SP 44-10

STRENGTH AND DEFORMATION OF STEEL FIBER REINFORCED MORTAR IN UNIAXIAL TENSION

By
Colin D. Johnston and Ronald A. Coleman

Synopsis: The paper provides information not previously available on the properties of steel fiber reinforced mortar, and by implication concrete, subjected to uniaxial tensile stress. Uncoated circular, rectangular and Duoform and brass-coated circular cross-section fibers were utilized in concentrations of up to 6% by weight and aspect ratios of 30-150. The results, based on a total of forty mixes, illustrate the combined influence of fiber shape, size, aspect ratio and concentration on tensile strength, deformation and toughness. Fiber concentration and aspect ratio are apparently the only two important variables, regardless of shape and size of cross-section. The increases in strength, deformation and toughness are essentially directly proportional to fiber concentration, and, on the basis of the observed data, are related to fiber aspect ratio raised to a power of about 1.5. The most effective combination of these variables, 6% of fibers of aspect ratio about 100, corresponds to increases of the order of 31% for strength, 28% for strain at failure and 68% for toughness.

Keywords: deformation; fiber reinforced concretes; flexural strength; metal fibers; mortars (material); research; stresses; tensile strength; tension.

ACI member Colin D. Johnston is an associate professor of civil engineering at the University of Calgary, Calgary, Alberta, Canada and a graduate of Queen's University, N. Ireland, B.Sc. in 1962 and Ph.D. in 1967. Engineering experience includes highway construction and ready-mixed concrete production. Research interests are primarily in plain concrete, fiber reinforced concrete and ferro-cement.

Ronald A. Coleman is a graduate of the University of Sydney, Australia, B.Sc. in 1961 and B.E. in 1963. He received his M.Sc. from the University of Calgary in 1972 and is currently Supervising Engineer in the Materials Testing Section of Spratt Bailey Laboratories Ltd., Vancouver, British Columbia.

INTRODUCTION

Most published investigations of the properties of randomly oriented steel fiber reinforced concrete or mortar have dealt principally with the stress-deformation behavior under static loading in flexure, splitting tension and compression. A major deficiency in the overall picture of material properties is the lack of comprehensive information on behavior under uniaxial tension. Fundamentally, this is significant because relief of tensile stress at the tip of a crack which would otherwise propagate is the principle originally advocated for including fibers in concrete. Moreover, the strengthening effect associated with pullout of the fibers and its relationship to fiber parameters can be more clearly distinguished when a relatively large volume of material is subjected to uniform uniaxial tension, than when nonuniform or complex stress conditions exist and the calculation of stress is based on assumptions which are not entirely valid, as is the case for flexure and splitting. In practice, tension can also be important in applications for which fiber reinforced concrete is proposed, for example in pavements subject to thermal contraction.

The need for information on behavior in tension and the desire to clearly establish the influence of variables associated with the fiber, namely shape, size, surface characteristics, aspect ratio and concentration, were the basis for undertaking the work reported herein. The choice of mortar was based on the fact that previous studies (1,2) indicated that property changes induced by inclusion of fibers are more marked in mortar, so the resultant behavioral trends are therefore likely to be more obvious and less subject to matrix variation.

TEST PROGRAM

The schedule of 40 mixes utilized 0.022 in. brass-coated fibers and hard drawn bright finish fibers in four different cross-sections, 0.010 in. and 0.016 circular, 0.01 x 0.02 in. rectangular and 0.016 in. Duoform (20% circular + 80% deformed to 0.01 in. thick). (0.01 in. = 0.25 mm). Fibers varied from 0.5 - 3.3 in. (12.5 - 84 mm) in length and in concentration from 1 - 6% by weight of mortar. The mortar was made using Type I cement and had a water/cement ratio of 0.50 and a sand/cement ratio of 3.0, but the quantity of sand in the fibrous mixes was reduced by an amount equivalent to the fiber volume to partially compensate for the stiffening effect of the fibers. As similarity in all respects between fibrous and plain mixes is not possible (3), the logic of this procedure, also used by Dixon and Mayfield (4), is that the influence of fiber parameters alone is best assessed under conditions of constant matrix strength, that is constant water/cement ratio and nearly constant workability.

