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Fibrous Concrete-Construction Material for the Seventies (May 1-3, 1972)

Army Construction Engineering Research Laboratory

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13. ABSTRACT

This Conference Proceedings contains many of the papers presented at the May 1972 Fibrous Concrete Conference sponsored by the U.S. Army Corps of Engineers, Construction Engineering Research Laboratory (CERL). The conference emphasized fibrous concrete as a construction material for the 1970's. The papers fall under two main topic headings--"State of the Art" and "Pavement Applications." Photographs of the Conference are also included.

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FOREWORD

In just one decade, fibrous concrete has developed from a laboratory theory into a proven construction material. Over 100 reports on the subject have been published (with an even larger number unpublished). Yet despite this research and development activity, fibrous concrete information has not been reaching a vast field of potential users. Recognizing this situation, the Materials Division of the Construction Engineering Research Laboratory (CERL), in Champaign, Illinois, and Mr. B. H. Gray, principal investigator of fibrous concrete for the laboratory, initiated plans for a conference to be held at the laboratory in May 1972. The main objective: to bring together those who were working in the field of fibrous concrete and those who were engaged in concrete work in general, and could perhaps find applications for fibrous concrete. Attendance at the conference verified the fulfillment of this objective. Some 265 attendees from 38 states and two foreign countries represented 10 federal agencies, 15 state highway departments, 20 Corps of Engineers Districts, 11 universities and over 100 private concerns and consultants.

The theme of the conference emphasized the practical aspects of fibrous concrete, although there were several papers that discussed the theoretical aspects as well. The presentations were grouped into two categories: "State of the Art" and "Pavement Applications." The papers in this proceedings are arranged in order of presentation at the conference. Session I introduced fibrous concrete theory and presented a discussion of the various constituents used in the production of the material. Session II consisted of a visit to CERL for demonstrations and displays of fibrous concrete. Session III dealt with basic properties of fibrous concrete, and Session IV presented information on actual full scale placement of pavement applications.

CERL personnel actively engaged in the conference development, planning, and conduct were: Col. E. S. Townsley, CERL Director; Mr. B. H. Gray, Conference Chairman; Mr. J. L. Rice, Session Chairman; Dr. J. L. Lott, Session Chairman; Mr. E. A. Lotz, Chief of Materials Division; and Mr. R. A. Bechmann, Chief of Administrative Services.

The Conference Proceedings were prepared by Mr. B. H. Gray; Dr. G. R. Williamson, visiting professor at CERL on a summer academic appointment from Youngstown State University, Youngstown, Ohio; Dr. G. B. Batson, visiting professor at CERL on sabbatical leave from Clarkson College of Technology, Potsdam, New York; and the Technical Information Branch of CERL.

For their assistance to CERL with the fibrous concrete display and demonstration items in Session II, acknowledgment is given to: The National Standard Company, The United States Steel Corporation, Owens-Corning Fiberglas Corporation, C. T. Harris and Associates, and CERL

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personnel Messrs. P. A. Howdyshell, L. P. Suddath, III, R. C. Gunkel, and Capt. J. Allen. Appreciation is also extended to the speakers, who not only took the time to present their papers at the conference, but did so at no expense to the conference.

Col. R. W. Reisacher is currently Director of CERL and Dr. L. R. Shaffer is Deputy Director.

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by

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Presented at
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"Fibrous Concrete--Construction Material for the Seventies"
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May 1972

ABSTRACT

The paper presents a definition of fibrous concrete and a short review of the various kinds of materials and the physical shape of fiber elements as disclosed in various patents granted during the past 50 to 75 years in the United States and foreign countries, and in technical literature.

Theoretical concepts relevant to the mechanics of fiber reinforcing of mortar and concrete will be reviewed, including the fracture of brittle materials, linear elastic fracture mechanics, crack arrest mechanism, composite action based on law of mixture, and energy considerations.

A summary of the properties of fibrous concrete, including the static tensile, compressive and flexure strength, dynamic and fatigue strength, and durability are presented.

INTRODUCTION TO FIBROUS CONCRETE

by

Dr. G. B. Batson

INTRODUCTION

Historically fibers have been used to reinforce brittle materials since ancient times; straw was used to reinforce sunbaked bricks, horse hair was used to reinforce plaster and more recently, asbestos fibers are being used to reinforce portland cement. The fiber reinforcing compensated for the low tensile strength and brittle character of the matrix material. The requirement of improving the strength-to-density ratio of materials in the aircraft and space industry has been met by fiber reinforcement with metallic fibers in metallic matrices and ceramic fibers in metallic matrices.[1] Fiberglass is a very common fiber reinforced plastic.

The discussion in this paper will be restricted to fiber reinforced concrete or mortar. The fibers not only compensate for low tensile strength and brittle character af the concrete, but also improve the mechanical and physical properties of the composite.

Fiber reinforced concrete is concrete made of hydraulic cements containing fine or fine and coarse aggregate and discontinuous discrete fibers. Continuous meshes, woven fabrics, and long thin rods or wires are not considered to be discrete fiber type reinforcing elements.

The idea of using discrete fibers, whether metallic, organic or inorganic, is not new. Many patents have been granted since the turn of the century for various methods of incorporating wire segments or metal chips into concrete. Reference 2 lists three of the many patents granted in the United States. There are European patents also. Generally these patents did not further our understanding of the mechanics of fiber reinforcement. The more recent patents by Romualdi[3] and the United States Steel Corporation[4] are significant because they demonstrate advances in the understanding of the mechanics of fiber reinforcement and resulting ability to predicate the mode of action and the strength properties for various loading conditions. The reasons for using steel fibers in mortar are similar to those for using straw in bricks or horse hair in plaster. The developments of the last ten years in our understanding of the mechanics of fiber reinforcement and the success of field applications make a conference such as this possible. This is not to imply that every aspect of fibrous concrete is understood; R and D work is still needed. Information for the successful application of fibrous concrete will be presented by the speakers at this conference.

FIBERS AND MATRIX

Fibers may be metallic, organic or inorganic, but the most common are steel, glass, plastic and natural materials in various sizes and shapes. A convenient numerical parameter describing a fiber is its aspect ratio, defined as the length divided by an equivalent fiber diameter. Typical aspect ratios range from about 30 to 150 for fiber lengths dimensions of 0.25 to 3 in.

Round steel fibers are produced by cutting or chopping wire, typically having diameters between 6 and 30 mils. Flat steel fibers having typical cross sections ranging from 6 to 16 mils in thickness by 10 to 35 mils in width are produced by shearing sheets or flattening wire. Crimped and deformed steel fibers have been produced.

Typical glass fibers (chopped strand) have diameters of 0.2 to 0.6 mils, but these fibers may be bonded together to produce glass fiber elements with diameters of 0.5 to 50 mils.

Typical plastics such as nylon, polypropylene, polyethylene, polyester, and rayon have been made into fibers with diameters of 0.8 to 15 mils.

Fibers processed from natural materials like asbestos and cotton provide a wide range of sizes.

Table 1 lists some typical properties of fibers.

Research on closely spaced steel wire was conducted by Romualdi and Batson,[5,6] and on random steel fibers by Romualdi and Mandel.[7] In the early 1960's, experiments using plastic fibers in concrete with and without steel reinforcing rods or wire meshes were conducted.[8,9] Experiments using glass fibers have been conducted in the United States since the early 1950's[8,10] as well as the United Kingdom[11-14] and Russia.[15]

Matrix material is cement paste, mortar or concrete. Aggregate size distribution is of particular significance. The best performance has been obtained using only sand or sand and a coarse aggregate not exceeding 3/8 in.

Table 2 lists typical properties of a matrix material of cement paste, mortar and concrete.

Table 1. Typical Properties of Fibers

	Tensile Strength ksi	Young's Modulus 10^3 ksi	Ultimate Elongation, %	Specific Gravity
Acrylic	30-60	0.3	25-45	1.1
Asbestos	80-140	12-20	∿0.6	3.2
Cotton	60-100	0.7	3-10	1.5
Glass	150-550	10	1.5-3.5	2.5
Nylon (high tenacity)	110-120	0.6	16-20	1.1
Polyester (high tenacity)	105-125	1.2	11-13	1.4
Polyethylene	∿ 100	0.02-0.06	∿ 10	0.95
Polypropylene	80-110	0.5	∿ 25	0.90
Rayon (high tenacity)	60-90	1.0	10-25	1.5
Rock wool (Scandinavian)	70-110	10-17	∿0.6	2.7
Steel	40-600	29	0.5-35	7.8

Table 2. Typical Mechanical Properties of Portland Cement Matrix Materials

	Tensile Strength, psi	Approx. Young's Modulus, 10^6 psi	Ultimate Elongation, %
Portland Cement Paste	800-1000	3	0.030
Portland Cement Mortar	600-800	5	0.015
Portland Cement Concrete	400-600	2-6	0.010

MECHANICS OF FIBER STRENGTHENING

Any mechanism proposed to explain the fiber strengthening of mortar or concrete must be consistent with observed response of the material to loading. A schematic load-deflection curve of a beam with sufficient fiber content, Figure 1, is linear up to point A, defined as the first crack strength. Beyond point A the curve is nonlinear and reaches a maximum at point B, the ultimate strength.

The mechanism proposed by Romualdi and Batson[6] predicts that the first crack strength is inversely proportional to fiber spacing for a given percentage of fibers by volume of mortar.

The basic rationale behind the theoretical development is illustrated in Figure 2. A side view of an internal crack is shown located between two wires or fibers. In the presence of a gross stress, σ, the extensional strains in the vicinity of the crack tip, by virtue of the stress concentration, are larger than average strains. These strains, however, are resisted by the stiffer fiber and there is created a set of bond forces (assuming the bond between the concrete and the steel is intact) that act to reduce the magnitude of stresses at the crack tip. Under proper conditions of fiber spacing and diameter, an internal flaw could be prevented from propagating, thus permitting the material to experience a larger section stress, σ, before crack propagation commences at a local internal level. The theoretical result linking first crack propagation stress and wire spacing, for a given value of G_c (see Appendix A) and various reinforcement volumes by percent, are shown in Figure 3. It should be carefully noted from Figure 4 that the increase in first-crack strength occurs if the bond between the fibers and mortar is maintained. For certain fiber sizes and percentage, the bond stress may be exceeded before significant increase in the first-crack strength develops. Romualdi and Mandel[7] showed that the expected result could be achieved by mixing short fibers directly into the mortar. Results of their tests are shown in Figure 5 which compares strength ratio (ratio of first-crack strength of fiber reinforced concrete to cracking strength of plain concrete) as a function of wire spacing. The inverse square root relationship predicted by σ in Figure 3 is implied by these tests.

Tests by Snyder and Lankard[16] shown in Figure 6, also demonstrate the effect of fiber reinforcement upon first-crack strength. All tests are conducted at a constant steel content of 2 percent by volume. Variations in spacing were accomplished by varying fiber diameter in accordance with the following expression for average fiber spacing.[7]

$$s = 13.8d \sqrt{\frac{1.0}{p}} \qquad (1)$$

where s is the spacing between centroids of fibers, d is fiber diameter and p is percent reinforcement by volume. The results of Snyder and Lankard also illustrate the sensitivity of results on the length of the fiber as well as the average spacing between fibers.

Further evidence of this phenomenon is provided by J. L. McKenny.[17] These data, shown in Figure 7, are for concrete reinforced with 17 mil diameter wire and the various spacings were obtained by varying the steel content from 0 to 1.5 percent in 0.5 percent steps. Note that the increase in first-crack observed when the spacing varies from about 0.57 in. to 0.32 in. cannot be explained solely on the basis of the corresponding increase in steel content from 0.5 to 1.5 percent of randomly oriented wires.

McKee[18] has derived an equation for fiber spacing that is slightly different than Equation 1. The spacing is given by

$$s = \sqrt[3]{\frac{V}{p}} \qquad (2)$$

where V is the volume of one fiber and p is the volume percentage of fiber in the mortar. Equations 1 and 2 are shown in Figure 8.

Another approach to strengthening mechanism of fibers has been suggested[19] based on a "law of mixtures" to predict the strength properties, but there are not much experimental data to support it. It is suggested that the influence of fibers on the elastic properties of the composite can be obtained by using the following equation:

$$E_c = E_f V_f + E_m V_m \qquad (3)$$

where E_c, E_f, and E_m are moduli of elasticity for the composite fibers and the matrix. V_m is the volume fraction of matrix and V_f is the volume fraction of fibers adjusted for the effect of randomness.

Equation 3 is strictly valid for composites with continuous fibers, elastic behavior of the components and no slippage between fibers and matrix. Since fibers are finite in length, there may be some microcracking before the proportional limit, because debonding may occur with fibers. As a result, this equation is only an upper bound solution for modulus of elasticity and the proportional limit in the case of fiber reinforced concrete.

In Figure 1 the load-deflection curve is nonlinear beyond point A and the spacing concept does not apply since it is based on linear elastic fracture mechanics. The maximum load is controlled primarily by fibers gradually pulling out, and the stress in the fiber at the ultimate load is substantially less than the yield stress of the fiber. After the maximum load, the decrease in load with increasing deformations is much less for fiber reinforced concrete than that for plain concrete.[46] As a result, the total energy absorbed before complete separation of a beam is at least an order of magnitude higher for fiber reinforced concrete than for plain concrete. The energy is absorbed in debonding and stretching of fibers. The relative magnitude of each effect depends upon the stress-strain curve of the fibers themselves. The ultimate strength of fibrous concrete depends upon the volume percentage of fibers and the aspect ratio. The specific surface area, defined as the surface of the fibers in a unit volume of mortar or concrete, may be a more appropriate parameter for predicating the ultimate strength.[20] At maximum load in flexure, part of the cross section of the beam is cracked and some of the fibers may have been partly debonded. As a result it is not possible to rationally predicate the ultimate strength of fibrous concrete. An empirical approach is suggested based on theories developed for composites. The ultimate strength of a composite when failure occurs by debonding of the fibers is given by

$$S_c = A\, S_m (1 - V_f) + B\, V_f\, L/d \qquad (4)$$

where S_c and S_m are the stress value of the composite fiber reinforced concrete, and the matrix, mortar, or concrete, respectively. L denotes the length of the fiber and d is the diameter of the fiber. A and B are constants which can be determined by a plot of composite strength against V_f L/d.

Note that the first term on the right hand side of Equation 4 represents the contribution of the matrix at the maximum load. The maximum value of the constant A is unity. Constant B depends on the bond strength between the fibers and the matrix and on the randomness of the fibers. The higher the bond strength and the better aligned the fibers are in the direction of the load, the higher the constant B. Note that B has the same units as those of S_c and S_m. There is not much data presently available to verify results as Equation 4.

Toughness is defined as the total energy absorbed prior to complete separation of the specimen. This energy can be measured by taking the area under the complete tension or compression stress-strain curve or by the area under the load-deflection curve in flexure. Energy absorbed can also be measured by an impact test. It is apparent that toughness will depend on the type and rate of loading. Toughness versus fiber content is shown in Figure 9.

When the fibers are present, the cracks cannot extend without stretching and debonding the fibers. As a result, considerable additional energy is necessary before complete fracture of the material occurs. Several investigators have shown that the toughness of the fiber reinforced concrete is at least an order of magnitude higher than that of plain concrete. Thus, increase in toughness is a significant improvement resulting from the addition of fibers.

It is reasonable to assume that some of the same parameters that influence the maximum load will also influence the toughness. These include orientation of fibers, volume percentage of fibers and the aspect ratio. In addition, the stress-strain curve of the fiber itself influences the total energy absorbed. Increase in toughness is observed when untreated high strength steel fibers are annealed.[47] This may result from the additional energy absorbed by fiber stretching.

MECHANICAL AND PHYSICAL PROPERTIES

The mechanical and physical properties depend on the volume concentration, aspect ratio, type and kind of fiber used for reinforcing. There is very little standardization with respect to size of specimen and the test loading among the reported investigations. Thus ranges in the test results are given and one should refer to a specific reference for the conditions of testing.

Steel fibers, up to about 4 percent by volume, were found to increase the "first crack flexural strength" of concrete up to 2.5 times the strength of the unreinforced materials,[7,9,16,20,21] and slightly increased the compressive strength.[9,21,23] Splitting tensile strength of mortar reinforced with steel fibers was reported to be about 2.5 times that of the unreinforced mortar when 3 percent fiber by volume was used[7] and 2 times when 1.5 percent was used.[17] Direct tensile strength of mortar reinforced with 1.5 percent steel fibers was also reported to be about 1.4 times that of unreinforced material.[17]

Asbestos fibers of 2 to 16 percent volume were found to increase the flexural strength of reinforced paste up to 1.6 times.[25]

Considerable research has been done on the use of glass fibers in portland cement products.[12-14,24] The main problem in such use is that of chemical attack of the glass by the high alkalinity found in hydrated portland cements. Solutions to the chemical attack problem have included the development of alkaline resistant glass fibers[14] and resistant coatings on the glass.[8,10,26]

Plastic fibers, such as nylon, polypropylene, and polyethylene, although not subject to chemical attack in concrete, have generally been found to contribute little, if any, to the static strength of concrete.[8,9] However, high denier nylon and polypropylene increased the flexure and impact strength.[27] Fibers that are subject to alkaline attack, such as cotton, rayon, acrylic, and polyester, were found ineffective as reinforcement in portland cement products.

The dynamic strength[8,10,23,28] of concrete reinforced with various types of fibers and subjected to explosive charges, dropped weights and dynamic tensile and compression loads have been measured. Generally the dynamic strengths for various types of loadings were greater for the fiber reinforced than for plain concrete. The greater energy requirements to strip or pull out the fibers provides the impact strength and resistance to spalling and fragmentation.

Extensive experimental fatigue studies have been conducted on steel fiber reinforced concrete; however, beam sizes, loading conditions and fatigue failure criteria have varied. Generally there is an increase in fatigue strength with increasing percentage of steel fibers.

Tests results for steel fiber reinforced concrete indicate fatigue strengths of 90 percent of the first crack strength at 2 x 10^6 to 50 percent at 10 x 10^6 cycles for nonreversal type loading using 2 to 3 percent steel fiber by volume.[18,29-31] Reversal type fatigue loadings indicated fatigue strengths of 73 percent for 2 to 3 percent steel fiber by volume at 2 x 10^6 cycles.[32]

Postfatigue static flexural strength was 10 to 30 percent greater than for similar beams with no fatigue loading history. One explanation is that the cyclic loading reduced initial residual tensile stresses due to shrinkage of the matrix by accelerating the creep.[33]

The limited test data[18] indicated that wire fiber reinforcement had no significant effect on the creep behavior of portland cement mortar. For expansive mortars reinforced with steel fibers, the fibers provided a restraint which contributes to early creep, termed "precreep."

One study[34] showed insignificant corrosion by salt water on portland cement mortar reinforced with 2 percent steel fibers and no change in the flexural strength was observed for up to 90 days of rotation in and out of a saturated salt water solution.

The thermal conductivity of steel fiber reinforced mortar with 0.5 to 1.5 percent by volume of fiber at atmospheric pressure showed small increases with increasing fiber content.[35] Unpublished data for 2 percent fiber by volume in a mortar for vacuum condition over a range of 120 C to -20 C showed a 30 percent increase in thermal conductivity.[36]

Unpublished laboratory data on test samples 2.5 percent by volume of fiber reinforced and plain concrete were conducted using a modified NBS wear testing machine.[37] Test slabs of fiber concrete with pea gravel abraded to a depth 27 percent less than plain concrete with gravel.

Abrasion and erosion of fiber reinforced concrete surfaces and plain concrete surfaces have been simulated by sand blasting and electrically driven rotary steel brush. Based on visual examination, the fiber concrete surface exhibited less spread and depth deteriorations with increasing fiber content.[38]

Static friction, skid and rolling resistance of fiber reinforced concrete were compared to identical plain concrete laboratory size slab samples in a simulation test for a comparative study only.[38] The fiber reinforced concrete had 3/8-in. maximum size aggregates. Test results showed that for dry concrete surfaces before wear, erosion, or deterioration of the surface the coefficient of static friction was independent of the steel fiber content. With simulated abrasion and erosion of the surface, the fiber reinforced surfaces had up to 15 percent higher skid and rolling resistance than plain concrete under dry, wet, and frozen surface conditions.

The tensile, compressive and flexural strength of fibrous concrete using various kinds of fibers are fairly well documented for both static and dynamic loadings. However, more information in the area of durability with respect to corrosion in adverse environments, freeze-thaw cycles, and creep are needed. Research is presently going on to provide this information throughout the world.

SUMMARY

The advance of the last ten years in fibrous concrete compared to the state of knowledge previously has been in the understanding of the mechanics of fibrous reinforcing and how it affects the mechanical and physical properties.

ACKNOWLEDGMENT

Material used in this paper is adapted from various drafts of ACI Committee 544 on the state of the art in fiber reinforced concrete. Several members of Committee 544 are speakers at this conference.

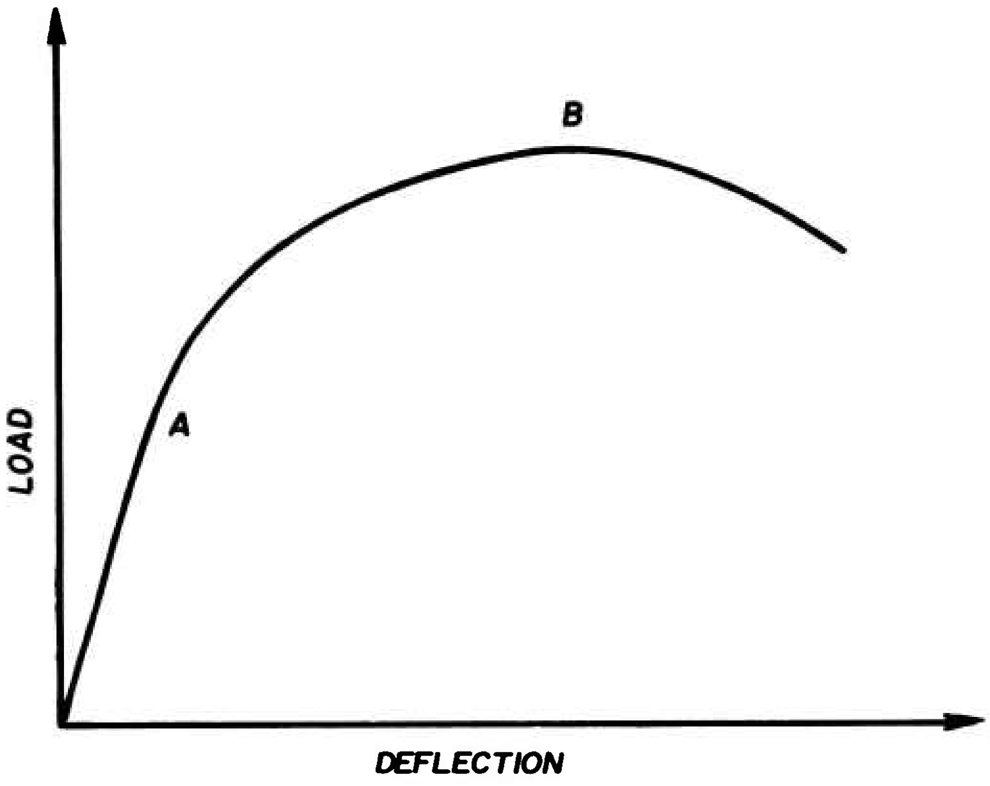

Figure 1. Schematic Load-Deflection Diagram of a Steel or Glass Reinforced Beam

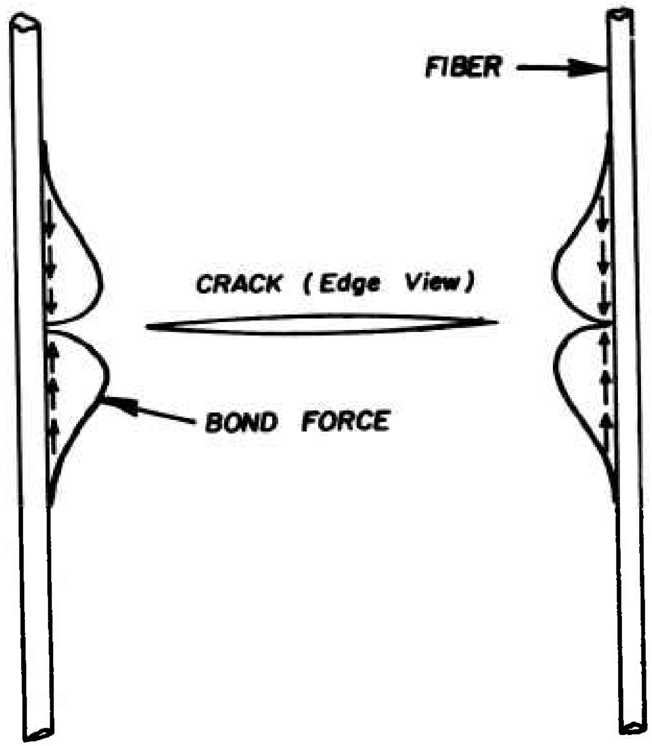

Figure 2. Section Through Crack and Adjacent Fibers

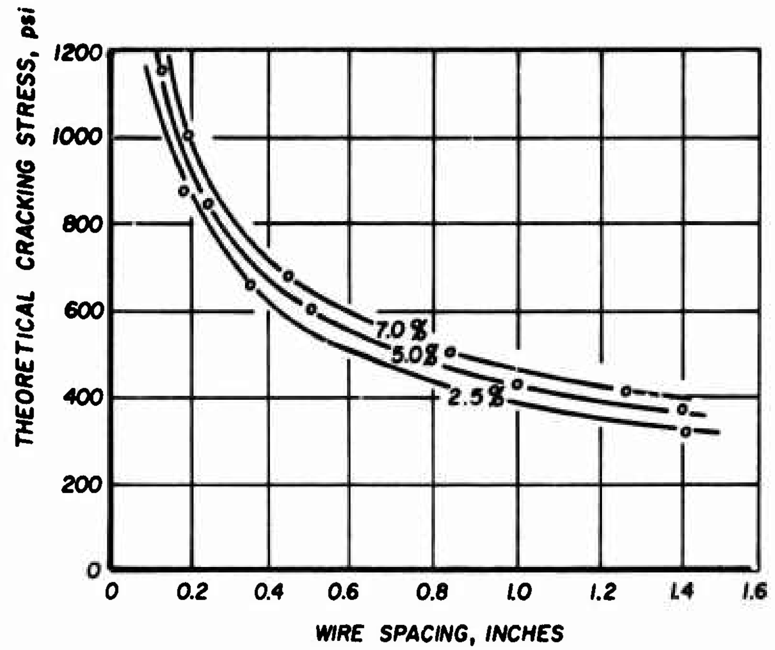

Figure 3. Cracking Stress as a Function of Wire Spacing (G_c = 0.02 in.-lb per sq in.)

