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Shear Behaviour of Fiber Reinforced Concrete Beams

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Abstract

This paper presents the results of shear/flexure tests on steel and polypropylene fiber reinforced concrete beams. In addition to analyzing the influence of fibers on the structural performance in situations of different ratios of shear reinforcement, some aspects of the properties of fresh and hardened concrete are introduced.

Fourteen square-section beams were tested. The beams were prepared from seven different mix proportions, varying the type and the volume of fiber added. There were two beams for each composite mix: one model with and the other without stirrups.

The main alterations resulting from the use of fibers were increased shear strength, stiffness (particularly after first cracking stage) and ductility. Other parameters used in analyzing performance were the properties of the hardened concrete (compressive strength, tensile strength, and modulus of elasticity), and stresses in the stirrups, in the longitudinal reinforcement and in the concrete (at the web and compression zone). © 1997 Elsevier Science Ltd.

Keywords: Concrete, steel fiber, polypropylene fiber, shear strength, fiber reinforced concrete.

INTRODUCTION

The addition of short fibers to concrete improves mainly its post-cracking behavior (ductility, performance under dynamic loading and cracking control) and can also alter tensile strength. These advantages vary according to the type and volume of fiber added to the matrix. The characteristics of the concrete change significantly when a large volume of fiber is added. In these cases it is usual to use steel fibers and special production techniques are required. The tensile strength of the concrete is not modified significantly when the volume of fiber added is low, up to 2%, but it improves ductility and control of cracking, even in the case of very low volumes, under 0.5%.[1–5] In these cases, other types of fiber are used besides steel fiber, including low modulus fibers such as polypropylene or organic fibers.[6]

The alteration of the concrete properties with the use of fibers is basically due to the different deformation capabilities of the fibers and the matrix. This is controlled by two phenomena: the bonding forces at the fiber–matrix interface and the bridging forces crossing the cracks on the advanced loading stages.[3,4]

Increased ductility is associated mostly with bond failure in the interface and with successive pull-out of the fiber, which uses large amounts of energy. Analysis of bond stress in the interface is normally based on the pull-out phenomenon,[3,4,7,8] that is essential to understand the behavior of the tensioned composites, based on the ACK model.[3] The principal parameters used in this model were determined by the law of mixtures, the concepts of fracture mechanics[9] and the mechanisms of multiple cracking.[10]

The advantages provided by the fibers to the properties of concrete and their variations with the type (material, geometry, surface) and the volume of fiber used have been recorded by several authors, for steel fiber[11,12] and for polypropylene.[13,14]

The influence of fibers on shear strength can be associated with two factors: direct action on inclined cracks (in a similar way to stirrups) and the indirect contribution on the transfer mechanism of transverse forces, which increase concrete strength contribution (dowel effect of the longitudinal reinforcement and crack friction) due to improved control of cracking. Several studies have been done in this area: evaluation of shear strength increase, using a calculation method that incorporates the influence of fibers (based on usual models)[15–18] or not;[19–21] estimation of fiber influence on the transfer of transverse forces by dowel effect and crack friction;[22] and the possibility of substituting stirrups for fibers,[23] among others.

This paper analyses the influence of fibers on the structural performance of square-section concrete beams subjected mainly to shear forces. Two types of fiber, steel and polypropylene, in different volumes were used. In each case, the influence of the fibers for different ratios of shear reinforcement were analyzed.[24]

EXPERIMENTAL PROGRAM

Materials

The materials used in the concrete mixes were: high initial strength Portland cement, river sand, crushed basalt stone, and, in the beams with fiber, a superplasticizing admixture. The mix proportions (by weight) were kept constant at 1:2:1.3 (cement:sand:coarse aggregate) and 0.45 water/cement ratio. Fibers used were multifilament type polypropylene, with 42 mm length and 0.05 mm diameter, and crimped rectangular-section steel fiber ($0.2 \times 2.3\ mm^2$), in two different lengths: 25.4 mm and 38.1 mm.