The casting schedule for each mix comprised three 6 x 3 in. (150 x 100 mm) plain mortar control cylinders and four 30 x 4 x 4in. (750 x 100 x 100 mm) fiber reinforced prisms. The prisms were tested in uniaxial tension using a friction grip technique described in an earlier paper (5) to apply load and a pair of transducers to monitor average strain over a 4 in. gauge length. Specimens were loaded continuously in a closed loop hydraulic system incorporating an X-Y plotter which recorded load-strain behavior to failure. Stroke rather than strain control was adopted because the electronic noise sensitivity of the system did not permit strain control via the transducers. However, bearing in mind that stroke is the cumulated deformation of the two tension grips and the specimen, the control approximates constant rate of strain more closely than constant rate of stress application.

DISCUSSION OF RESULTS

Variables not associated with the fiber reinforcement are mortar strength, degree of compaction and factors associated with the testing technique. Variation in control cylinder strength over the six month period can be judged from the coefficient of variation of 4.5% derived from the mean strengths of the 40 sets of cylinders made in the program. Air contents calculated on a specific gravity basis were less than 2% for all mixes and less than 1% for many, so the degree of compaction achieved appears adequate. In earlier work (5) the average within-batch coefficient of variation obtained when using this testing technique for plain concrete was 4-5% for aggregates of up to 3/4 in. (19mm) maximum size. On the same basis, that is four specimens per mix, the average in this study was 6.8%. The increase is probably largely due to additional variability associated with the uniformity of distribution and orientation of the fibers.

Strength

The data in Fig. 1 illustrate the absolute and percentage increases in strength for the five fiber types in terms of fiber concentration by weight and aspect ratio. Careful comparison of the best-fit curves applicable to aspect ratios in the range 30-100 shows no obvious and consistent difference in the results for the four different cross-sections of uncoated fiber. Therefore, shape of cross-section and size in the range covered (0.01-0.016in.(0.25-0.41mm)) seem to be unimportant in their own right, aspect ratio and concentration being the significant parameters. Of particular interest is the fact that the Duoform fiber, which should have a higher pullout resistance because of its stepped surface, is no more effective than circular or rectangular fibers of about the same size.

Before discussing in detail the trend towards greater strength with increasing fiber concentration or aspect ratio apparent in the majority of the relationships shown in Fig. 1, some of the discrepancies and the possible reasons for them should be mentioned. The difficulty of achieving reasonable workability, uniform fiber distribution and proper compaction with fibers of aspect ratio greater than 100 noted by other workers was again apparent here, particularly with 4% of 1.5 x 0.01 in. (38 x 0.25 mm) uncoated fibers. Moreover, mixes with the relatively long (2.2-3.3in.(56-84mm)) brass-coated fibers of aspect ratio 100-150 were also rather stiff and difficult to handle. As all of these mixes exhibited unsatisfactory or borderline miscibility, the results are not included in subsequent analyses. Unfortunately, varying degrees of success in mixing and compaction are probably responsible for the inconsistency and scatter of the data in the bottom section of Fig. 1, so a firm conclusion on the effect of brass coating cannot be reached. However, the magnitude of the higher extremes in the data, probably associated with more successful mixing and compaction, and some recent work with concretes in flexure, suggest that the coating is unlikely to significantly affect relationships between strength and fiber concentration or aspect ratio.

The influence of fiber concentration and aspect ratio, already apparent in a general sense in Fig. 1, can be more precisely illustrated by plotting group average increases in strength, calculated by combining individual results for the four uncoated types of fiber at corresponding values of aspect ratio and concentration, as shown in Fig. 2 and 3 (number in parenthesis is number of mixes represented by each plotted point). The data in Fig. 2, based on 27 mixes, show that increase in strength is essentially proportional to fiber concentration for a given aspect ratio. However, the data points in Fig. 3a (the curves will be referred to subsequently) suggest that increase in strength is not directly proportional to aspect ratio, but rather to a power of aspect ratio. This becomes more obvious when actual increases in strength are expressed as increases per unit percent fiber concentration, that is the proportionality implied in Fig. 2 is assumed, and the overall group average values plotted, as shown in Fig. 3b. Clearly, a curvilinear function is more appropriate than a linear function, and for aspect ratios up to 100 a power relationship based on $(L/D)3/2$ closely approximates the actual data. For aspect ratios greater than about 120 the increase in strength appears to reach a maximum of about 6% per unit percent fiber concentration, but it must be emphasized that this is conditional upon the achievement of proper fiber distribution and compaction, as was obviously not the case for some of the mixes shown.