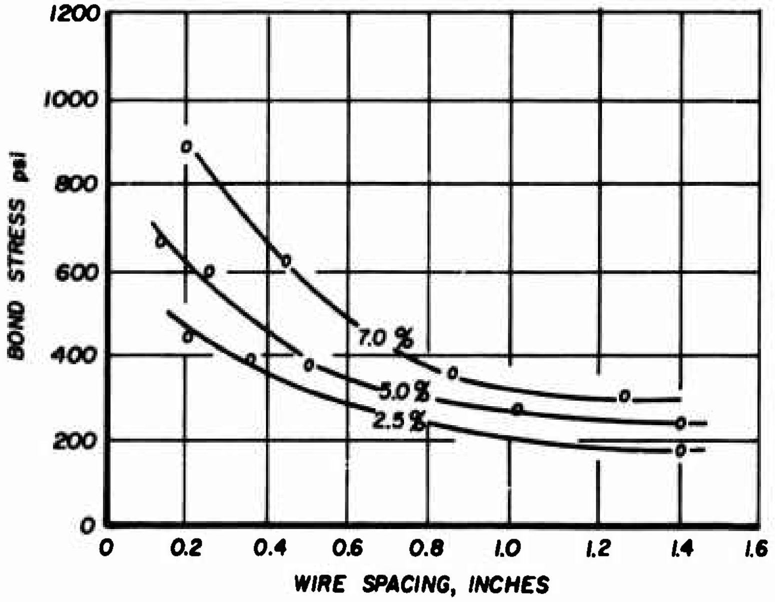

Figure 4. Maximum Bond Stress as a Function of Spacing (G_c = 0.02 in.-lb per sq in.)

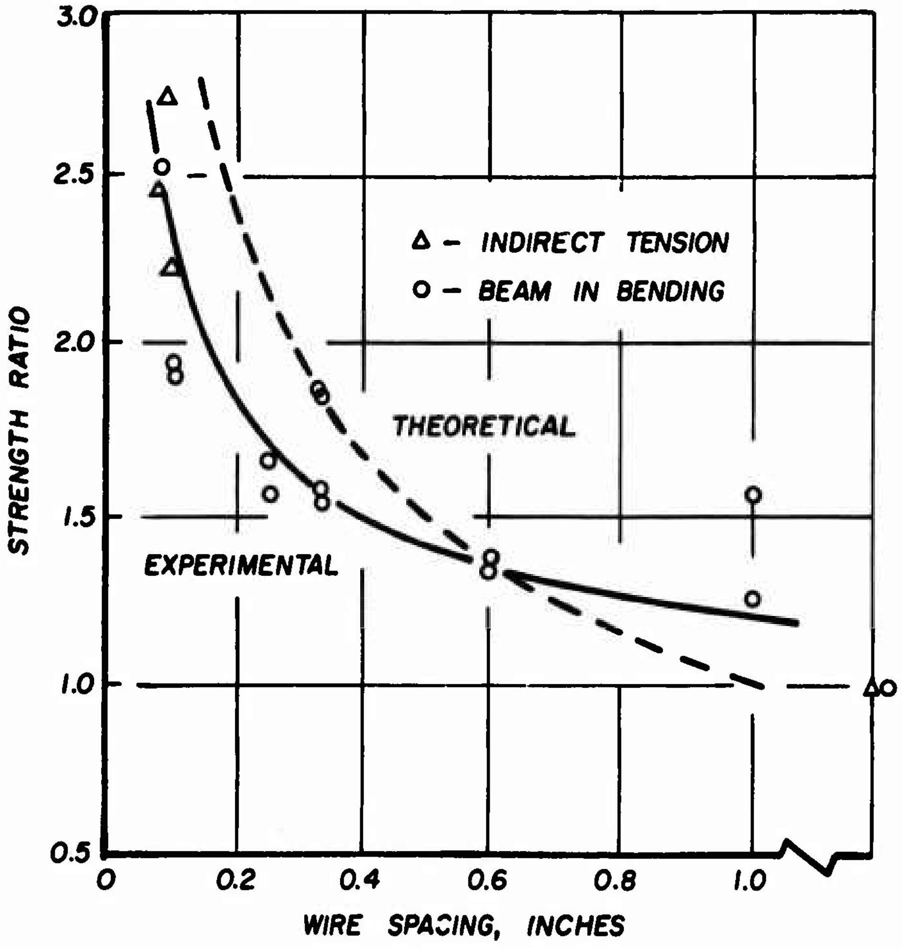

Figure 5. Theoretical and Experimental Strength Ratio as a Function of Wire Spacing

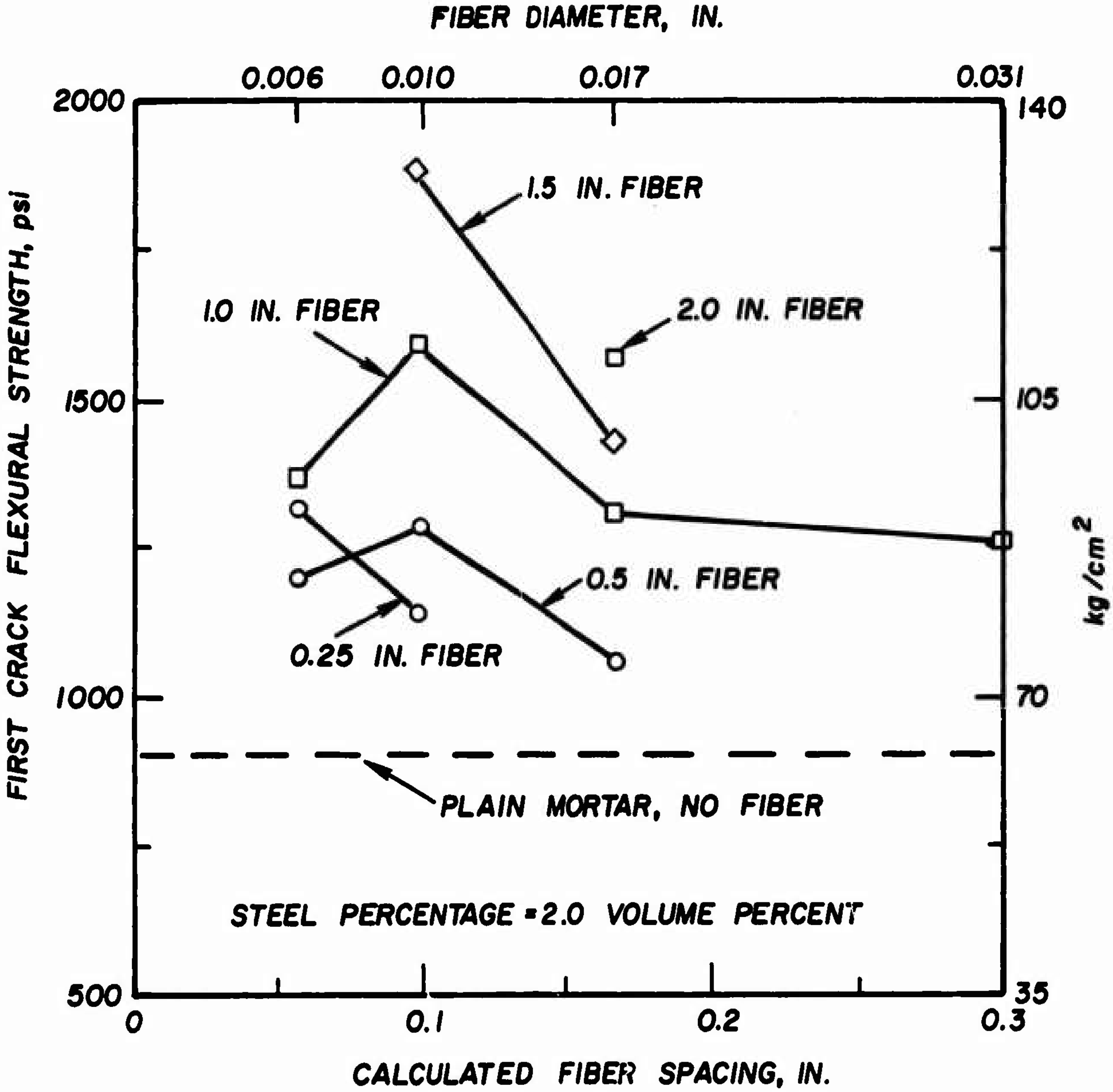

Figure 6. Effect of Spacing on First Crack Flexural Strength of Fiber Containing Mortar

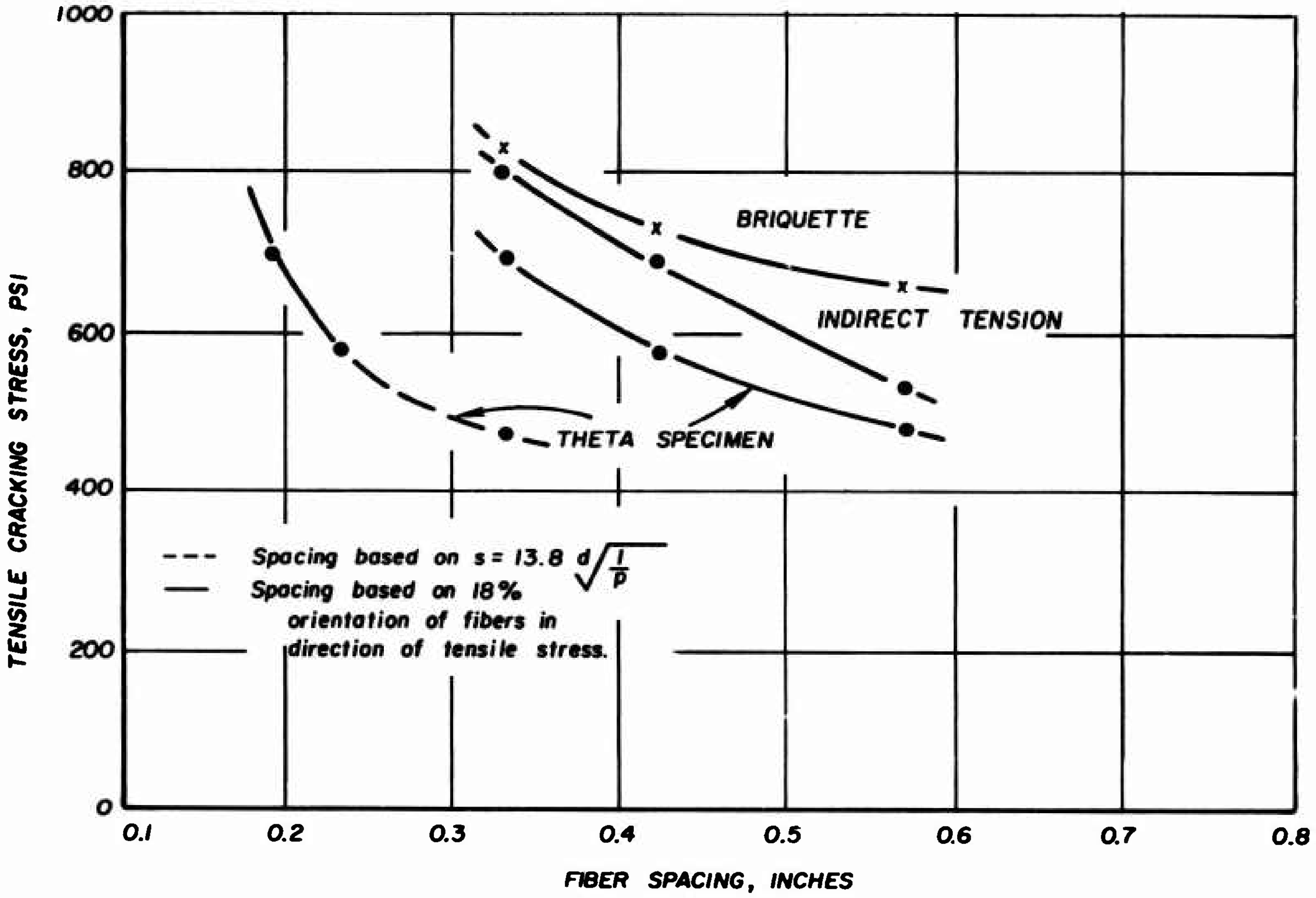

Figure 7. First Crack Tensile Stress Versus Fiber Spacing for 0.5, 1.0, 1.5 Percent by Volume of 17 Mil Round Steel Fiber

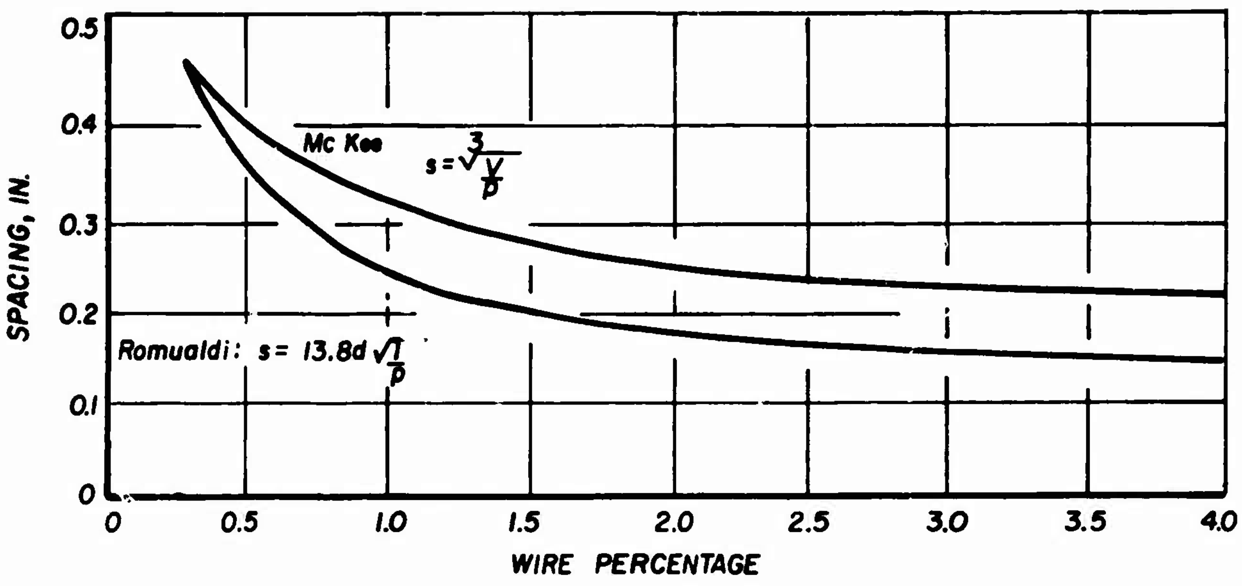

Figure 8. Comparison of Spacing Equations

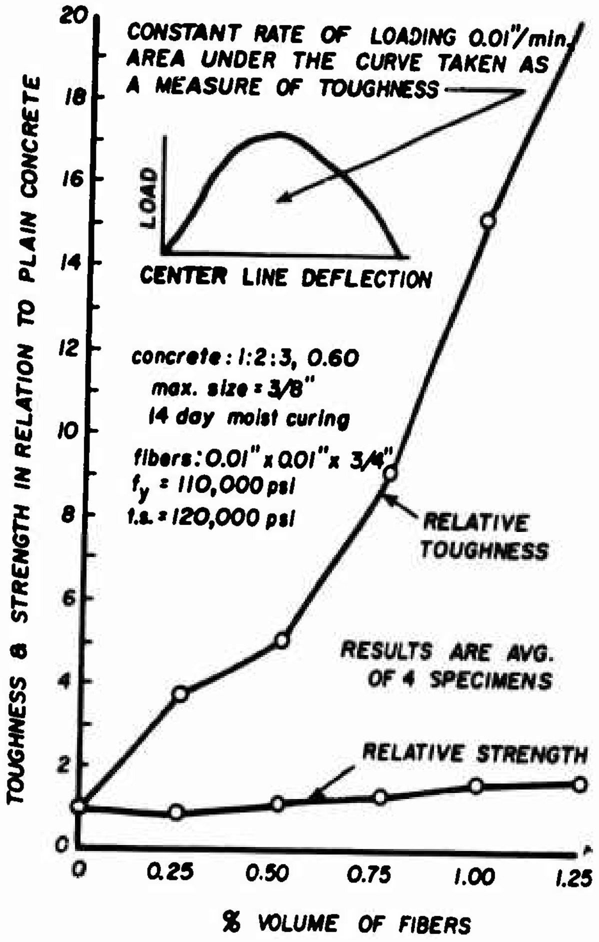

Figure 9. Effect of Volume of Fibers in Flexure

APPENDIX A

FRACTURE OF BRITTLE MATERIALS

The basic knowledge of fracture of brittle materials rests mainly on the works published by A. A. Griffith[39] in 1921 and by W. A. Weibull in 1939.[40]

Griffith postulated an energy release concept which provided the criterion for crack extension in a brittle material. A crack will propagate when the rate of release of stored elastic strain energy per unit increase in crack surface area equals the rate at which surface energy is created. For a crack of length 2a in a thin stressed plate subjected to a remotely applied tensile stress, σ, shown in Figure 1A, the condition for crack initiation for plane stress conditions is

$$\frac{\pi\sigma^2 a}{E} = 2T \tag{1A}$$

where E is the modulus of elasticity, and T is the surface energy per unit area. The left hand side of Equation 1A represents the rate at which elastic energy is released with respect to increases in crack length, a, and is denoted by the symbol G. G is commonly referred to as the crack extension force, suggested by the units of G. The right-hand side of Equation 1A is denoted by G_c, the work rate to extend the crack, the critical value of G. G_c is generally considered a material property, whereas G is primarily a function of the geometry and loading configuration. The general condition for crack extension given by Equation 1A can be expressed as

$$G \geq G_c \tag{2A}$$

where G_c is the energy required to create a unit of new crack area.

Irwin[41] introduced the parameter, K, called the stress intensity factor which relates the elastic stress field at the tip of a crack to the geometry and the loading configuration at onset of fracture propagation. It can be shown that K is proportional to the square root of the energy release rate G.

$$K^2 = \frac{EG}{\pi} \tag{3A}$$

The condition for crack extension in terms of the parameter K is

$$K \geq K_c$$

For brittle material such as glass, ceramics, and mortar, Griffith theory predicts cracks on the dimension of 10^{-4} to 10^{-1} in. will produce fracture. For mortar and concrete, these crack dimensions are the same order of size as the flaws, cracks and voids found to exist naturally. Thus the strength of concrete depends on the largest flaw concept rather than the maximum cohesion.

W. A. Weibull[40] proposed that the strength of brittle materials is based on a statistical distribution of strengths which depended on the distribution of flaw sizes in the volume of material. The average strength is determined by the largest probable flaw for a given volume of material. The distribution of flaws is best described by distributions of extreme value statistics and leads to the familiar relationship between stress and volume of material, called the size effect phenomenon, given by

$$\frac{\sigma_1}{\sigma_2} = \left(\frac{V_2}{V_1}\right)^{1/m} \qquad (4A)$$

where m is an experimentally determined constant and σ_1 and σ_2 are the failure stresses for the corresponding volume V_1 and V_2. The larger the volume the lower the failure stress, because a larger flaw is more likely to occur in the larger volume. Experimentally this is observed in the flexural strength of small mortar beams being greater than for larger beam specimens.[42]

Kaplan[43] was the first to apply the theory of fracture mechanics to concrete. Using notched beams he determined that the energy to create new crack surface area was an order of magnitude greater than that calculated from the surface energy of the material. He attributed the difference to the extensive formation of small branched microcracks that form and coalesce in advance of the moving crack required greater energy than predicted by the total surface energy of the apparent fracture surface area. Hsu, Slate, Sturman, and Winter[45] showed that the shape of the stress-strain curve of concrete is affected by a process of microcracks development and that the cracks begin to increase in size at about 30 percent of the ultimate compressive load. Glucklich[44] has shown the importance of the stored elastic energy in the fracture of concrete in compression where there is a variability in strain-energy release-rate due to the multiphases (paste, mortar, and aggregate) of concrete.

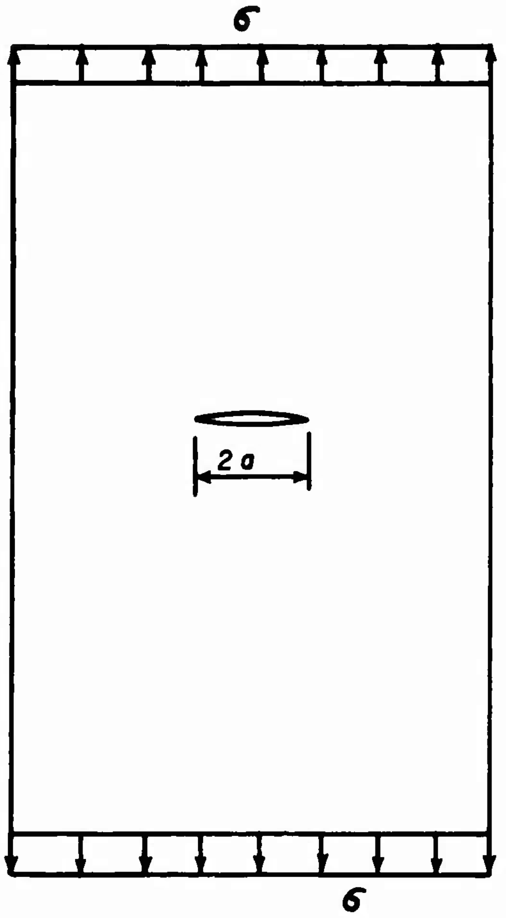

Figure 1A. Thin Stressed Plate with Central Crack

REFERENCES

1. Vasilos, T. and E. G. Wolff, "Strength Properties of Fiber Reinforced Composites," *Journal of Metals* (May 1966), p. 583.

2. United States Patent Office, Patent Number 1,349,901; 1,633,219; 2,677,955.

3. United States Patent Office, Patent Number 3,429,094 and 3,500,728.

4. United States Patent Office, Patent Number 3,650, 785.

5. Romualdi, J. P. and G. B. Batson, "Behavior of Reinforced Concrete Beams with Closely Spaced Reinforcement," *Journal of the ACI,* (June 1963).

6. Romualdi, J. P. and G. B. Batson, "Mechanics of Crack Arrest in Concrete," *Proceedings of the ASCE,* Vol. 89, No. EM3, (June 1963), pp. 147-168.

7. Romualdi, J. P. and J. A. Mandel, "Tensile Strength of Concrete Affected by Uniformly Distributed Closely Spaced Short Length of Wire Reinforcement," *Journal ACI,* Proceedings, Vol. 61 (June 1964), pp. 675-671.

8. Goldfein, S., "Plastic Fibrous Reinforcement for Portland Cement," U.S. Army Engineer Res. & Div. Labs. AERDL TR1757TR (October 1963), p. 16.

9. Williamson, G. R., "Fibrous Reinforcement for Portland Cement Concrete," U.S. Army, Corps of Engineers, Ohio River Div. Latest Tech. Report 2-40 (May 1965).

10. Abbud-Klink, S. A., "FYCRETE, A New Material for Structures," Ph.D. Dissertation, Rensselaer Polytechnic Institute, Troy, N.Y., November 1967.

11. Majumdar, A. J. and J. F. Ryder, "Glass Fiber Reinforcement of Cement Products," *Journal of Glass Technology,* Vol. 9, No. 3, (June 1968), pp. 78-84.

12. Grimer, F. J. and M. A. Ali, "The Strengths of Cements Reinforced with Glass Fibers," *Magazine of Concrete Research,* Vol. 21, No. 66 (March 1969), p. 23.

13. Majumder, A. J., "Glass Fiber Reinforced Cement and Gypsum Products," *Proc. Roy. Soc.,* Lond. A 319 (1970), pp. 69-78.

14. Majumdar, A. J. and J. F. Ryder, "Reinforcement of Cements and Gypsum Plasters by Glass Fibers," *Science of Ceramics*, Vol. 5 (1970), pp. 539-564.

15. Biryukovich, K. L., L. Yu, and D. L. Yu, "Glass Fiber Reinforced Cement," Kiev, Budivel'nik. Translated by G. L. Cairns of the Civil Engineering Research Association, London (1965), 41 pages. CERA Translation No. 12.