Beams

Fourteen square-section ($100 \times 100 \times 1000\ mm^3$) beams were prepared, varying only the type and volume of fiber. One of the seven concrete mixes contained no fiber. In the other mixes, all of them with fibers, a superplasticizing admixture was used to keep the mix workable for a constant water/cement ratio. Two beams were prepared for each type of mix, the only variation being the shear reinforcement: one with stirrups (series A beams) and one without stirrups (series B beams). Table 1 summarizes the characteristics of the mixes and the corresponding beams.

Simultaneously to the preparation of the beams, four cylindrical $150 \times 300\ mm^2$ concrete samples were molded to determine the mechanical properties. The beams were tested applying two point-loads on the thirds of the span. The relation between the distance of the loads to the supports and the effective height of the beams was equal to 3.5. Figure 1 illustrates the loading scheme and beam reinforcement.

The beams were instrumented with electrical strain gages in the concrete compression zone (symbol C), on the longitudinal reinforcement (symbol A) and on the stirrups (symbol E). In addition LVDT gages were installed on the supports and in the middle of the span, in order to measure the beam deflections. Figure 2 shows the position of the gages and the loading scheme.

RESULTS AND DISCUSSION

Properties of the concrete

The addition of fibers decreased the workability of the fresh concrete, particularly in the case of polypropylene fiber, which had a very high

Table 1. Characteristics of the concrete mixtures

Concrete mixture	*Beam*	*Type of fiber*	*Volume of fiber* V_f *(%)*	*Superplasticizer (%)*
1	P1A/P1B	—	—	—
2	P2A/P2B	polypropylene	0.5	1.0
3	P3A/P3B	steel 25.4 mm	1.0	1.0
4	P4A/P4B	steel 25.4 mm	2.0	1.0
5	P5A/P5B	steel 38.1 mm	1.0	1.0
6	P6A/P6B	steel 38.1 mm	2.0	1.0
7	P7A/P7B	steel 38.1 mm	0.5	1.0

