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THE MECHANICS OF FIBER REINFORCEMENT OF CEMENT MATRICES

By

R. N. Swamy, P. S. Mangat, and C. V. S. K. Rao

Synopsis: The various factors which influence the fiber reinforcement of cement matrices are briefly discussed. It is shown that the existing geometrical spacing equations are inadequate in certain important respects, and that, they do not show a unique relationship with the flexural strength of steel fibrous concrete. Rather, they lead to a family of curves for different fiber lengths and fiber diameters. By considering the interfacial bond stress due to stress transfer and a crack in relation to short discontinuous fibers, a new effective spacing equation is derived. A crack control-composite mechanics approach is used to develop equations to predict the first crack and ultimate flexural strength of randomly oriented steel fibrous concrete. It is then shown that the new effective spacing equation leads to unique relationships between fiber spacing and flexural strength. The theoretical equations show excellent correlation to available test data from various sources.

Keywords: bonding; cements; cracking (fracturing); deformation; fiber reinforced concretes; flexural strength; metal fibers; reinforced concrete.

ACI member R. Narayan Swamy is Senior Lecturer in the Department of Civil and Structural Engineering, University of Sheffield, England. Currently a member of ACI Committees 544 and 548, Dr. Swamy is interested in concrete material behaviour and structural design.

Pritpal S. Mangat is a Research Assistant at Sheffield University, England, and is working for his doctorate in Civil Engineering. He received his B.Sc. from London University and M.A.Sc. from University of Windsor, Canada. He has industrial experience in bridge construction and reinforced concrete design.

C.V.S. Kameswara Rao is Independent Research Worker at University of Sheffield, England. After receiving his Bachelor's degree from India, he worked as Junior Engineer and Associate Lecturer. He received his M.Tech. and Ph.D. degrees from Indian Institute of Technology, Kanpur, where he was a research engineer. He is the recipient of Nanjundaiah Medal of Andhra University.

INTRODUCTION

The use of fibrous reinforcement to improve the strength and deformation properties of the cement matrix is now well established. The concept of fiber reinforcement is to use the deformation of the matrix under stress to transfer load to the fiber. Substantial improvements in static and dynamic strength properties could then be achieved if the fibers are strong and stiff, and loaded to fracture provided, of course, there is a minimum fiber volume fraction.

Fibers currently being used in concrete can broadly be classified into two types. Low modulus, high elongation fibers, such as nylon, polypropylene and polyethelene, are capable of large energy absorption characteristics; they do not lead to strength improvement, however - rather, they impart toughness and resistance to impact and explosive loading. High strength, high modulus fibers such as steel, glass, asbestos and carbon, on the other hand, produce strong composites. They impart primarily characteristics of strength and stiffness to the composite, and to varying degrees, dynamic properties.

In the current development of fiber reinforced concrete, short, discontinuous fibers are used. The fiber-matrix bond then becomes irregular and discontinuous. Apart from the fiber geometry and its length-diameter ratio, other factors such as fiber volume, fiber orientation and fabri-

cation techniques profoundly influence the properties and mode of failure of the fibrous composite. The role of fibers is essentially to arrest any advancing cracks by applying pinching forces at the crack tips, thus delaying their propagation across the matrix, and creating a distinct slow crack propagation stage. The ultimate cracking strain of the composite is thus increased to many times greater than that of the unreinforced matrix.

The properties of the matrix of the fibrous composite are equally important. The mechanics of composites in which the fibers are embedded in a metal or plastic matrix is well known. With metal matrices, stress transfer between the matrix and the fiber occurs through plastic deformation of the matrix. With plastic matrices, the elastic extensibility of the matrix transfers the load to the fibers. The fundamental difference of cement-based fiber composites from other fiber reinforced materials is that the matrix failure strain is only a fraction of the fiber yield strain. Further, the matrix is viscous and porous, so that the precise mechanism of how short discrete fibers reinforce the cement matrix is not yet fully understood.

This paper discusses the mechanics of fiber reinforced cement-matrices containing uniformly distributed but randomly oriented short steel fibers. It is shown that the existing geometrical spacing equations are inadequate in certain important respects and do not lead to a unique relationship with the flexural strength of steel fibrous concrete. By considering the interfacial bond stress due to stress transfer and cracking in relation to short discontinuous fibers, a new effective spacing equation is derived. A crack control-composite mechanics approach is used to develop equations to predict the first crack and ultimate flexural strength of randomly oriented steel fibrous concrete. It is then shown that the new spacing equation leads to unique relationships between fiber spacing and flexural strength. The theoretical equations show excellent correlation to available test data from many sources on fiber reinforced paste, mortar and concrete involving numerous parameters of mix proportions, fiber geometry, fiber volume, and size and volume of aggregates.

CRACK ARREST MECHANISM OF FIBER REINFORCEMENT

The mechanism of fiber reinforcement of cement matrices was first explained by Romualdi and Batson (1,2). They suggested that fibers act as crack arrestors by producing pinching forces which tend to close a crack. By considering a direct tensile stress field and applying the principles of linear elastic fracture mechanics they showed that

the first crack tensile strength was inversely proportional to the geometrical spacing of fibers for a given fiber volume content. The geometrical spacing of fibers thus becomes a critical factor in their crack arrest mechanism. Romualdi and Mandel (3) subsequently showed that this increase in first crack strength could be obtained by mixing short fibers directly into the matrix.

The Spacing Concept

While spacing of fibers is easily defined for systems in which fibers are arranged in a specific direction, visualising spacing in composites with randomly oriented fibers is conceptually complicated. Spacing of fibers is basically a geometrical quantity that characterises the pattern of distribution of fibers. While the concept of fiber spacing is important, a purely geometrical concept without relevance to the interaction between the fiber and matrix, and the mode of failure cannot fully explain the mechanism of fiber reinforcement or the strength and deformation properties of the composite.

The crack arrest mechanism of Romualdi and Batson (1,2) is primarily based on a geometrical fiber spacing concept which establishes a relationship between the first crack tensile strength of the composite and fiber spacing. They assume that the shear forces at the fiber-matrix interface are absent until the occurrence of a crack when the additional concrete displacements caused by the extensional strains in the neighbourhood of the crack cause a distribution of shear forces along the wires that act to close the crack. Although these assumptions are valid for long, continuous fibers where the shear stress distribution in the absence of a crack extends only up to half the critical length

($l_c/2$) from each end of the fiber, thus leaving a major proportion of the fiber length free from any shear stresses, these assumptions are not valid for short fibers (of length $< l_c$) where the shear stress distribution in the absence of a crack extends along the whole length of the fiber. The calculation of "effective spacing" of short fibers, therefore, necessitates the consideration of these shear forces along the fiber-matrix interface in addition to any stresses developed at the occurrence of a crack.

The crack arrest or the geometrical fiber spacing concept (1,2) also assumes that the bond between the fiber and the matrix is intact which is not necessarily true for discrete fibers. It does not also fully recognise the influence of the geometry of the fiber (3). Further, the application of linear-elastic fracture mechanics to Portland cement pastes, mortars and concretes is questionable. Recent tests have shown that in concrete materials there is

significant crack growth prior to fracture. Even in the cement paste, which is probably the nearest to an elastic homogenous cementitious material, some slow micro-cracking does occur at the crack tip (5). Similarly, the mechanism of crack propagation is not independent of specimen geometry, and the stress intensity factor also varies with the crack geometry (6). The stress intensity factor may not therefore be a valid criterion for concrete fracture. The existence of microcracking zones in concrete materials implies that in applying energy criteria to concrete fracture, energy dissipating mechanisms other than surface energy need to be considered (7).

Probably, the major drawback of the geometrical fiber spacing concept (1,2) is that it is based on a direct tensile stress field whereas the results used to prove the concept are based on flexural or indirect tension tests (1,3). Data based on direct tension tests (8,9) do not appear to follow the predictions of the theory, and data based on flexural and indirect tension tests (10) are lower than those predicted by the theory. Further, the crack arrest or fiber spacing concept recognises only the initial cracking strength and does not explain the post-cracking behavior and the ultimate strength of the composite. These are significant properties of great value in design and need to be accounted for.

Effective Spacing

In considering composites with randomly oriented fibers, a spacing concept based entirely on a geometrical or an assumed ordered distribution of fibers is unlikely to lead to a clear understanding of the mechanism of fiber reinforcement. A formal definition of such a composite should not only relate to a statistical description of the spacing of the centroids of the fibers but also incorporate the fiber-matrix interaction and the mode of failure. This is accomplished by the concept of "effective spacing".

Even though the "spacing" of fibers is essentially a geometrical quantity (with hardly any relevance to any physical process involved such as cracking or fracture), the case is different with "effective spacing". Deducing the effective spacing with randomly oriented fibers in a composite requires information regarding the physical interaction involved, the bond stress at the fiber-matrix interface and the mode of fracture in addition to fiber geometry. Effective spacing in some sense, enables reduction of a statistically isotropic system into an equivalent transversely isotropic system (or a system strengthened with aligned fibers in a single direction) which simplifies the study of the medium under uniaxial loading conditions.

In a study of the spacing of short fibers, Kar and Pal (11) have attempted to take these factors into consideration by including a bond efficiency factor in their effective spacing equation. However, the shear stress distribution at the fiber-matrix interface in the absence of a crack has been overlooked, and the shear stress distribution due to the presence of a crack in the vicinity of a fiber alone has been considered.

Relationship Between Existing Spacing Equations

The two spacing equations of Romualdi and Mandel(3), and Kar and Pal (11), and the centroidal spacing equation (defining the distance between centroids of fibers without taking into account the overlapping effect of long fibers) (12) are all derived for randomly oriented short fibers by assuming the fibers to be arranged in a square array. The interrelationship between these equations can best be understood by studying the factors which govern fiber spacing.

The relation between fiber length and spacing (as calculated by the three spacing equations) for a mix containing 1.91 per cent fibers by volume of matrix (excluding aggregate) and fiber diameter of 0.46 mm (0.018") is shown in FIG.1. The centroidal spacing increases as the fiber length increases since, for a constant volume of fibers the number of fibers is reduced as fiber length is increased. The overlapping effect of fibers on spacing has been considered by Romualdi and Mandel (3), and hence their spacing remains constant with variation in the length of fibers. In Kar and Pal's equation (11), spacing decreases with increasing length of fibers, since the bond efficiency of longer fibers is greater than that for short fibers.

The influence of fiber diameter on spacing is shown in FIG. 2 for a mix containing various diameters of fibers, and a constant fiber length (25 mm) and fiber volume (2%). The spacing increases with increasing fiber diameter since, to keep the fiber volume constant, the number of fibers decreases as their diameter is increased, thus increasing the spacing between them.

The relationship between the fiber spacings as calculated from the three equations for four different lengths and nine different diameters of fibers is shown in FIG. 3. The volume percentages of fibers used is shown in the figure. The results show that for each length and diameter of fiber, a different relationship exists. FIGS. 1,2, and 3, show conclusively that the three spacing equations are not generalised to include the two important factors of fiber geometry (namely, length and diameter) which influence fiber spacing.

In order to establish the application of these spacing equations (3,11,12) to various lengths and diameters of fibers, the results of an extensive series of tests, in which fibers of eight different diameters ranging from 0.27 mm to 1.82 mm (0.0108 to 0.073 in) and four different lengths from 12.5 mm to 50 mm ($\frac{1}{2}$ in to 2 in) were used, are shown in FIGS. 4,5 and 6.

In these tests, a concrete mix of 1:2:5:1.2 with a water-cement ratio of 0.55 was used. Ordinary Portland cement and crushed gravel of 10 mm ($\frac{3}{8}$ in) maximum size was used throughout. The fibers were interannealed, hard drawn mild steel wires with a plane surface.

The results (FIGS. 4,5 and 6) show that in all three cases different relationships are obtained for different lengths and diameters of fibers, and that none of the spacing equations take into account fully the different parameters involved in fiber spacing. The results also show no unique relationship between the flexural strength and the spacing equation for all the test data.

A Combined Crack Arrest-Composite Mechanics Approach to Fiber Reinforcement

The discussion so far has shown that none of the conventional crack arrest mechanisms and spacing equations can adequately explain all the factors involved in the mechanics of fiber reinforcement of cement matrices. If the fibers are not continuous or aligned, but instead if the composite consists of short, discontinuous fibers which are randomly oriented and uniformly dispersed in the matrix, then there are three basic considerations related to the transfer of stress from matrix to fiber. These are: (1) critical fiber length or the fiber transfer length (which is analogous to the transmission length of the tendon in prestressed concrete); (2) the fiber-matrix interfacial bond, and (3) the fiber efficiency or the orientation factor for random fibers. Both the critical fiber length and the interfacial bond are interdependent and also closely related to the fiber length-diameter ratio (i.e. aspect ratio). To get a clear understanding of the mechanism of fiber reinforcement all these factors need to be considered.