16. Snyder, M. J. and D. R. Lankard, "Factors Affecting Cracking Strength of Steel Fibrous Concrete," *Proc., Journal ACI*, Vol. 69, No. 2 (February 1972), pp. 96-100.

17. McKinney, J. L., "Tensile Strength of Steel Fiber Reinforced Concrete," unpublished MS Thesis, Clarkson College of Technology, Potsdam, New York (May 1964).

18. McKee, D. C., "The Properties of an Expansive Cement Mortar Reinforced with Random Wire Fibers," Ph.D. Thesis, University of Illinois, Urbana, Illinois (1969).

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

20. Shah, S. P., "Ferro Cement as a New Engineering Material," Report No. 70-11, College of Engineering, University of Illinois at Chicago Circle.

21. Untrauer, R. E. and R. E. Works, "The Effect of the Addition of Short Lengths of Steel Wire on the Strength and Deformation of Concrete," Paper presented at ACI Fall Convention, Cleveland, Ohio (1965).

22. Blood, G. W., "Properties of Fiber Reinforced Concrete," unpublished MS Thesis, The University of Calgary, Calgary, Alberta (July 1970).

23. Birkimer, D. L. and J. R. Hossley, "Comparison of Static and Synamic Behavior of Plain and Fibrous-Reinforced Concrete Cylinders," Ohio River Division Labs., Corps of Engineers, Cincinnati, Ohio, Technical Report No. 4-69 (December 1968).

24. Krenchel, H., "Fiber Reinforcement," *Akademush Forlag*, Copenhagen, Denmark (1964), p. 159. (English translation of the original Danish book)

25. *Engineering News-Record* (January 30, 1969), p. 19.

26. Agbin, C. C., "Concrete Reinforced with Glass Fibers," *Magazine of Concrete Research*, Vol. 16, No. 49 (December 1964).

27. Goldfein, S., "Fibrous Reinforcement for Portland Cement," *Modern Plastics*, Vol. 42, No. 8 (April 1965).

28. Williamson, G. R., "Response of Fibrous-Reinforced Concrete to Explosive Loading," U.S. Army, Corps of Engineers, Ohio River Div. Labs. Tech. Report 2-48 (January 1966), p. 83.

29. Bailey, L. E., "Fatigue Strength of Steel Fiber Reinforced Concrete," unpublished MS Thesis, Clarkson College of Technology, Potsdam, N.Y. (October 1966).

30. Landers, E. A., "Fatigue Strength of Concrete Beams Reinforced with Steel Fibers," unpublished MS Thesis, Clarkson College of Technology, Potsdam, N.Y. (November 1967).

31. Ball, C. G., "The Fatigue Behavior of Steel Fiber Reinforced Concrete," unpublished MS Thesis, Clarkson College of Technology, Potsdam, N.Y. (October 1967).

32. Hooks, J., "Fatigue Strength Steel Wire Reinforced Concrete," unpublished MS Thesis, Clarkson College of Technology, Potsdam, N.Y. (February 1963).

33. Romualdi, J. P., "The Static Cracking Stress and Fatigue Strength of Concrete Reinforced with Short Pieces of Steel Wire," International Conference on the Structure of Concrete, London, England (1965).

34. Shroff, J. K., "The Effect of a Corrosive Environment on the Properties of Steel Fiber Reinforced Portland Cement Mortar," unpublished MS Thesis, Clarkson College of Technology, Potsdam, N.Y. (September 1966).

35. Morel, K. C., "The Thermal Conductivity of Steel Fiber Reinforced Portland Cement Mortar," unpublished MS Thesis, Clarkson College of Technology, Potsdam, New York (September 1961).

36. Lankard, D., Unpublished Data, Battelle Memorial Institute, Columbus, Ohio.

37. Schwarz, A., Unpublished Data, United States Steel Corporation, Pittsburgh, Pennsylvania.

38. Mikkelmeni, M. R., "A Comparative Study of Fiber Reinforced Concrete and Plain Concrete Construction," MS Thesis, Mississippi State University, State College, Mississippi (1970).

39. Griffith, A. A., "The Phenomena of Rupture and Flow in Solids," *Philosophical Transactions of the Royal Society*, A221 (1921), pp. 163-198.

40. Weibull, W., "A Statistical Theory of the Strength of Materials," Stockholm, Ingeriorsvetenskapakadienis, No. 151 (1939).

41. Irwin, G. R., "Analysis of Stresses and Strains Near the End of a Crack Traversing a Plate," *Journal of Applied Mechanics*, No. 24 (1957), pp. 361-364.

42. Glucklich, J. and L. J. Cohen, "Sizes as a Factor in the Brittle-Ductile Transition and The Strength of Some Materials," Technion, Israel Institute of Technology, TDM 67-10 (May 1967).

43. Kaplan, M. F., "Strains and Stresses of Concrete at Initiation of Cracking and Near Failure," *Proceedings, Journal of the ACI*, Vol. 60, No. 7 (July 1963), pp. 853-877.

44. Glucklich, J., "On the Compression Failure of Plain Concrete," Urbana, University of Illinois, T. & A.M. Report No. 215 (March 1962).

45. Hsu, T. T. C., F. O. Slate, G. M. Sturman, and G. Winter, "Microcracking in Plain Concrete and the Shape of the Stress-Strain Curve," *Journal of the ACI*, Vol. 19 (February 1962).

46. Shah, S. P. and B. V. Rangan, "Effects of Reinforcements on Ductility of Concrete," *Journal of the Structural Division*, ASCE Proceedings, Vol. 96, No. ST6 (June 1970), pp. 1167-1184).

47. Shah, S. P., "Micromechanics of Concrete and Fiber Reinforced Concrete," *Proceedings*, International Conference on Civil Engineering Materials, Southampton (1969).

MIX DESIGN CONSIDERATIONS

by

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"Fibrous Concrete--Construction Material for the Seventies"
Champaign, Illinois
May 1972

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ABSTRACT

Fibrous concrete requires a considerably greater amount of fine material in the mix than does plain concrete for it to be conveniently handled and placed by current procedures and equipment. It has been common practice to use up to 850 lbs of cement per cubic yard in fiber reinforced concrete to achieve the required workability. Tests have shown that the cement content can be reduced significantly and quality maintained if fly ash is substituted for a portion of the cement, a water reducer is used, the concrete is air entrained and the fineness modulus of the aggregate is increased. Such a mix may have a slightly lower total paste content, but can be easier to place.

The more sophisticated mix is suitable for nearly all uses of steel fiber reinforced concrete, but is particularly advantageous for use in slabs-on-grade, such as sidewalks and pavements, because of the significant gains in strength which occur in such slabs due to the pozzolanic nature of the fly ash.

MIX DESIGN CONSIDERATIONS

by

Professor Clyde E. Kesler

INTRODUCTION

Fibrous concrete requires a considerably greater amount of fine material in the mix than does plain concrete for it to be conveniently handled and placed by current procedures and equipment. It has been common practice to use up to 850 lbs of cement per cubic yard in fiber reinforced concrete to achieve the required workability. Tests have shown that the cement content can be reduced significantly, and quality maintained if

1. Fly ash is substituted for a portion of the cement,
2. A water reducer is used,
3. The concrete is air entrained, and
4. The fineness modulus of the aggregate is increased.

Such a mix may have a slightly lower total paste content, but can be easier to place by conventional methods.

The more sophisticated mix is suitable for nearly all uses of steel fiber reinforced concrete, but is particularly advantageous for use in slabs-on-grade, such as sidewalks and pavements, because of the significant gains in strength which occur in such slabs due to the pozzolanic nature of the fly ash. It is a mix that can be hand placed as well as being placed with currently available equipment. It is a mix for today. As handling and placing equipment is improved, fiber reinforced mixes can be improved just as plain concrete mixes have in past years.

The work I am reporting on was supported by the United States Steel Corporation and the Chicago Fly Ash Company. Any patentable ideas have been assigned to United States Steel. My comments are based on a minimum number of tests. Many more are needed. All the mixes I will discuss have 1-1/2 percent by volume of 1 in. fibers unless I indicate otherwise.

TYPICAL MIXES WITH AND WITHOUT FLY ASH

Table 1 shows typical quantities of materials for an all cement mix and a cement and fly ash mix. The first mix contains 800 lbs of cement and requires 430 lbs of water for a 4-in. slump. The second mix contains only 500 lbs of cement per cu yd but also 234 lbs of fly ash. It requires only 290 lbs of water for a 4-in. slump. The all cement mix requires 48 percent more water for a 4-in. slump than the cement and fly ash mix. The strengths are comparable but the mix containing fly ash is easier to handle.

Table 1. Typical Mixes for Fiber Reinforced Concrete

Water-Cement Ratio	Mix Materials, lbs/cu yd				
	Water	Cement	Fly Ash	Sand	Pea Gravel
0.54	430	800	---	2780	---
0.58	290	500	234	1310	1410

RELATIVE PASTE CONTENTS

Table 2 shows the paste content of the two mixes for which we have just seen the proportions. I have assumed that the paste consists of the cement, any fly ash, the water and the entrapped or entrained air. If we assume that the air in the all cement mix is not purposely entrained but entrapped, we see that we have approximately a total paste content of 11.50 cu ft. In the case of fly ash we have always used an air entraining agent, and have approximately 1.6 cu ft of entrained air for a total paste content of 10.27 cu ft which is somewhat less than the total paste content of the all sand mix. There is merit in keeping the paste content low in a mix if the other desired properties can be obtained such as durability and strength In this case the strengths are comparable and air entrainment provides the necessary durability, however, the smaller paste contents result in smaller shrinkages, thus in less shrinkage cracking.

MIXES WITH AND WITHOUT FLY ASH USING SLAG AGGREGATE

Table 3 shows proportions used in making a series of mixes of

Table 2. Typical Paste Contents

Components	Cement and Sand Mix	Cement, Fly Ash, Sand and Gravel Mix
Cement, cu ft	4.07	2.54
Fly ash, cu ft	--	1.47
Water, cu ft	6.89	4.64
Air, cu ft	0.54[1]	1.62[2]
TOTAL, cu ft	11.50	10.27

[1] Entrapped air

[2] Entrained air

fiber reinforced concrete using in one case only cement and in another case both cement, but a lesser amount, and fly ash. The mixes labeled A in this table contained 654 lbs of cement and no fly ash but required 280 lbs of water to obtain a 2-in. slump. The B mixes contained less cement, 500 lbs, but in addition, 234 lbs of fly ash and required significantly less water for the 2-in. slump. Note that the volume of fibers varied from a 1/2 percent to 1-1/2 percent for each set of mixes. Both mixes were air entrained; the B mixes had a water reducer added.

Table 3. Mixes With and Without Fly Ash Made With Slag Coarse Aggregate

Mix	Water-Cement Ratio	Mix Materials, lbs/cu yd					Steel Fibers, %	Water Reducer fl oz	Entrained Air %
		Water	Cement	Fly Ash	Sand	Slag			
A	0.43	280	654	---	1300	1644	0.50	---	6.0
A	0.43	280	654	---	1300	1634	0.75	---	5.4
A	0.43	280	654	---	1300	1622	1.00	---	5.6
A	0.43	280	654	---	1300	1634	1.50	---	5.0
B	0.44	220	500	234	1312	1370	0.50	20	5.6
B	0.44	220	500	234	1300	1370	0.75	20	5.6
B	0.50	250	500	234	1290	1370	1.00	20	5.8
B	0.50	250	500	234	1268	1370	1.50	20	5.2

Table 4 shows both the compression and tensile strength for the A and B mixes for the four different percents of fibers. As you can see in each case the mix with the fly ash, although it contained less cement, is the strongest. I should point out to you that these specimens were cured simply by removing them from the mold at an age of one day, wrapping them in polyethylene and storing for 13 days until they were tested at an age of 14 days.

Table 4. Strength of Mixes With and Without Fly Ash Made With Slag Coarse Aggregate

Mix	Compression, psi	Tension, psi
1/2 percent fibers		
A	4300	790
B	5750	910
3/4 percent fibers		
A	4090	830
B	6330	940
1 percent fibers		
A	4330	870
B	6180	960
1-1/2 percent fiber		
A	4450	940
B	6180	1020

EFFECT OF VARIOUS COMBINATIONS OF CEMENT AND FLY ASH ON WATER CONTENT AND COMPRESSIVE STRENGTH

I'll now explain why we chose a mix containing 500 lbs of cement and 234 lbs of fly ash as the more or less standard mix.

The work leading to this conclusion is summarized in Figure 1. This figure is a bit complicated but I will try to explain it so that it can be understood. The straight line at the bottom indicates the relative amounts of cement and fly ash. For instance, if we assume that we are using a mix with 500 lbs of cement we would use about 235 lbs of fly ash to give us a total fines which would result in an easily worked mix, even by hand if found necessary. The middle pair of curves shows the water content for various proportions of cement fly ash. The top two curves show the compressive strengths for the various combinations.

It is easily noted that as the proportion of cement to fly ash is increased there is a significant increase in water content. However, of considerable significance is the fact that until one gets to less than 500 lbs of cement and more than 234 lbs of fly ash in the mix the strengths are comparable. If less than this amount of cement is used there is some drop off in the strength. We noted on a number of tests that the mixes containing 500 lbs of cement and 234 lbs of fly ash seem to be stronger than the mixes containing more cement.

Figure 2 shows how the flexural strength varies with different amounts of cement and fly ash. Again you can see that for cement contents from 500 lbs/cu yd and higher the strengths are fairly comparable, particularly at 28 days and again the mix containing 500 lbs/cu yd of cement, 234 lbs/cu yd of fly ash appears quite strong.

Figure 3 shows the same type of information in slightly different form. In this case it shows the volume of fly ash as a percentage of the total volume of fly ash and cement. Again the mix that represents the 500 lbs of cement, 234 lbs of fly ash appears quite adequate when reinforced with 1-1/2 percent of fibers.

EFFECT OF FINENESS MODULUS

The information I have been showing you has been based on mixes which contain some coarse aggregate of about 3/8 in. maximum size. Figure 5 shows how fineness modulus affects flexural strength for both cement only and cement and fly ash mixes. The mixes are comparable in that the total amount of cementitious material, cement only or cement plus fly ash are equal in volume. The points to the left are for an all sand mix, those to the right contain a coarse aggregate with a maximum size of 3/4 in. The points in between contain pea gravel or crushed stone. There is very little data here and I won't draw any conclusions but I thought it was worthwile showing.

Figure 6 shows the relationship between the fineness modulus and the water content required for a 4-in. slump for mixes made with cement only or cement and fly ash. Again the points on the left represent an all sand mix and those on the right represent a mix containing coarse aggregate with 3/4-in. maximum size and the points in between represent, in one case, a mix with pea gravel and in the other case a mix with 3/8 in. crushed stone. One can clearly see that as the fineness modulus is increased the water content for a given slump drops rapidly. It is also quite clear that there is a significant additional amount of water required for a cement only mix.

CONCLUDING COMMENTS

In concluding I might just say that practical economical mixes with improved workability and without any loss in strength can be made if a significant amount of fly ash is substituted for a portion of the cement.

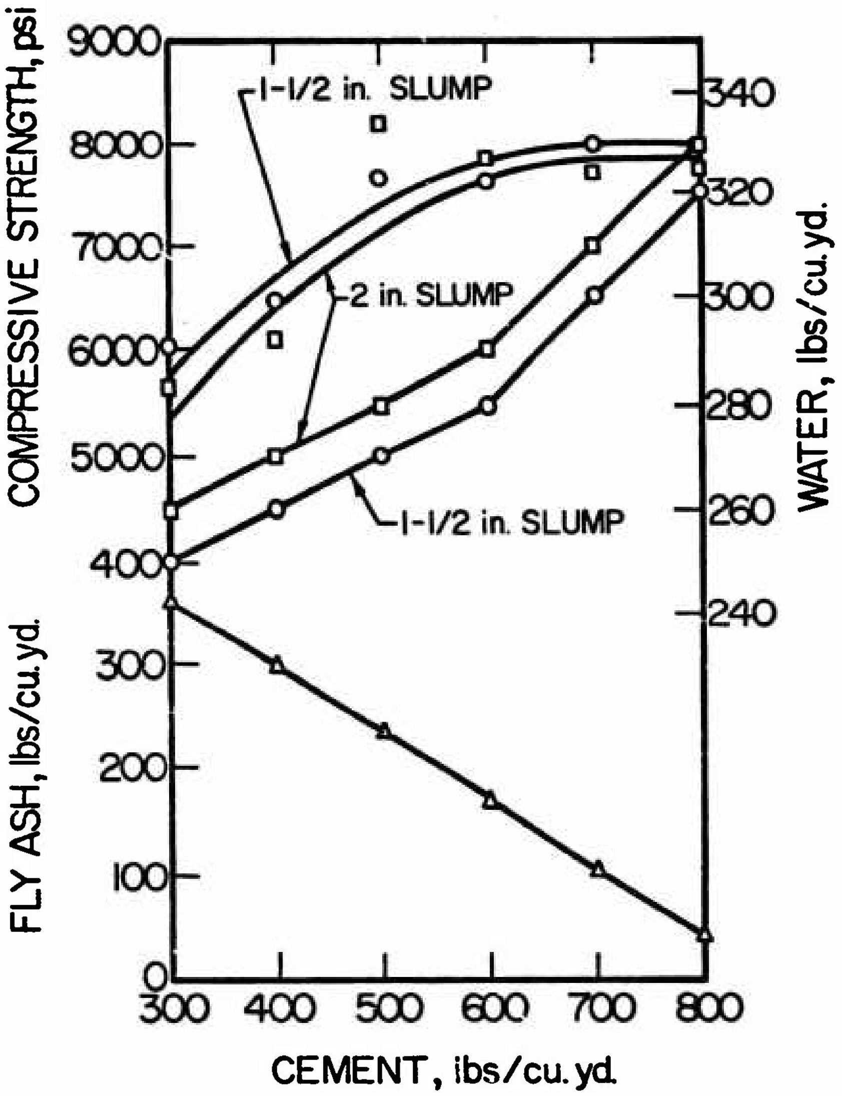

Figure 1. Effect of Different Combinations of Cement and Fly Ash on Water Content and Compressive Strength - 1-1/2 and 2 Inch Slump

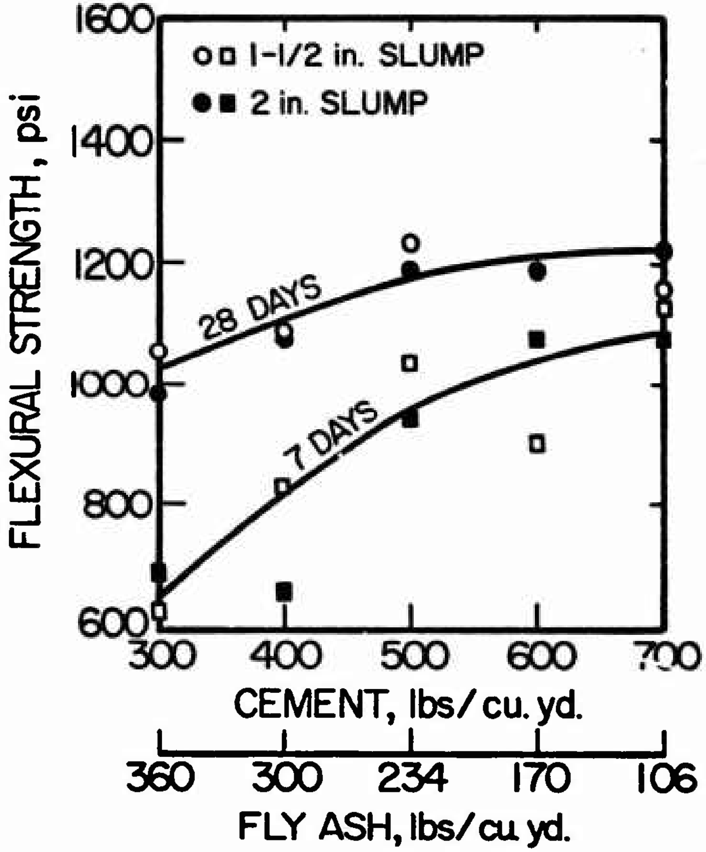

Figure 2. Effect of Different Combinations of Cement and Fly Ash on Flexural Strength - 1-1/2 and 2 Inch Slump

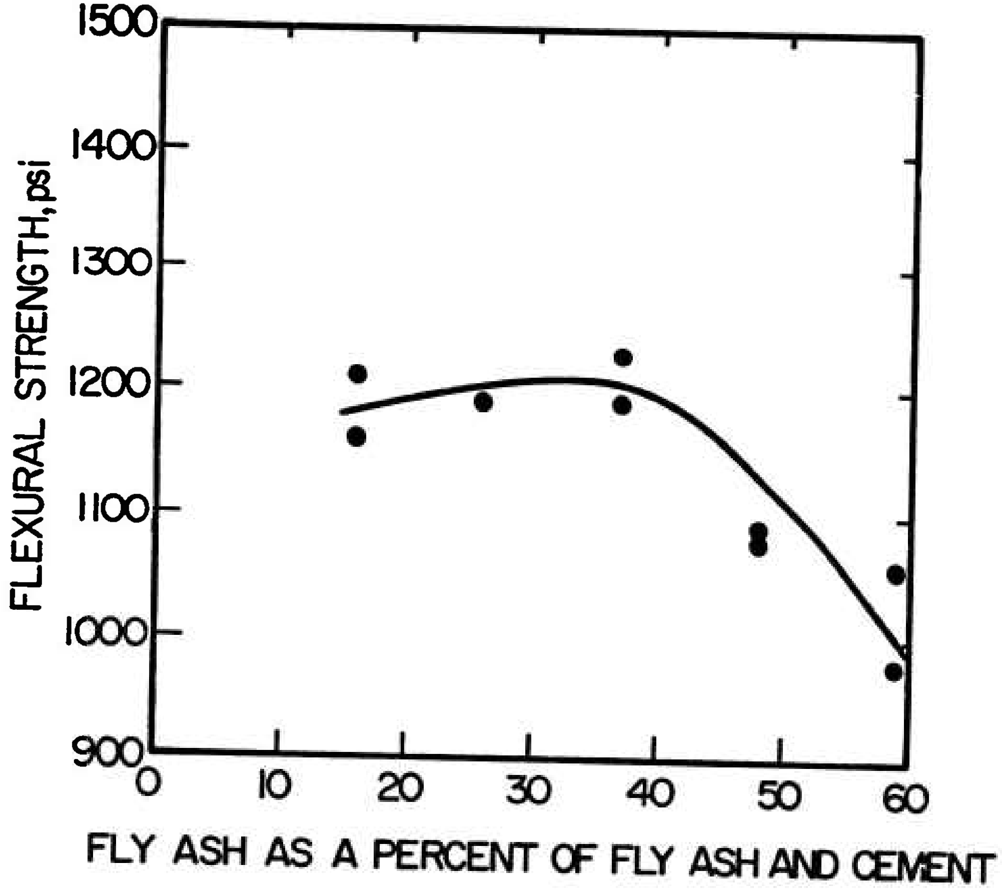

Figure 3. Effect of Different Amounts of Fly Ash on Flexural Strength - 1-1/2 and 2 Inch Slump

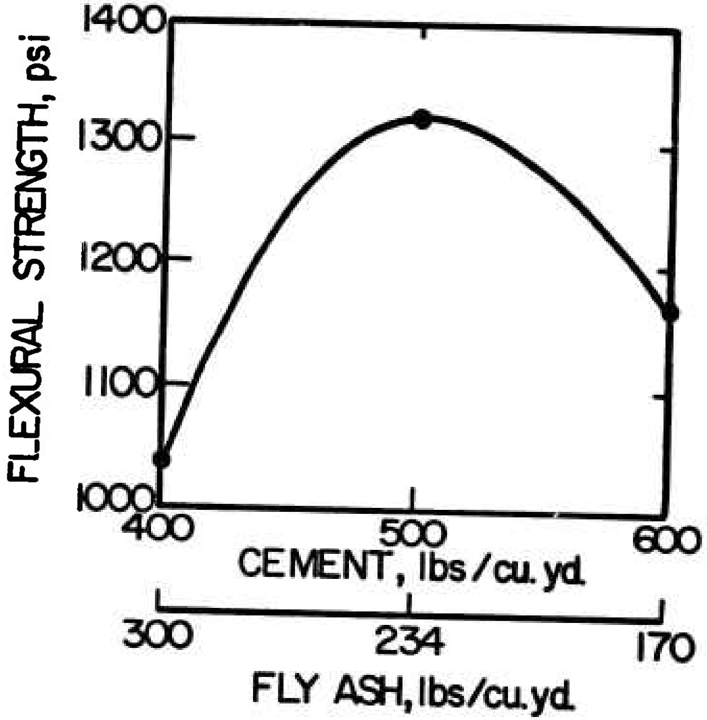

Figure 4. Effect of Different Combinations of Fly Ash and Cement on Flexural Strength - 4 Inch Slump

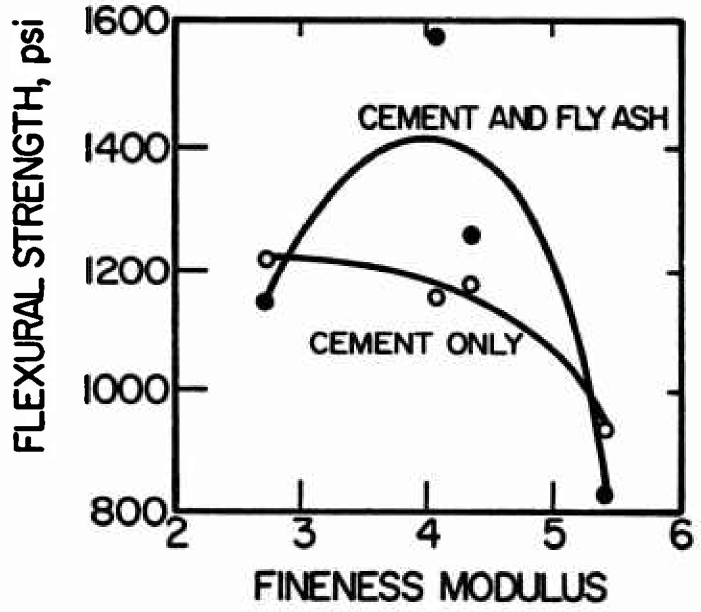

Figure 5. Effect of Fineness Modulus on Flexural Strength - 4 Inch Slump

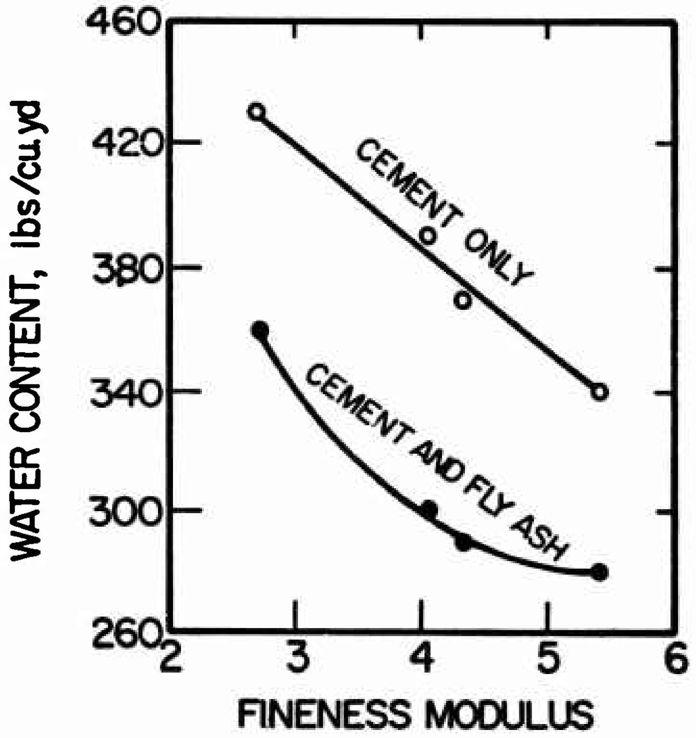

Figure 6. Effect of Fineness Modulus on the Water Content Required for a 4 Inch Slump

A DISCUSSION OF FIELD CONSIDERATIONS

by

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ABSTRACT

This paper presents field considerations which are associated with the use of a concrete containing randomly oriented uniformly distributed short lengths of fibers (fibrous concrete). Mix formulation and field handling characteristics often determine whether a new material is suitable for an application. Any alterations in the standard procedures will be reflected in different uses of the material. The results of field experience with the use of fibrous concrete are presented.