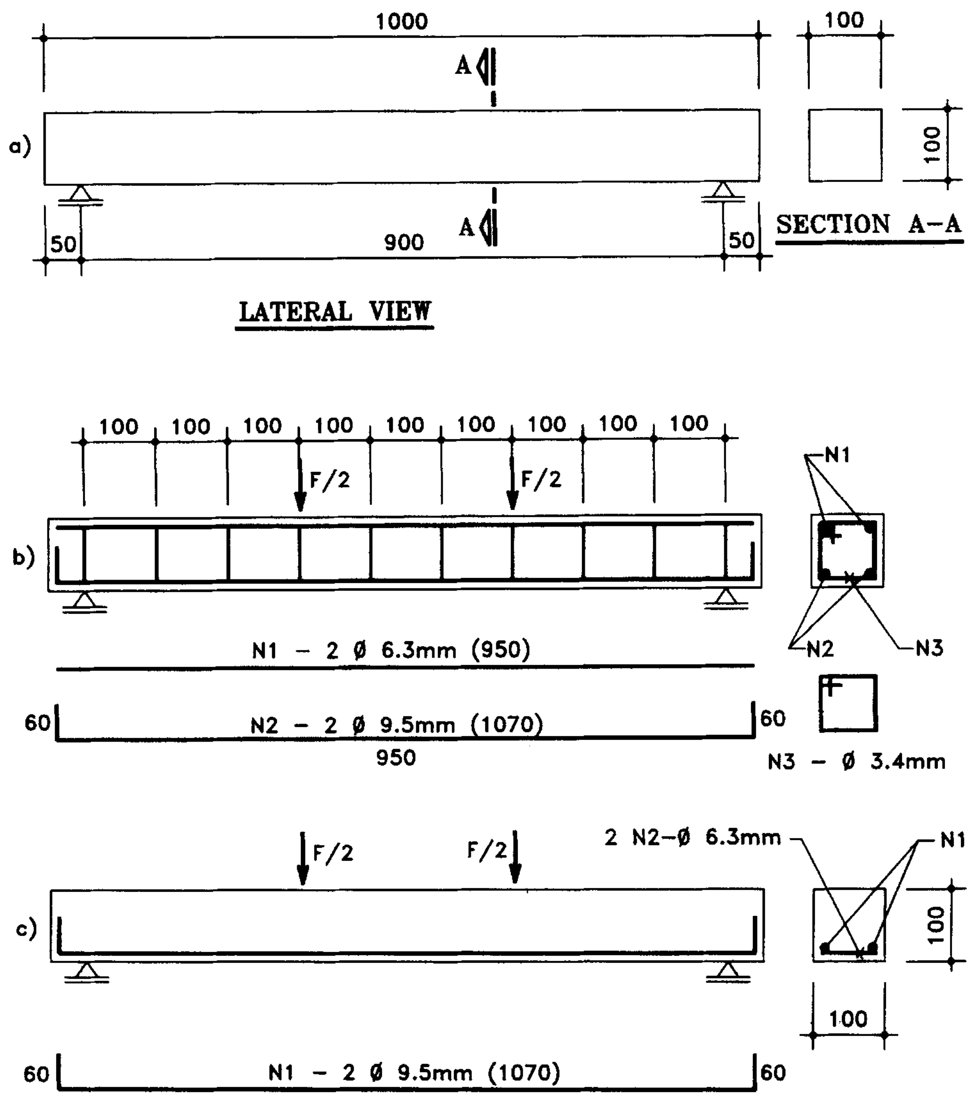

Fig. 1. (a) Geometry. (b) Reinforcement of the series A beams. (c) Reinforcement of the series B beams.

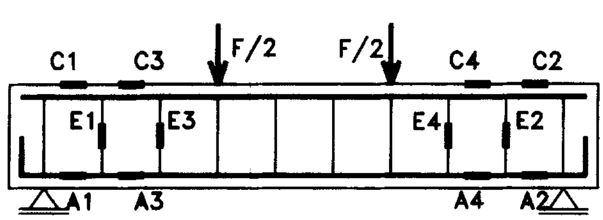

Fig. 2. Position and number of strain gages.

aspect ratio (length/diameter ratio). The results of compressive and split tensile strength and the initial modulus of elasticity obtained from the concrete samples are shown in Table 2. A small increase in modulus of elasticity and in strength was noted in the fiber-reinforced concrete, especially in the case of steel fibers. The last column of Table 2 shows the values of the modulus of elasticity divided by the square-root of

Table 2. Properties of the concrete mixtures

Mix	*Compressive strength* f_c *(MPa)*	*Tensile strength* f_t *(MPa)*	*Modulus of elasticity* E_c *(MPa)*	*Relative modulus of elasticity* $(E_c/f_c)^{0.5}$
1	43.8	3.4	29000	4381
2	48	3.45	34740	5014
3	54.8	3.3	38720	5230
4	50	4.2	41490	5868
5	49.3	3.85	33740	4805
6	53.7	4.3	36270	4949
7	53.5	3.6	37550	5134

compressive strength, as an attempt to minimize the influence of concrete strength on this parameter. Even so, the mixes with fibers showed higher values of the relative modulus of elasticity.

Ultimate strength

Views of the beams after testing are shown in Figs 3 and 4. Table 3 contains the data on failure. Theoretical values of ultimate shear forces were evaluated according to formula of the Brazilian Code. Shear failure in the beams with stirrups was expected at a load close to 37 kN, at the same time the longitudinal reinforcement was yielding (disregarding any influence of the fibers in this calculation). In the beams without stirrups, shear failure was expected at a much lower load, close to 8 kN.