In the following, the critical fiber length, the interfacial bond and the orientation factor in relation to short discontinuous fibers are briefly discussed. Based on these, three new concepts in relation to fiber reinforced concrete are presented. Firstly, a new effective fiber spacing equation is derived for randomly oriented short fibers uniformly distributed in a concrete matrix. Bond

deficiency is taken into account in this spacing equation by introducing bond efficiency factors for both the length and diameter of fibers. Secondly a combined crack control-composite mechanics approach is presented to predict the first crack and the ultimate flexural strength of steel fiber reinforced concrete. These equations reflect the crack arrest criterion, the interfacial bond and the randomness of fibers in the matrix. Finally, it is shown that the concepts presented here lead to a unique relationship between effective fiber spacing and the first crack and ultimate flexural strengths of the fibrous concrete.

MECHANISM OF FIBER REINFORCEMENT

In a general composite system comprising a matrix phase and a fiber phase, several modes of failure are possible, depending on the relative values of the failure strains of the matrix and the fibers, as well as the fiber geometry and the fiber-matrix interfacial bond strength. It is common for the fibers in a metal or plastic matrix to fracture at the failure stress of the composite whereas in steel fiber reinforced concrete, bond failure at the fiber-matrix interface usually occurs at the ultimate strength of the composite.

The mechanism of fiber reinforcement in a steel fiber reinforced concrete composite can be explained by considering a specimen under uniaxial tension. The reinforcing action by fibers occurs through the fiber-matrix interfacial bond stress. Cracks in the matrix occur when the composite strain exceeds the cracking strain of the matrix. Since the fibers are stiffer than the matrix ($E_f > E_m$), they deform less and hence exert a pinching force at the crack tips. In this respect, the role of fibers is analogous to the role of aggregates as crack arrestors in the paste or mortar matrix. The problems of interfacial bond, of size and shape of the inclusion, and of the stiffness of the inclusion relative to that of the matrix are all factors common to both systems (13).

In this manner the cracks are prevented from propagating until the composite ultimate stress is reached when failure occurs either by the simultaneous yielding of the fibers and matrix, or by fiber-matrix interface bond failure. The criterion that determines whether yielding or bond failure occurs is the fiber length and surface geometry. In general, if the fiber length is greater than the critical length, fibers should yield at the failure of the composite whereas for shorter lengths than the critical, bond failure occurs.

Critical Fiber Length

Consider a fiber of size $l \times d$ embedded in the surrounding matrix. The load is transferred by an average interfacial shear stress τ , and the longitudinal tensile stress in the fiber σ_f varies from zero at the ends of the fiber to the fracture stress σ_{fu} , if the fiber is long enough (FIG. 7). For a short fiber σ_f might not reach the value for fiber fracture and "pull-out" or sliding of the interface would occur. The ratio $l/2$ is defined as the transfer length where l_c is the critical fiber length. From equilibrium considerations,

$$\frac{\bar{\sigma} d^2}{4} \frac{d\sigma}{dl} = \bar{\sigma} d \tau$$

or

$$\frac{dl}{d\sigma} = \frac{d}{4\tau} \dots\dots\dots (1)$$

The fracture stress can be reached only when

$$\frac{l_c}{2} = \sigma_{fu} \cdot \frac{d}{4\tau}$$

or

$$l_c = \sigma_{fu} \cdot \frac{d}{2\tau} \dots\dots\dots (2)$$

The aspect ratio or the shape of the fiber must then be

$$\frac{l_c}{d} \geq \frac{\sigma_{fu}}{2\tau} \dots\dots\dots (3)$$

The value of l_c depends on τ , and if bond failure occurs, τ will then represent merely the frictional force per unit area between matrix and fiber. Even then, the frictional force may be adequate to impart to the composite a measure of ductility, crack resistance and toughness. The fiber tensile stress is also not constant along the length (FIG. 8) and thus in considering the strength of a discontinuous fiber composite, the average stress must be used instead of σ_{fu} . The average fiber stress over the length l_c is $\sigma_{fu}/2$ (assuming linear distribution), but if the fibers are much longer than l_c , the average stress will approach the maximum σ_{fu} , and the fibers will effectively act as continuous fibers. It is clear that discontinuous

fibers will strengthen less effectively than continuous ones, but with longer fibers the difference in strength should become progressively less.

Fiber-matrix Interfacial Bond

Thus both the interfacial bond stress and the fiber tensile stress are closely related to the fiber aspect ratio. The interfacial bond stress of a steel fiber in a concrete matrix can be considered to consist of two parts;

- (1) the interfacial bond stress due to load transfer from matrix to fiber. FIG. 8 shows a schematic representation of the interfacial shear stress τ along the length of the fiber as well as the fiber tensile stress σ for various fiber aspect ratios in relation to the critical value. The tensile stress in the fiber is zero at the ends and builds up towards the centre of the fiber, analogous to the development of the pre-stressing force in the tendon. The shear stress is maximum at the fiber ends and decays to zero at a distance $l_c/2$ from the end. For long fibers ($l > l_c$), the central zone is free from shear stresses; for short fibers ($l < l_c$), the bond stress is present throughout the fiber length.
- (2) the interfacial bond stress due to the presence of a crack. This distribution occurs in the vicinity of the crack, increases to a maximum and then decreases with increasing distance from the crack edge (FIG. 9). A crack thus brings discontinuity to the bond stress distribution.

For short fibers both the above bond stress distributions need to be considered, and the combined effect is shown in FIG. 9. In the derivation of the spacing equations, the former bond stress distribution has not been considered by some investigators (3,11). However, Kar and Pal (11) considered a bond efficiency factor to fiber length alone, but did not take into account the relative bond efficiency of different diameters of fibers.

Efficiency of Randomly Oriented Fibers

When short discontinuous fibers are randomly oriented in the matrix, there is the further problem of determining the "efficiency factor" or "effective length" or the "orientation factor" of the fibers. With random orientation only those fibers which are parallel or nearly parallel to the tensile stress trajectories are effective in crack control. For those fibers that are less effectively oriented in space, a correction must be applied. Assuming

uniform distribution of fibers in the matrix, various orientation factors have been derived based upon various assumptions (14, 15). The relative merits of these orientation factors depend upon the validity of the assumptions made, but it can be shown that for the case of randomness in which the fibers can be oriented in any direction with equal probability, the orientation factor, of $0.41 L$ (3) is exact.

EFFECTIVE FIBER SPACING FOR SHORT DISCONTINUOUS FIBERS

In deriving the spacing equation, the interfacial bond stress distribution due to load transfer, and the presence of a crack as shown in FIG. 9, is considered. Bond deficiency is taken into account by introducing bond efficiency factors for both the length and diameter of fibers. The bond efficiency factor for length, η_l , is defined as the ratio of the bond strength of a randomly oriented fiber of length l and diameter d to the bond strength of a fiber of length l_c and diameter d . Assuming the bond stress distribution shown in FIG. 9e, it can be shown that

$$\eta_l = \frac{0.82 l \tau}{\sigma_{fu} d} \dots\dots\dots (4)$$

The bond efficiency factor for diameter, η_d , is defined as the ratio of the bond strength of a fiber of diameter d and length l_c to the bond strength of a fiber of diameter $\bar{d}$, and length $\bar{l}_c$. Then, from equation (2), it can be shown that

$$\eta_d = \frac{d}{\bar{d}} \dots\dots\dots (5)$$

The parameter η_d provides a means of comparing the mechanism associated with fibers of different diameters but of the same length. It may also be noted that the choice of $\bar{d}$ is arbitrary and is purely the one with reference to which the others are compared. Introduction of η_d in conjunction with η_l thus enables one to derive a more general spacing equation as shown below.

Assuming a cube of matrix of side L containing p volume per cent of fibers in the matrix,

$$p = \frac{25 N \bar{A} d^2 l}{L^3} \dots\dots\dots (6)$$

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where N is the number of fibers of diameter d and length l . Applying bond efficiency factor η_l and orientation factor of 0.41 to l , and bond efficiency factor of η_d to d . The effective volume per cent of fibers in matrix

$$p_e = \frac{25 N \bar{A}}{L^3} \left(\frac{d}{\bar{d}}\right)^2 \cdot 0.41 \cdot \left(\frac{0.82 l \tau}{\sigma_{fu} \cdot d}\right)^1$$

or

$$\frac{p_e}{p} = \frac{0.41 \times 0.82 l \tau d}{\sigma_{fu} \cdot \bar{d}^2} \dots\dots\dots (7)$$

The effective volume of fibers in the matrix which are effective in the direction of uniaxial stress, and the equivalent number of fibers of length L aligned in the direction of uniaxial stress are given by

$$v_{fe} = \frac{p_e}{100} L^3, \text{ and,}$$

$$N^1 = \frac{p_e L^2}{25 \bar{A} d^2} \dots\dots\dots (8)$$

Assuming a rectangular array of fibers, the effective spacing s_e is given by

$$s_e = \sqrt{L^2 / N^1}$$

substituting for N^1 and for p_e in terms of p , and reducing, one obtains,

$$s_e = 15.287 \sqrt{\frac{\sigma_{fu} \bar{d}^2}{\tau}} \sqrt{\frac{d}{p l}} \dots\dots\dots (9)$$

By evaluating σ_{fu} and $\bar{d}$, and the interfacial bond stress τ for both at first crack and at ultimate load in modulus of rupture, the effective spacings are given by:

For first crack modulus of rupture

$$s_e = 27 \sqrt{\frac{d}{p l}} \dots\dots\dots (10)$$

For ultimate modulus of rupture

$$s_e = 25 \sqrt{\frac{d}{pl}} \dots\dots\dots (11)$$

FLEXURAL STRENGTH OF CONCRETE REINFORCED WITH RANDOMLY ORIENTED SHORT DISCONTINUOUS FIBERS

A combined crack control-composite materials approach is presented here to predict the first crack modulus of rupture and the ultimate modulus of rupture of concrete reinforced with randomly oriented short discontinuous fibers. In steel fiber reinforced concrete the composite failure generally occurs due to bond failure at the fiber-matrix interface. The first crack in the composite occurs when the composite strain exceeds the cracking strain of the matrix (FIG.10). On further loading, the stiffer fibers act as crack arrestors, analogous to coarse aggregates in plain concrete, and a period of slow crack propagation with progressive debonding of fibers (FIG. 11) occurs. Near the ultimate load, unstable crack propagation occurs simultaneously with the interfacial bond reaching the ultimate bond strength (τ_u) between the fiber and the matrix, and failure by fiber pull-out occurs.

Composite fracture thus occurs simultaneously due to unstable crack propagation and bond failure. Both the matrix and the fiber act together as a two-phase composite until failure, and contribute to the strength of the composite. However, because of the bond failure, the maximum tensile stress σ_f in the fiber is less than its ultimate strength σ_{fu} , and the fibers do not make their full contribution to the composite strength.

For equal elastic strain in fibers and matrix, the direct tensile strength of a composite, σ_{ct} , containing uniaxial continuous fibers can be expressed by the law of mixtures as:

$$\sigma_{ct} = \sigma_{mt} V_m + \sigma_f V_f \dots\dots\dots (12)$$

where σ and V represent stress and volume fraction respectively, and the suffixes c, m and f represent composite, matrix and fiber respectively, and t direct tension.

Equation (12) depends only on the properties and volume fractions of the constituents, and is independent of the state of stress to which the composite is subjected

Although the theory has so far been applied to a direct tensile stress field, it can be extended to a bending tensile stress field with a slight modification.

The modulus of rupture of the matrix, $\sigma_{mr.m}$, is known to be related to its direct tensile strength,

$$\sigma_{mr.m} = \beta \cdot \sigma_{mt}$$

where β normally varies between 1.3 and 1.5. Multiplying equation (12) throughout by β ,

$$\beta \cdot \sigma_{ct} = \sigma_{mr.m} V_m + \beta \sigma_f V_f \quad \dots\dots\dots (13)$$

The modulus of rupture of the composite is more difficult to define (FIG.12). In plain concrete, there is some plastic stress distribution in the tension zone prior to failure, but linear stress distribution is generally assumed (FIG. 12). If this were true for fibrous concrete the composite modulus of rupture $\sigma_{mr.c}$ is related to the section modulus Z by

$$M = \sigma_{mr.c} \cdot Z \quad \dots\dots\dots (14)$$

where M is the applied moment. However, it is known that linearity does not hold for fibrous concrete; and the non-linear flexural stress distribution (FIG.12) is related to the direct tensile strength as follows:

$$M = \sigma_{ct} \cdot (\alpha Z) \quad \dots\dots\dots (15)$$

where (αZ) is analogous to plastic modulus, and more specifically, α is a factor that relates the extreme fiber stress, the elastic section modulus and the applied moment.