A DISCUSSION OF FIELD CONSIDERATIONS

by

Bobby H. Gray

INTRODUCTION

Definition of Fibrous Concrete

Fibrous concrete is a composite material consisting of a concrete matrix containing a random dispersion of small fibers. The fibers act as arrestors which restrict the growth of flaws in the concrete matrix from enlarging under stress into cracks which cause failure. Conventional reinforcing steel which is intended to act as a substitute for the tensile strength of concrete, does not generally become effective until after the concrete has cracked. On the other hand, once fibrous concrete cracks, the fibers retain the characteristics of reinforcing steel in that the tensile stress is transferred to the fibers.

The general properties and the advantages of fibrous concrete are shown in Tables 1 and 2.

Table 1. Fibrous Concrete Advantages

Property	Advantages over Plain Concrete (time higher)
First Crack Flexural Strength	1-1/2
Ultimate Modulus of Rupture Strength	2
Ultimate Compressive Strength	1-1/4
Ultimate Shear Strength	1-3/4
Flexural Fatigue Endurance Limit	2-1/4
Impact Resistance	3-1/4
Sand Blast Abrasion Resistance Index	2
Heat Spalling Resistance Index	3
Freeze-Thaw Durability Index	2

Table 2. General Advantages

Much greater resistance to cracking
Far superior resistance to thermal shock
Significantly thinner sections for a given design
Elimination or reduction of other types of reinforcing materials
Increase production rate with thinner sections
Less maintenance and longer life

Definition of Fiber

Fibers have been produced from steel, plastic, glass, asbestos and cotton materials in various shapes and sizes.

A convenient numerical parameter describing a fiber is its aspects ratio, defined as the fiber length divided by an equivalent fiber diameter. Typical aspect ratios range from about 30 to 120 (and from 10 to 600 experimentally) for length dimensions of 0.5 to 1.5 in. (and from .25 to 3 in. experimentally).

Round steel fibers are produced by cutting or chopping wire, typically having diameters between 10 and 20 mils (and from 4 to 40 mils experimentally). Flat steel fibers having typical cross sections ranging from 8 to 16 mils in thickness by 10 to 25 mils in width (and from 5 to 25 mils in thickness and 8 to 150 mils in width experimentally) are produced by shearing sheets or flattening wire. Crimped and deformed steel fibers have also been produced.

Glass fibers (chopped strand) have diameters of 0.2 to 0.6 mils but these fibers may be bonded together to produce glass fiber elements with diameters of 0.5 to 50 mils.

Plastics such as nylon, polypropylene, polyethylene, polyester, and rayon have been made into fibers with diameters of 0.8 to 15 mils.

Fibers processed from asbestos and cotton provide a wide range of sizes.

BATCHING CONSIDERATIONS

Fiber Handling

At present, fibers are shipped in cardboard boxes containing quantities of 40 to 100 lbs. The 40-lb box of 1 cu ft is more typical and for manual batching it has been optimum based on the workman capacity to handle it (Figure 1). Future projections for large scale applications which require large amounts of fiber suggest that bulk shipments will be handled by rail or trucks equipped with special bodies for weather protection and discharging. This may require that the fibers be handled similar to bulk cement. Dependable and efficient methods for handling fiber out of storage into the batching or mixing system have been slow in development. Fibers can nest together by fiber interlocking to form bridges over discharge openings. The typical batch plant storage and weighing hoppers and discharge systems are unable to efficiently handle fiber materials. It is not uncommon to poke and prod the bridged fibers with various devices from simple wooden and metal rods to elaborate mechanical and pneumatic vibrations. These methods are tedious, hazardous, and very ineffective. Their limitation, of course, is controlled by the quantities of fibers required in the application.

Tests have been conducted with a bin and hopper activator system which utilizes a vibrating internal baffle unit and bin bottom designed for positive and continuous movement of fibers from storage bin. This unit with refinements should provide an accurate, dependable, and efficient method of handling bulk fiber out of large volume storage bins and hoppers. Units of this type should allow the use of higher aspect ratios which would provide greater benefits for fibrous concretes.

It should be noted that in applications where manual fiber batching methods are used, workmen should be equipped for safety purposes with protective gloves and goggles. For aiding in fiber handling, the workmen should be equipped with three-pronged garden forks for handling the tightly nested fibers and long wooden or metal rods for unjamming collecting hopper and discharging gates.

Fiber Mixing

The mixing of fibrous concrete can be accomplished by more than one method. The choice of method will depend on the job requirements and the facilities available; i.e., central mix plant, ready-mix transit trucks, or hand mixing small quantities in the laboratory. Above all, it is necessary to have a uniform dispersion of the fibers during mixing.

Experience with steel fibers has shown that segregation or balling during mixing is related to three major factors: the aspect ratio of the fiber, the volume percentage of the fibers, and the mixing procedure. This suggests that aspect ratios of less than 60 are best from the viewpoint of fiber handling, plant batching and transit mixing; but it is desirable from a strength viewpoint to use an aspect approaching 100. Aspect ratios above 100 are almost impossible to mix in quantities using present day field batching techniques. Also fiber addition in excess of about 4 percent by volume is difficult to mix in quantities.

It is important that the fibers be dispersed uniformly throughout the mix. For small laboratory mixes, shaking the fibers through a central plant and ready-mix transit trucks, mixing methods in order of preference are:

Method 1--Blend fiber and aggregates prior to charging the mixer, as might be done on a conveyor belt or aggregate chute. Use standard mixing procedure throughout (Figure 2). By blending the fiber with the aggregates before they enter the mixer, the aggregates can act as a fiber separator which prevents the fibers from nesting together to form fiber balls.

Method 2--Blend fine and coarse aggregates in mixer. Then add fibers at the suggested mixing speed of the mixer (Figure 3). Finally add cement, additives, and water simultaneously. This method is usually used when it is not possible to add the fiber in the batch plant system. The ready-mix transit truck is removed from the batch plant after the aggregates are charged and returns to the plant for the cement, water, and additives after the fiber is added.

Method 3--Add fiber to a hopper that contains aggregate (Figure 4). Use standard mixing procedures throughout. Typically, in this method, there is access to the weighing hopper and after aggregate weighing, the fibers are dumped on top of the aggregate. Then the standard plant batching procedures are used.

Method 4--Add fiber to the ready-mix truck which contains a completed mix of plain concrete (Figure 5). In this method, the batch size should be less than 40 percent of the rated capacity of the mixer and lower aspect ratios and fiber percentages should be used.

During the early stages of fibrous concrete development, batching methods were dictated by the problems of convincing batch plant owners and operators to allow the fibers to be introduced into the batch plant system and at times the ready-mix truck. Their concerns were that the normal production concrete would be contaminated with fibers. Also, most placements were of small size, one shot deals, and the future of the material was unsure.

Water Control

If uniform batches of fibrous concrete of proper proportions and consistency are to be secured, it is essential that all ingredients be carefully controlled and accurately measured for each batch. A troublesome factor is the effect of the varying amounts of moisture nearly always present in the aggregates. The amount of free moisture introduced into the mixer with the aggregates can be determined and allowance made for it. A recently encountered example of this troublesome factor was the failure of a recycling ready-mix transit truck to discharge all of the wash water used for cleaning the mixing drum after delivery of the concrete. Three trucks which had been parked overnight and inspected for this were batched with the same mix design. For each batch, allowances were made for moisture measure in the aggregates. The consistency was exactly the same for each with a measure slump of 3-1/4 in. When the first truck recycled, the truck was not inspected for wash water, but the allowance for aggregate moisture was determined and made. The slump was 5-1/4 in.; after that, each truck's drum was inspected and the excess water removed and the measure slump for the next three batches was 4 in., which was in the limits set for this placement.

Mixing Times

All fibrous concrete should be mixed thoroughly until it is uniform in appearance with all ingredients uniformly distributed. The time required for thorough mixing should be the same as for conventional concretes. Excess mixing has a tendency to develop fiber balls in certain types of mixers (Figure 6). If the balls were formed during mixing, they will tend to be made up of fiber and mortar and will be very strong, but will reduce the amount of fiber available for random distribution. If these balls were formed during batching, they will tend to be made up of only fiber and voids with an outer coating of mortar, and as above, they will reduce the amount of fiber available for random distribution.

Usually, specification requires that conventional concrete must be delivered and discharged from the truck mixer or agitator truck within 1-1/2 hrs after introduction of the water to the cement. But with the high cement factors usually used in fibrous concretes, the required time should be shorter because of the quicker setting characteristics of high cement contents.

Mixer Capacity

Mixers should not be loaded above their rated capacity and should be operated at approximately the speeds for which they are designed. In most large scale fibrous concrete applications using ready-mix trucks, the batch size has been reduced to less than 75 percent of the truck's rated capacity. This reduction tends to inhibit the formation of fiber balls during mixing.

The mixing characteristics of the newer high capacity ready-mix transit trucks are less effective in producing uniform mixes when utilizing certain batching methods. The truck's mixing units have a low axis of rotation which is ineffective when the batching sequences suggested in Methods 2 and 4 in the section on fiber mixing are utilized.

PLACEMENT CONSIDERATIONS

General

Each step in handling, transporting, and placing the fibrous concrete should be carefully controlled to maintain uniformity within an application. The current methods of handling and transporting, and the types of equipment used have placed restrictions on the use of fibrous concrete. Some of these restrictions have been overcome by using larger chutes, steeper slope, larger discharge gate openings, and additional manpower at the batching site.

Consistency

Despite considerable evidence against the practice, many specifications still rely on the slump test as an indication of workability. The slump test is a measure of consistency and it should not be used to compare mixes of wholly different proportions or of conventional concrete with fibrous concretes. Characteristically, fiber additions tend to decrease the slump of plain concrete mixes (Figure 7).

The standard method of slump test for workability may be misleading in fibrous concrete. The test procedure requires the concrete sample to be placed in three layers, each of which is rodded to consolidate the concrete. This rodding action may give the fibers a vertical orientation. This orientation may tend to produce higher slumps if, used as an indication of workability, it refers to the ease or difficulty in placing concrete in a particular location. Under conditions of uniform operation, changes in consistency as indicated by the slump are useful in indicating changes in the character of the material, the proportions or the water content.

An example of consistency and workability considerations was experienced with the placement of a conventional and fibrous concrete sidewalk using a slipform sidewalk paving unit. For satisfactory placement, conventional concrete required a slump of 1-1/2 in. to produce the desired product and production rate. Fibrous concrete requires a slump of 4-1/2 in. to produce the same workability results.

Vibration

As with conventional concrete, the fibrous concrete should be placed as nearly as practicable in its final position. It should not be placed in large quantities at a given point and allowed to be worked over a long distance. This practice results in fiber and aggregate segregation. A fibrous concrete mix generally requires somewhat more vibration to move and consolidate it into forms. Properly controlled internal vibration is acceptable, but external vibration of the forms and exposed surfaces are preferable for concrete consolidation. Garden type forks, hoes, and rakes are preferred for manual handling of fibrous concrete.

Surface Finishing

Fibrous concrete placements have been screeded to consolidate and strike off the excess concrete by manual and mechanical methods. Screeding methods include using a wooden board, a portable vibrator mounted on wooden boards, or mechanical methods using full scale conventional concrete units such as a roadway or sidewalk paver (Figures 8 - 11). These methods have produced satisfactory results within, generally, one or two passes of the unit.

Soon after screeding and while the concrete is still plastic, the fibrous concrete surface can be floated by means of conventional tools and techniques (Figure 12).

A scored surface can be produced by brooming the concrete with a stiff hair brush, but scoring by wet burlap drag is not desirable, since fiber can hang in the burlap and the dragging action of the hanging fiber tends to scar the concrete surface. Experience suggests that scoring by brooming should be delayed as long as possible to prevent the possibility of pulling fibers to the surface.

A future projection for obtaining surface texture on fibrous concretes is using a roller unit with a machined surface to produce the desired texture. By rolling the texture, the fibers near the surface would be pushed down rather than exposed or pulled up, as by other scoring methods.

Curing

Standard methods and techniques for curing and protecting should be used for fibrous concrete products, structures, and pavement. Concrete can be kept moist by a number of methods, such as by leaving forms in place, sprinkling and ponding, use of moisture-retention covers, or by a seal coat of curing compound.

CONCLUDING REMARKS

Interest in the area of fibrous concrete has been developing at a very rapid pace during the last year. Each new placement is more refined and the willingness shown by the construction industry will surely advance the state of the art of field considerations to the required refinements.

Figure 1. Steel Fibers as Received from Manufacturer

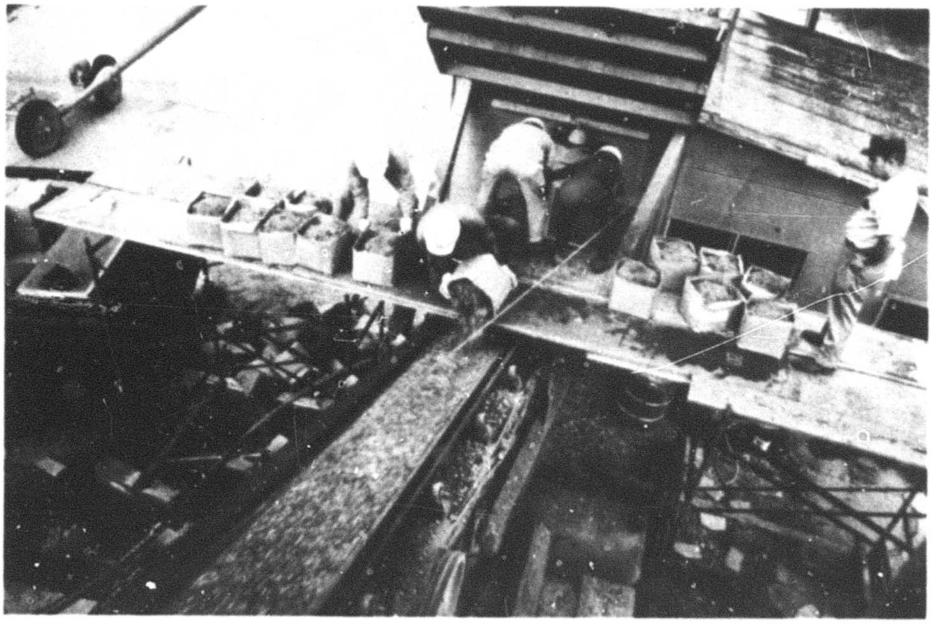

Figure 2. Method 1 Used to Introduce Steel Fibers in the Concrete Batching Operation

Figure 3. Method 2 Used to Introduce Steel Fibers in the Concrete Batching Operation

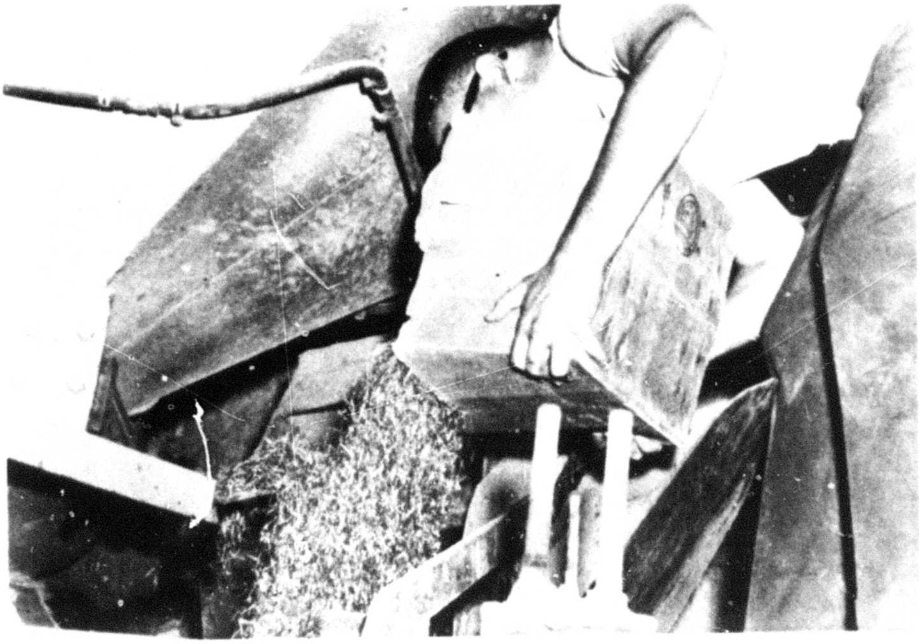

Figure 4. Method 3 Used to Introduce Steel Fibers in the Concrete Batching Operation

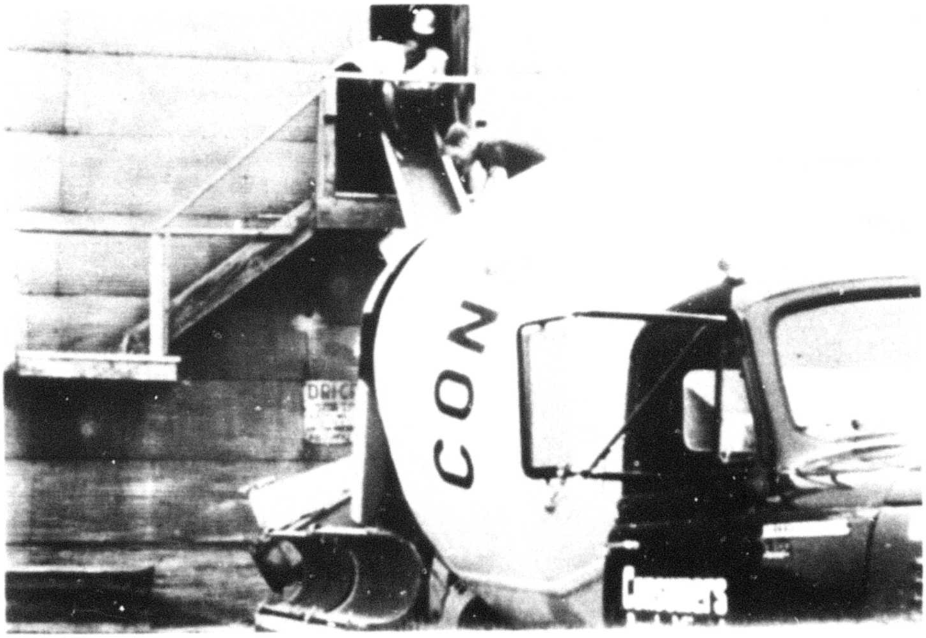

Figure 5. Method 4 Used to Introduce Steel Fibers in the Concrete Batching Operation

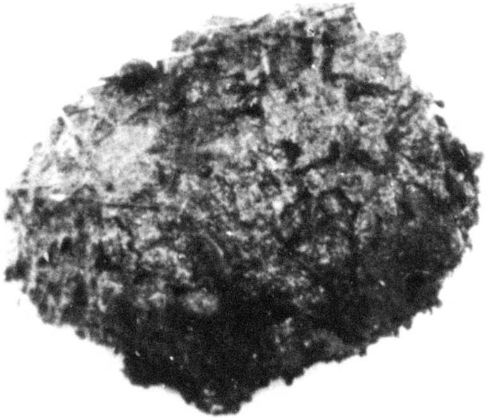

Figure 6. Fiber Ball Formed During Mixing

Figure 7. Comparison of Plain Concrete Slump (on right) with Fibrous Concrete Slump (on left)