In attempting to establish a single overall parameter to which the percentage increase in strength, P_d, is closely and simply related, two combinations of the important variables, fiber concentration, W, and aspect ratio, L/D, are considered. The first, illustrated in Fig. 4a, incorporates the findings of Figs. 2 and 3 by using $W(L/D)3/2$ as the parameter. The second, illustrated in Fig. 4b, uses the mathematically simpler expression W(L/D). Based on 31 mixes, the correlation coefficients are 0.887 and 0.878 respectively. Both values are well in excess of the 0.554 corresponding to a significance level of 0.1%, thus indicating a high degree of correlation. Unfortunately, their similarity does not help in distinguishing which parameter is most closely related to increase in strength. The choice can only be made on the basis of Fig. 3b, which clearly favors the use of a parameter involving $(L/D)^{3/2}$, and on the better fit of a power function, $P_{\sigma} = 0.005\, W(L/D)^{3/2}$, derived by rounding of the regression equation of Fig. 4a to include the origin, to the data in Fig. 3a compared with the fit of any linear function based on W(L/D).

Another feature of the relationships in Fig. 4 is the good mix of data for the four uncoated fiber types, thus again indicating the relative unimportance of fiber shape and size already noted in the discussion of Fig. 1.

Deformation

The tensile strains referred to in this section correspond to the maximum stress, as failure always occurred at this point and a descending portion of the stress-strain curve was not detectable, probably because of the relatively low stiffness of the gripping mechanism and the fact that precise control by constant rate of strain was not possible. A problem associated with strain measurement at failure, at least in this and similar previous work (6), is that the results are subject to much greater variation than the corresponding values of stress. However, in spite of this and the consequent greater scatter of data, relationships between the apparent increase in strain, P^{*}_{ϵ}, and parameters $W(L/D)^{3/2}$ and W(L/D) are still discernible, as shown in Fig. 5. The correlation coefficients are respectively 0.692 and 0.706, less than their counterparts for strength, but still in excess of the 0.554 corresponding to a significance level of 0.1%. Once again, the similarity of the values does not help in distinguishing which parameter is most appropriate, and the group average method of analysis must be employed to resolve the question.

Before following this procedure, it should be noted that in both relationships in Fig. 5 the reference strain of 143×10^{-6}, based on 6 plain mortar specimens, does not match the prediction of the regression analysis based on 124 fibrous specimens. In view of the scatter problem already mentioned, this discrepancy of about 5% is hardly surprising, but subsequent analyses are based on the reference value which has greater statistical weight, 150×10^{-6} in this case. With regard to the expected order of magnitude of strain for mortar of water/cement ratio 0.5, a value of 150×10^{-6} is in good agreement with the prediction of a chart of tensile strains at failure published in earlier work (6).

When values of the corrected increase in strain, P_{ϵ}, based on 150×10^{-6}, are plotted as group averages in the same manner as for strength (Fig. 2 and 3), trends similar to but less clearly defined than for strength can be distinguished, as shown in Fig. 6 and 7. However, as extreme variations from the norm can unduly distort these trends because the group averages are based on only four mixes, it was arbitrarily decided to omit two of the worst cases (marked E in Fig.5) from the analyses. Although selective omission of specific points in a set of random data cannot be justified on statistical grounds, it can perhaps be justified by stating that the two data points seem to be markedly unrepresentative of the general trend and by noting that the affected proportion of data, 2 out of 31 results, is small. On this basis, the data in Fig. 6 show that increase in strain is essentially proportional to fiber concentration for a given aspect ratio. It is not clear from the data in Fig. 7a whether the relationship involving aspect ratio is linear or nonlinear. However, when overall group averages are calculated on the basis of increase in strain per unit percent fiber concentration, the nonlinearity of the relationship becomes more obvious, as shown in Fig. 7b. Once again, a relationship involving $(L/D)^{3/2}$ closely approximates the actual data. Further support for this conclusion is provided by comparing the fit of a power function, $P_{\varepsilon} = 0.0045\, W(L/D)^{3/2}$, derived by rounding off the regression equation of Fig. 5a to include the origin, to the data in Fig. 7a with the fit of any linear function based on W(L/D).