The maximum force of model P1A reached 40 kN, when shear failure occurred. In this series of beams with stirrups, only two beams (P5A and P7A) presented the same failure mode, but strength increased by 7.5% and 12.5% respectively. In the other four beams with stirrups, the ultimate shear strength was not reached. The increase in strength in these cases (beams P2A, P3A, P4A and P6A) was at least 13%, 17%, 15% and 17% respectively. The results for bending are not conclusive, since flexure strength was not exhausted in the beam without fibers. However, it can be stated that an increase in strength, if any, was minimal, since

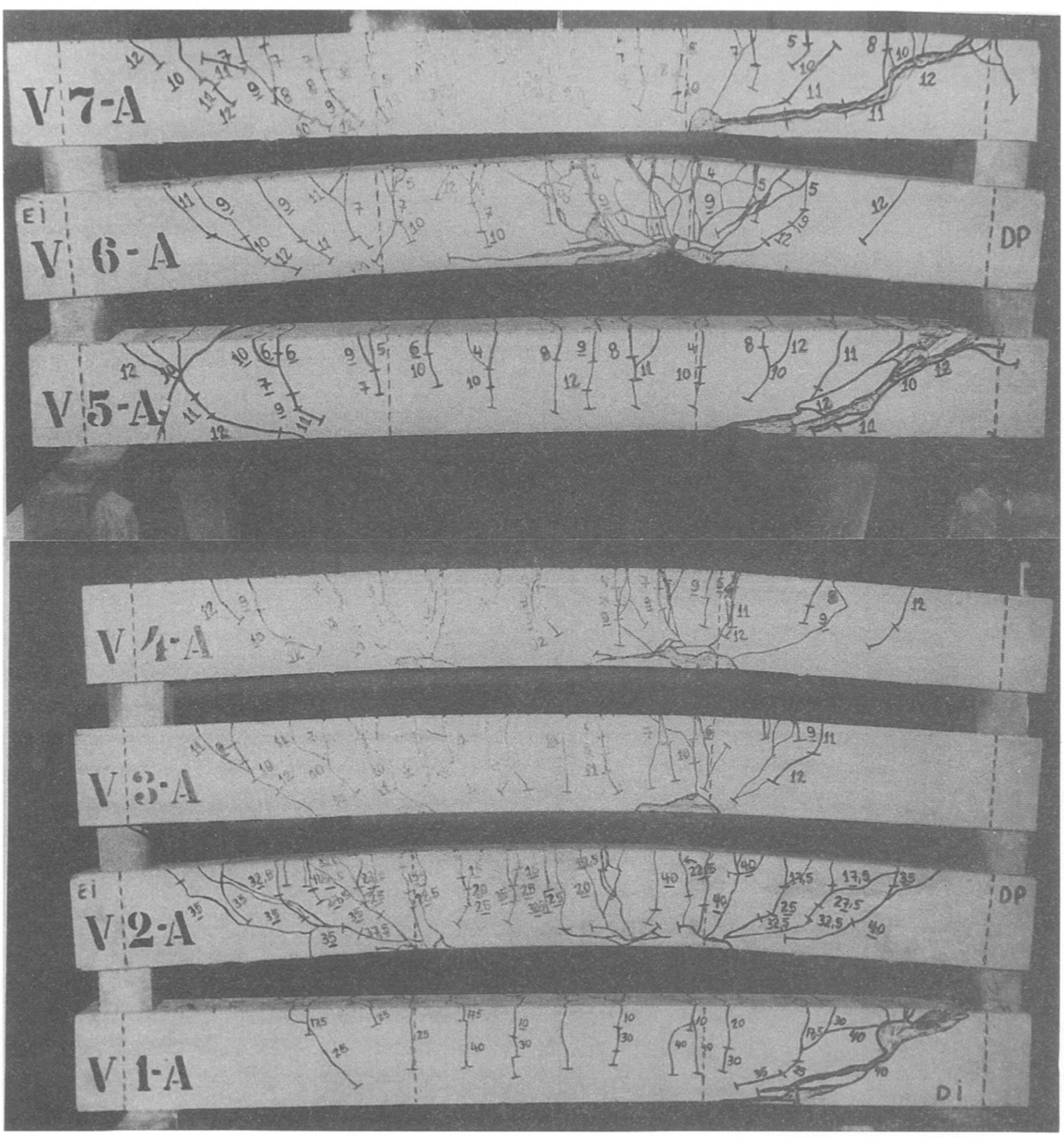

Fig. 3. View of the series A beams after testing.

there had not been any yielding in the longitudinal reinforcement at 40 kN in beam P1A. The stronger beams, P3A and P6A, where longitudinal reinforcement yielding occurred, the maximum force was 47 kN.