From equations (14) and (15),

$$\sigma_{mr.c} = \sigma_{ct} \cdot \alpha \quad \dots\dots\dots (16)$$

From equations (13) and (16)

$$\alpha \beta \sigma_{ct} = \alpha \sigma_{mr.m} V_m + \alpha \beta \sigma_f V_f$$

or

$$\sigma_{mr,c} = \frac{\alpha}{\beta} \sigma_{mr,m} V_m + \alpha \sigma_f V_f \dots\dots\dots(17)$$

In randomly oriented steel fiber reinforced concrete composite failure occurs by fiber pull-out. Substituting therefore for σ_f from equation (2), and replacing V_f by the effective volume fraction of fibers.

$$\sigma_{mr,c} = \frac{\alpha}{\beta} \sigma_{mr,m} V_m + \alpha \cdot 0.82 \tau V_f^{1/d} \dots\dots\dots(18a)$$

In equation 18(a), the constant α relates the extreme fiber stress of the composite to the external applied moment; the extreme fiber stress depends on the interfacial bond stress, τ , and hence there is no loss of generality in rewriting equation 18(a) as:

$$\sigma_c = A \sigma_m V_m + 0.82 \tau V_f^{1/d} \dots\dots\dots(18b)$$

where the value of τ includes the influence of α .

Equation 18(b) can be applied to predict both the first crack and the ultimate flexural strength with suitable values for τ , and is valid whether the matrix is hardened paste, mortar or concrete. At the first crack stage, the interfacial bond stress τ in equation (18b) corresponds to the average bond stress when bond slip commences. At the failure stage, the interfacial shear stress reaches the ultimate average bond strength τ_u between the fiber and the matrix.

The flexural strength test data of the authors and other investigators (11,16,17) were checked against equation (18). The test results relate to fiber reinforced paste, mortar and concrete, and cover a wide range of mix proportions and fiber geometry, various curing methods and two types of cements. FIG. 13 shows the correlation between equation (18b) and the first crack flexural strength; FIG. 14 shows the theoretical correlation to ultimate flexural strength. In both cases, regression analysis was carried out, and the following equations obtained.

First crack composite strength:

$$\sigma_{cf} = 0.843 \sigma_m V_m + 2.93 V_f^{1/d} \dots\dots\dots(19)$$

The coefficient of correlation for the regression analysis was 0.98. From equations (18) and (19), the average bond stress at first crack is given by $\tau = 3.57 \text{ N/mm}^2$ (515 psi)

Ultimate composite flexural strength

$$\sigma_{cu} = 0.97 \sigma_m V_m + 3.41 V_f \frac{l}{d} \dots\dots\dots (20)$$

from which the ultimate bond stress $\tau_u = 4.15 \text{ N/mm}^2 (600 \text{ psi})$.

The excellent correlation of the test data in FIG. 13 and 14 with the form of equation (18) derived theoretically justifies the mechanisms of failure considered in deriving the equation.

The results show that the average bond stress τ is largely independent of the matrix mix proportions. The constant in the first term on the right hand side of equations (19) and (20) should theoretically be unity. A possible explanation for the discrepancy is that the flexural strength of concrete is a somewhat unreliable quantity, and can vary significantly for different specimens of the same mix proportions; it thus represents the effect of all parameters which influence flexural strength.

RELATIONSHIP BETWEEN FIBER SPACING AND FLEXURAL STRENGTH

The fiber spacing equation (9) derived for short, discontinuous fibers can be correlated to the first crack flexural strength (Equation 19) and the ultimate flexural strength (equation 20). FIG. 15 shows the relation of the authors' spacing equation to the first crack flexural strength, and the theoretical prediction shows close correlation with test data obtained from other investigators (3,16,17). FIG. 15 shows two theoretical curves based on the flexural strengths reported by Waterhouse and Luke and Lankard (17). The same data when plotted against other spacing equations (3,11) showed wide scatter and no unique relationships.

FIG. 16 shows the relation between the authors' spacing equation (9) and the ultimate flexural strength equation (20). The three theoretical curves shown refer to the data of Waterhouse and Luke (16) Kar and Pal (11), Lankard (17) and the authors. The differences in the theoretical curves arise from the varying matrix strength and aggregate content used by the various investigators. The unique relationships between fiber spacing and flexural strength shown in FIGS. 15 and 16 confirm the theoretical reasoning behind the development of the spacing equation and flexural strength equations of the authors.

CONCLUSIONS

Factors such as fiber-matrix stiffness, the interfacial bond stress and the fiber-matrix strain compatibility determine the role of fibers in cement matrices. It is shown that existing crack arrest mechanism and geometrical spacing equations cannot adequately explain the behaviour of steel fibrous concrete. They do not lead to a unique relationship between fiber spacing and flexural strength. Variations in fiber geometry lead to a family of curves. When considering randomly oriented short discontinuous fibers, the interfacial bond stress distribution due to load transfer and the presence of a crack should be considered. This recognition leads to unique relationships between the new spacing equation and the first crack and ultimate flexural strength. It is shown that a crack control-composite materials approach can satisfactorily predict the flexural strength of steel fibrous concrete.

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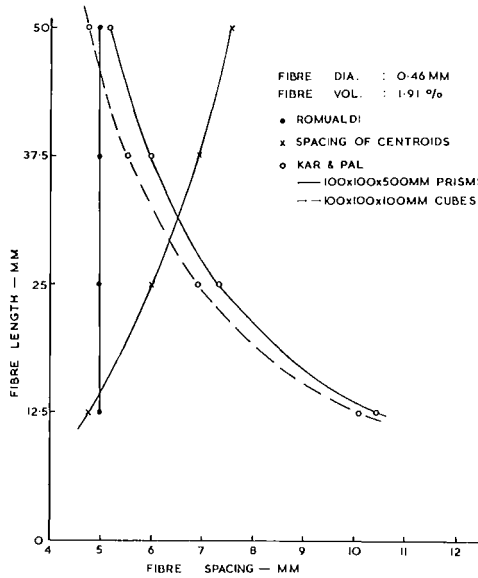