Toughness

Toughness or the amount of energy required to cause failure is given by the area under the stress-strain function which is proportional to the product of stress and strain at failure. The constant of proportionality of 0.58 used to allow for curvature is based on a dimensionless stress-strain curve obtained in previous work (6).

As increase in strength and increase in strain have both been shown to correlate with $W(L/D)^{3/2}$ and W(L/D), it follows that similar relationships apply to the increase in toughness, P_T, as shown in Fig. 8. The correlation coefficients are respectively 0.849 and 0.850. In view of the earlier analyses of stress and strain, the relationship based on $(L/D)^{3/2}$ is considered more appropriate, and for aspect ratios up to 100 the expression $P_T = 0.0104\, W(L/D)^{3/2}$ closely represents the experimental data.

RELEVANCE OF PREVIOUS WORK

The results obtained by Shah and Rangan (1) using 1 x 0.01 in. (25 x 0.25 mm) fibers aligned in the direction of loading confirm the direct proportionality between strength and fiber concentration illustrated for randomly oriented fibers in this paper. Moreover, the effect of orientation is clearly demonstrated by comparison with the authors' results. For example, 5% of fibers of aspect ratio 100 increase tensile strength by about 133% for aligned fibers, compared with 24% for randomly oriented fibers. A small proportion, but by no means all of this major difference, may be due to the sizes of cross-section tested, 2 x 1 in. (50 x 25 mm) in the work of Shah and Rangan (1) and 4 x 4 in. (100 x 100 mm) in this work.

Analysis of the results of this investigation in terms of the spacing concept proposed by Romualdi and Mandel (7), as shown in Fig. 9 indicates that the increase in strength induced by inclusion of fibers is dependent not only on fiber spacing, $25.2D/\sqrt{W}$, but also on aspect ratio, L/D. Thus, spacing is not the fundamental governing parameter, as it does not include L. However, in the expression given by Romualdi (8) for critical strain energy release rate, $G_c = \mu \pi \alpha WL/1266D$, where μ is the shear bond stress (assumed constant by Romualdi) and α is the angle at the tip of a propagating crack, the variable part is W(L/D) if μ and α are in fact constant.

Recently. Lankard (9) has shown for mortars that the increase in flexural strength obtained with various sizes and amounts of fiber is related to the effective bond area of the fibers passing through a unit area of the fracture plane and that this bond area is in turn directly proportional to the product W(L/D).

CONCLUSIONS

1. The percentage increases in uniaxial tensile strength, strain at failure and toughness resulting from the inclusion of steel fibers in mortar are:-

(i) independent of the shape of fiber cross-section including variable cross-section Duoform fiber,

(ii) independent of fiber size at constant aspect ratio for diameters of 0.01-0.016 in. (0.25-0.41 mm). (Analysis of the results of a number of investigations of flexural strength (3) involving diameters of 0.006-0.06 in. (0.15-1.5 mm) supports this conclusion),

(iii) directly proportional to fiber concentration, for a constant aspect ratio,

(iv) proportional to fiber aspect ratio to a power of about 1.5 for values up to about 120.

2. The strength, deformation and toughness of fiber reinforced mortar in uniaxial tension are governed by the simple product of two variables, fiber concentration which is the major cost parameter, and fiber aspect ratio which is the performance parameter. This product is apparently related to critical strain energy release rate, as defined by Romualdi (8), and effective fiber bond area per unit area of fracture surface, as defined by Lankard (9).