The ultimate strength of the beams without stirrups was much higher than evaluated theoretically because the strength provided by alternative mechanisms (dowel effect, crack friction, and the contribution of the compression zone), represented in a simplified manner by V_c, is underestimated in non-reinforced beams.

All the beams without stirrups showed shear failure, whereas all the beams with fibers showed an increase in shear strength of 9% to 37%, depending on the volume of fiber.

Cracking

In the fiber reinforced beams, in comparison with the beams without fibers, control of cracking resulting from normal stress was more effective. Additionally, there was a larger number of closely spaced cracks. In some fiber-reinforced beams (2% volume fraction of steel fiber) without stirrups, cracking was similar to those with stirrups and without fiber. This fact confirms that the effectiveness of fibers may be similar to that of stirrups, both in strength and cracking control.

With regard to inclined cracks, it was noted that in the beams without stirrups failure occurred soon after the appearance of the diagonal

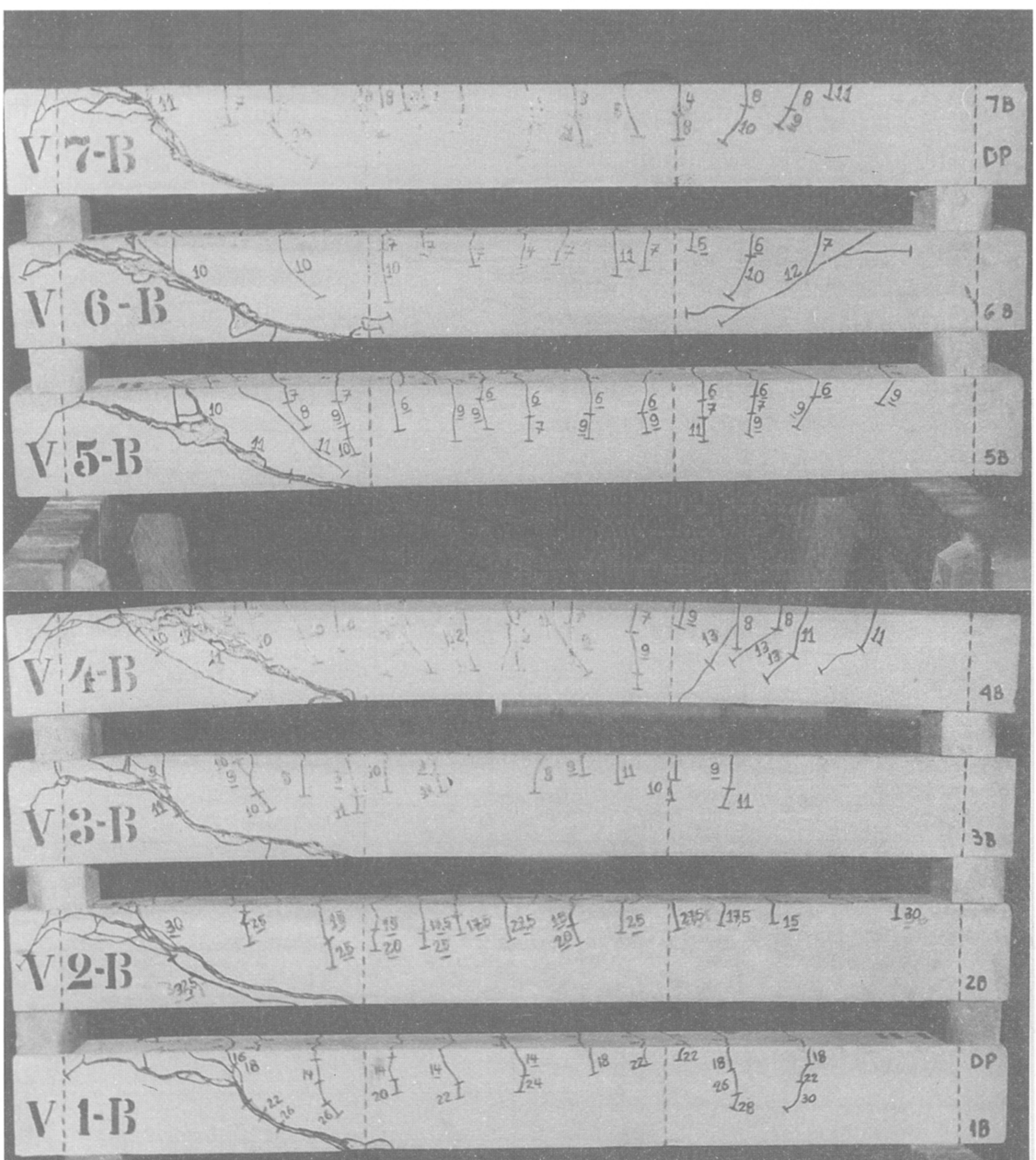

Fig. 4. View of the series B beams after testing.

Table 3. Parameters on failure

beam	*Ultimate force (kN)*	*Experimental/ theoretical ratio*	*Variation of strength in relation to P1 (%)*	*Type of failure*
P1A	40	1.16	—	shear–tension
P1B	32	2.22	—	shear–tension
P2A	45.2	1.28	13.0	flexure
P2B	35	2.36	9.4	shear–tension