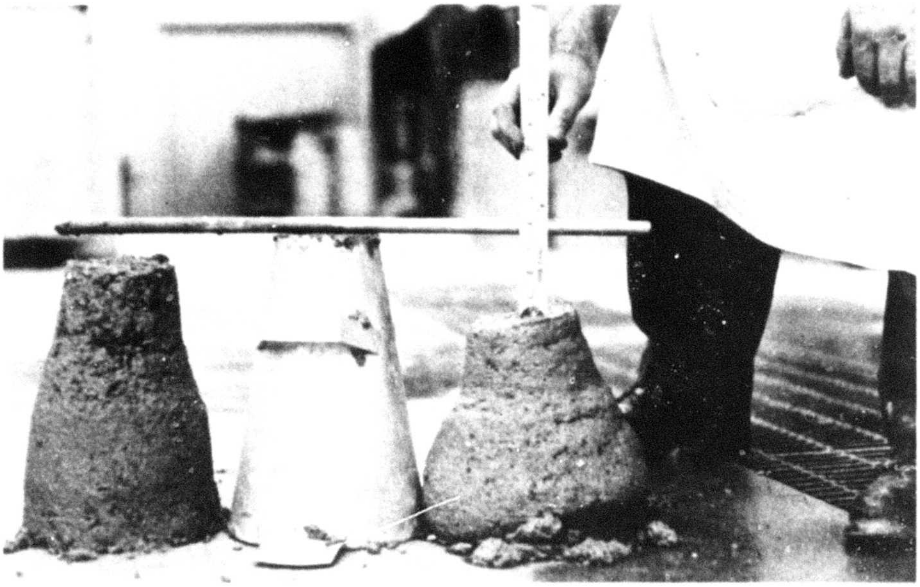

Figure 8. Portable Vibrator Mounted on Wood Boards

Figure 9. Sidewalk Slipform Paver

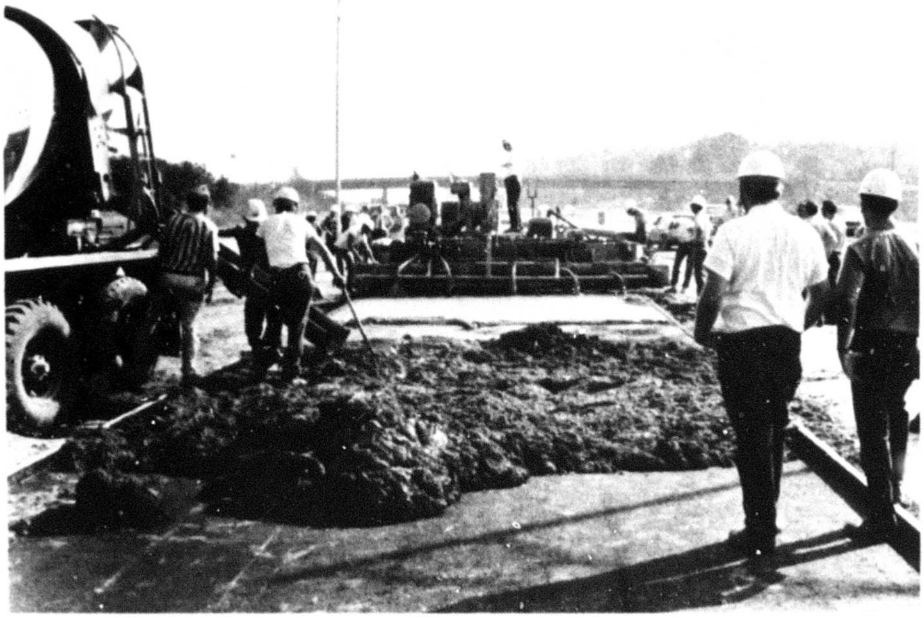

Figure 10. Side-Form Roadway Paver

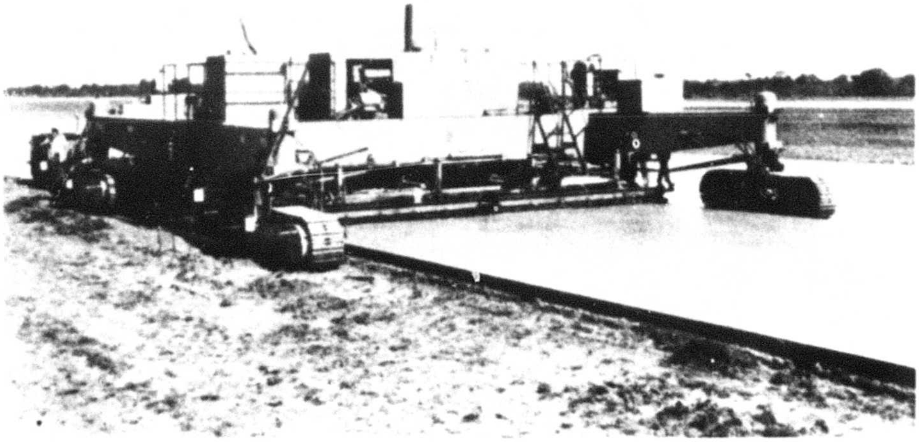

Figure 11. Slipform Paver

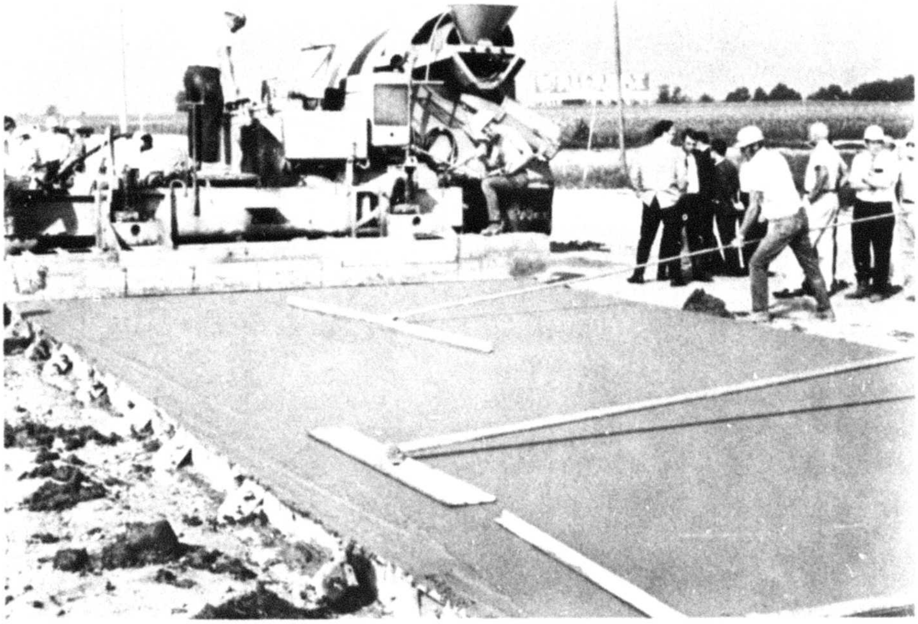

Figure 12. Hand Floating a Fibrous Concrete Surface

STEEL FIBER PRODUCTION AND RELATED CONSIDERATIONS

by

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CERL Fibrous Concrete Conference:
"Fibrous Concrete--Construction Material for the Seventies"
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ABSTRACT

The term "availability" is more appropriate than "production" with respect to both steel fiber and steel fiber concrete at this stage of development. Relatively small quantities of both materials have been available up to this time. However, considerable work has been done and will be continued in the areas of steel fiber design, packaging and handling. U. S. Steel's work in this area--with regard to fiber cross section, length, shape and other parameters--is summarized. Pertinent aspects of steel fiber manufacture and fibrous concrete preparation as presently carried out and as envisioned several years hence are also considered.

STEEL FIBER PRODUCTION AND RELATED CONSIDERATIONS

by

Alan W. Schwarz

~~This discussion, "Steel~~ Fiber Production and Related Considerations," is largely confined to United States Steel's new product, USS Fibercon Steel Fiber. It should be noted, however, that other steel fibers as well as a number of nonferrous fiber materials--metallic, organic and ceramic--are presently being evaluated by the numerous individuals and organizations associated with fibrous concrete development.

The *applicability* of the term "production" in relation to current levels of fibrous concrete activity will be considered first. Then steel fiber design considerations, manufacturing techniques, packaging and handling problems, and a final very important consideration, steel fiber concrete workability, will be examined.

The word production, to most, implies volume and it is doubtful that 5,000 tons of steel fiber for concrete have been produced during the past ten years. What does five thousand tons--and this is probably high--mean in the steel industry? Contrast this tonnage with today's steel making capabilities such as the new basic oxygen process furnaces which turn out over 200 tons of steel every 45 minutes. Fiber's average to date --no more than 500 tons a year--is lost in the comparison.

Translating 5,000 tons of estimated fiber production into end product yields about 50,000 cu yd of fibrous concrete. Based on cement shipments in 1971, concrete usage for that one year was about three hundred million cu yd. Fibrous concrete's 50,000 yd are spread out over ten years. Probably the largest steel fiber reinforced concrete installation in this country, through March 1972, involved approximately 300 cu yd, or only 1 millionth of a year's volume.

The logical conclusion is that the term production is not applicable to today's level of activity in either steel fiber or fibrous concrete. A more appropriate title for this discussion would be steel fiber *availability*. Both the fiber reinforcing material and the concrete end product have been and remain available in quantities appropriate for developmental needs. However, these needs have been small up to now.

The first problem in making a fiber available is to design one which provides optimum performance and mixability in concrete. Unfortunately, it has been found to be a general rule that as *mixibility* is improved, *performance* is diminished. The two considerations must, therefore, be studied simultaneously, in order to achieve an optimum. *Mixability* relates principally to achieving a nonsegregated-nonballing-homogeneous fibrous concrete mix. *Performance* at present is largely assessed in terms of flexure, or more correctly, flexural modulus of rupture. Other performance criteria are, of course, also being studied. These include direct and indirect tension, compression, shear and torsion, abrasion resistance, freeze-thaw behavior, corrosion, thermal and electrical conductivity, impact resistance and fatigue. Indeed, steel fiber concrete offers advantages in all of these respects, generally varying directly with the amount of steel fiber used and always assuming satisfactory mixability.

Fiber length and aspect ratio have pronounced effects upon both *mixibility* and *bond*. The latter is an indirect way of saying *performance*. Generally, *the longer the length and the higher the aspect ratio, the better the bond and the performance--providing that satisfactory mixability and consolidation are achieved.* U. S. Steel's present standard fiber is 1-in. long. Lengths have been varied from as little as 1/4 in. to as much as 3 in. with most field trials having utilized 1-1/4 in., 1-1/2 in. and, more recently, 1-in. long fiber.

The term "aspect ratio," which is length divided by diameter, is commonly referred to in regard to fiber for concrete. The state-of-the-art paper now under preparation by ACI Committee 544 on fibrous concrete recommends aspect ratios of from 30 to 150. Our work to date, however, suggests that an aspect ratio of 50 to 70 is more practical, at least for typical laboratory and transit mix equipment.

What is the aspect ratio--length divided by diameter--of U. S. Steel's standard fiber which besides being 1-in. long is .010-in. thick and .022-in. wide? Because the diameter of a rectangle cannot be calculated, *equivalent* diameter is used. The latter refers to that diameter which corresponds to a circle of the same cross-sectional area as the non-round configuration. The equivalent diameter of a .010-in. by .022-in. rectangle is .01675 in. and the aspect ratio for this cross section in a 1-in. length is 60.

Several recent field trials indicate that certain concrete mixers, particularly mobile or stationary central mix units, can handle aspect ratios substantially higher than 60. As previously indicated, better bond and thereby better overall performance would be anticipated if both length and aspect ratio could be increased while maintaining satisfactory mixability.

What are the advantages of this rectangular or flat .010-in. by .022-in. cross section? It obviously provides more surface and, therefore, more bond than a round fiber having the same cross-sectional area. The flat fiber also seems to enhance performance through improved mechanical lock as compared to a round. Rectangular flats evidence better flow characteristics and less tendency toward balling--i.e., better mixability--than round fibers of the same cross-sectional area and length.

Although both rounds and squares are presently being used, there is the possibility that a decidedly different configuration may eventually be adopted. Channel, ring or crescent shaped cross sections, if they can be produced economically, could prove superior.

In arriving at a fiber design, aspects of shape other than cross section and length must be considered. For example, a flat fiber may be twisted. At the present time, the USS Fiber varies in end-to-end twist from a few degrees to as much as 360 degrees. However, the pros and cons of maintaining a constant twist of a specific degree have not yet been established.

Fibers have been crimped, cambered, deformed and produced with dumbbell shapes. Fibers, if they can be called fibers at this point--having shapes ranging from circles to paper clips to staple configurations--have also been studied in laboratories. There does not appear to be sufficient evidence at present in terms of improved performance to warrant the additional costs of manufacturing such complex configurations.

Other steel fiber design imponderables include coatings, both metallic and organic, steel temper and ductility and steel chemistry. Frankly, it is doubtful whether the many considerations already mentioned cover the full gamut of possibly significant variations pertinent to the design of a fiber.

Assuming, however, that the design has been accomplished, what then are the techniques one might consider for the *manufacture* of a steel fiber? Probably the most romantic approach would be the conversion of junked automobiles and waste steel cans to a fibrous material for concrete reinforcement. Perhaps at some point in time, cryogenic processing of such material will yield fibers or particles of a size and shape suitable for this purpose. Right now, this is not the case nor have the logistics of collecting and processing these materials been shown to be economically attractive.

For the present then--and even for the future--the approach selected must utilize the lowest possible input in terms of man hours and equipment costs devoted to material handling and processing. Steel conversion possibilities include broaching or milling stacked sheet and strip; rotary and reciprocal cutting or shearing of wire, sheet or strip; direct conversion of molten steel to discontinuous fiber in a fashion not wholly unlike processes now being used in the glass industry. The selection of the ultimate conversion process--and, indeed, there may well be more than one--must await further resolution of desired fiber characteristics and continued assessment of the relative economics of each potential conversion process.

In addition to steel fiber design and manufacture, there is another important production consideration--the manner in which the fibers are packaged and shipped. Up to the present, field work with fiber has been limited to manual handling of suitably sized small containers. Shipping units for USS Fibercon Steel Fiber have been standardized for this stage of development at 40-lb, 1 cu ft cardboard boxes. The 40-lb bulk density of 1 cu ft of fiber, as it is now packaged, represents only about 8 percent of the weight of a solid cubic foot of steel. Unfortunately, this means that air alone accounts for over 90 percent of the volume shipped.

At present, the 40-lb cartons of USS Fibercon Steel Fiber are "banded" 48 to a 3 by 4 ft skid providing a net weight of 1920 lbs of steel fiber per pallet. Having arrived at the site, the cartons are unloaded and, before charging any fiber, the tops are removed from a sufficient number of cartons to accommodate fiber needs for the day. One man handling already opened 40-lb cartons can charge from 4 to 6 units, or from 160 to 240 lbs of steel fiber to a moving belt or into a transit mixer, each minute. This is not easy work and the undesirability of this situation is well appreciated. Considerable effort is being directed toward eliminating manual handling. Individual shipping units weighing at least 1 ton must be designed and a way must also be found to provide bulk shipment in covered gondolas and trucks. When the fiber has arrived at the point of use, it must be stored. Closed hoppers, comparable to those now used for the storage of cement and fly ash, will be required, or arrangements must be made to hold the fiber on the truck or rail car.

The process of removing the fiber from storage, weighing it and charging it must be automated. What does this entail? A typical mix design calls for 1.5 percent by volume steel fiber reinforcement or 200 lbs/cu yd of concrete. It would certainly be desirable to add 200 lbs or 0.1 of a ton/cu yd--at the charging speed common to the other aggregates. Modern central mix plants produce 8 to 15 cu yd of concrete every 1 to 2 minutes, with charging times as little as 1/4 of that. This means that dispensing and handling mechanisms capable of weighing and charging up to 3000 lbs of fiber in 15 seconds will be needed. At present, 1000 lbs of steel fiber can be weighed and charged in about a minute, based on laboratory experiments. This has not been confirmed in the field and even this rate is less than 10 percent of the goal.

A final and most important consideration, of course, is concrete workability which is a function of the fibrous concrete mix design. U.S. Steel has devoted considerable attention to mix design. The objectives of this work are reduction in cement factor, increased workability at lower slump and the use of increased aggregate size and increased ratios of coarse to fine aggregate in fibrous concrete.

A significant advancement has been achieved in this respect through the use of a pozzolannic fly ash admixture in amounts substantially greater than customarily employed. Besides the primary function of the fly ash in a fibrous concrete mix--which is to achieve better workability--there are additional advantages in using fly ash which include increased resistance to water penetration, greater long-term strength under normal outdoor exposure and lower cost. Fly ash in a fibrous mix provides the necessary fine material to coat the fiber, enhance *workability* of the mix and permit effective use of more and larger aggregates.

In order to achieve satisfactory workability, the inherent harshness of steel fiber mixes had to be overcome. This harshness is attributable to the fact that 1 percent by volume of .010 by .022 by 1 in. USS Fibercon Steel Fiber is equivalent not only to 132.3 lbs/cu yd, but also to approximately 78,400 individual fiber elements or over 5,000 sq in. of surface area per *cubic foot* of concrete. Earlier work with all sand mixes was not a suitable solution. The use of fly ash appears to be a step in the right direction.

In summary, the term "production" in view of the small volumes involved at this stage of development is a misnomer with respect to both steel fiber and fibrous concrete. However, every effort is being made to provide sufficient fiber over the next year or so to accomplish the necessary field development required before fibrous concrete can properly be considered a commercial product. During this period, United States Steel and others will continue work aimed toward optimizing fiber design, fiber production techniques, packaging, shipping and field handling, and the design and preparation of the fibrous concrete mix.

Steel's long recognized compatibility with concrete suggests that a steel fiber will prove optimum from the standpoints of both performance and cost. Others anticipate the use of glass and possibly organic fibers for concrete reinforcement. Regardless, however, of which fiber ultimately proves best, fibrous concrete indeed appears to be a most promising construction material, not only for the 70's, but for many decades to come.

(Illustrations which accompanied this presentation on May 3, 1972, could not be reproduced for these proceedings. The illustrations, which were designed to accompany an oral presentation, are not vital to the printed text.)

STEEL FIBER OPTIMIZATION

by

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ABSTRACT

An investigation has been made on the effect of several steel fiber variables on the flexural strength of reinforced concrete. Data is presented which shows the effect of wire length, diameter, shape, tensile and fiber content on first crack and ultimate flexural strengths in concrete and mortar formulations.

STEEL FIBER OPTIMIZATION

by

Bruce L. Waterhouse and Clare E. Luke

INTRODUCTION

Concrete, one of the world's most versatile building materials, is essentially composed of aggregate, such as sand and gravel, bonded together by a hardened cement paste. With the addition of precision, short lengths of wire as reinforcement, properties of normal concrete are improved to such an extent that it can better serve the known concrete application and also be considered as a material for many different new applications.

Work by many investigators has led to some knowledge of the strength of fiber wire reinforced concretes. Although not all of these investigators agree as to the function of the fibers, be it crack stopping or not, there is little doubt that fiber wires improve the physical properties of concrete.

An infinite number of combinations of fiber variables, i.e. length, diameter, shape and percentage by volume, are possible within the limits set by the difficulties encountered in conventional mixing operations. It has been shown that with higher volumes of fiber, higher strengths are possible, but with a decrease in workability. So we must make a choice between strength and workability, giving up one to gain the other.

National-Standard has carried out an investigation to determine the optimum fiber lengths, diameters, and volumes which produce significant increases in first crack and ultimate flexural strengths. The purpose of this paper is to report our results, which will enable you to make a sensible choice between strength and workability.

TEST PROGRAM

Test beams, 2-1/2 by 3 by 16 in., were cast in wooden molds, using external vibration, from the following basic mortar mix:

Cement:	Type III - High Early - 9 Bag	845 lbs
Water:	.52 Water/Cement Ratio	439 lbs
Sand, Aggregate and/or Fiber Wires:		2,415 lbs

Batch size was .75 ft^3 which was sufficient for three beams, slump, air content and density tests. Batches were mixed in a regular drum type cement mixer for a three minute cycle. Materials were supplied from the same source and in sufficient quantity, so that a particular test series could be run with the same supply of material. Workability was determined by the laboratory technician and was based on comparison with a normal mix without fiber wires added. If balls were present in the mix it was considered unworkable.

Curing was accomplished by covering the beams with a wet cloth for 24 hours, removing the beams from the mold and storing them in lime water solution until breaking 28 days after molding.

The tests performed on the specimens conformed to the requirements of ASTM C293-68, Flexural Strength of Concrete, using a simple beam with a center point loading. Particular care was taken in recording the load-deflection curve, so the first crack strength could be easily delineated. The stress at which the load-deflection curve first deviated from linearity was taken as the first crack strength, while the ultimate flexural strength was taken as the maximum stress attained during the test.

TEST RESULTS

During the course of our investigation, over 275 batches of concrete have been mixed and results obtained on approximately 850 beams. The results that are given in the following tables and on the accompanying graphs are averages of all the beams made with the noted fiber reinforcement. Thus, the averages given are of a minimum of three beams up to a maximum of twenty-four beams. For ease of understanding, the following amounts of fiber wire correspond to percent loading in this test series:

1/2% = 67 lbs/yd^3
1% = 133 lbs/yd^3
1-1/2% = 200 lbs/yd^3
2% = 265 lbs/yd^3

Initially, specimens were prepared with 1 by .016 in. fibers, increasing the volume percent until workability became a problem. Table 1 lists the results obtained, while Figure 1 graphically illustrates the increase in strength that is obtained. Thus an increase in volume percent of .016 in. round fibers increases the strength, so that a 100 percent increase in the ultimate strength is obtainable.

The length of a fiber has a bearing on strength, also. Table 2 illustrates the increase in strength made possible by increasing the length of a round fiber of .016 in. diameter while the volume percent remains constant. At 1 percent volume loading the first crack strength remains fairly uniform, while the ultimate strength increases as the length increases. At 2 percent volume loading, there is a definite increase in both first crack and ultimate strengths, until the length reaches 1-1/2 in. when the mix becomes unworkable and test results then are affected by the nonuniform fiber distribution and voids within the specimen.

With a given volume loading of fibers, results show that the smaller the diameter of fiber, the higher the strength possible at a given length. Table 3 shows for example that a 1 percent loading to obtain a first crack flexural strength of 1,250 psi you would need a 1-1/4 by .010 in., a 3/4 by .016 in., and at least a 2-1/2 by .020 in. fiber. A similar statement can be shown graphically when ultimate strengths are considered as shown in Figure 2.

First crack strengths remain fairly constant with changes in fiber diameter as fiber length and volume loading remain constant. However, as volume percent of fibers is increased, with length remaining constant, the level of first crack strength is improved. This is shown in Table 4, where the higher volume loading at a given length shows a higher first crack strength. Ultimate strengths at the higher volume percentages show even greater increases, with smaller diameter fiber exhibiting highest results. Figures 3 and 4 show these effects.

All the above data pertained to round fibers, while our investigation also incorporates other shapes. Flat fibers and a National-Standard patented shape, Duoform* fibers, were also included in the test work. The Duoform fiber combines the benefits of both round and flat wires, one example being .010 by .020 in. flat sections separated by round sections of .016 in. diameter. Tables 5 and 6 show the benefits that can be obtained by using a shaped fiber over a round fiber. For example, at 2 percent volume loading, a 3/4 in. Duoform yields an ultimate strength that is higher than that yielded by a 1 in. round fiber, and the handling conditions, with a 3/4 in. Duoform fiber are better, that is, it is more workable, and easier to handle. Thus, one gains strength and workability in a shorter fiber. This is illustrated in Figure 5.

A series of beams were prepared using 25 and 50 percent of the aggregate in the basic formulation as 3/8 in. maximum limestone and a series with 3/4 in. maximum limestone. Coarse aggregate definitely

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* National-Standard Company Patent 3,592,727.

affects the workability of the mix. None of the mixes of 50 percent-3/4 in. aggregate were considered workable, while most of the 50 percent-3/8 in. aggregate mixes were workable and produced respectable flexural strengths. Tables 7 and 8 list results that were obtained in this test series.

CONCLUSIONS

From the multitude of results that have been obtained and analyzed, some general conclusions can be stated.

1. Fiber length, fiber diameter and fiber shape have relatively little effect on first crack flexural strengths.

2. Ultimate flexural strengths are affected by length, diameter, quantity and shape of wire fibers. Longer lengths, smaller diameters, higher volume loading and the Duoform shaped fibers independently improve the ultimate strength of fiber wire reinforced concrete.

3. Workability of the concrete mixture is affected by length, volume loading and aggregate size and quantity. Long length fibers with higher volume loading become decreasingly workable, while high coarse aggregate (50 percent) content causes poorer workability as the aggregate size increases.

4. With the many possibilities of fiber length, diameter, and shape available that give acceptable strength results, workability and cost then become important criteria.

Table 1. Effect of Fiber Volume on Flexural Strength

1" x .016" Round	Volume Percentage	First Crack psi	Ultimate psi	Workability
	.3%	910	910	*Good*
	.5%	1055	1055	*Good*
	1%	1115	1115	*Good*
	1.5%	1200	1325	*Good*
	2%	1265	1470	*Good*
	2.5%	1480	1880	*Good*

Table 2. Effect of Fiber Length on Flexural Strength

Fiber Length	1%–.016" Round		2%–.016" Round	
	First Crack psi	Ultimate psi	First Crack psi	Ultimate psi
¾"	1155	1155	1260	1295
1"	1115	1115	1265	1470
1¼"	1110	1165	1440	1905
1½"	1070	1180	1505 ◪	1945 ◪
1¾"	1255	1370	1155 ◪	1675 ◪
2"	1245	1455	1265 ◪	1595 ◪

◪ = Poor Workability — (Unworkable)

Table 3. Fiber Length and Diameter Comparisons

Fiber Length	1%—.010"		1%—.016"		1%—.020"	
	First Crack psi	Ultimate psi	First Crack psi	Ultimate psi	First Crack psi	Ultimate psi
½"	1190	1190				
¾"	1185	1265	1155	1155		
1"	1215	1320	1115	1115		
1¼"	1250	1500	1110	1165		
1½"	1240 ◢	1255 ◢	1070	1180	1050	1050
1¾"			1255	1370		
2"			1245	1455	1020	1280
2½"			1150 ◢	1585 ◢	1155	1580

◢ = Poor Workability — (Unworkable)

Table 4. Effect of Fiber Diameter on Flexural Strength

Fiber Diameter (Round)	1"–1%		1"–2%		2"–1%		2"–1½%	
	First Crack psi	Ultimate psi	First Crack psi	Ultimate psi	First Crack psi	Ultimate psi	First Crack psi	Ultimate psi
.030"					1240	1240	1205	1705
.025"					1245	1260	1360	1715
.020"					1020	1280	1300	1850
.016"	1115	1115	1265	1470	1245	1455	1265 ◢	1595 ◢
.014"	1215	1215	1275	1615				
.012"	1160	1230	1325	1645				
.010"	1215	1320	1240 ◢	1470 ◢				
.006"	1270	1795						

◢ = Poor Workability — (Unworkable)

Table 5. Effect of Fiber Shape on Flexural Strength

Fiber Shape	Fiber Diameter	Fiber Volume	¾" First Crack psi	¾" Ultimate psi	1" First Crack psi	1" Ultimate psi	1½" First Crack psi	1½" Ultimate psi
Round	.016"	1%	1155	1155	1115	1115	1070	1180
Flat	.016"	1%			1135	1210	1115	1465
Duoform	.016"	1%	1050	1090	1120	1210	1105	1565
Round	.016"	2%	1260	1295	1265	1470	1505 ◢	1945 ◢
Flat	.016"	2%			1355	1695	1280 ◢	1730 ◢
Duoform	.016"	2%	1290	1560	1345	1845	1870 ◢	2380 ◢

◢ = **Poor Workability — (Unworkable)**

Table 6. Effect of Fiber Shape on Flexural Strength

Fiber Shape	Fiber Diameter	Fiber Volume	Fiber Length	First Crack Flexural psi	Ultimate Flexural psi	Workability
Round	.020"	1%	1½"	1050	1050	*Good*
Flat	.020"	1%	1½"			
Duoform	.020"	1%	1½"	1165	1210	*Good*
Round	.020"	1%	2"	1020	1280	*Good*
Flat	.020"	1%	2"	1075	1490	*Good*
Duoform	.020"	1%	2"	1120	1570	*Good*

Table 7. Effect of 3/8 Inch Aggregate on Flexural Strength

Fiber Length and Diameter	Volume Percentage	25%–3/8" Agg.		50%–3/8" Agg.	
		First Crack psi	Ultimate psi	First Crack psi	Ultimate psi
1" x .010"	2%	1200 ◢	1330 ◢		
1" x .016"	1%	1295	1370	1250	1315
1" x .016"	1½%	1465	1635	1225 ◢	1245 ◢
1½" x .020"	1%	1280	1280	1275	1455
1½" x .020"	1½%	1590	1700	1565	1870
1" x .016" (Duoform)	1%			1340	1430
1" x .016" (Duoform)	1½%			1455	1745