FIG.1 RELATION BETWEEN FIBER LENGTH AND SPACING

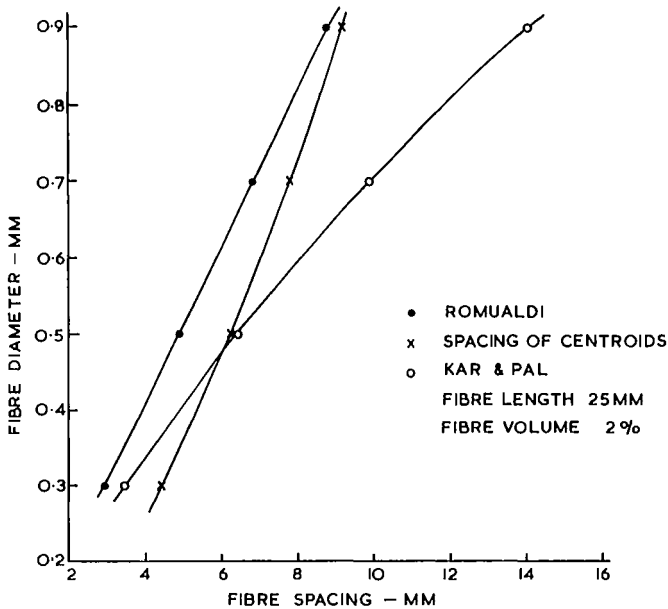


FIG.2 INFLUENCE OF FIBRE DIAMETER ON SPACING

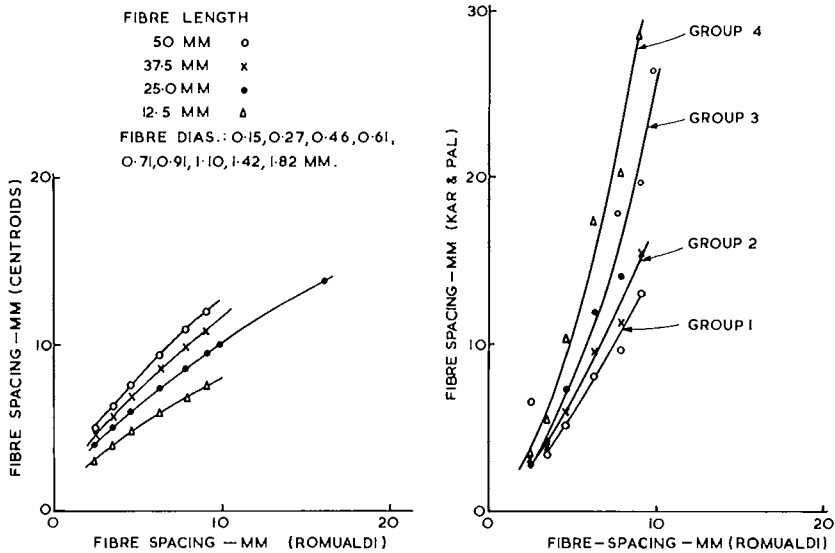


FIG.3a RELATIONSHIP BETWEEN FIBRE SPACING OF VARIOUS INVESTIGATORS

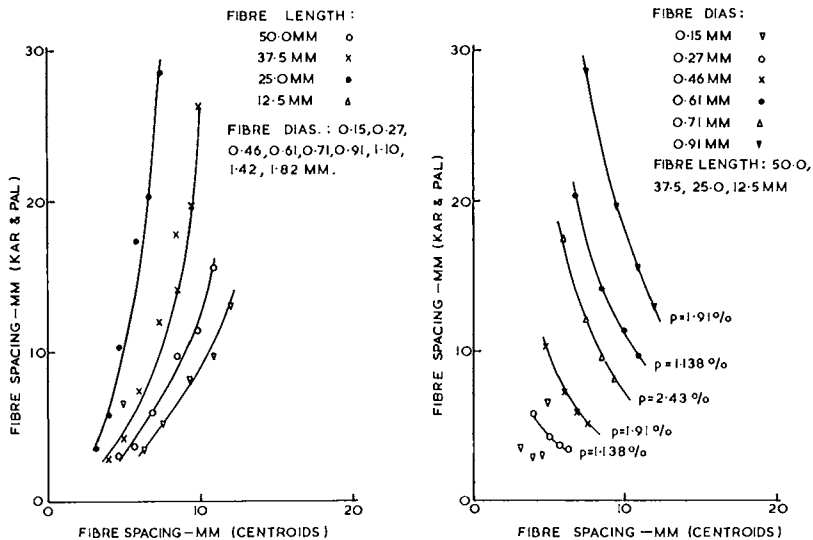


FIG.3b RELATIONSHIP BETWEEN FIBER SPACING OF VARIOUS INVESTIGATORS

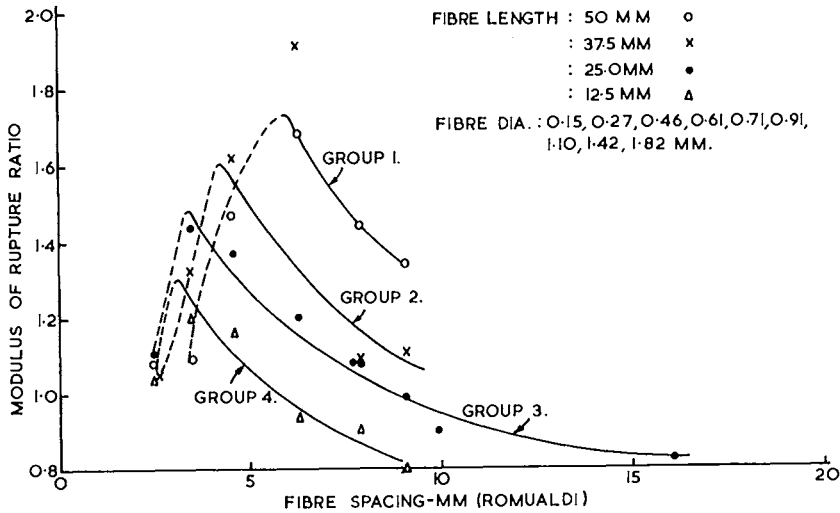


FIG. 4 RELATION BETWEEN MODULUS OF RUPTURE RATIO AND FIBRE SPACING

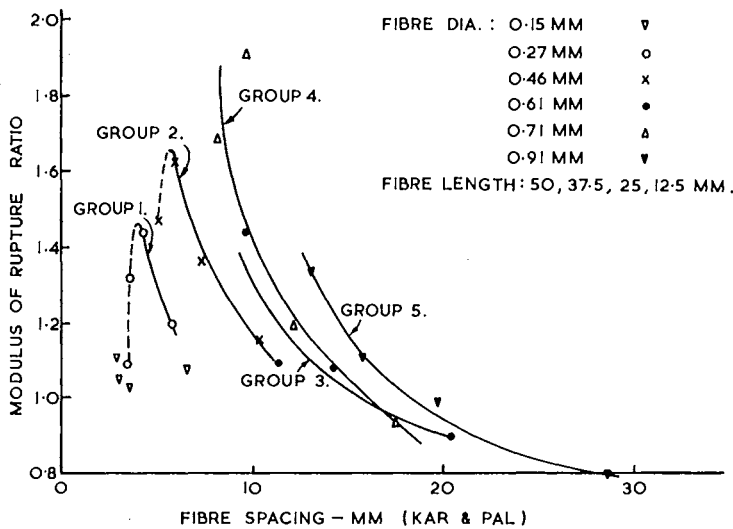


FIG. 5 RELATION BETWEEN MODULUS OF RUPTURE RATIO AND FIBRE SPACING

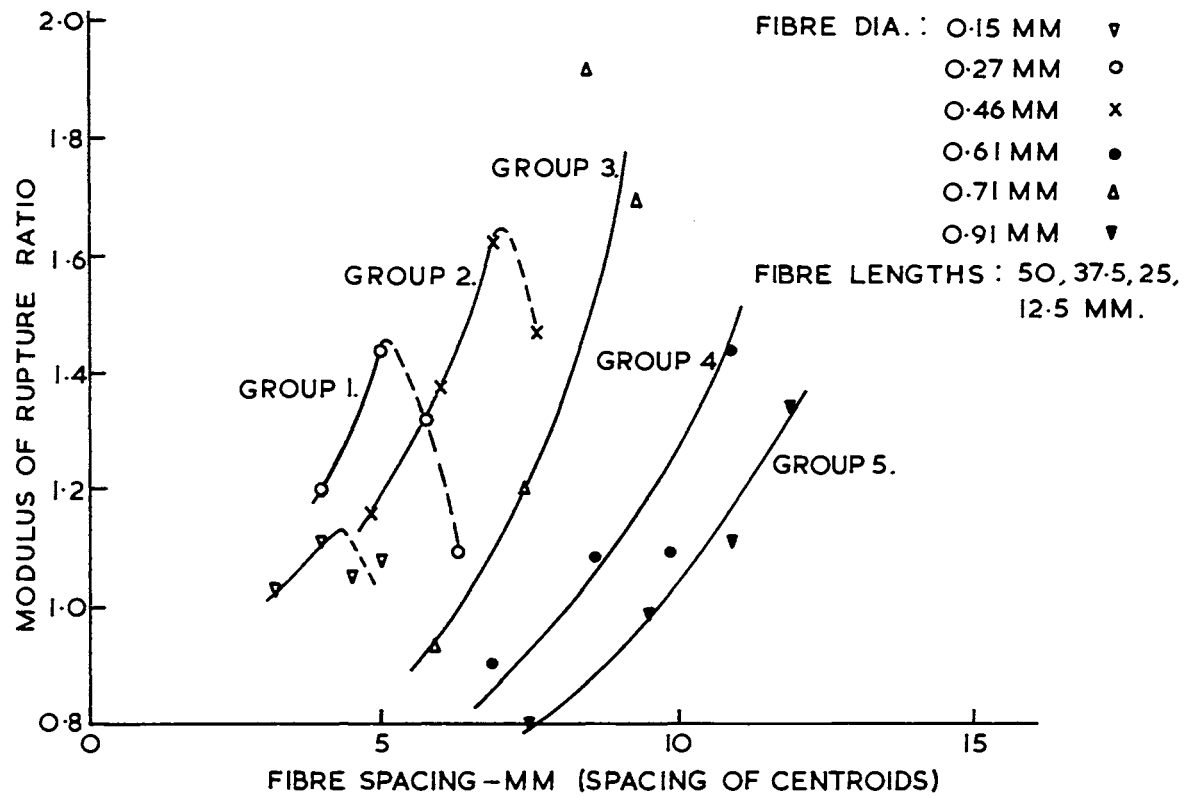


FIG. 6 RELATION BETWEEN MODULUS OF RUPTURE RATIO AND CENTROID SPACING

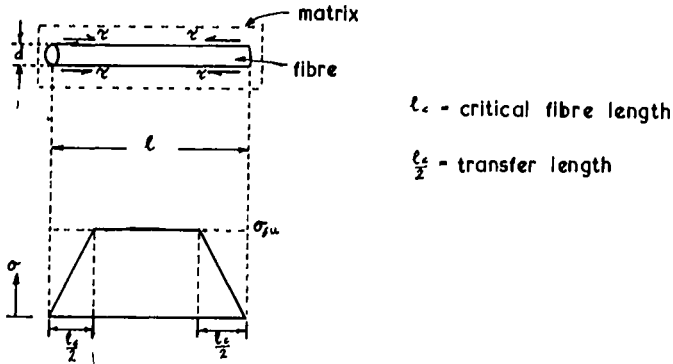


FIG.7 FIBRE STRESS DISTRIBUTION

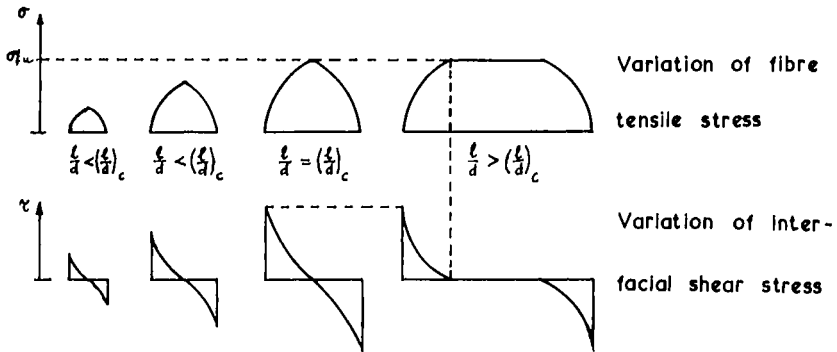


FIG.8 SCHEMATIC VARIATION OF INTERFACIAL SHEAR STRESS AND FIBRE TENSILE STRESS

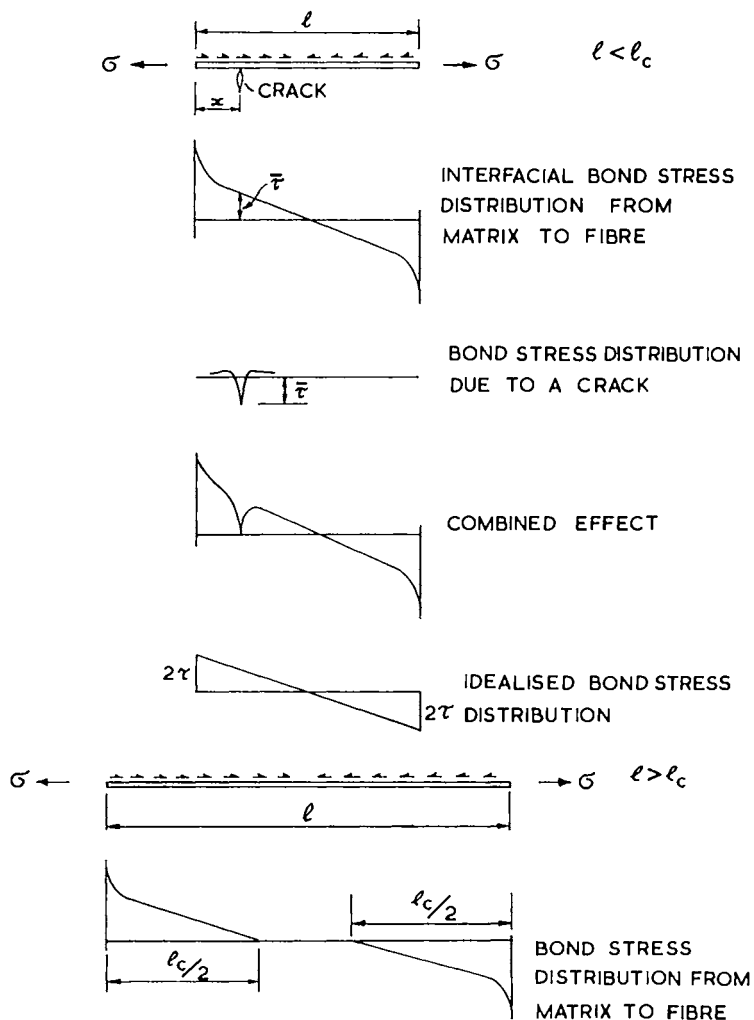


FIG. 9 SCHEMATIC BOND STRESS DISTRIBUTION AT FIBRE MATRIX INTERFACE

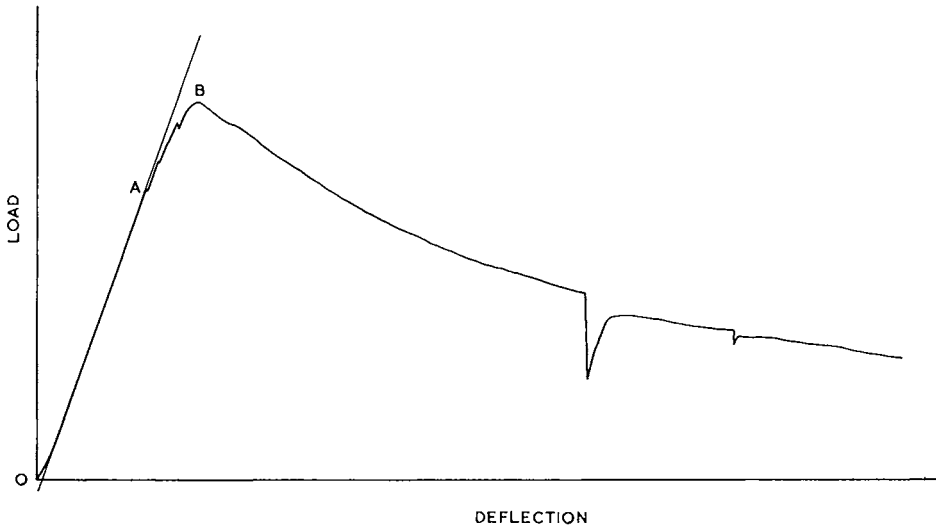


FIG. 10 TYPICAL AUTOMATIC LOAD-DEFLECTION CURVE IN FLEXURE FOR STEEL FIBRE REINFORCED CONCRETE

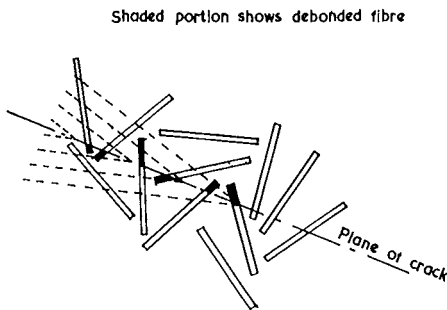


FIG. 11 SCHEMATIC REPRESENTATION OF SLOW CRACK PROPAGATION AND PROGRESSIVE DEBONDING OF SHORT FIBRES

WHAT IS MODULUS OF RUPTURE OF COMPOSITE ?