P3A	47	1.29	17.5	flexure
P3B	40	2.5	25	shear–tension
P4A	46	1.29	15	flexure
P4B	44	2.86	37.5	shear–flexure
P5A	43	1.22	7.5	shear–tension
P5B	37	2.43	15.6	shear–tension
P6A	47	1.3	17.5	flexure
P6B	40	2.53	25	shear–tension
P7A	45	1.25	12.5	shear–tension
P7B	35	2.22	9.4	shear–tension

crack, except in the beams containing 2% of steel fibers. In these cases the fibers acted effectively as shear reinforcement, increasing the strength and ductility. In the beams with stirrups the diagonal cracking was more intense and shear strength was increased in all beams. The fibers prevented shear failure in four cases, where the collapse mechanism was changed from shear to flexure.

Deflections

Figures 5 and 6 illustrate the progress of deflections in the A and B series' beams respectively. It can be noted that the fibers provide increased stiffness after cracking. Reduction of deflections is due to more effective control of cracking, regardless of the value of the modulus of elasticity. However, it is not possible to observe a direct relation between the deformability of the beams and the volume of fibers.

The analysis of the load–deflection diagram suggests that, among the beams with stirrups, the one without fibers had less ductility. Yielding strains were reached in the longitudinal reinforcement of the P2A, P3A, P4A and P6A beams. These results are aligned with the occur-

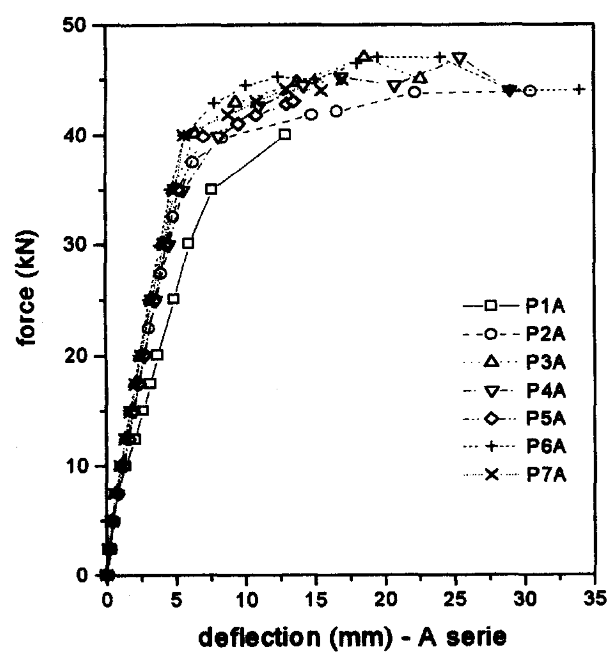

Fig. 5. Deflections on A series beams.

