) increase the ultimate strength of the control case (S-C) by only 18% on average, whereas in the one-way bending case the corresponding improvement was with 10% even less[13]. Thus, the effectiveness of fibers is considerably higher in two-way than in one-way bending. This implies that the use of beam theory to design fiber-reinforced two-way slabs would lead to overly conservative results.

In the test, a sudden change in the slope of the load-deflection curves corresponded to a major crack transverse across the specimen's center at the bottom face. As the applied load was further increased, more cracks appeared in the center region, and the cracks continued to propagate primarily in a radial direction. Typical cracking patterns at failure are shown in Fig. 5. The cracking patterns of samples S-C, S-G1 and S-G2 are very similar, while those of fiber mesh reinforced slabs (S-G3 and S-G4) are quite different. The better bridging effect of mesh-reinforced specimens causes more cracks and increases the ultimate load capacity. Since the two orthogonal sets of fiber yarns in a mesh have different wavy yarn structure and different geometries, their bridging effects are also different, as shown in Fig. 5 (specimens S-G3 and S-G4), where the warp direction is horizontal and fill direction vertical. After cracking, the horizontal warp yarns assume a larger share of the applied load since they are stronger. Thus, more cracks appear in this direction.

PUNCHING SHEAR TEST RESULTS

The punching shear load-displacement curves are shown in Fig.6, and the ultimate punching shear loads are listed in Table 2. According to these results, sample RS-G1, which was reinforced with short randomly distributed fibers, had the highest ultimate punching shear load and ductility. The fiber mesh reinforced specimens failed at slightly lower load, but whether the mesh was positioned at the top or bottom face of the slab, or both, seems to have had relatively little effect (RS-G2, G3, G4). The reason is that a concrete slab cracks when the diagonal tension or combined action of shear and direct stress exceeds the tensile strength of the concrete. In this case, fiber mesh is less effective, because it has been placed in areas of maximum flexural stress, not maximum diagonal tension. Short fibers, on the other hand, are uniformly distributed and randomly oriented such that some of them effectively bridge the diagonal tension cracks, thereby increasing the slab's shear strength. By comparing the two control specimens, it is seen that sample RS-C2 with crushed glass as aggregate has a higher punching shear strength than the sample RS-C1 with river sand as aggregate. This may be due to the glass aggregates' irregular shapes and sharp angles, which can increase shear transfer across cracks.

Figures 7 and 8 present the crack patterns of confined specimens after punching shear failure. The crack patterns at the top face were all nearly identical, with a small circle of a diameter, which is almost the same as that of the loading plate. On the bottom face, the crack patterns of the last five specimens are very similar, Fig. 8. Flexure cracks do not appear to be extensive. Maximum principal tension occurs near the mid-plane, initiating web-shear cracks that propagate toward the top and bottom faces of the slab and creating the typical conical failure surface.

When comparing the bottom face cracks of sample RS-C1 with that of RS-C2, Fig. 8, a marked difference is noted. In RS-C1, near-vertical flexural cracks formed at the bottom face when the applied moment exceeded the cracking moment. With increasing load, these cracks propagated toward the middle surface of the slab to form flexure-shear cracks, followed by the appearance of a transverse cracks that then led to punching shear failure. This observation implies that glass aggregate gives a higher flexural strength than ordinary river sand, possibly because the irregular shapes and sharp angle increase the bond between aggregate and matrix. Also the punching shear strength of the glass aggregate concrete slab is higher. According to the load-deflection curves of Fig.5, specimens made with glass aggregate are not more brittle than those made with river sand.

To further investigate the relationship between flexural and punching shear strengths of slabs and the effect of confinement, two additional control specimens were prepared and tested, A-C1 with river sand and A-C2 with glass aggregate. The mix proportions were identical to those of specimens RS-C1 and RS-C2, but the boundary was left unconfined. Both specimens failed in typical flexure. The flexural cracks initiated at the center of the bottom face and propagated towards the circular edge. The ultimate strengths are given in Table 2 and found to be lower than those of the specimens with constrained edges. As is known, the edge confinement facilitates compressive membrane action, which increases the shear friction across cracks and therefore the punching shear strength. In fact, this boundary restraint also increases the flexural strength, and this increase is proportional to the slab thickness.