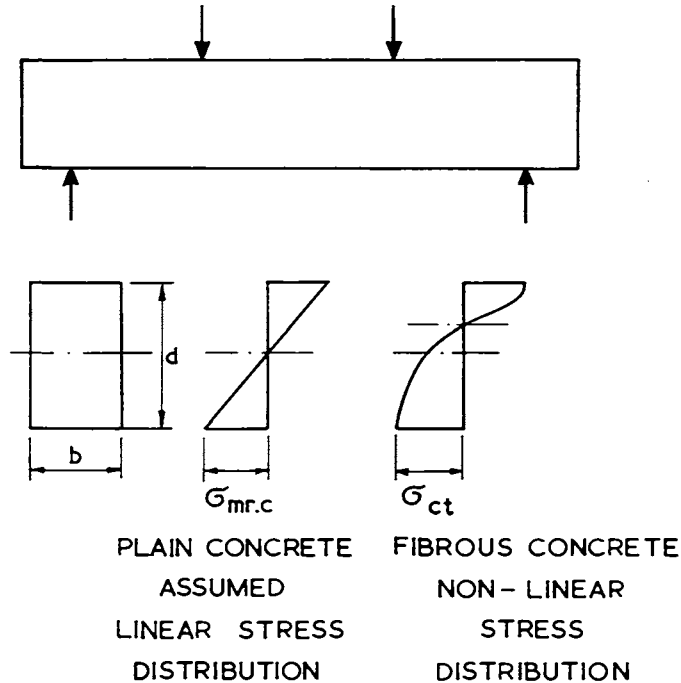


FIG.12 MODULUS OF RUPTURE STRESS DISTRIBUTION AT FAILURE



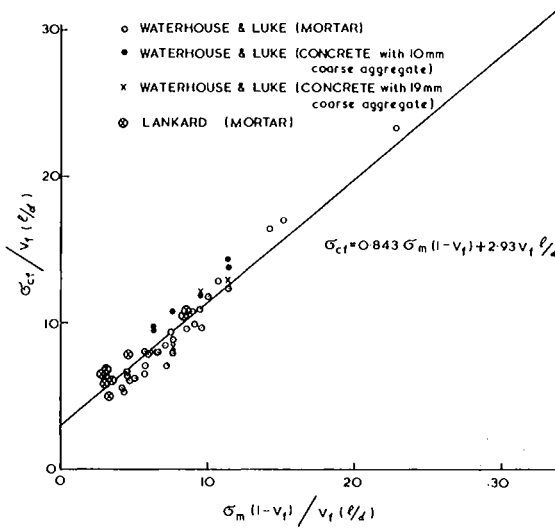


FIG.13 CRACK CONTROL-COMPOSITE MATERIALS EQUATION FOR FIRST CRACK FLEXURAL STRENGTH OF STEEL FIBROUS CONCRETE

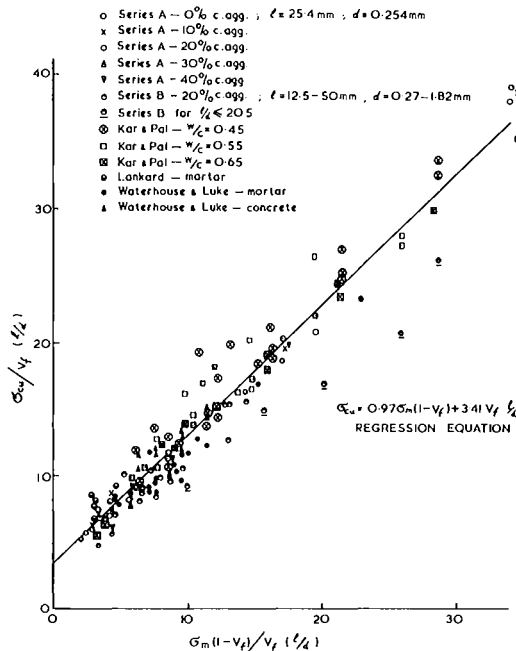


FIG.14 CRACK CONTROL - COMPOSITE MECHANICS EQUATION FOR ULTIMATE FLEXURAL STRENGTH OF STEEL FIBROUS CONCRETE

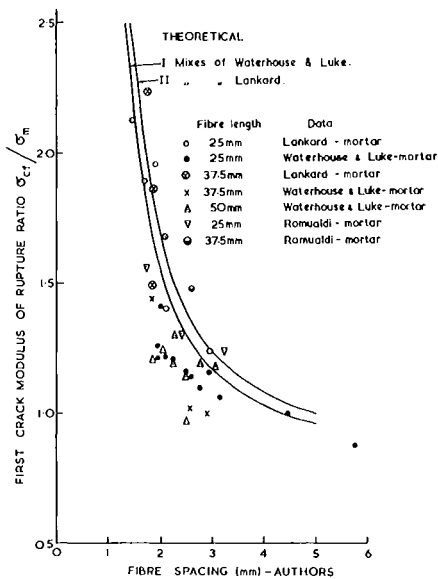


FIG 15 RELATION BETWEEN FIBRE SPACING (AUTHORS) AND FIRST CRACK MODULUS

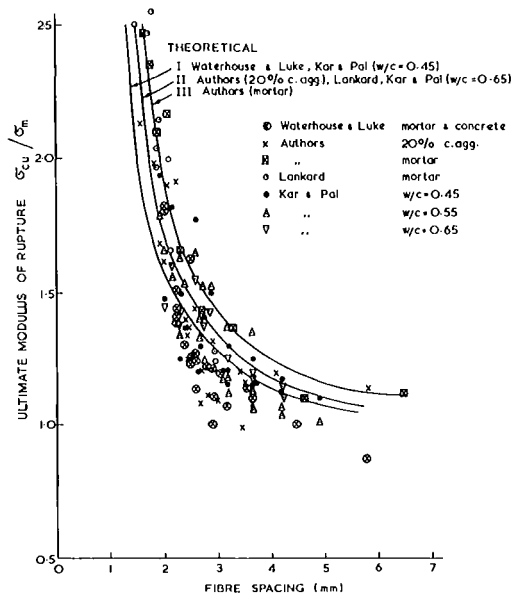


FIG 16 RELATION BETWEEN ULTIMATE MODULUS OF RUPTURE RATIO AND AUTHORS SPACING EQUATION

SP 44-2

THE EFFECT OF FIBER REINFORCEMENTS ON THE RHEOLOGICAL PROPERTIES OF CONCRETE MIXES

By

A. G. B. Ritchie and T. A. Rahman

Synopsis: This research project, which forms part of a continuing line of rheological activity, investigated the effect of introducing various percentages of chopped fibres into a range of concrete mixes. A comparison was made between unreinforced mixes, chopped wire mixes and mixes containing polypropylene fibres. The effect of particle interference on the efficiency of the fibres was studied by using mixes ranging from a cement/sand mortar to a 20 mm, maximum aggregate size, concrete. The rheological investigation was subdivided into two main parts. The first objective was to study the effect of fibre content and different types of fibre on the flow properties at zero time. The rheological characteristics covered were stability (as defined by internal water bleeding and mix segregation) and mobility (as determined by cohesion and internal resistance recorded by a newly developed vane test). The second stage was to extend sections of the initial investigation to cover the effect of the fibres in the various mixes on the rate of stiffening and early strength development. The findings confirm that fibres do have a significant effect on the rheological properties of fresh concrete. Fibre mixes are much more stable and exhibit a significant reduction in surface bleeding. The cohesion is greatly improved and the internal resistance increases with fibre concentration. The rate of development of stiffness with time of the fresh concrete is significantly increased which should imply a reduction in lateral pressure on formwork and facilitate early striking.

Keywords: bleeding (concrete); cohesion; concretes; fiber reinforced concretes; flexural strength; fresh concretes; metal fibers; mix proportioning; plain concrete; polypropylene fibers; research; rheological properties; segregation; stiffness; water-cement ratio; workability.

Dr. A.G.B. Ritchie is a Senior Lecturer in the Civil Engineering Department, University of Strathclyde, Glasgow, Scotland. He gained his Ph.D. in 1964 for research on the rheology of fresh concrete and its application to the pressure of concrete on formwork. He has recently been associated with research projects for the Construction Industry Research and Information Association (CIRIA) on the effects of mix characteristics on the rate of stiffening and the influence of early striking of formwork on the structural strength of concrete members.

T.A. Rahman is a postgraduate research student in the Civil Engineering Department of the University of Strathclyde. He was formerly with the Engineering Department of the Sudan Railways.

INTRODUCTION

The production of structural concrete can and should always be considered in two well defined phases, namely the fresh and the hardened. Each phase must be considered carefully at the mix design stage and each presents its own particular characteristics and related constructional or structural problems. However, since cement paste, and hence concrete, is a time dependent material, there is also a linking phase where the fluid mix gradually stiffens and exhibits embryonic structural properties which eventually develop to give the final specified product, at an arbitrary twenty-eight days or its equivalent in maturity.

The first named author has had a continuing interest in the rheology of natural (1) and lightweight aggregates and the application of the concepts of mobility and stiffness gained from these investigations as applied to constructional problems such as the lateral pressure developed by concrete on formwork (2,3,4) and the effect of early stripping time on the structural strength of concrete members (5,6).

The advent of fibre reinforcement has brought about an almost unprecedented rate of application of this virtually new material to civil engineering construction before research has really had much time to provide a lead in promoting its obvious constructional potentialities on the one hand, or, pointing out any possible problems or limitations on the other. This unusual state of affairs has prompted the leading author to extend his research activities to investigate the effect of fibres on certain rheological properties, and also to study the influence of these inclusions on the rate of gain of stiffness and early strength development.

MATERIALS AND MIXES

The basic materials used were blended Ordinary Portland Cement and 20 mm down graded material of irregular shape and a water worn surface texture.

The polypropylene fibres of 1/700 type (single ply of which one pound would measure 700 yards) were selected by a previous research investigation (7) to be the most stable and economic type of those available, for use in concrete mixes. The cross-sectional area was averaged out at 0.71 mm^2 and the length adopted was 25 mm.

The wire fibres were selected from those commercially available, and were 0.38 mm dia. x 25 mm long (Duoform Type).

Because of the number of variables involved it was decided to concentrate, in the first instance, on a basic unfibred mix using 20 mm down material with a Type 2 overall grading (8), an aggregate/cement ratio of 4.5, and a high workability obtained by using a water/cement ratio of 0.55 (Mix designation CU).

The rheological comparison between the fibres added in various percentages to the basic mix was achieved by keeping the volume content of the two fibres constant. The initial investigation used 0.9% (by weight of the dry mix) of polypropylene fibres (Mix designation CP). The wire fibre concrete (CW) contained a weight of wire fibres whose volume was equal to the volume of polypropylene fibres in mix (CP). With some of the later tests the effect of varying the maximum particle size on the internal cohesion and resistance developed was investigated by progressively omitting the 20 mm material to give 10 mm concretes (designated BU, BP and BW) and then omitting the 10 mm material to give mortar mixes (designated AU, AP and AW respectively).

In all cases the fibres were dispensed by hand into the premixed dry ingredients, and after uniform distribution was achieved, the water was added and mixing was continued for a further three minutes, using a pan-type mixer.

STANDARD WORKABILITY TESTS

In order to establish a basis for comparison, use was made of three British Standard Tests (9) namely, slump, vee and compacting factor. This initial investigation determined the effect of increasing percentages of fibre on the flow characteristics at zero time as recorded by these basic tests. The findings are illustrated in Figs. 1, 2 and 3.

As was anticipated, the internal resistance of the basic CU mix increased steadily with increase in fibre concentration. However, it was interesting to note the effect of the individual fibre characteristics for equal volumes. The reduction in mobility brought about by the polypropylene fibres was much greater than that caused by the wire. For example, 0.11% by weight of polypropylene fibres

decreased the slump by 50%, while the same volume of wire fibres only produce a 5% reduction. This was also confirmed by the vee test. The compacting factor test, which is not so much a measure of workability as an indication of vertical compactability or relative density (1), again showed that the wire fibres did not appear to impede flow and compaction in the vertical direction so much as did the polypropylene fibres.

STABILITY

The stability of a mix has been shown to be an important aspect in the rheology of fresh concrete (10). It can be characterised by bleeding and segregation tendencies, and is of considerable importance in the production of a satisfactory and durable concrete.

Bleeding occurs when the mortar forming the matrix is in an unstable condition and consequently, displaces free water. This normally finds its way to the surface during compaction and forms excessive laitance giving a surface that is prone to dusting. However, some excess water may also be collected en route by aggregate particles, reinforcing bars or fibres. This tends to reduce the adhesion or bond strength of the item and hence the overall structural quality of the concrete member. This phenomenon was successfully investigated for ordinary concrete mixes using the principle of flotation developed by Valore, Bowling and Blaine (11). The same procedure, using carbon tetrachloride as a displacement medium, was therefore adopted to investigate the effect of fibre inclusions on bleeding. The apparatus is shown in Fig. 4. Measurements of bleeding rate and capacity were made on samples containing a range of polypropylene fibres from 0.3% to 0.9% by weight and on a further set containing a corresponding equal volume of wire fibres.