3. Fiber balling and inadequate mix workability impose an upper limit in the range 600-700 on the value of the product W(L/D) beyond which increases in strength and other properties are no longer fully realized when using conventional mixing procedures.

4. Using 6% by weight of fibers of aspect ratio 94-105, increases averaging 31% for strength, 28% for strain at failure and 68% for toughness were obtained with the four types of uncoated fiber employed in this investigation.

5. Although based on mortar, there is no reason to believe that the above conclusions are not qualitatively applicable to concrete, but the increases in strength and other properties can be

expected to be less (1).

ACKNOWLEDGMENTS

This work is part of a continuing study of fiber reinforced concrete supported principally by grants from the National Research Council and the Defence Research Board of Canada.

REFERENCES

1. Shah, S.P. and Rangan, B.V., "Fiber Reinforced Concrete Properties", ACI Journal, Proceedings Vol. 68, No. 2, February 1971, pp.126-135.

2. Snyder, M.J. and Lankard, D.R., "Factors Affecting the Flexural Strength of Steel Fibrous Concrete", ACI Journal, Proceedings Vol. 69. No. 2, February 1972, pp.96-100.

3. Johnston, C.D., "Steel Fiber Reinforced Mortar and Concrete - A Review of Mechanical Properties", Proceedings of an International Symposium on Fiber Reinforced Concrete, October 1973, ACI Special Publication SP-

4. Dixon, J. and Mayfield, B., "Concrete Reinforced with Fibrous Wire", Concrete, Vol. 5, No. 3, March 1971, pp.73-76.

5. Johnston, C.D. and Sidwell, E.H., "Testing Concrete in Tension and Compression", Magazine of Concrete Research, Vol. 20, No. 65, December 1968, pp.221-228.

6. Johnston, C.D., "Strength and Deformation of Concrete in Uniaxial Tension and Compression", Magazine of Concrete Research, Vol. 22, No. 70, March 1970, pp.5-16.

7. Romualdi, J.P. and Mandel, J.A., "Tensile Strength of Concrete Affected by Uniformly Distributed and Closely Spaced Short Lengths of Wire Reinforcement", ACI Journal, Proceedings Vol. 61, No. 6, June 1964, pp.657-671.

8. Romualdi, J.P., "The Static Cracking Stress and Fatigue Strength of Concrete Reinforced with Short Pieces of Thin Steel Wire", The Structure of Concrete, Proceedings of an International Conference, London, September 1965, pp.190-201.

9. Lankard, D.R., "Flexural Strength Predictions", Conference Proceedings M-28, Fibrous Concrete - Construction Material for the Seventies, December 1972, pp.101-123. (Available from the National Technical Information Service, Springfield, Va.22151).