Whether the edge is constrained or not, specimens with glass aggregate have higher punching shear capacity than those with river sand, Table 2. By comparing the strength of specimen RS-C1 with that of RS-C2 and A-C1 with A-C2, it is seen that the strength difference is larger for the unconfined case (18%) than the one with confinement (12%). Similarly, the confinement increases the sample with sand by 21% and that with glass by 16%. This implies that the specimen with river sand tends to expand in the radial direction more than that with glass aggregate or the flexural cracks of the specimen with river sand are wider than that of the specimen with glass aggregate. This means that glass aggregate provided a better bridging effect in the specimen than the normal river sand due to its irregular and sharp shapes. So, the specimen with river sand is more likely to be influenced by the boundary restraint. Whereas the confinement changed the failure mode of the glass concrete slab from a flexural to a punching shear failure, in the case of the specimen with river sand, the two failure modes were coupled. This implies that the flexural resistance of the glass concrete slab is more easily improved by the arch action than the ordinary concrete slab. From a design point of view, this result suggests that the restrained glass concrete slab is more likely to fail in punching shear. In either case, proper reinforcement has to be provided.

To calculate the shear stress associated with punching shear failure, the failure load is usually divided by the slab depth, h, and the average circumference of the failure surface, l. l is determined on the assumption that the effective section is located a distance kh from the face of the loaded area and has a geometrically similar shape. For a round patch load with diameter d, the effective length, l, can be expressed as[14]:

$$l = \pi(d + kh) \tag{1}$$

The failure surface is typically assumed to have a 45° slope, for which k=1. The value of k can be determined by measuring the top and bottom diameters of the failure surface. Using the average of six measurements, the value of k was estimated for each slab using the following expression:

$$k = \frac{D - d}{2h} \tag{2}$$

where D is the average diameter of the bottom face of the failure cone. The values thus obtained are listed in Table 2. They vary from 1.62 to 1.73, with a mean value of 1.68, which corresponds to a failure surface inclination angle of about 30°. There are no significant differences between the plain, short fiber-reinforced and fiber mesh-reinforced glass concrete specimens. This k-value agrees with others reported in the literature[12,15], where values of about 1.5 were given for steel fiber-reinforced concrete slabs with either confined or free boundary.

CONCLUSIONS

The use of crushed waste glass as aggregate for concrete is a relatively novel concept. The reservations against such use out of concern about long-term alkali-silica reaction problems have been addressed by extensive research efforts reported elsewhere. Solutions to overcome ASR-related problems are available, therefore it is now possible to address other issues related to glass concrete products. The question of flexural and punching shear of fiber-reinforced glass concrete slabs has been the topic of this paper.

Two-way bending and punching shear behavior of slabs with and without restraints are two different phenomena. The introduction of fiber reinforcement, either short and randomly distributed or fiber mesh, makes them more difficult to analyze. Both types of reinforcement are gaining acceptance in practice. The attractiveness of short fibers is due to their simplicity and economy of concrete production, especially for lower fiber volume ratios. The use of high-performance polymeric fiber mesh has gained increased attention in structural engineering applications since the mid-1980's. Advantages of such 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 and strengthening of existing structures. Such thin sheet reinforcements can provide a complete integrated armature system to enhance the bending and shear resistance of beams and slabs.