The findings are illustrated in Figs. 5-8, and indicate a significant reduction in the quantity of bleeding water which reached the surface of the fibre reinforced samples. This reduction increased as the fibre content was increased, but the total quantity involved was dependent on the type and size of fibre. Thus although corresponding samples contained the same volume of polypropylene as wire fibres, the latter tended to hold internally slightly less of the bleeding water, despite the fact that it contained a much larger actual number of wires and hence a greater total surface area. The quantity of water held per unit length of fibre would be much less in the case of the wire fibres. Since both the fibres were non absorbent, it would seem possible that this water which normally found its way to the surface was being held around the individual fibres and hence tending to reduce the rate of gain of strength and the ultimate bond strength of the fibres. This in turn would reduce the overall structural efficiency of the member. It is therefore very important to consider the bleeding stability of all mixes which contain fibre reinforcement.

SEGREGATION

The characteristics of segregation and cohesion were recorded quantitatively by adopting a stability test developed by Hughes (12) and later used by Ritchie (10) as part of the rheological measurement

of fresh concrete. In this test the various mixes were forced to split up by being dropped from a standard height on to a cone-shaped target. The degree of segregation was determined by weighing the relative coarse aggregate content of samples taken before and after test. Visual observation confirmed that the fibres increased the cohesiveness and stability of the concrete as their content increased. Unfortunately the basic mix CU was in itself very stable and hence not prone to marked segregation and therefore the results do not indicate any significant improvement with the addition of fibres (see Fig. 9). The increase in bulk cohesion with fibre content was more obvious as indicated in Fig. 10. In both cases the polypropylene fibres gave a greater increase in mix stiffness than the wire fibres. The fact that fibres in general do increase stability has already been verified with reference to a much larger range of mixes (7).

STIFFNESS

Previous research on the lateral pressure of concrete on formwork (3) and the early striking of shuttering (6) had indicated that although a knowledge of mobility at zero time was of value in studying the procedures of placing and compaction, it was the rate of stiffening and the internal resistance developed that was of prime significance when it came to time dependent constructional problems. The progressive stiffening of a cement paste matrix which in turn makes it more difficult for the individual aggregate particles to translate and rotate, can be expressed in terms of the internal resistance of the mix. This property when it is related to lateral pressure, governs the arching limits with reference to the lateral dimensions of the formwork. It also determines the amount of vertical pressure from a head of fresh concrete that is translated into lateral pressure on the forms. The increasing stiffness with time governs the critical head and hence the maximum pressure developed. When related to early stripping, it is the property that, coupled with early strength development, determines the time at which the concrete can literally stand up for itself when forms are removed or slid, without causing surface damage, excessive deformation or reduction in subsequent structural properties.

The progressive stiffening of a mix can be readily illustrated by using any acceptable workability test such as the slump or vebe (4) but their value is very limited since the workability of the mix soon drops below the designed range of the apparatus and the results cease to be meaningful.

In order to study and compare stiffening rates more precisely, it was decided to monitor the development of direct tensile strength and the internal resistance of the fresh concrete. Both these properties had been measured successfully in previous investigations by means of a simple tensile test (1) and a newly developed vane test (4) respectively.

In the first test the sample was compacted into a split gauge box and the force required to pull the sample apart at any specified

time was recorded and the stiffness developed was expressed in terms of tensile stress. The gradual development of tensile strength within the matrix with time is shown in Fig. 11. The addition of fibres increased the cohesion of the mix by a significant percentage, but the actual magnitude of the maximum tensile strength was surprisingly small. The corresponding reduction in deformability is recorded in Fig. 12.

A schematic arrangement of the apparatus for the second test is shown in Fig. 13. This vane apparatus was specifically developed to measure internal resistance and recorded stiffness in terms of shear strength developed. A series of separate vane and shaft units were compacted into samples of fibred concrete in individual moulds. After a suitable time interval the vane was rotated at a standard rate and the shear resistance was recorded by means of a torque head and then related to shear strength in absolute units, depending on the size of vane used. This test was repeated using individual samples at increasing time intervals to produce a plot of stiffening and early strength development. The effect of maximum particle size and fibre content on internal resistance was investigated using a range of mixes from mortar to 10 mm maximum size concrete, and then on to 20 mm maximum size concrete. The relative shear strengths developed and the rate of gain of stiffnesses experienced are shown in Figs. 14-16. The effect of particle size was demonstrated by comparing the unfibred mortar mix (AU) with the plain 10 mm (BU) and 20 mm (CU) concretes. The mortar mix with a water/cement ratio of 0.4, compared with 0.55 for the concrete mixes, eventually reached a much higher structural strength, but its early internal resistance was much less because of lower particle interference. A change over point between the mortar and the concretes with respect to the internal resistance - early strength development graphs was eventually reached where the situation was reversed. A comparison of the two concrete mixes with the same water/cement ratio and similar aggregate content illustrated that the larger particle size developed a greater internal resistance. This concept of internal resistance related to time and particle interference was confirmed with reference to the addition of various quantities of fibres. Again individual fibre characteristics had a significant influence on the final results. Thus each of the mixes which contained wire fibres (on an equal volume basis) had a much greater effect on the stiffening rate and maximum shear strength developed than the polypropylene fibres. The 20 mm aggregate particles did not appear to hinder in any way the effectiveness of the fibres, even with the relatively short lengths used in this investigation.

From the results obtained, it would appear that significant reductions in lateral pressure on formwork for fibre reinforced mixes could be anticipated and lead to economies in shuttering. Also the higher internal resistance developed which would indicate an increase in strength during the very early part of the structural phase would imply that fibred concrete would lend itself to earlier removal of shuttering and faster sliding of forms, while still producing satisfactory surface finish and strength.

CONCLUSIONS

The results obtained from the various sections in this investigation confirm that fibre reinforced concrete requires a special understanding of its fresh and stiffening characteristics if full use is to be made of it as, what might be called, a new structural material. There are still several significant aspects of fibre mixes that have not been covered in this part of the investigation, such as the influence of admixtures and lightweight aggregates on the results obtained. However, it is clear from what has been reported that the proven selective structural strength advantages associated with specific fibre forms are not necessarily obtained at the expense of adverse fresh concrete properties. On the contrary, it would appear that several significant constructional advantages could be gained by virtue of fibre inclusions in the mix and several more are merely awaiting research and practical verification.

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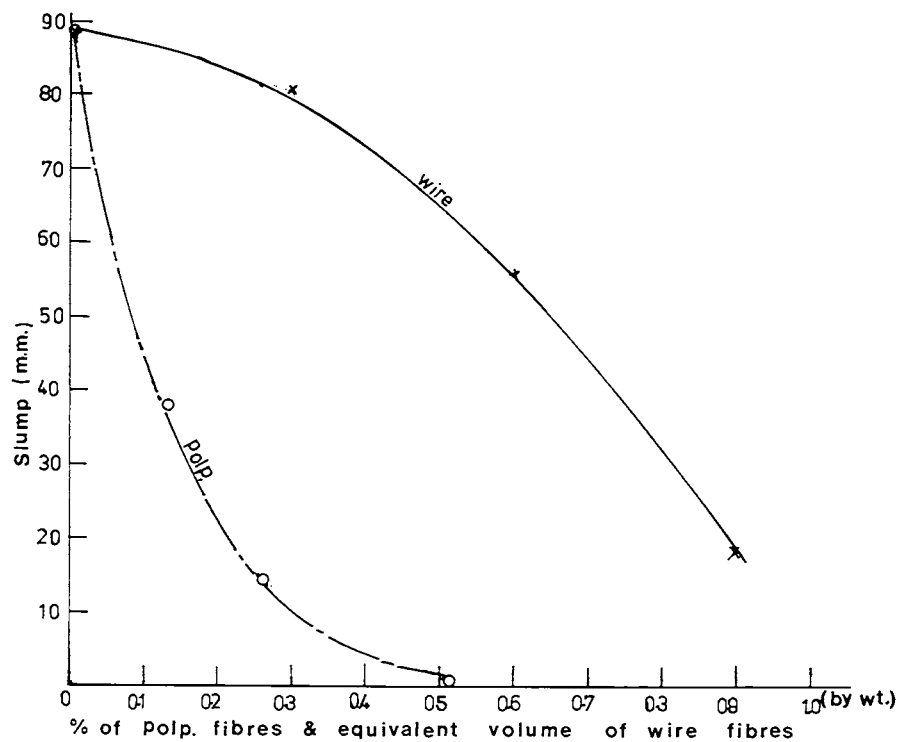


Fig. 1--The effect of fiber concentrations on slump

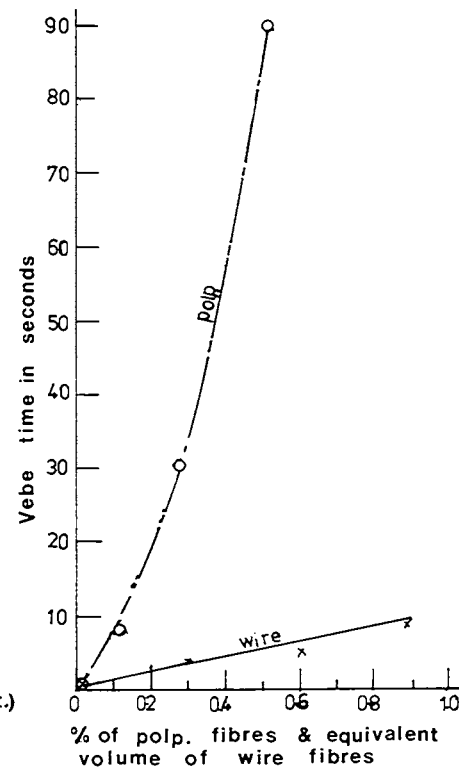


Fig. 2--The effect of fiber concentrations on vebe time

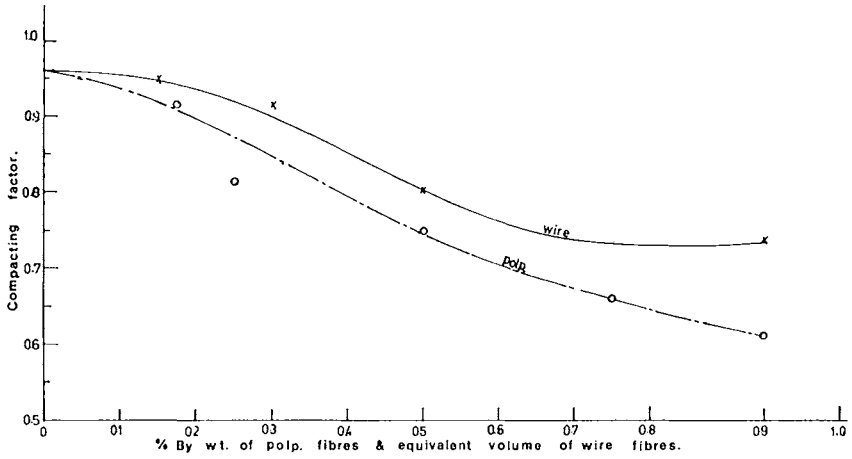


Fig. 3--The effect of fiber concentrations on compacting factor

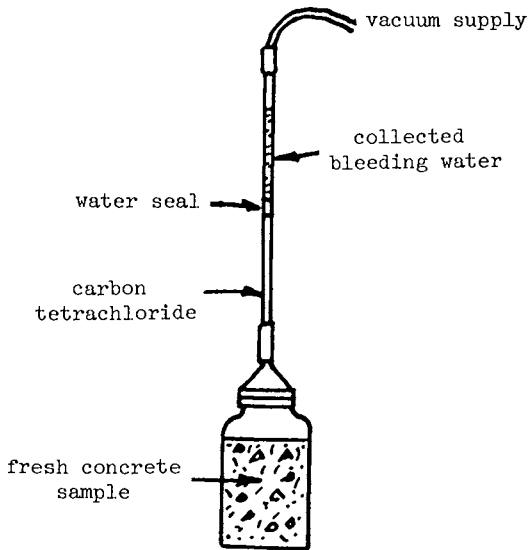


Fig. 4--Bleeding test apparatus

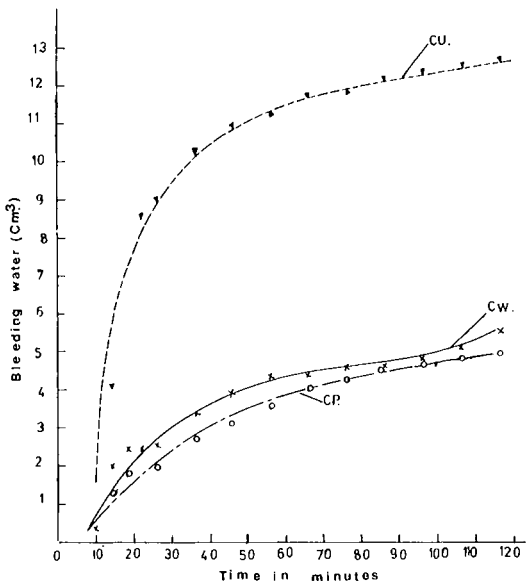


Fig. 5--Bleeding for 20 mm concretes

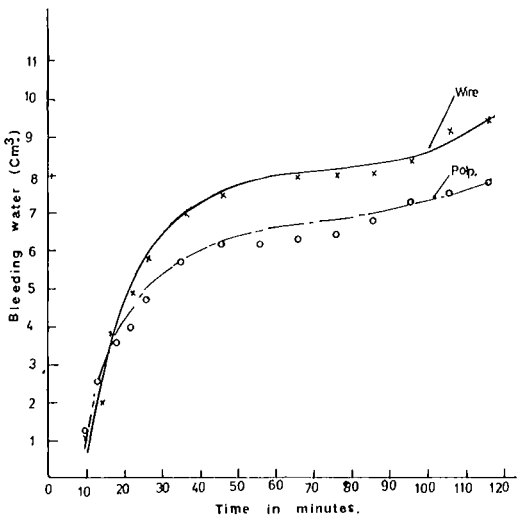


Fig. 6--Comparison of bleeding for concrete mixes containing polypropylene fibers (0.3 percent by weight) and wire fibers (equal volume)