◢ = Poor Workability — (Unworkable)

Table 8. Effect of 3/4 Inch Aggregate on Flexural Strength

Fiber Length and Diameter	Volume Percentage	25%–¾" Agg.		50%–¾" Agg.	
		First Crack psi	Ultimate psi	First Crack psi	Ultimate psi
1" x .010"	1%			925 ◢	925 ◢
1" x .010"	2%	1080 ◢	1105 ◢	675 ◢	675 ◢
1" x .016"	1%	1165	1330	1030 ◢	1185 ◢
1" x .016"	1½%	1120	1560	1290 ◢	1400 ◢
1½" x .020"	1%	1285	1400	1170 ◢	1250 ◢
1½" x .020"	1½%	1280	1450		
1½" x .020" (Duoform)	½%			1165 ◢	1300 ◢
1½" x .020" (Duoform)	1%			875 ◢	1055 ◢

◢ = Poor Workability — (Unworkable)

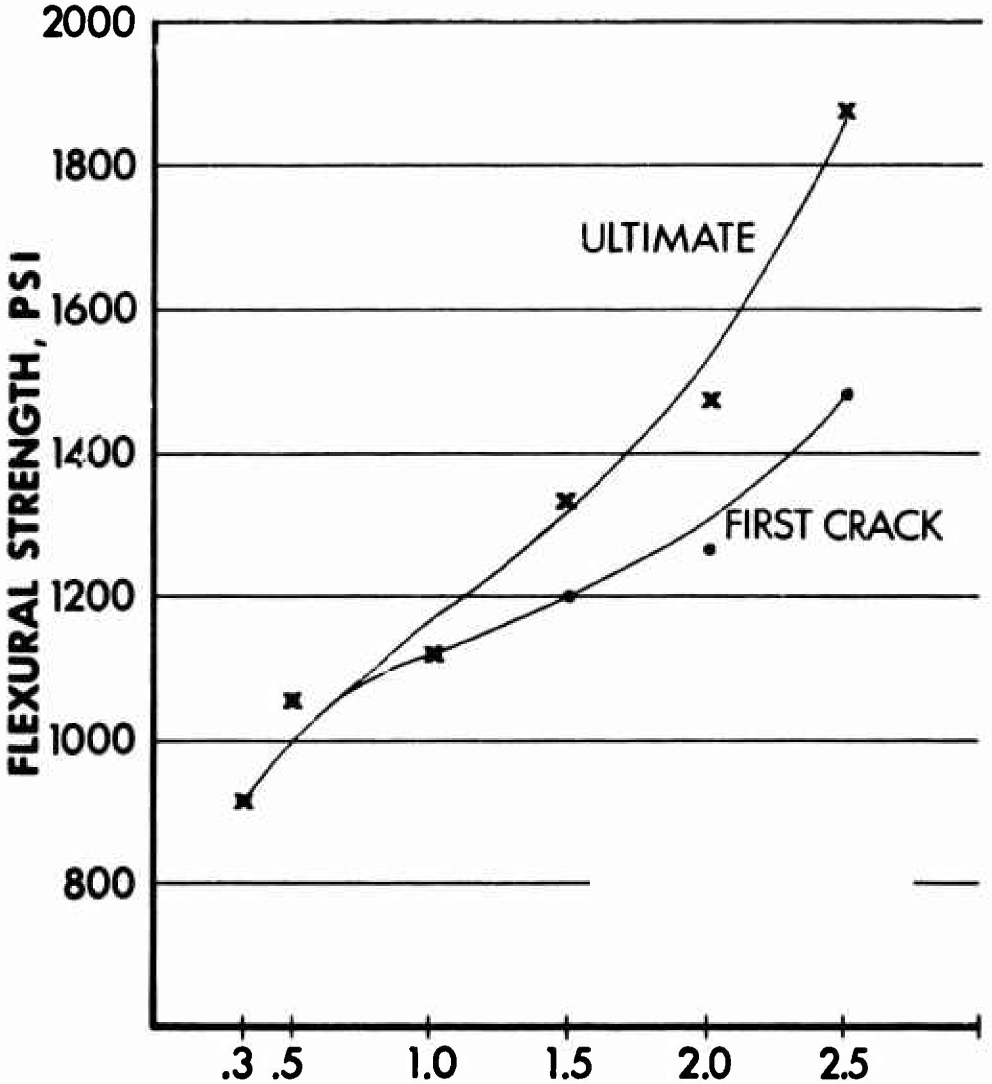
2000
1800
1600
1400
1200
1000
800
FLEXURAL STRENGTH, PSI
ULTIMATE
FIRST CRACK
.3
.5
1.0
1.5
2.0
2.5
VOLUME PERCENT OF 1" x .016" ROUND FIBERS

Figure 1

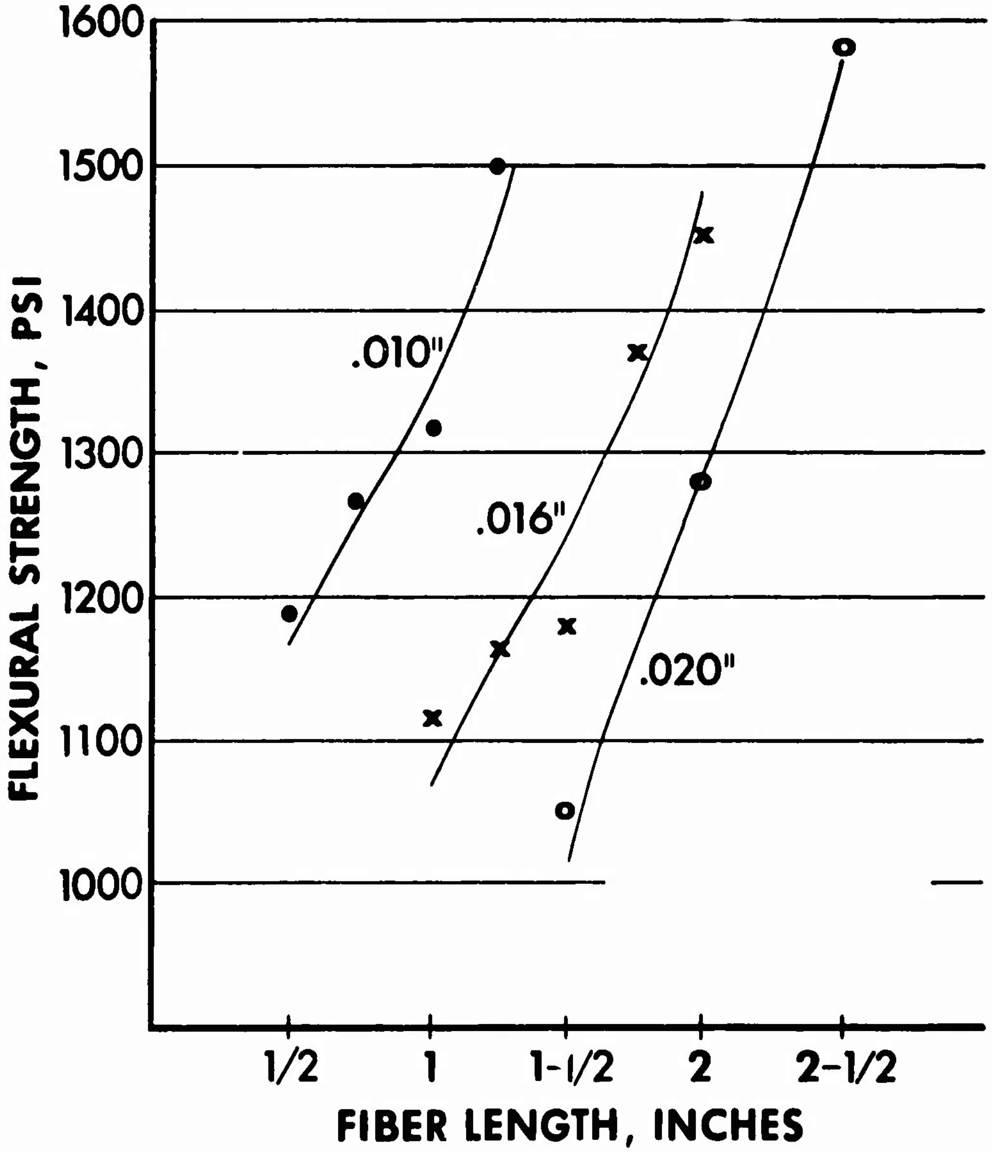

Figure 2. Ultimate Strengths, Round Fibers,
1% Volume Percent

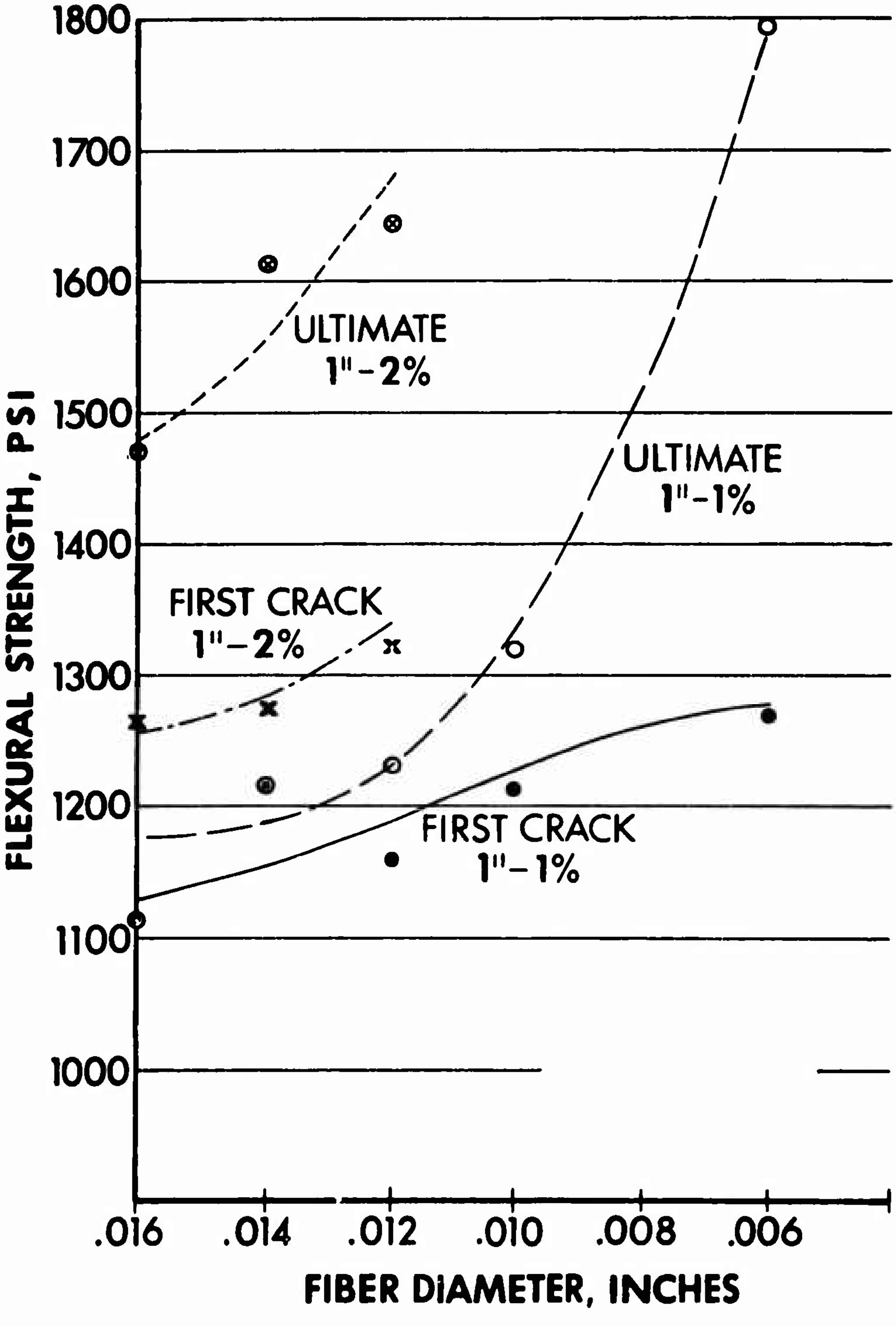

Figure 3. First Crack and Ultimate Strengths Round Fibers

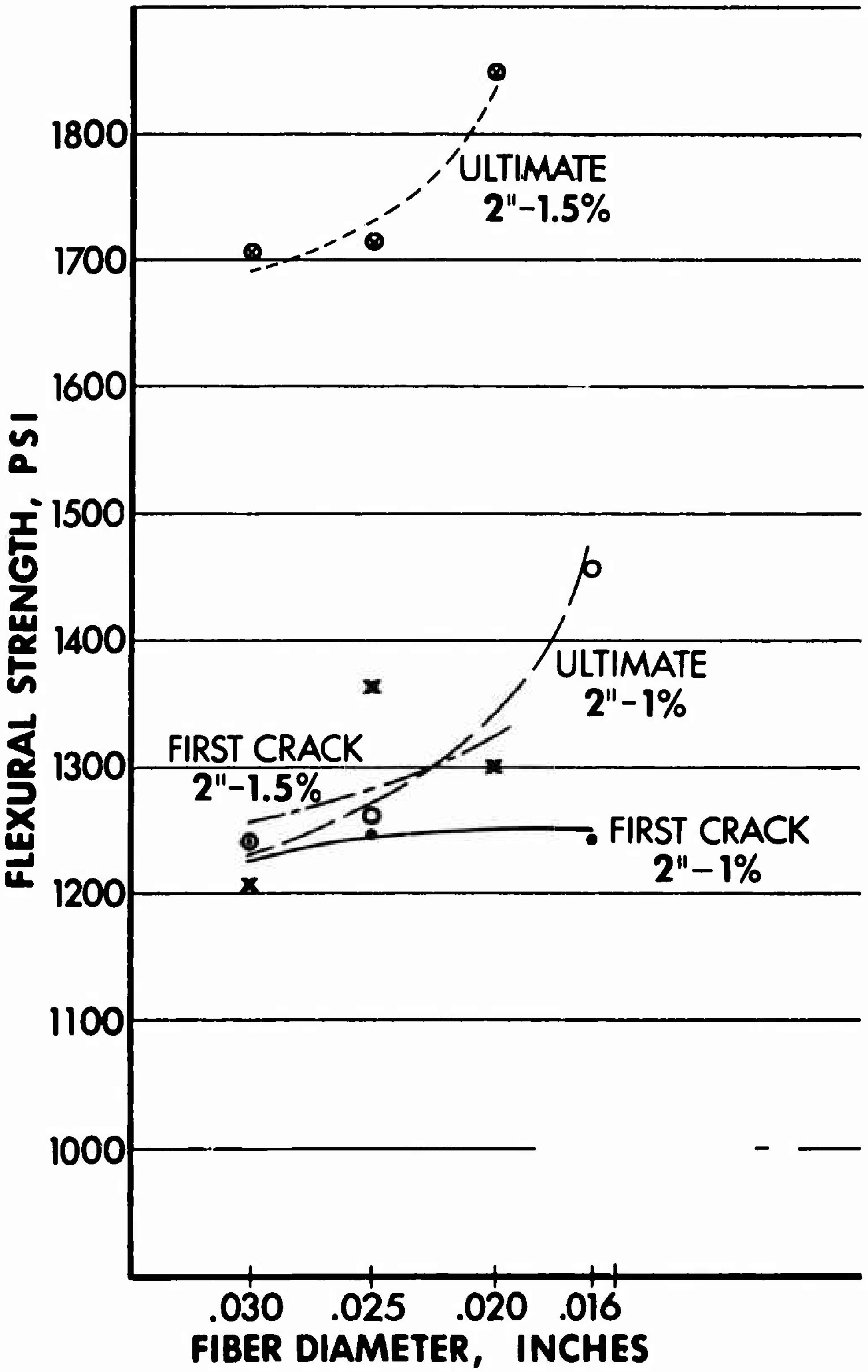

Figure 4. First Crack and Ultimate Strengths Round Fibers

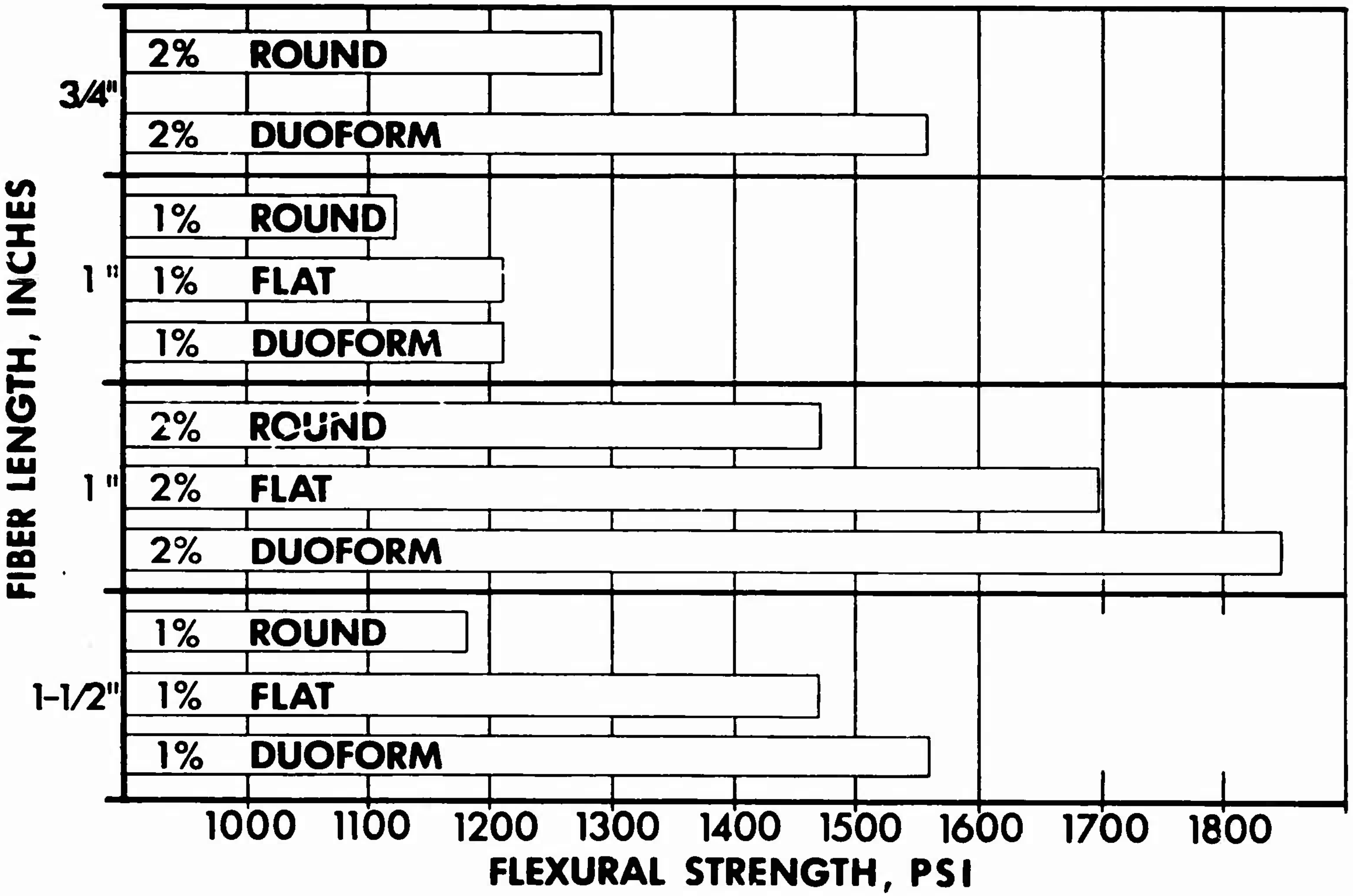

Figure 5. Flexural Strength, .016 Inch Fibers

GLASS FIBERS IN CONCRETE: THE CURRENT STATUS

by

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Presented at
CERL Fibrous Concrete Conference:
"Fibrous Concrete--Construction Material for the Seventies"
Champaign, Illinois
May 1972

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ABSTRACT

Glass fibers have been investigated as a reinforcement for concrete for many years. Current research in England and the United States utilizes fibers where alkali resistance is obtained by changes in basic glass composition.

This paper describes process development carried out by the British Building Research Station and illustrates several products that have been prototyped.

Data is presented showing the improvements in flexural and impact strength of neat cement resulting from the addition of varying percentages of glass fibers.

A construction system and several candidate architectural products which use the glass fiber reinforced cement are described and additional applications are suggested.

GLASS FIBERS IN CONCRETE:
THE CURRENT STATUS

by

Henry N. Marsh, Jr.

The use of glass fibers in concrete dates back to the early 1950's. Much of this work was not fibrous concrete by the current definition but rather the use of glass fiber rods to replace conventional steel reinforcing in prestressed elements. This work was generally unsuccessful because of attachment and gripping problems. In addition, conventional E glass fibers progressively lost strength in the highly alkaline environment of portland cement concrete.

Several approaches have been attempted to overcome the alkali attack of the glass fibers. Russian[1] and English[2-6] researchers have utilized high alumina cement which is a much less alkaline matrix. Goldfein,[7] Klink,[8] and Agbim[9] relied on organic coatings to protect the fibers from the free alkali. The majority of recent research has utilized glass fibers where alkali resistance is obtained by changes in the basic glass compositions. The balance of this paper will be concerned with research using alkali resistant glass fibers manufactured originally in England by Fibreglass Ltd., a subsidiary of Pilkington Ltd. and more recently by Owens-Corning Fiberglas Corporation in the United States.

Since 1967, an extensive program has been carried out by the British Building Research Station utilizing alkali resistant glass fibers and a number of articles have been published by Majumdar, Ryder, Grimer, Ali and others.[2,6,10-14] This work utilized very high levels of fiber loading, from 2.9 to 8 percent by volume, with most samples being prepared by a spray suction technique. The process is similar to the spray-up process for manufacturing reinforced plastic laminates and can be described briefly as follows: A relatively wet slurry of cement is pumped from a spray gun onto a suction mold. Glass roving is chopped into the cement during the spraying operation. Following this, the composite is leveled and suction applied to remove the excess water. In this manner high glass loadings and a laminar orientation of fibers can be achieved. Such a technique produces material having a much higher tensile strength but lower levels of internal bond strength than composites produced by premixing the glass into a dilute cement slurry.

In addition to the spray suction technique, materials have been made by casting followed by pressure compaction and suction and also by centrifugal casting. Postforming of complex shapes following suction is a further process refinement. One researcher also reported utilizing a filament winding process where continuous roving was passed through a cement slurry followed by winding on a rotating mandrel. Later indications are that this technique is less favored than others mentioned above. Majumdar and Ryder reported[6] 28 day flexural strengths of 2210 psi at 2.9 volume percent of 2 in. glass and 3760 psi at 7.3 volume percent of 2 in. glass. Impact strengths also increased from 19 in.lb/in.^{2} with 2.9 volume percent glass up to 94 in.lb/in.^{2} for 7.3 volume percent glass. A later publication by Majumdar[10] indicated flexural strengths approaching 6000 psi were achieved with 4 volume percent glass content.

In addition to the basic data generated, the Building Research Station and various private companies in England have prototyped a number of glass reinforced cement products. These include cladding panels, centrifugally cast pipe, permanent formwork for concrete columns, fences, box sections, floor sections, sandwich panels, window frames, channel sections, chimneys, silos and boat hulls.

The balance of this paper will describe the work carried out by our company on several fronts. The first activity was the development of fibers having alkali resistance and the expectation of reasonable production economics. This has been accomplished and development scale production facilities are running on a continuous basis.

Secondly, some basic physical property data on glass fiber reinforced cement have been developed. Figures 1, 2, and 3 show the impact and flexural strength improvement compared to unreinforced cement obtained by adding varying volume percentages of fibers. This series of experiments was run by simply casting test bars using 1/2 in. fibers at a water cement ratio of 0.45 and moist curing for 21 days. The cured density was 100 to 105 pcf.

The impact strength of the fiber composites increased linearly with increased volume percentages. As can be noted, the addition of 2 volume percent fibers resulted in an increase in impact strength of greater than 6 times that of unreinforced cement.

Both the first crack flexural strength and ultimate flexural strength curves show a linear relationship over much of their strength. With ultimate flexural strength, the strengths fell off at the high volume percentages. This is attributed to fiber interference and poor wet out. As the British work demonstrated, the use of higher water-cement ratios followed by extraction would permit the efficient utilization of volume percentages greater than 2 percent.

This study resulted in ultimate flexural strengths in the 1300 to 1400 psi range. Later experiments utilizing fly ash and a lower water-cement ratio of 0.39 resulted in ultimate flexural strengths of approximately 1900 psi with 1/2 in. fibers at about 2-1/4 volume percent addition.

A third phase of our overall program was the utilization of the alkali resistant fibers in cementitious systems. This work has taken several forms. The first of these is a system called Fiberglas Surface Bonding or Bloc/Bond.[16,17] This concept, which was conceived by U.S. Department of Agriculture personnel at Athens, Georgia,[15] involves the dry stacking of standard concrete block followed by the parging of a glass fiber reinforced cement on both wall surfaces (Figures 4 through 9). The resulting wall has a somewhat lower compressive strength than a standard mortar wall because of point contact between the unground block, an equal racking strength nearly twice that of a standard mortar wall. In addition to the significantly increased flexural strength, the surface bonded wall has a number of other advantages:

1. It can be erected much more rapidly than a conventional wall,
2. It requires less labor for installation and the labor can be less skilled,
3. It has a pleasing finished surface,
4. It eliminates the need for conventional damp proofing, and
5. It can lead to factory fabrication of transportable wall sections.