The study reported herein systematically compared the reinforcing effects of short randomly distributed fibers and fiber meshes on both the two-way bending and punching shear behavior of glass concrete slabs. It permits to draw the following conclusions:

1. For two-way bending, fiber mesh is very efficient as reinforcement. Even at the very low fiber volume ratio of 0.25%, strain-hardening response can be achieved. For the same fiber volume ratio, the fiber mesh is clearly superior over randomly distributed short fibers, because of better interfacial bond between the matrix and the yarns and the locking phenomenon at the yarn intersections. This superior reinforcing effect is even more pronounced in two-way bending than was observed in one-way bending.
2. Short randomly distributed fibers improve the flexural strength and ductility of glass concrete slabs, but do not change their failure modes. The yield lines are very similar to those of unreinforced glass concrete slabs. For the same fiber volume ratio, fiber mesh not only greatly increases the strength and ductility of glass concrete slabs but also forces multiple cracking and consequently strain hardening.
3. All restrained circular concrete slabs failed in punching shear. Glass concrete slabs reinforced with short randomly distributed fibers had somewhat higher shear strengths than those reinforced with fiber mesh, whether this was positioned on the slab tension side, compression side, or both. In specimens with boundary restraints, the beneficial effect of arch action on the flexural strength is more pronounced in the case of glass concrete than with ordinary concrete.
4. Fiber form and volume ratio, fiber mesh position and restrained boundary condition do not significantly influence the shape of the punching shear failure cone.

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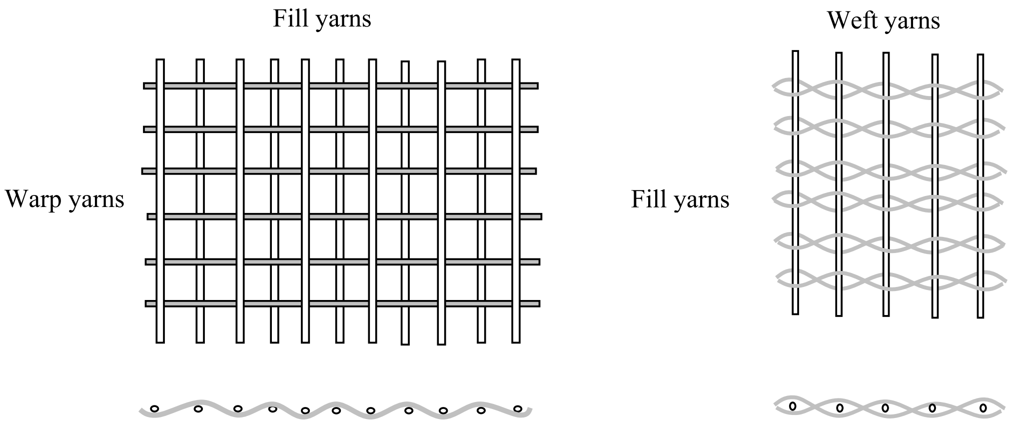
Table 1 Test program for two-way bending specimens

Slab	Type of Fiber	No. of Mesh Layers	Volume of Short Fibers, V_f(%)	Ultimate Load, kN
S-C	-	-	-	2.41
S-G1	AR-Glass	-	0.25	2.75
S-G2	AR-Glass	-	0.50	3.44
S-G3	AR-Glass	1	-	4.13
S-G4	AR-Glass	2	-	5.14
S-A1	PVA	-	0.44	2.91
S-A2	PVA	-	0.88	3.86
S-A3	PVA	1	-	4.38
S-A4	PVA	2	-	5.46
S-P1	Polypropylene	-	0.67	2.87
S-P2	Polypropylene	-	1.34	3.72
S-P3	Polypropylene	1	-	4.08
S-P4	Polypropylene	2	-	4.98

Table 2 Test program for punching shear specimens

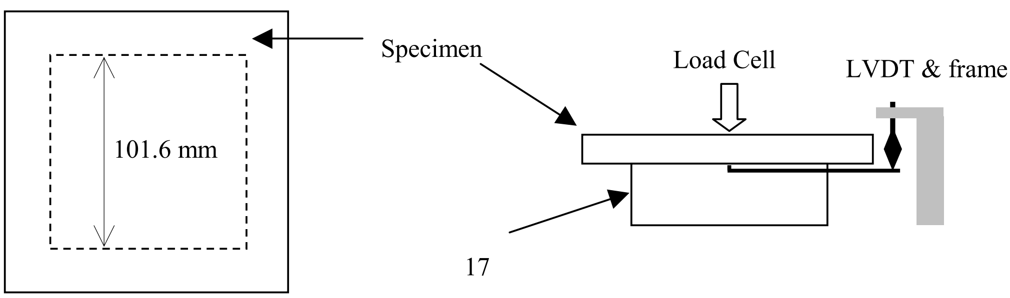
Slab	Type of Aggregate	No. of Mesh Layers	Position of Fiber Mesh	Short Fiber Volume, %	Ultimate Load, kN	Coefficient k
RS-C1	River Sand	-	-	-	3.45	-