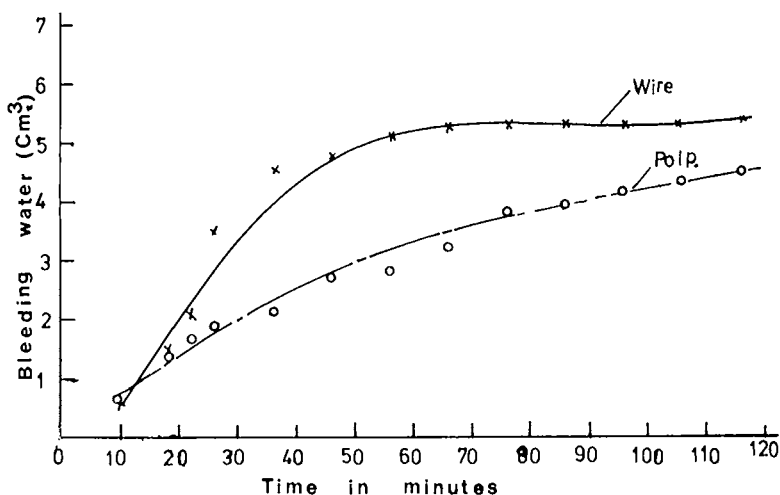


Fig. 7--Comparison of bleeding for concrete mixes containing polypropylene fibers (0.6 percent by weight) and wire fibers (equal volume)

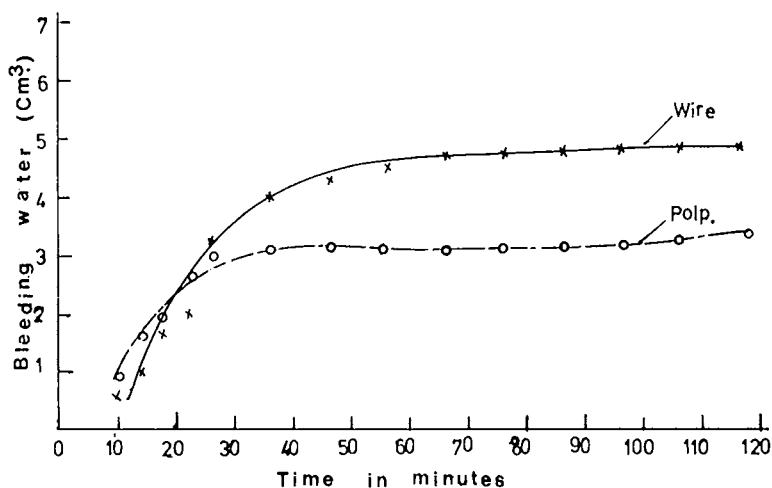


Fig. 8--Comparison of bleeding for concrete mixes containing polypropylene fibers (0.9 percent by weight) and wire fibers (equal volume)

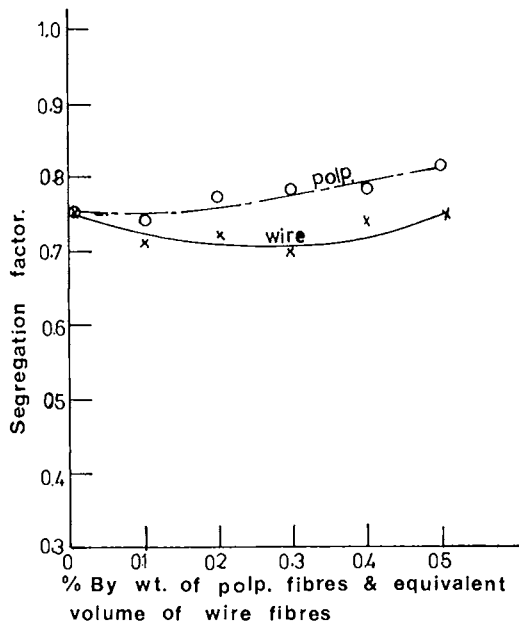


Fig. 9--Comparison of segregation factors for concretes containing various percentages (by weight) of polypropylene fibers and wire fibers (equal volume)

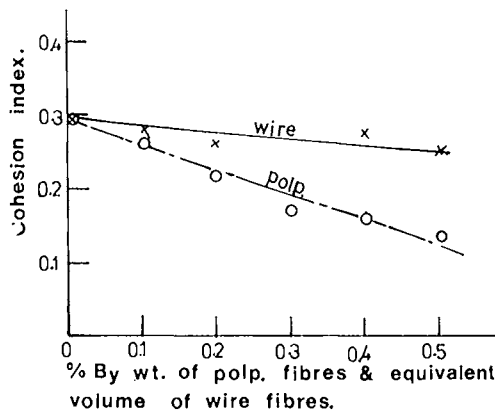


Fig. 10--Comparison of cohesion index for concretes containing various percentages (by weight) of polypropylene fibers and wire fibers (equal volume)