The second phase of our application program involved architectural products made from fiber reinforced cement and concrete. The first product developed was a simulated wood shake shingle made by casting fiber reinforced cement into patterned molds (Figure 10). The product weighs about 4 lbs/ft^2 of exposed roof surface and is applied by nailing directly through the tab area. Several trial installations were made and with very promising reactions from the roofing contractors and owners (Figures 11 through 13). This product has the advantages of very attractive appearance, significantly reduced installation cost, incombustibility, lightweight, ease of handling and fabrication, excellent resistance to breakage during installation and an ability to conform to variations in the roof surface.

As an extension of this casting work, simulated brick siding panels were prototyped (Figures 14 and 15). The development work on these panels is not complete but we visualize the advantages of attractive appearance, lightweight and low installation cost. The process can also easily make a wide variety of attractive surface appearances other than brick.

The basic physical property data given above were obtained on neat cement systems. Similar data is now being generated on mortar and concrete systems. From the work done to date, we can see a number of advantages for glass fibers as a reinforcement in these mixes:

1. Glass fibers are lightweight being less than 30 percent of the weight of steel fibers for a given volume percentage;

2. They do not stain or discolor on weathering;

3. They mix easily into concrete with little evidence of balling;

4. They can be blown pneumatically into a mixer as a means of combination;

5. They are nonmagnetic which may be of advantage in future electrically controlled highway systems;

6. There is a high degree of flexibility of product form in terms of filament diameter, bundle size and filament dispersion.

The last point may require additional explanation. When the fibers are formed, the individual filaments are coated with a small amount of an organic sizing and then combined into a strand for chopping. The chemistry of the sizing can be tailored to result in the filaments remaining tightly bound in a strand throughout the concrete mixing and placing or conversely dispersing completely into individual filaments when the strands are placed in the concrete mix. A complete range of dispersibility between these two extremes can be obtained and specific products tailored for each process and application (Figures 16 and 17).

We have seen a few possible disadvantages. The first is the somewhat higher water demand of the glass fiber mixes due to adsorption on the surface of the fibers. Whether this water should be considered bound water as in lightweight aggregates or actual free water which would produce lower strength concrete has yet to be established. We can visualize a number of possible solutions to this potential problem and expect that the effects of high water demand can be overcome. A second minor disadvantage is that excessive mixing may result in mechanical damage and abrasion of the glass fibers. Proper workmanship should prevent this problem.

Overall we certainly believe the advantages far outweigh the possible disadvantages and we are actively pursuing development work in a number of areas. We believe the most promising of these are replacement for asbestos in cement asbestos products, thin cladding panels, sandwich panels, pipe, various architectural products such as the shake shingles and of course highway and runway paving and patching.

It has been a pleasure to have the opportunity to tell you about the status of glass fibers in concrete. We are very encouraged by what we have seen to date and are looking forward to working with many of you on various applications in the future.

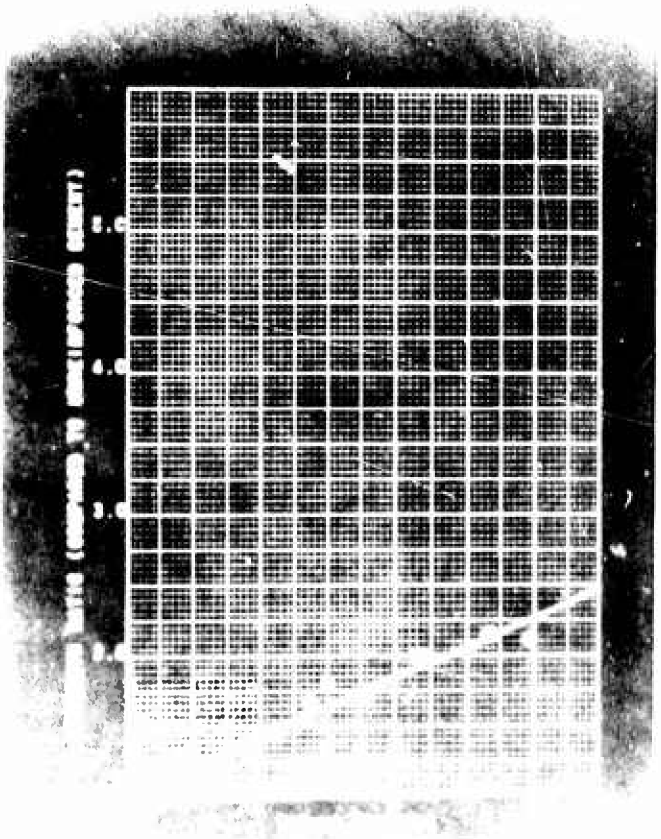

Figure 1. First Crack Flexural Strength Improvement Glass Fiber Reinforced Cement

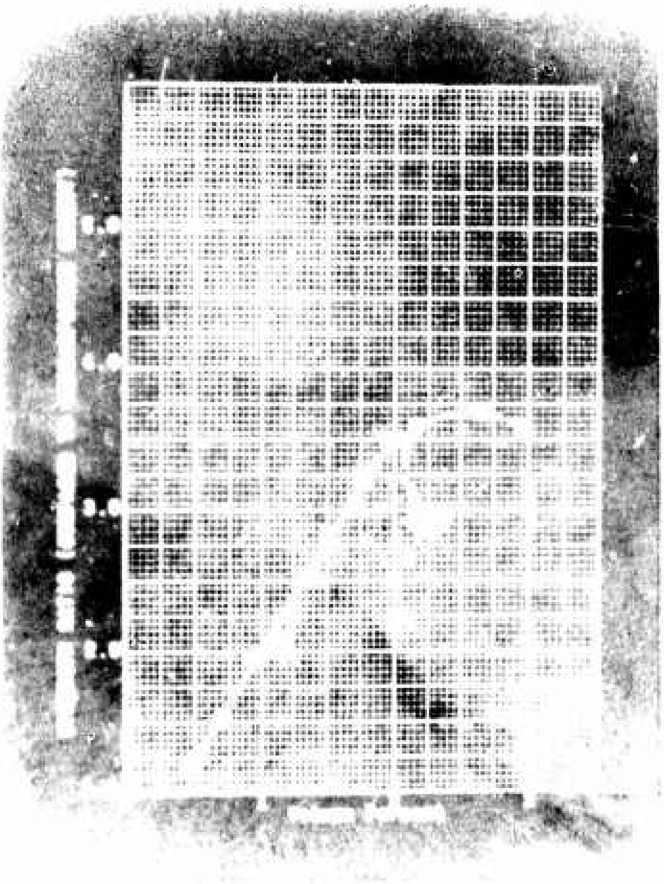

Figure 2. Ultimate Flexural Strength Improvement Glass Fiber Reinforced Cement

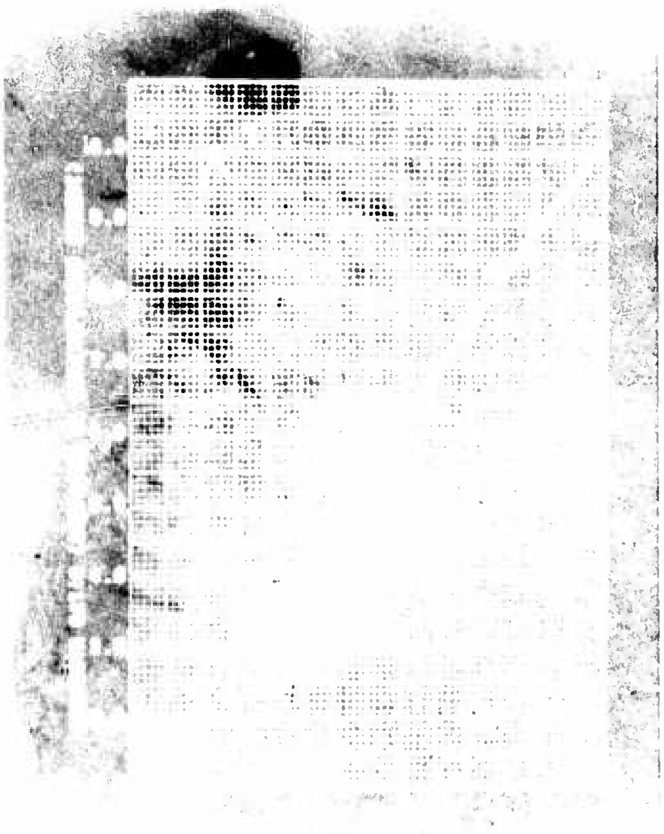

Figure 3. Impact Strength Improvement
Glass Fiber Reinforced Cement

FIBERGLAS SURFACE BONDING (BLOC/BOND) APPLICATION

Dry Stacking of Block

Figure 4.

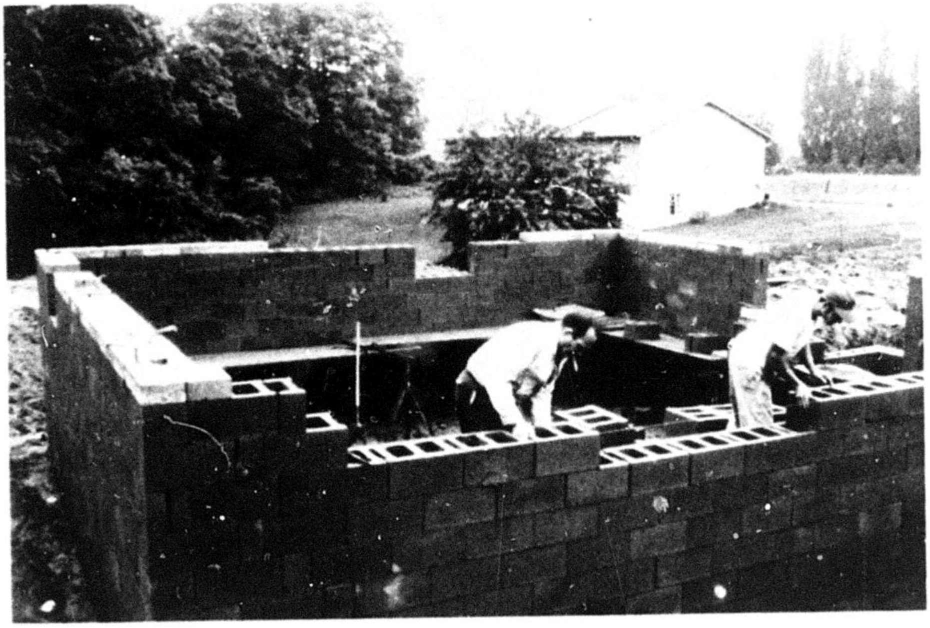

Figure 5.

FIBERGLASS SURFACE BONDING (BLOC/BOND) APPLICATION

Parging of Fiberglas Reinforced Cement Surface

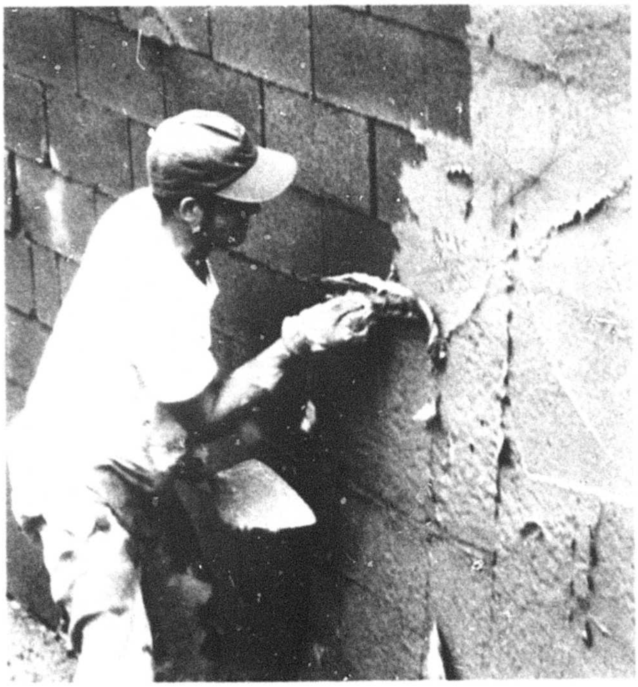

Figure 6.

Figure 7.

FIBERGLAS SURFACE BONDING(BLOC/BOND) APPLICATION

Finished Wall

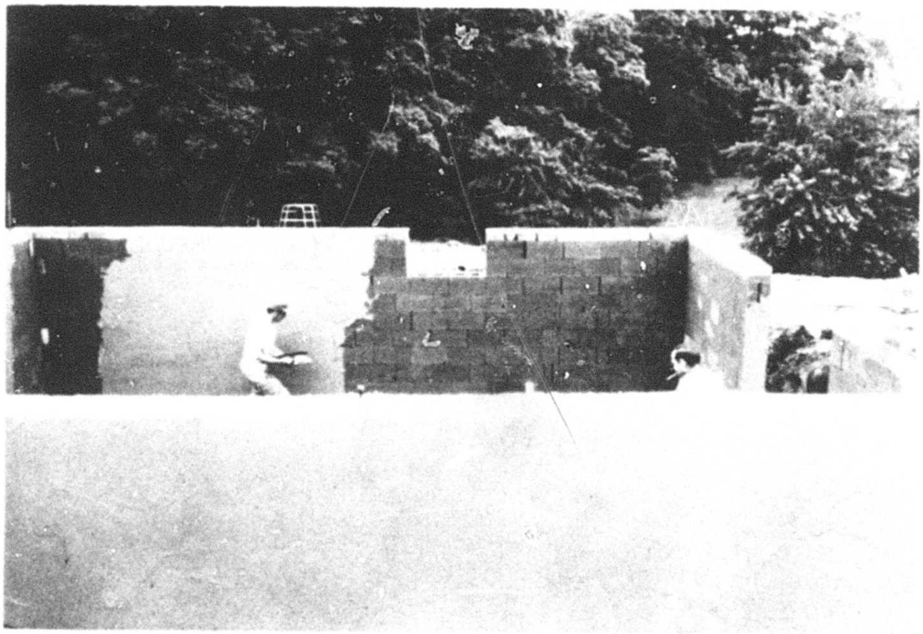

Figure 8.

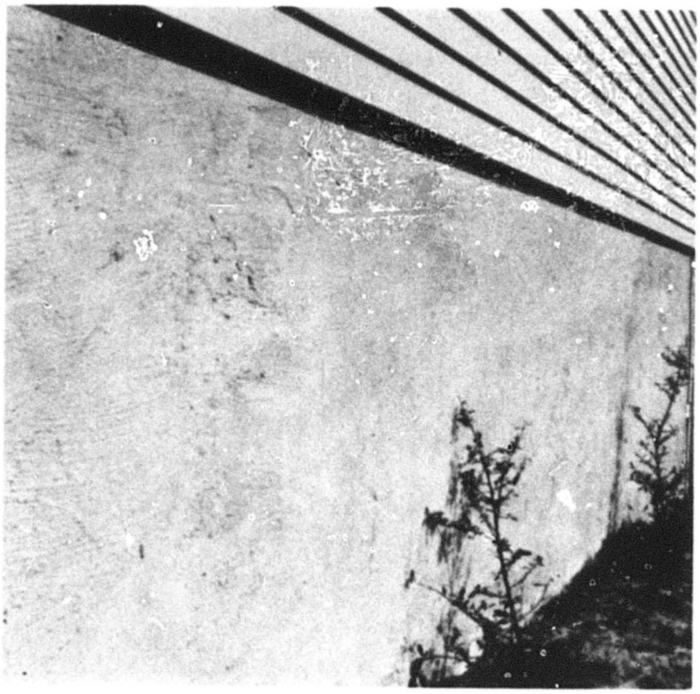

Figure 9.

FIBERGLAS REINFORCED CEMENT SHAKE SHINGLE

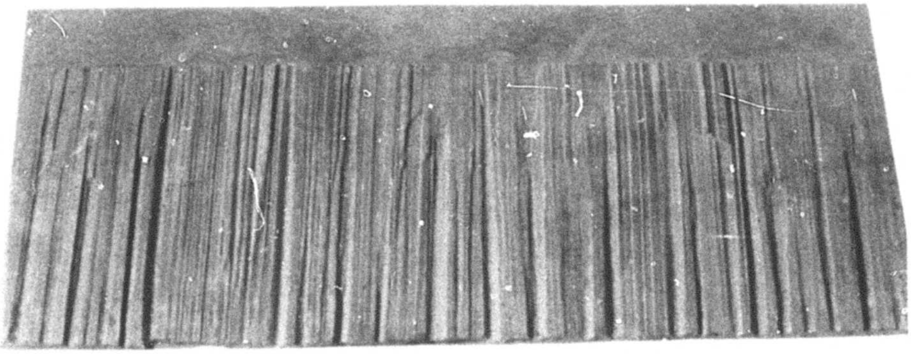

Figure 10. Individual Shake Shingle 15 in. by 36 in.

Figure 11. Trial Installation--Residential Construction

FIBERGLAS REINFORCED CEMENT SHAKE SHINGLE

Figure 12. Trial Installation--Light Commercial Construction

Figure 13. Trial Installation--Light Comercial Construction

FIBERGLAS REINFORCED CEMENT BRICK SIDING PANEL

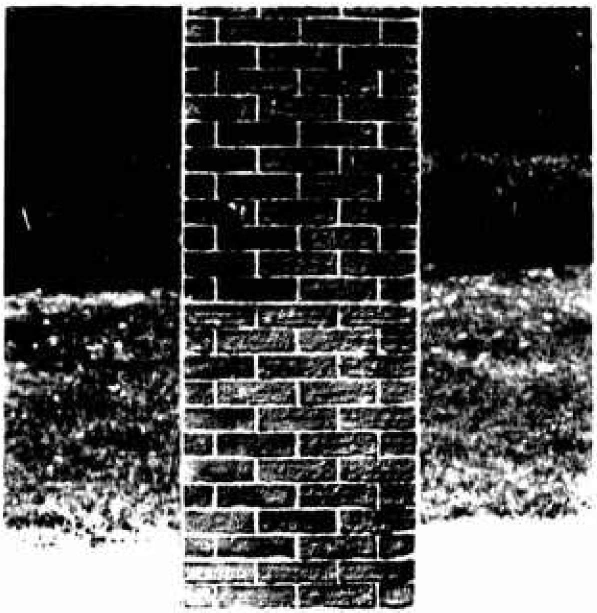

Figure 14.

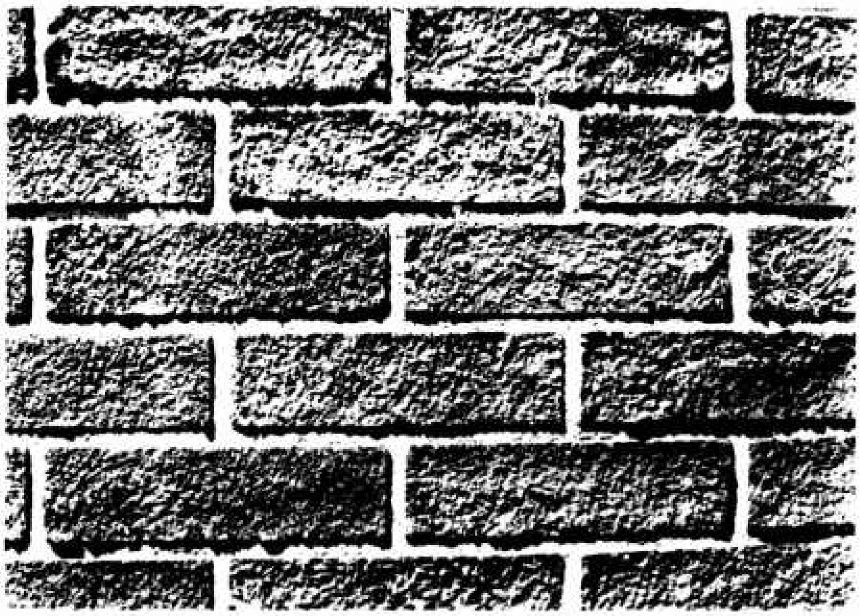

Figure 15.

GLASS FIBERS IN WATER

Figure 16. Nondispersible Size--6 Minutes in Water

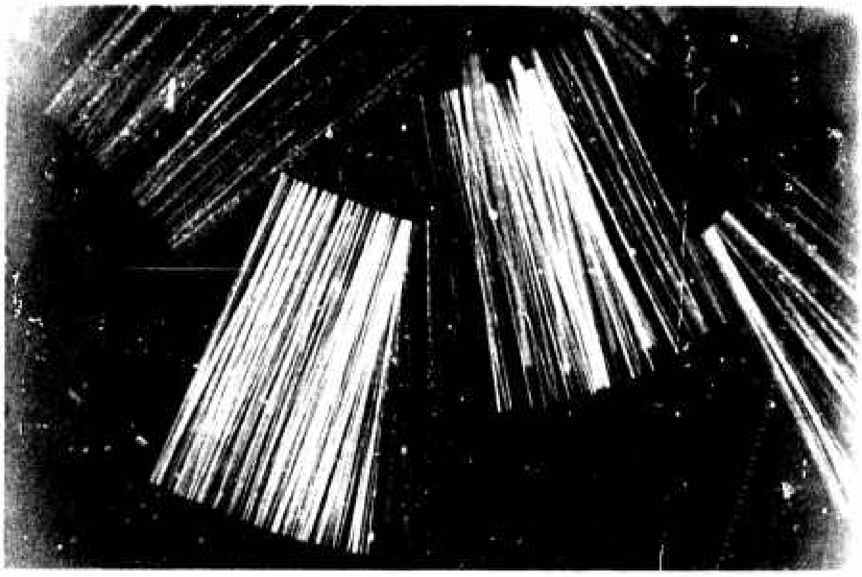

Figure 17. Water Dispersible Size--2 Seconds in Water

REFERENCES

1. Biryukovich, K. L., L. Yu and D. L. Yu, "Flass Fiber Reinforced Cement," Kiev, Budivel'nik, Translated by G. L. Cairn of the Civil Engineering Research Association, London, CERA Translation No. 12 (1965).

2. Grimer, F. J. and M. A. Ali, "The Strengths of Cements Reinforced with Glass Fibers," *Magazine of Concrete Research,* Vol. 21, No. 66 (March 1969), p. 23.

3. Allen, H. G., "Stiffness and Strength of Two Glass Fiber Reinforced Cement Laminates," *Journal Composite Materials,* Vol. 5 (April 1971), p. 194.

4. Maries, A. and A.C.C. Tseung, "Factors Influencing the Strength of Cement/Glass Fibre Composites, *Proceedings of the Materials Conference,* John Wiley & Sons, Baffuns Lane, Chiceser, Sussex (1969).

5. Chan, H. C. and W. A. Patterson, "Effects of Aging and Weathering on the Tensile Strength of Glass Fibre Reinforced High Alumina Cement," *Journal of Material Science*, Vol. 6 (1971), pp. 342-346.

6. Majumdar, A. J. and J. F. Ryder, "Glass Fiber Reinforcement of Cement Products," *Journal of Glass Technology,* Vol. 9, No. 3 (June 1968), pp. 78-84.

7. Goldfein, S., "Plastic Fibrous Reinforcement for Portland Cement," U.S. Army Engineer Res. & Div. Labs. AERDL TR1757TR (October 1963), p. 16.

8. Abbud-Klink, S. A., "FYCRETE, A New Material for Structures," Ph.D. Dissertation, Rensselaer Polytechnic Institute, Troy, N. Y. (November 1967).

9. Agbim, C. C., "Concrete Reinforced with Glass Fibers," *Magazine of Concrete Research,* Vol. 16, No. 49 (December 1964).

10. Majumdar, A. J., "Glass Fibre Reinforced Cement and Gypsum Products," *Proceedings, Royal Society,* London, A319 (1970), pp. 69-78.

11. Majumdar, A. J. and J. F. Ryder, "Reinforcement of Cements and Gypsum Plasters by Glass Fibres," *Science of Ceramics,* Vol. 5 (1970), pp. 539-564.

12. Thomas, J.A.G., "Glass-Fibre-Reinforced Cement," *Composites,* (June 1971), pp. 95-97.

13. DeVekey, J. C. and A. J. Majumdar, "Interfacial Bond Strength of Glass Fibre-Reinforced Cement Composites," *Journal of Material Science*, Vol. 5, No. 2, pp. 183-5.

14. Allen, H. G., "The Fabrication and Properties of Glass Reinforced Cement," *Composites* (September 1969), pp. 19-24.

15. "Surface Bonding - A Technique for Erecting Concrete Block Walls Without Mortar Joints," U. S. Department of Agriculture, Athens, Georgia, CA-42-57 (January 1970).

16. "Fiberglas Surface Bonding from Owens-Corning Fiberglas," Publication 1-SB-5433, Owens-Corning Fiberglas Corporation, Toledo, Ohio 43659.

17. "How to Work with Bloc/Bond," Publication 1-SB-5734, Owens-Corning Fiberglas Corporation, Toledo, Ohio 43659.

PREDICTION OF THE FLEXURAL STRENGTH PROPERTIES OF STEEL FIBROUS CONCRETE

by

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Presented at
CERL Fibrous Concrete Conference:
"Fibrous Concrete--Construction Material for the Seventies"
Champaign, Illinois
May 1972

ABSTRACT

The presentation on "Flexural Strength Predictions" will describe our research on the effect of wire parameters, length, diameter, and quantity on the flexural strength of mortar and concrete. Formulas have been described for calculating the amount of any wire required to achieve a given level of flexural strength. Background limitations on the formulas will be discussed.