RS-C2	Crushed Glass	-	-	-	3.88	1.62
RS-G1	Crushed Glass	-	-	0.25	4.39	1.69
RS-G2	Crushed Glass	1	Top	-	4.05	1.70
RS-G3	Crushed Glass	1	Bottom	-	4.09	1.67
RS-G4	Crushed Glass	2	Top & Bottom	-	4.17	1.73
A-C1	River Sand	-	-	-	2.84	-
A-C2	Crushed Glass	-	-	-	3.35	-



(a) Woven mesh (b) Knitted mesh

Fig.1 Structures of fabric mesh



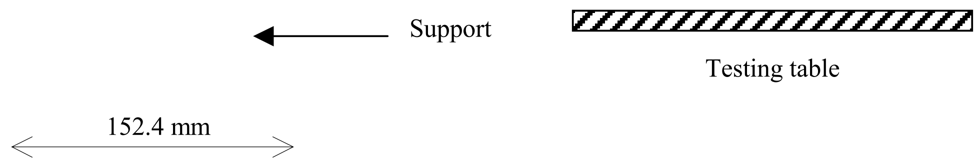
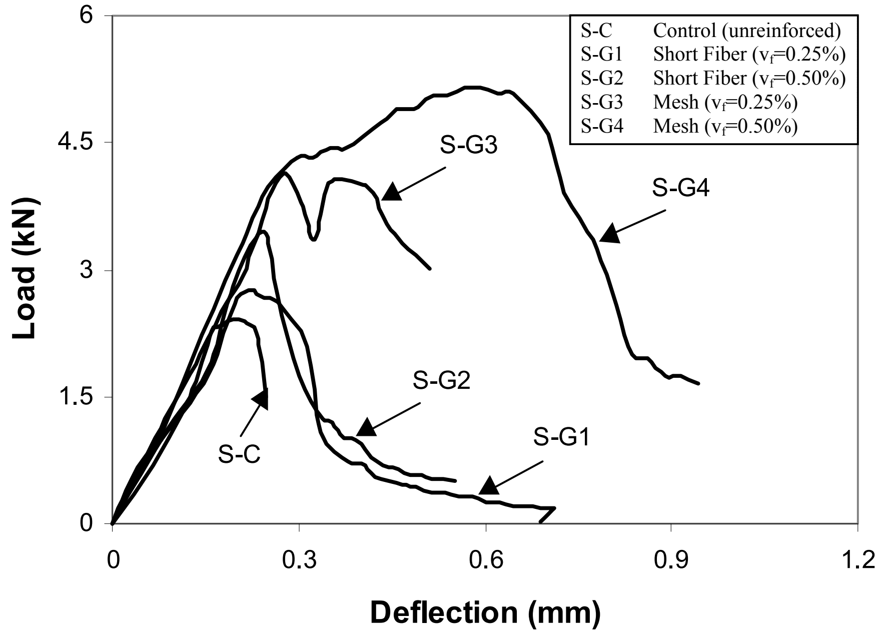
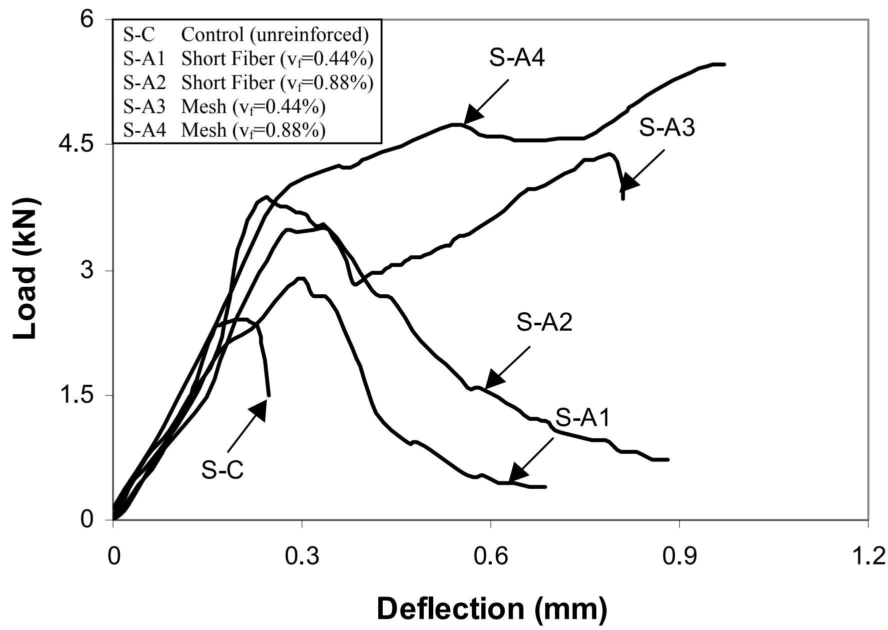