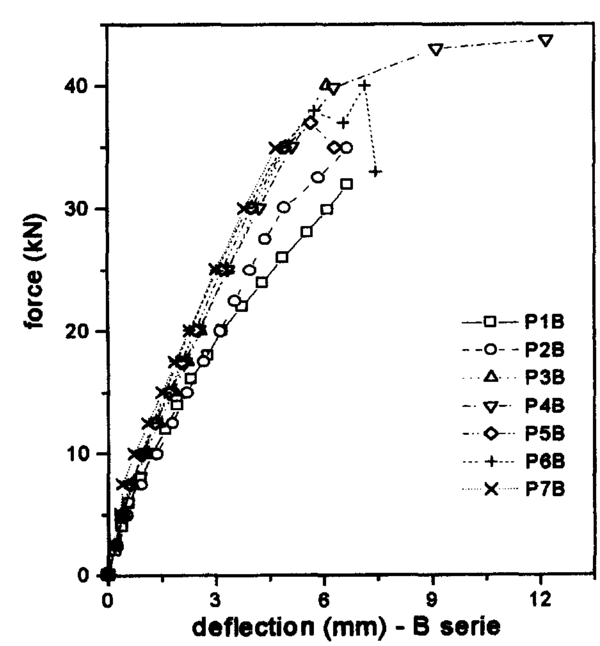

Fig. 6. Deflections on B series beams.

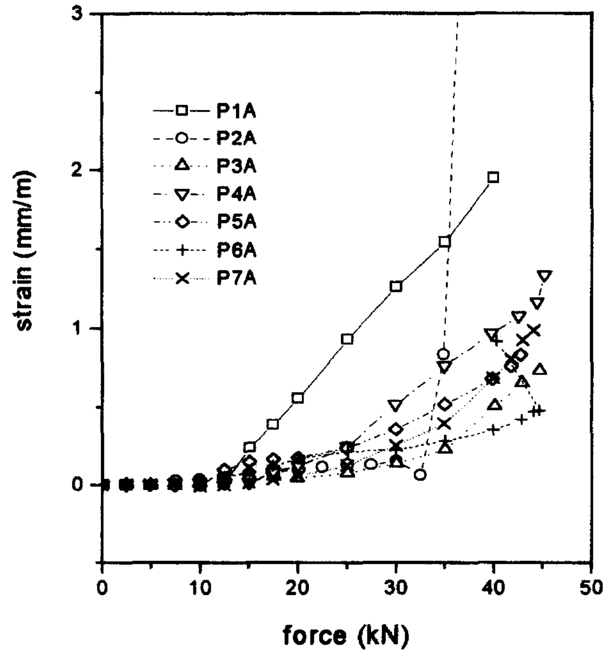

Fig. 7. Strains in the stirrups at the points E3–E4.

rence of the diagonal failure observed in beams P1A, P5A and P7A.

Shear failure occurred in all the beams without stirrups. However, the large plastic deformation observed on beam P4B suggests that longitudinal reinforcement yielding had occurred before collapse, leading to the conclusion that the introduction of fibers can alter the failure mode even in the absence of stirrups.