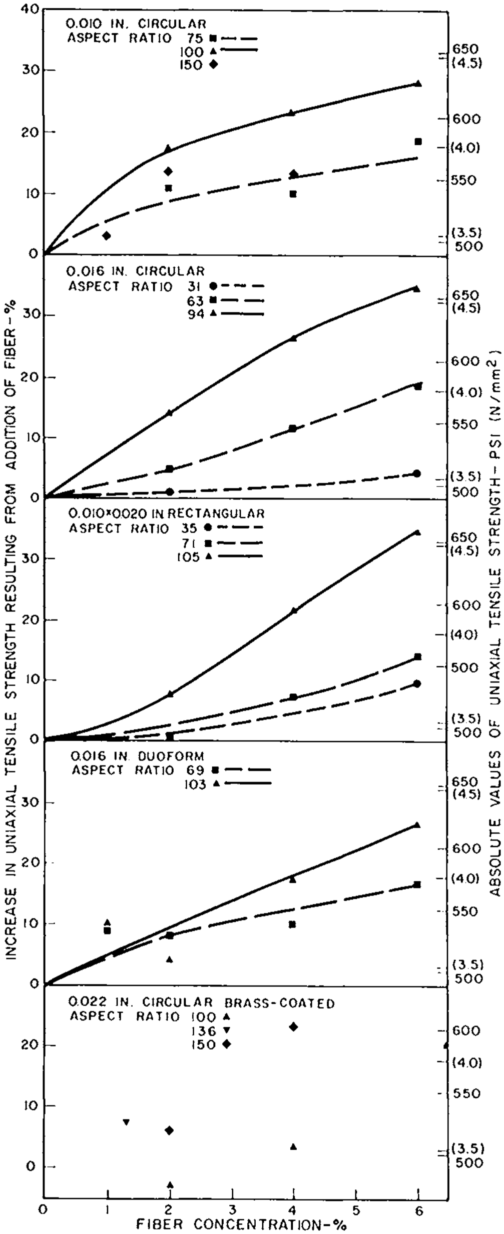

Fig. 1--Influence of fiber concentration and aspect ratio on tensile strength for five types of fiber

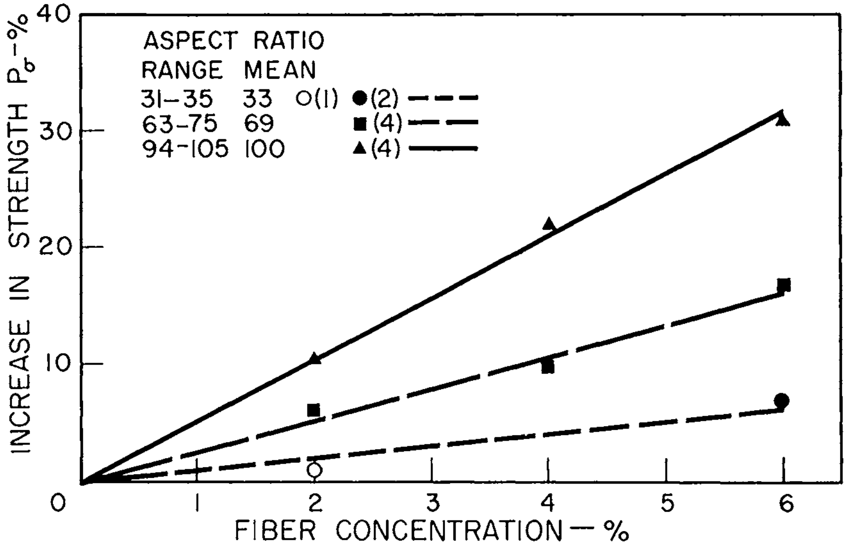

Fig. 2--Influence of fiber concentration on tensile strength

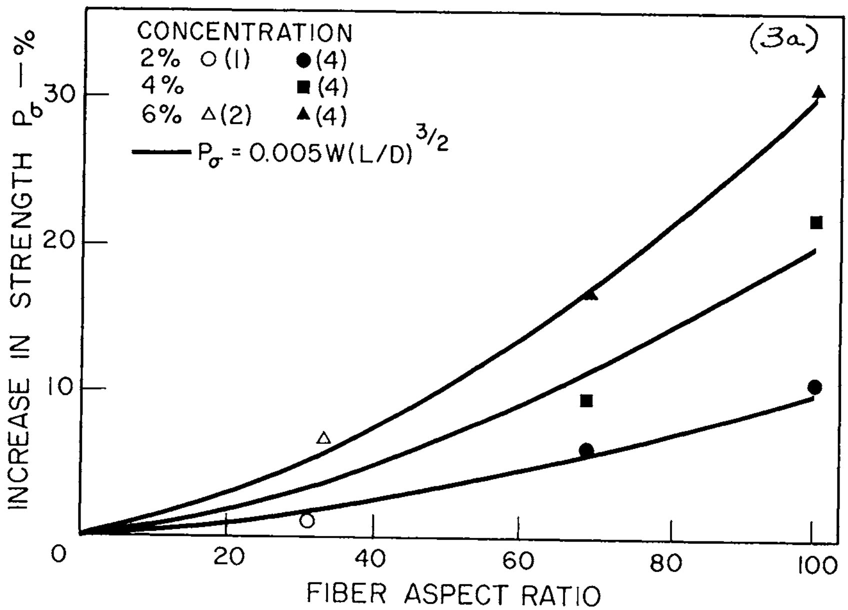

Fig. 3--Influence of fiber aspect ratio on tensile strength