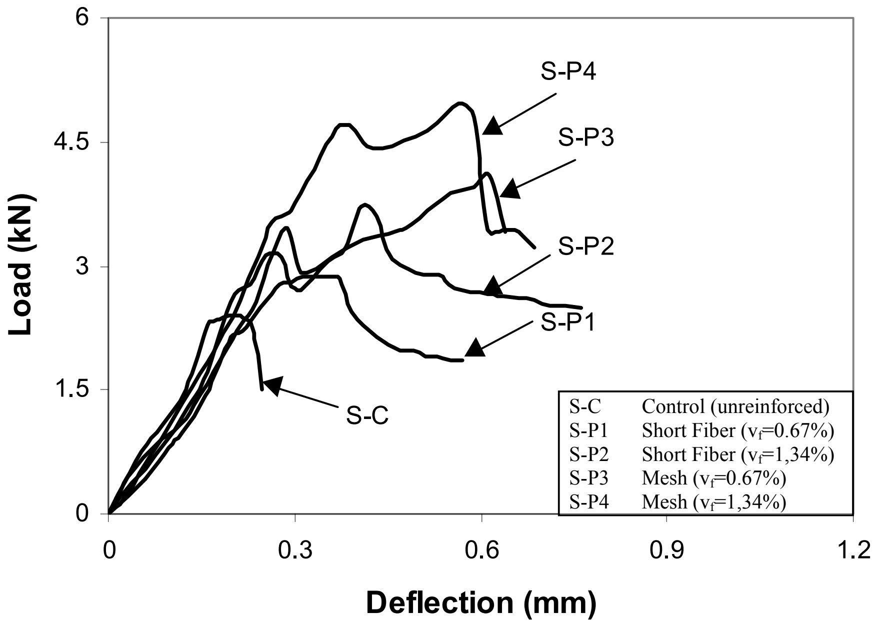
Fig.2 Test setup for two-way bending of glass concrete slab