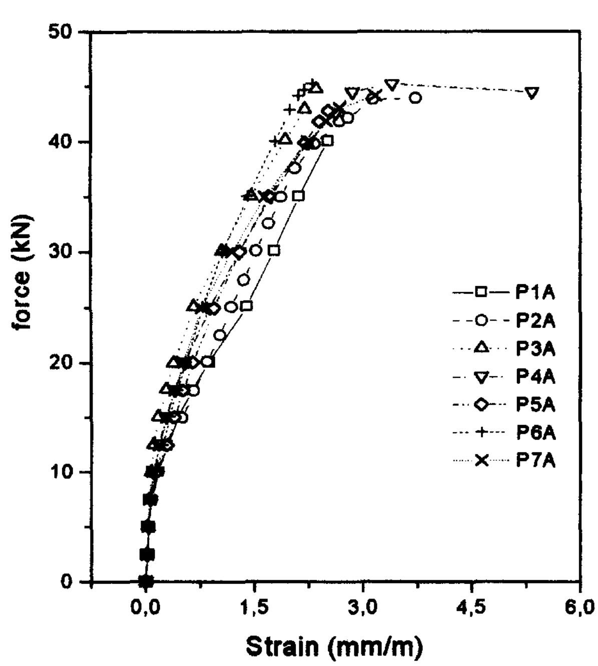

Fig. 8. Strains in the strands at the points A3–A4.

Stirrups

The progress of stresses in the stirrups is a parameter that indicates the contribution of concrete and fibers to shear strength. Figure 7 shows the progress of stresses in the stirrups of the series A beams.

The stresses in the stirrups in the region of higher bending moments (where the first inclined cracks appear) were delayed in the beams with fibers. The stresses in the stirrups of the steel fiber reinforced beams were, in every case, comparatively less. In addition to the direct action of the fibers on the inclined cracks, an indirect contribution is provided by sustaining the alternative mechanisms (dowel effect and crack friction) for longer periods.

It was noted that steel and polypropylene fibers act differently. Due to its low modulus of elasticity, polypropylene fiber is less effective. However, it can improve cracking control at initial loading stages and allow the action of alternative mechanisms. As the cracking spreads, there is an increase of stress in the stirrups, but failure is still retarded because a great amount of energy is needed for pull-out of the fibers in the area of the critical crack.

On the other hand, steel fibers are more effective as a reinforcement that bridges the inclined cracks, and the fiber's action is similar to that of the stirrups.

Longitudinal reinforcement and concrete

The behavior of the concrete in the compression zone and the stress variation in the longitudinal reinforcement were not altered significantly by the introduction of fibers.

At the internal points of the reinforcement (A3 and A4), the strain is practically free of the influence of the strut support effect. The strain measured was slightly less in the beams with fibers. Figure 8 shows the strains at these points. At the points near the supports (A1 and A2), normally there was an increase of stress when shear failure was imminent, due to the tied-arch mechanism. The highest stress in the reinforcement occurred in the beams with fibers, possibly because dowel action was more effective.

CONCLUSIONS

The addition of fibers decreased the workability of concrete, particularly in the case of polypropylene fiber.

The main advantages to the concrete mechanical properties resulting from the addition of steel fibers were a slight increase in tensile strength, in the case of long fibers, and in the modulus of elasticity, especially in the case of short fibers.

The progress of cracking in fiber reinforced concrete was relatively slow and, consequently, deflections were reduced. Cracking configuration at the end of testing in the fiber reinforced beams was more intense.

Ductility only increased significantly for the beams without stirrups and with 2% addition of steel fibers. In the beam using 2% of short steel-fibers, performance was similar to the beam without fibers and with stirrups, proving the feasibility of substituting stirrups for fibers.

The addition of fibers increased the shear strength, and the failure mode was altered from shear to flexure in four beams with stirrups, which suggests improved effectiveness of fibers in this situation. Failure was more ductile in practically all the fiber reinforced beams.

There are differences in the way steel and polypropylene fibers act in shear, due principally to the difference in the materials' moduli of elasticity. This difference appears mainly in stirrup stresses, which are lower in the case of steel fiber reinforced concrete than for a polypropylene fiber reinforced beam. In any case, a more effective control of cracking increases the contribution of alternative strength mechanisms.

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