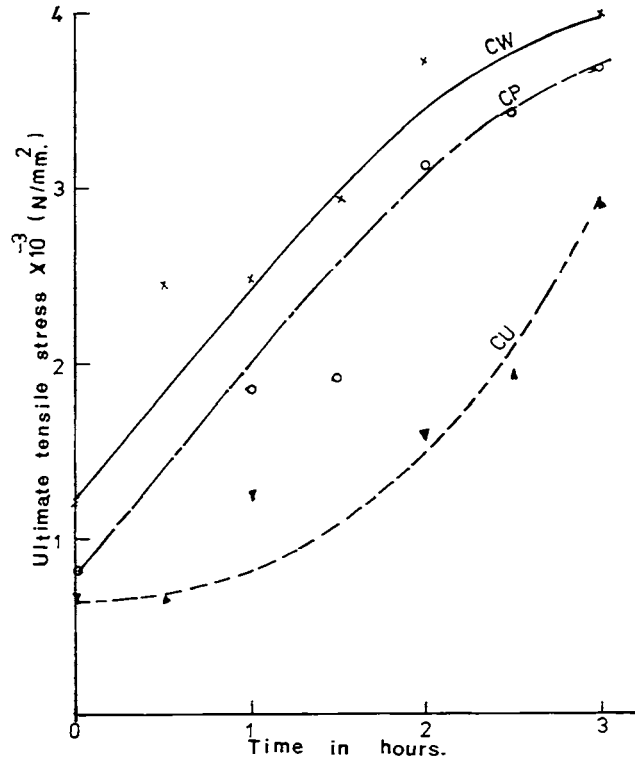


Fig. 11--Development of tensile strength with time for 20 mm concrete mixes

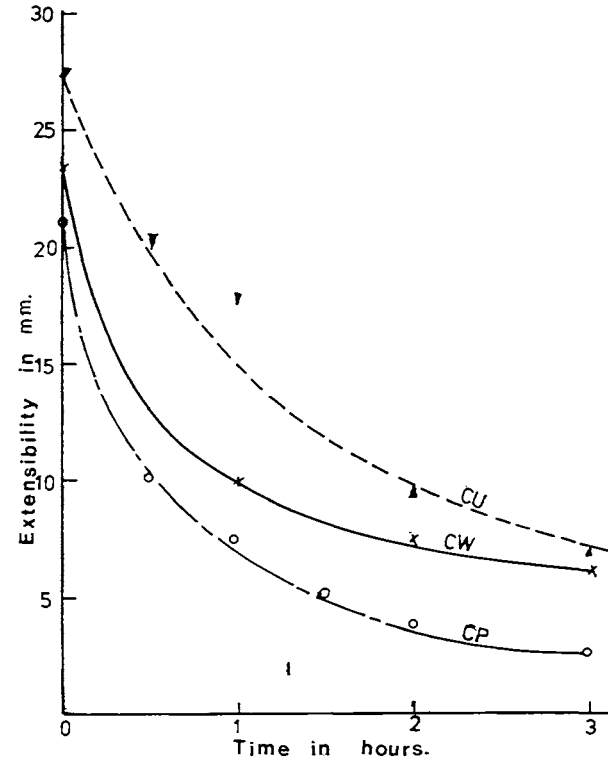


Fig. 12--Reduction in extensibility with time for 20 mm concrete mixes

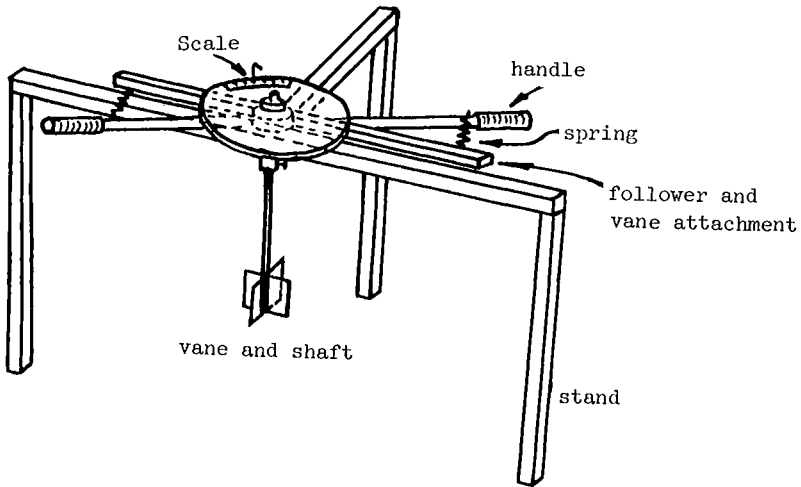


Fig. 13--Vane test apparatus

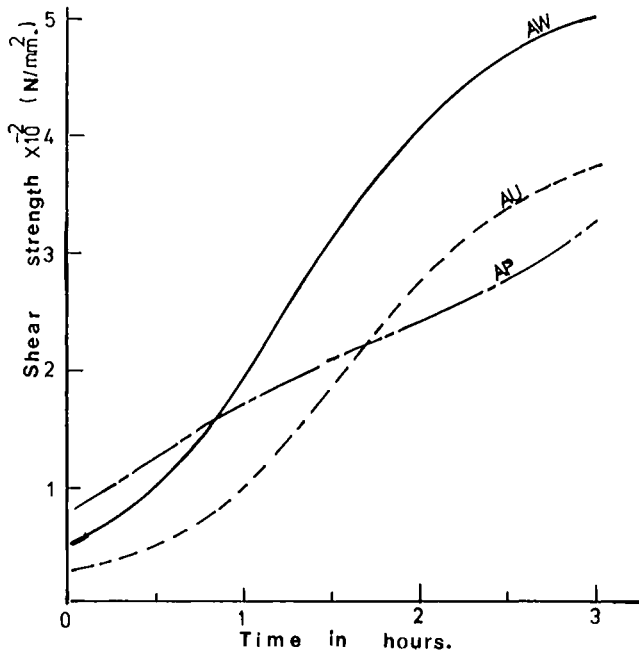


Fig. 14--Shear strength development for mortar mixes

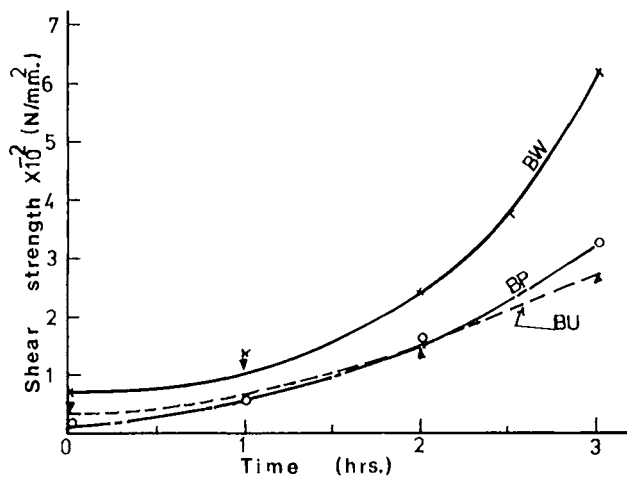


Fig. 15--Shear strength development for 10 mm concrete mixes

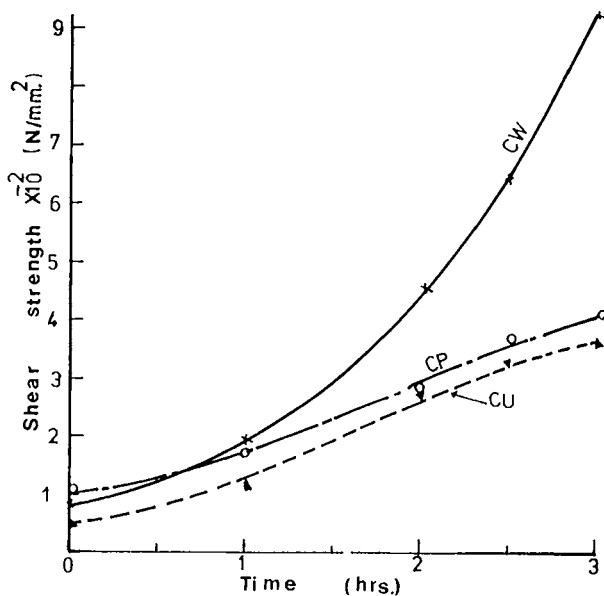


Fig. 16--Shear strength development for 20 mm concrete mm concrete mixes

SP 44-3

FIBER REINFORCED BRITTLE MATRIX MATERIALS

By
Herbert Krenchel

Synopsis: The specific problems involved in reinforcing cement materials with fibres are compared with those involved in reinforcing plastics with fibres. An analysis is carried out of why such high efficiencies of the reinforcement are obtained so easily with fibre-reinforced plastics but not normally with fibre-reinforced cement materials.

The different types of fibre materials that could be used as reinforcement for cement and concrete etc. are examined. Information is given regarding the mechanical properties and current market prices of these fibres. The special problems relating to the incorporation of the various types of fibres in the brittle matrix materials are discussed.

Best results are at present being obtained with asbestos and special glass fibres as reinforcement for neat Portland cement and gypsum plaster etc. and with glass fibres and steel fibres as reinforcement for cement mortar and concrete.

The synthetic mineral wool fibres and the cheapest and strongest types of plastic fibres have very promising strength/price factors, which indicate exceptional potentialities for these materials as reinforcement for cement and concrete, but the technological problems involved in fiberizing and incorporating them effectively in the brittle matrix materials have not yet been solved.

Keywords: curing; fiber reinforced concretes; flexural strength; glass fibers; metal fibers; mortars (material); plastics, polymers, and resins; portland cements; reinforcing materials; research; shrinkage; stiffness; synthetic fibers; tests.

Herbert Krenchel has worked as a research engineer at the Structural Research Laboratory of the Technical University of Denmark since 1950. He has concentrated on structural and materials research, with special emphasis on cement, mortar and concrete, reinforced concrete and reinforcing steel, and fibre-reinforced materials.

The author's thesis, "Fibre Reinforcement" (Dr.techn. dissertation, Technical University of Denmark, Copenhagen [9]) was published in 1964. Dr. Krenchel has been holding courses at the University on the theoretical and practical problems relating to fibre reinforcement.

INTRODUCTION

Fibre-reinforced materials and the problems relating to their production can be classified in two main groups according to the type of material used for the matrix. In the first group, the elongation at rupture of the matrix material is of the same order of magnitude as that of the fibres, while in the other group, it is far smaller.

The matrix material in the first group is normally an organic, polymeric material, e.g. epoxy, polyester, phenolic or melamine resin, while in the second group it is an inorganic cement material - Portland cement, high-aluminium cement, gypsum, calcium silicate, cement mortar or concrete - . (Two minor groups of fibre-reinforced materials, the fibre-reinforced metals and the ceramic materials, are neglected; they are specialities as yet of little practical interest in comparison with the first two groups mentioned).

It is typical of the composite material of the first group that quite a high fibre content is normally used ($V_f = 0.2 - 0.8$) and, further, that some sort of systematic orientation of the fibres is often used in order to achieve maximum efficiency of the reinforcement in the desired directions. Both fibre and matrix materials are in most cases rather costly, and the end product is normally manufactured for special structures, where hitherto unknown combinations of material properties are required - extraordinary strength and stiffness, low weight, high resistance to corrosion, ect.

The materials in the second group on the other hand, are normally some form or other of building materials, i.e. materials that must be produced at quite low prices in very large quantities and that are, furthermore, often subject to rigorous requirements as regards constant material properties over periods of, say, 50 years or more. The

cheapest possible basic materials are used and the fibre content is kept as low as possible ($V_f = 0.01 - 0.20$). Thus, many of the material properties of the end product do not deviate significantly from the corresponding properties of the matrix material, and the fibres are primarily added in order to remedy certain undesirable properties of the matrix.

Technical difficulties are seldom encountered in the production of the first group of materials. Various methods have been developed for building-up these composite materials, such as lamination, spraying-up, filament-winding, dough-moulding, etc., and all these result in a sound and well-constructed material with a very low air content and with a sufficiently uniform distribution of the fibres in the matrix.

In the case of the second group on the other hand, difficulties are frequently encountered. As yet only a few production methods have been developed for these types of materials, and it has been found that a method that is suitable for one combination of fibre and cement material is often useless for others.

A few types of fibres - such as asbestos and, to a certain extent, cellulose - can be successfully mixed with Portland cement, gypsum, calcium silicate and similar by several different production methods. However, for other combinations, the problem is far more complicated and - in most cases - as yet unsolved, and most of the materials of this type that have so far seen the light of day must be considered as experimental products or as representing only a temporary solution of the problem. In many instances, only a rather low utilization of the strength properties of the reinforcement is achieved in the composite material, primarily due to great variations in the fibre concentration from point to point within the material and because of poor anchorage of the fibres.

ORGANIC/INORGANIC MATRIX

There are various reasons why organic matrix materials are far more suitable for fibre reinforcement than inorganic materials:

1. Before curing - but possibly after suitable heating - the organic materials have the form of a fluid of such low viscosity that they can penetrate into and displace all air even in very densely packed bundles of parallel fibres, where the distance between the surfaces of the fibres may be of the order of magnitude of 1μ ($1\mu = \frac{1}{1000}$ mm) or less, and where each bundle of fibres contains hundreds or thousands of single fibres. The inorganic cement materials on

the other hand, come in powder form, with a maximum grain size of usually about 100μ and an average grain size of, for example, about $10\text{--}30\mu$. In most cases, therefore, it is necessary to pre-treat (fiberize) the fibre material in order to open this and separate the individual fibres sufficiently to permit the cement to penetrate to the entire surface of all the fibres. In many cases it is difficult to achieve a systematic pre-treatment of the fibre material without destroying the fibres.

2. When the material has been built up, the organic matrix can be hardened directly, whereas the inorganic cements, almost all of which are hydraulic materials, have usually been premixed with excess water, which must be removed before hardening can begin. Especially in the case of coarse fibres, the removal of this water can result in a certain degree of segregation and thereby impairment of the material.

3. A higher adhesion is obtained between matrix and fibres in the case of the organic materials than in that of the inorganic materials ($\tau_{cf.org} \sim 10\tau_{cf.inorg}$), and the risk of premature failure from pull-out of short-fibred reinforcement is thus considerably greater in the latter group.

4. In cases in which the elongation at rupture of the matrix is considerably smaller than that of the fibres, the efficiency of the reinforcement may be greatly reduced if, when the matrix cracks, the fibres cannot take over the load in the zones subjected to tensile stresses without being damaged.

The lower the fibre content and the greater the variation in fibre density and orientation from point to point within the material, the greater will be the risk of such damage to the reinforcement because the under-reinforced zones will have a notch effect on the rest of the cross-section. This risk is seldom encountered in the case of the first group of materials because the organic matrix materials have an ample elongation at rupture. But even when this is greatly reduced due, for instance, to a heavy shrinkage during hardening, there is unlikely to be a greater risk of damage to the reinforcement because of the high degree of reinforcement used and because, in this group of materials, it is easy to achieve a proper distribution of the fibres within the matrix.

In the case of the inorganic matrix materials on the other hand, there is a great risk of such damage because the elongation at rupture of the cement is considerably smaller than that of the fibres ($\epsilon_c^u \sim 0.1 \epsilon_f^u$ or less), due to the far lower fibre content used here and to the fact that it is often difficult to achieve a perfect di-

stribution of the fibres and sufficient bond between the components.

5. Finally, the hardened organic matrix materials are almost all chemically inactive, whereas most of the inorganic materials are reactive when they contain pore water. Thus, the cheapest and, for many purposes, most suitable inorganic cement - ordinary Portland cement - has a heavy alkaline reaction and can, for example, not be reinforced with ordinary A- and E-glass fibres because these are not alkali-resistant.

It will be seen from the above that there are great differences between these two groups of fibre-reinforced materials, and it is therefore quite natural that most of the research within the two groups is kept separate. On the other hand, it will be realized that there should be a possibility of utilizing certain experience gained on the first group of materials to solve the many difficulties encountered in the production of the fibre-reinforced materials in the second group.

In the following we will examine some of the problems involved in the production of fibre-reinforced inorganic materials. One very important question here is the production of asbestos-cement and related materials, but the fibre-reinforcement of mortar and of concrete is undoubtedly also of interest for many special purposes.

FIBRE MATERIALS

Asbestos

Up to about ten years ago, practically all fibre-reinforced cement materials were produced with asbestos as the reinforcement, and this fibre material still reigns almost supreme, even though, particularly within the last few years, intensive research has been aimed at finding suitable substitute fibres.

There is an extremely heavy consumption of this raw material by the asbestos-cement industry - of the order of magnitude of 20 million tons a year - and it is realized that it will be necessary to find a substitute fibre within the foreseeable future because the earth's asbestos resources are not inexhaustible and, further, because recent research in industrial medicine has drawn attention to the health hazards involved in working with asbestos.

Very great economic interests are thus involved in the quest for a suitable substitute fibre, but the problem is no easy one because nature has given asbestos certain special qualities that make it exceptionally suitable for this

special purpose, and not all these qualities are represented in the other types of fibres that might come into consideration.

Asbestos has a high chemical resistance and good mechanical properties, principally high tensile strength and modulus of elasticity (approx. $0.5 - 1.0 \text{ GN/m}^2$ and 150 GN/m^2 , respectively, for an absolute density of fibre of about 3.0 for the fibre qualities normally used *)). The fibres also have a high ductility, whereby they can withstand heavy pre-treatment in, for example, an edge runner or hammer mill and very heavy mechanical treatment during fiberizing and mixing with the cement. Because of their crystalline structure, the fibres show a clear tendency under such mechanical treatment to split up into ever thinner fibres and into partly cohesive bundles of parallel fibres, normally without any tangling of the material or any significant shortening of the fibre length.

Thus, with comparatively simple mechanical treatment, the asbestos can be fiberized to such an extent that it is, for example, possible in a water suspension to separate the individual fibres simply by diluting the suspension under continued mechanical stirring. This enables the cement particles to envelop all fibres and small bundles of fibres, thus permitting full anchorage of the reinforcement and producing a perfect structure in which the variation in fibre spacing from point to point is kept at a minimum.

When the excess water is removed, even from very thin suspensions, practically no segregation takes place in the built-up material. Thus, the above-mentioned perfect mixture of the components can be preserved from suspensions with, for instance, a water content of about 90% to a final product with a water content of only about 20%.

The reason for the latter phenomenon, which is regarded as one of the most valuable characteristics of asbestos in this context, is not known with certainty. It is called the buoyancy of the asbestos for cement and other powder materials, and has been attributed to special adhesion forces between the components; but it is also reasonable to assume that it is just a result of the very intense splitting-up of the fibre material - in the finished mix, many of the fibres have a diameter of far less than 1μ - whereby, even in the building-up of the very thin

*) Higher strength figures for asbestos fibres are mentioned in the literature, but for the fibre qualities normally used in the asbesto-cement industry, the values mentioned are more appropriate.