(a) AR – Glass Fiber



(b) PVA Fibers



(c) Polypropylene Fibers

Fig.3 Load-deflection curves for slabs in two-way bending

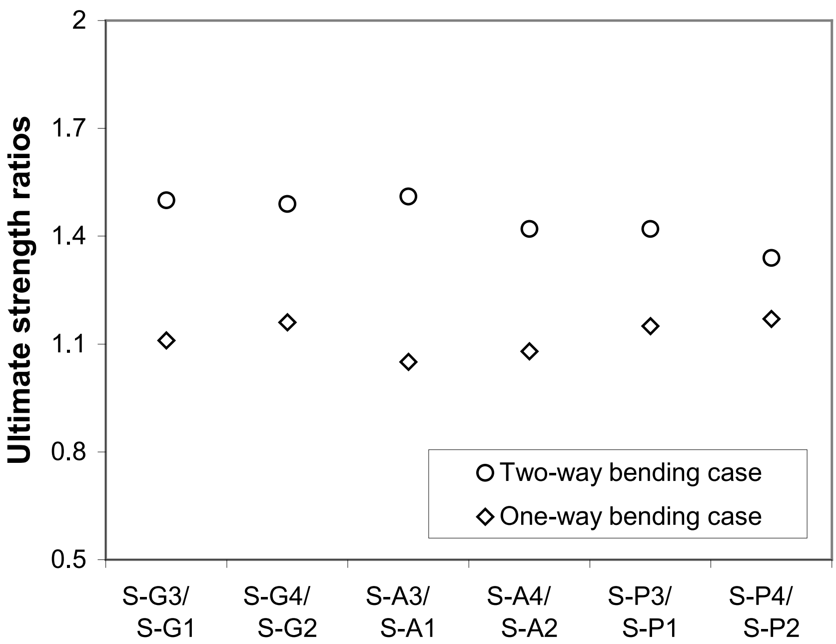


Fig.4 Ultimate strength ratios of specimens reinforced with fiber mesh and short fibers

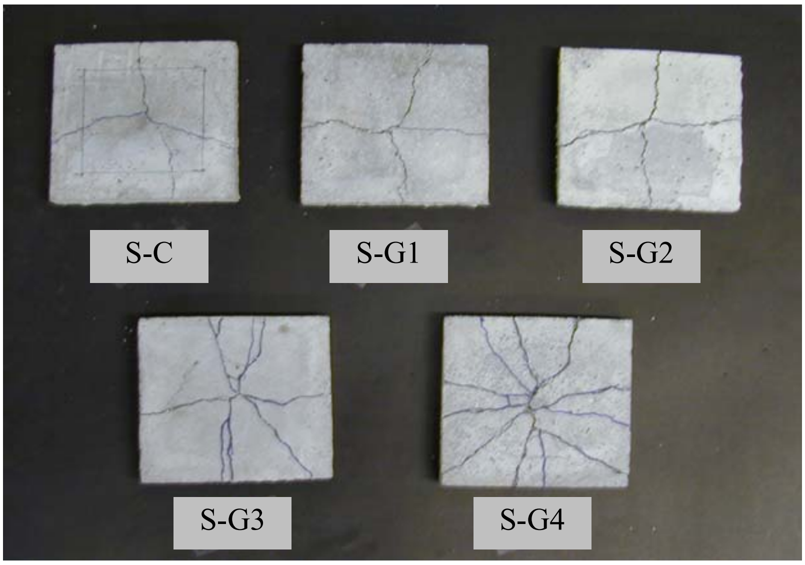


Fig.5 Typical cracking patterns of slabs after two-way bending

(For description of specimen IDs refer to table 1.)

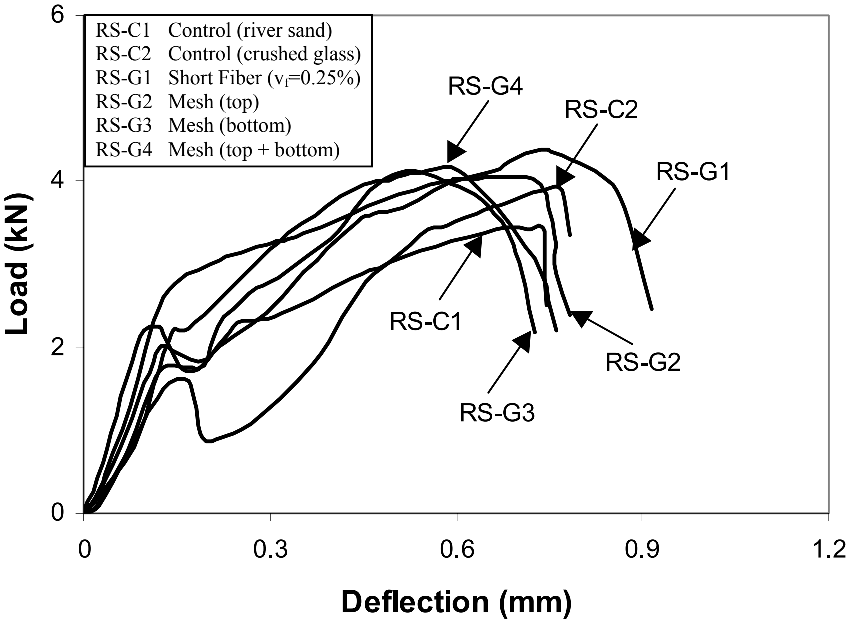


Fig.6 Load-deflection curves for slabs in punching shear

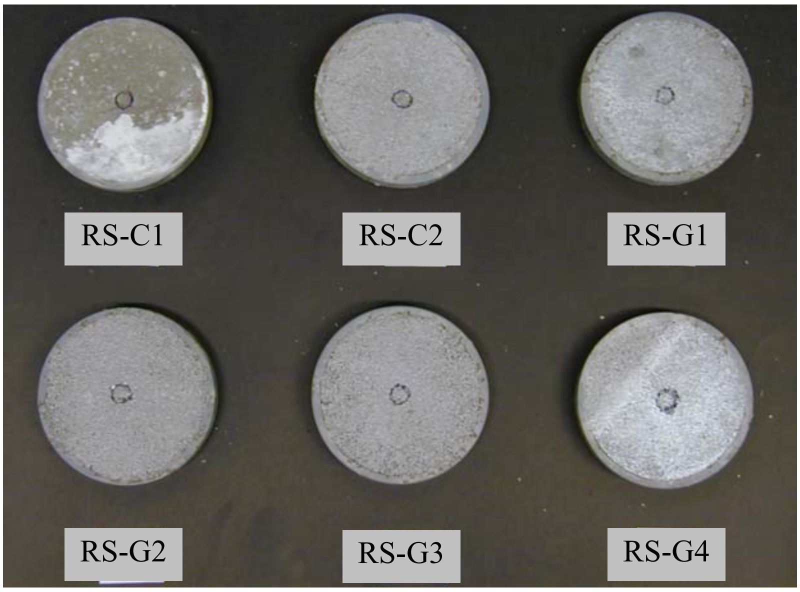


Fig.7 Typical cracking patterns of slabs after punching shear (top face)

(For description of specimen IDs refer to table 2.)

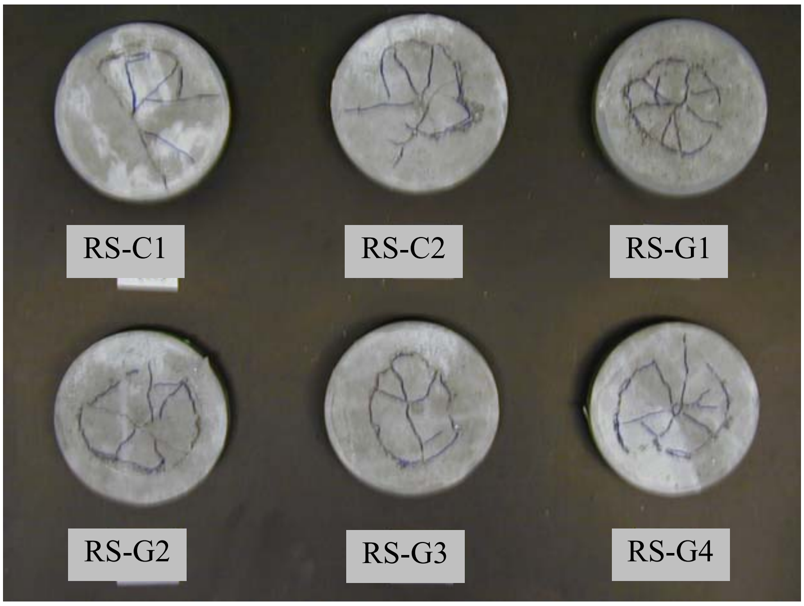


Fig.8 Typical cracking patterns of slabs after punching shear (bottom face)

(For description of specimen IDs refer to table 2.)