PREDICTION OF THE FLEXURAL STRENGTH PROPERTIES OF STEEL FIBROUS CONCRETE

by

Dr. David R. Lankard

INTRODUCTION

Research carried out over the last 10 years has demonstrated that the addition of steel fibers to mortar or concrete results in improvements in many of the engineering properties of these materials. Of particular importance regarding applications is the fact that the flexural strength of steel fibrous concrete* is significantly higher than that of the same concrete without fibers. In addition, the behavior of steel fibrous concrete during flexural loading is quite different from plain concrete. These differences are illustrated in Figure 1, which shows a typical load-deflection curve for a steel fibrous mortar beam subjected to a flexural load.

1. The steel fibrous mortar (or concrete) exhibits a deviation from linear load-deflection behavior prior to the achievement of the ultimate flexural load (unlike plain concrete). The point of deviation from linearity has been called, among other things, the first-crack load or proportional limit. There is still disagreement regarding the significance of the point of deviation from load-deflection linearity from a phenomenological viewpoint. The magnitude of the difference between the first-crack and the ultimate flexural load depends to a large extent on the quantity and type (length and diameter) of the fiber addition.

2. Once the deflection corresponding to the ultimate flexural load of plain concrete is exceeded, the concrete fails catastrophically. This is not, in general, true for fibrous

---

* Portland cement concrete containing short lengths of randomly dispersed steel wire fibers is covered by U. S. Patents 3,429,094 and 3,500,728 and is trademarked Wirand^R concrete by Battelle Development Corporation, Columbus, Ohio.

concrete which continues to sustain considerable loads even at deflections considerably in excess of the fracture strain (deflection) of the plain concrete.

3. The fatigue endurance limit of steel fibrous concrete in flexure is reportedly 80 to 90 percent of the first crack flexural strength, while that of plain concrete is only 50 to 60 percent. This situation obviously has significant implications regarding the use of steel fibrous concrete under dynamic loading conditions.

Some of the earliest published work on the strength of steel fibrous concrete was that of Romualdi, et al., in 1963 and 1964.[1,2,3] These researchers showed that the presence of high strength, high elastic modulus steel fibers in the concrete substantially increased its tensile strength, and further proposed that the function of the fibers was one of crack arrest. They reasoned that the stress required to extend a crack in the concrete beyond the area enclosed by adjacent groups of fibers was inversely proportional to the square root of the fiber spacing. The fracture mechanics concepts used in the development of this theory were covered in detail in their papers. It was claimed that the effect of the fibers on the tensile strength of concrete becomes quite significant at fiber spacings below about 0.5 in. even when the fibers are short and randomly oriented. The theoretical strength-spacing relationship suggested for steel fibrous concrete is depicted in Figure 2, along with experimental data obtained by Romauldi, et al. In this case, spacing was calculated as the average spacing between the geometrical center of randomly oriented fibers in a concrete matrix using the formula:

$$S = 13.8\ D\sqrt{\frac{1}{\rho}} \qquad (1)$$

where S = average spacing, in.
D = wire fiber diameter, in.
ρ = volumetric fiber content, percent.

Investigations by other researchers[4] of the strength-spacing relationship have not always produced the same results as are illustrated in Figure 2. In some instances the strength ratios (steel fibrous concrete/plain concrete) were well below that predicted by the theoretical curve of Figure 2, and in others the strength ratio at very low fiber spacing (<0.10 in.) was less than that observed at somewhat higher spacing as shown in Figure 3. An explanation for the latter behavior was offered recently by the author, et al.[5] It was suggested that the fall-off in strength in fibrous concrete at very low fiber spacings may be related to the decrease in workability and ease of consolidation of the fibrous concrete as more fibers (or fibers with large aspect ratios) are added.

It was suggested that many factors can influence the first-crack strength and ultimate flexural strength of steel fibrous concretes in addition to the length, diameter, and quantity of the steel fibers, including:

1. The degree of consolidation of the matrix which is influenced by the
    a. Water cement ratio,
    b. Consolidation technique,
    c. Type and amount of fiber.
2. The uniformity of fiber distribution which is influenced by the workability of the mix. Fiber distribution is also influenced by the water cement ratio, the consolidation technique, and the type and amount of fiber, as well as the mixing procedures used.
3. The surface condition of the fiber. A hydrophobic film on the fiber surface can prevent the development of an adequate fiber-matrix bond.

Aside from the practical limitations just discussed, a serious shortcoming of the strength-spacing relationship is the fact that it does not take into account the effect of fiber length on the flexural strength of steel fibrous concrete.

With a view toward providing a more rational guide for the prediction of the flexural strength properties of steel fibrous concrete, an attempt was made to identify the functional relationship between the main fiber parameters, quantity, diameter and length, and the flexural strength of the concrete.

PRACTICAL CONSIDERATIONS

Experience with the performance of steel fibrous concrete subjected to flexural loading suggested that one approach to the problem might be through a consideration of the bond area of the fibers in the fracture plane.

For purposes of this investigation, an "effective fiber bond area" (B) was defined as the surface area of all the fibers contained in the fracture plane of a beam-shaped flexural specimen and was calculated as follows

$$B = nA \qquad (2)$$

where B = effective fiber bond area, in.^{2}
n = number of fibers in the fracture plane of a beam in bending
A = surface area of a fiber of length (x) and diameter (D), in.^{2}

The surface area (A) of a round fiber is $A = \pi Dx$ (neglecting the ends of the fibers).

The calculation of the number of fibers (n) in the fracture plane (or any plane) requires some approximations and was arrived at as follows.

First, it was assumed that the fibers in the beam specimen were distributed as shown in Figure 4. The total number of fibers in the specimen (N) can be calculated as

$$N = \text{total number of fibers in specimen} = W/w$$

where W = total weight of fibers in beam specimen, grams, and
w = weight of one fiber of length (x) and diameter (D), grams.

The number of concrete volumes (fiber subunits [U]) defined by the thickness and width of the specimen and the length of the fibers (x) is then approximated as

$$U = \text{fiber subunits in specimen} = L/x$$

where L = length of beam specimen, in.
x = length of fiber, in.

Thus, the fibers contained in a given cross-sectional plane in the beam specimen (n) are approximated as

$$n = N/U$$

Substituting in Equation 1 gives

$$B = \left(\frac{W/w}{L/x}\right)\left(\pi Dx\right) = \pi Dx^2 \frac{W}{Lw} \tag{3}$$

Expressing B in terms of in.^{2} of fiber bond area per in.^{2} of fracture surface, Equation 2 becomes

$$b = B/a = \frac{\pi Dx^2 W}{Lwa} \tag{4}$$

where a = cross-sectional area of fracture surface in beam specimen (in.^{2}), and the units for b are in.^{2}/in.^{2}.

Initially, calculations were made using Equation 3 on existing flexural strength data obtained on 2-1/2 by 3 by 16 in. beam specimens of steel fibrous mortar (1.0 part cement:2.4 parts sand, w/c = 0.45) that had been steam cured for 7 days. The calculated fiber bond area data were plotted against ultimate flexural strength (shown in Figure 5) and, as can be seen, strongly indicated that a relationship between these variables did exist. This led to a decision to investigate the predicted relationship in a systematic manner.

EXPERIMENTAL PROCEDURE

Materials

All specimens were made using a mortar formulation consisting of 1.0 part cement to 2.4 parts of concrete sand at a water cement ratio of 0.45. The cement was from a single lot of Type I portland cement. The washed glacial sand used in the study was also from a single lot and had a fineness modulus of 3.0, a specific gravity (SSD) of 2.59, and an absorption of 2.55 percent.

All wire fiber used in the study was from a single lot of high carbon steel and was prepared especially for this project by the National Standard Company, Niles, Michigan.

Batch and Specimen Preparation

Mortar batches (1-1/2 ft^3) were prepared as follows:

1. The mortar (sand, cement, water) was prepared in a 3.0 ft^3 drum-type mixer.

2. Thirty pounds of mortar were taken from the batch and used in the determination of mortar unit weight and in the preparation of three beam specimens (2.5 by 3.0 by 16.0 in.).

3. Steel fiber in the desired quantity was added to the remaining mortar by hand dispersing the fiber into the rotating mixer. After all the fiber had been added, mixing was continued until a uniform dispersion was achieved.

4. Ten beam specimens (2.5 by 3.0 by 16.0 in.) were made from the fiber containing mix. Each beam was prepared from

individually weighed quantities of mix so as to achieve exactly the same amount of material in each beam. Light external vibration (60 cps) was used in the preparation of all specimens (including the plain mortar specimens).

5. Two beams from each batch were dumped on a 0.25 in. sieve shortly after casting (before any set occurred), and the mortar was washed away to determine the actual amount of fiber in each beam relative to that computed (fiber washout study).

6. The entrapped air content of the mix after addition of the steel fiber was determined using the pressure method (ASTM C231).

7. All specimens were cured in the molds in fog at 73 F for 24 hours.

8. After demolding, the beam specimens were cured in low pressure steam (140 F) for 7 days prior to study.

A complete description of the batches prepared in the study and the properties and other pertinent information on the fresh mixes are presented in Table 1.

Strength Measurements

Flexural strength measurements were made on the beam specimens using the center-point-loading technique on a span of 15 in. The long span was chosen to magnify the deflection of the steel-fiber-containing specimens during loading. All measurements were made using a 60,000 lb capacity Baldwin Universal Testing Machine and a loading rate of 0.04 in. per minute. Complete load-deflection records were obtained for each specimen tested (deflection recorded autographically as platen head travel).

EXPERIMENTAL RESULTS

Flexural Strength

Data obtained on the first-crack and ultimate flexural strength of the beams are presented in Table 2 and shown graphically in Figures 6 and 7. It appears that for the fiber types and quantitites studied, a linear relationship exists between ultimate flexural strength (σ_{ult}) and the effective fiber bond area and between first-crack flexural strength (σ_{fc}) and effective fiber bond area.

Table 1. Batch Identification and Properties of Fresh Steel Fibrous Concrete (1.0 Cement:2.4 Sand)

Batch Identification	Fiber Parameters			Calculated(a) Effective Fiber Bond Area, $in.^2/in.^2$	Unit Weight of Mortar Without Fiber, lb/ft^3	Air Content of Mortar With Fiber, Volume percent	Fiber Washout, gms.		
	Dia. in.	Length in.	Quantity, Volume Percent				Measured, Beam #1	Measured, Beam #1	Calculated
A	0.010	1.0	0.72	3.0	137.3	4.6	122	108	111
B	0.010	1.0	1.44	6.0	137.8	5.0	225	246	222
C	0.010	1.0	2.16	9.0	137.1	5.3	301	374	333
D	0.010	1.0	2.88	12.0	134.8	4.8	495	563	444
E	0.016	1.0	2.23	6.0	135.3	4.8	392	370	344
F	0.010	0.5	1.46	3.0	135.6	5.2	237	236	222
G	0.0059	0.5	2.36	9.0	136.1	4.8	319	404	364
H	0.020	1.5	2.72	9.0	137.8	4.2	429	431	420

(a) As per Equation 3, page 106.

Table 2. Flexural Strength Properties of Plain and Fiber-Containing Mortar Beams

Batch Identification	Fiber Parameters			Effective Fiber Bond Area, b, $in.^2/in.^2$	Ultimate Flexural Strength of Mortar, psi	Flexural Strength of Fiber Mix, psi		Ratio of Ultimate to First Crack Strength
	Dia., in.	Length, in.	Quantity, Volume Percent			First Crack	Ultimate	
A	.010	1.0	0.72	3.0	890	1100	1140	1.03
F	.010	0.5	1.44	3.0	905	1115	1130	1.01
B	.010	1.0	1.44	6.0	970	1630	1925	1.18
E(a)	.016	1.0	2.23	6.0	865	1205	1424	1.18
C	.010	1.0	2.16	9.0	975	1845	2410	1.31
G	.0059	0.5	2.36	9.0	920	1970	2350	1.20
H	.020	1.5	2.72	9.0	860	1920	2510	1.31
D(b)	.010	1.0	2.88	12.0	860	1830	2160	1.18

(a) The uniformity of fiber distribution was not good in beams made with this mix.

(b) Beams made from batch D were manifestly faulty. This mix was not workable at a w/c ratio of 0.45 which resulted in large air voids in the beams as well as poor fiber distribution.

Table 3. Flexural Strength of Steel Fibrous Concrete (1.0 Cement:2.4 Sand) Mixes Having Identical Effective Fiber Bond Area

Batch Identification	Fiber Parameters			Effective Fiber Bond Area (b) $in.^2/in.^2$	Ultimate Flexural Strength of Mortar, psi	Flexural Strength of Fiber Mix, psi	
	Diameter, in.	Length, in.	Quantity, v/o			First Crack	Ultimate
1	0.010	1.5	1.23	7.5	895	1330	1765
2	0.016	1.5	1.94	7.5	900	1590	1840
3	0.020	1.0	3.47	7.5	800	1575	1720
(Mixed Fiber) 4	0.020 0.010	1.0 1.0	1.73 0.86	7.5	825	1485	1670
(Mixed Fiber) 5	0.0059 0.016 0.020	0.5 1.0 1.5	0.63 0.93 0.76	7.5	905	1485	1700

Significantly, the plots of σ_{ult} versus b do not extrapolate back through the strength of the plain mortar. For the conditions of the present investigation, it is indicated that fiber additions resulting in effective fiber bond areas of about 1.5 in.^{2}/in.^{2} or less would provide no improvement in either σ_{ult} or σ_{fc} relative to the plain mortar.

Subsequently five more mortar batches were prepared which all had a calculated b of 7.5. Flexural strength measurements on these specimens are presented in Table 3. As can be seen, two of the batches were mixtures of two or three fiber types proportioned so as to yield a total b of 7.5. Although the absolute values fall somewhat below the curves of Figures 6 and 7, it is obvious that the level of flexural strength is about equal for the five mixes.

Load-Deflection Behavior

The load-deflection behavior of steel fibrous mortar beams having the same calculated fiber bond area was similar for deflections up to the deflection at ultimate flexural strength (as witness the same σ_{fc} and σ_{ult}) for beams with equal b independent of the type of fiber used. The post ultimate load-deflection behavior, however, was influenced by the length of the fibers as shown in Figure 8. Logically, the rate of load (σ) decreases with increasing deflection (ε) after ultimate has been exceeded ($d\sigma/d\varepsilon$) should be proportional to the rate of decrease of effective fiber bond area (b) with increasing deflection ($-db/d\varepsilon$). Thus, the rate of fall-off of load after ultimate should increase as fiber length is decreased (assuming constant D and v/o). For the mixes shown in Figure 8, it is expected that the highest $db/d\varepsilon$ should be exhibited by the mix containing 0.5 in. long, 0.006 in. in diameter fibers (Specimen G9).

DISCUSSION AND CONCLUSIONS

1. A method of calculating the effective fiber bond area for a steel fibrous concrete beam in bending has been derived. The equation used in the calculation of fiber bond area includes the three primary fiber variables, viz., length, diameter, and quantity.

2. For the mortar mix studied, a linear relationship existed between the ultimate flexural strength (σ_{ult}) of a beam in bending and the effective fiber bond area (b).

3. For the mortar mix studied, a linear relationship existed between the first-crack flexural strength (σ_{fc}) of a beam in bending and the effective fiber bond area (b).

4. It is expected that a linear relationship between σ_{ult} versus b and σ_{fc} versus b will exist for other mortar and concrete mixes, assuming an adequate fiber-matrix bond is developed and the workability of the mix is adequate.

5. The factors affecting the absolute values of the suggested effective fiber bond area of steel fibrous concrete include:

   a. The age of the specimen at testing,

   b. The water cement ratio of the mix,

   c. The cement factor of the mix,

   d. The aggregate size and gradation,

   e. The cement source,

   f. The uniformity of fiber dispersion,

   g. The type of tensile or flexural test used,

   h. The bond strength.

6. For the mortar mix studied there was an indication that a critical effective fiber bond area exists below which no increase in either σ_{fc} or σ_{ult} is achieved relative to the plain mortar.

7. The relationships derived for a beam specimen can be extended to cover all cases by considering that the volume of steel fiber (V) in any concrete specimen is

   $$V = N\left(\frac{\pi D^2 x}{4}\right) = \frac{W \ \pi D^2 x}{4w}$$

   and, the volume percent of fibers (p) is

   $$p = \frac{V}{La} \times 100.$$

   Substituting the volume relationship

   $$p = \frac{25 \ \pi D^2 \times W}{Lwa}$$

and further substituting the expression for p into Equation 3 yields

$$b = \frac{p}{25}\left(\frac{x}{D}\right) \text{ or more generally,}$$

$$b \; \alpha \; p \left(\frac{x}{D}\right)$$

8. The practical limitations that limit the applicability of the derived relationship must be kept in mind. Thus, while calculations show that 0.010 in. ϕ by 2.0 in. fiber may be suitable for a given application, it may not be possible to properly consolidate a mix containing this fiber if the loading is too high, resulting in low strength values. Workability (or lack of it) will still have to be experimentally determined.

Hopefully, the information contained in this paper will provide a means for more rational mix design and the minimization of fiber costs in steel fibrous concrete.

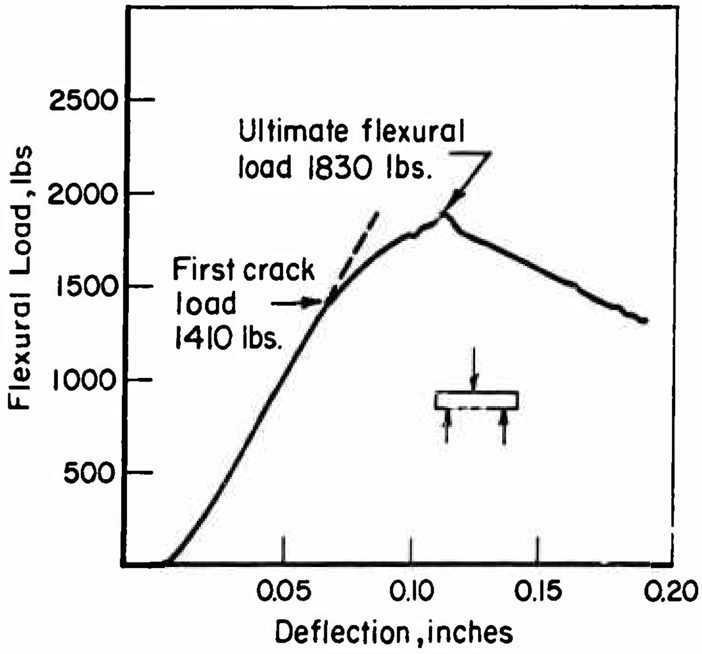


Figure 1. The Load-Deflection Behavior of Steel Fibrous Concrete

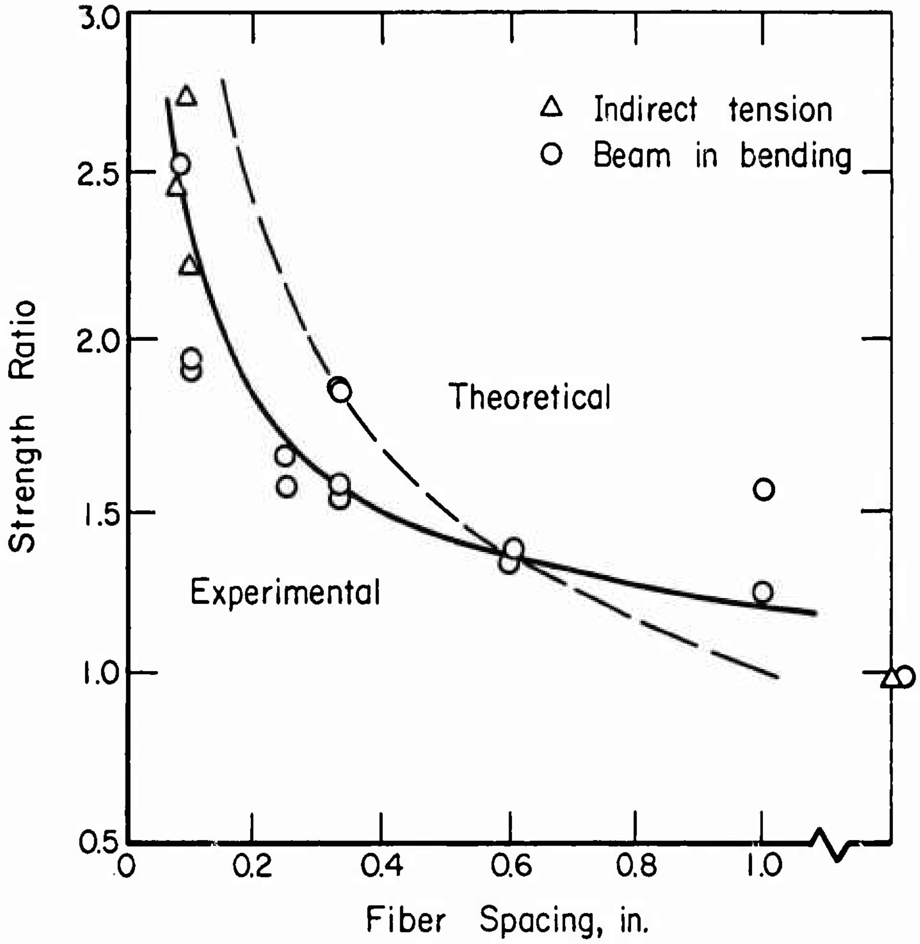


Figure 2. Theoretical and Experimental Strength Ratio (Steel Fibrous Concrete/Plain Concrete) as a Function of Fiber Spacing

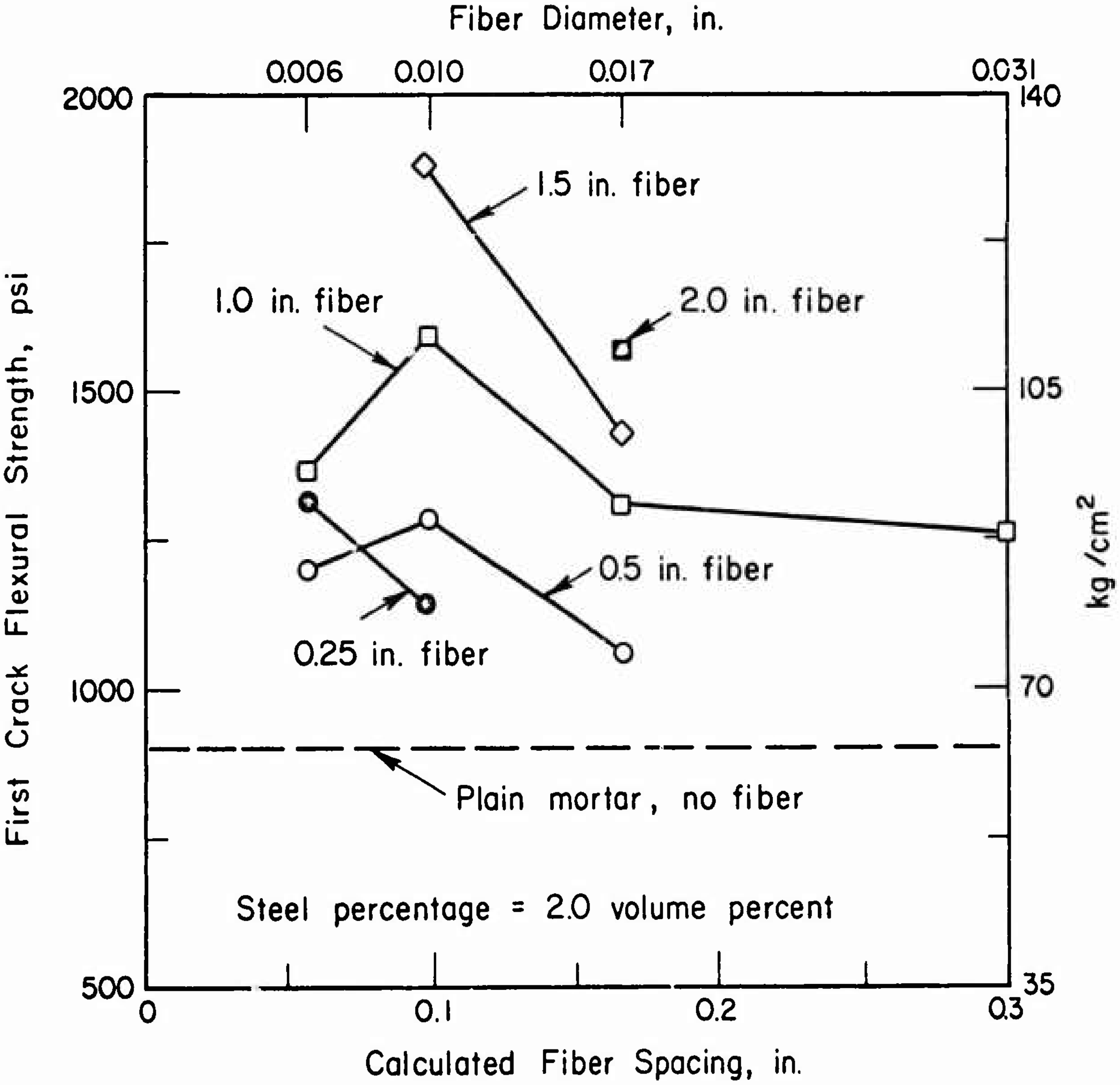
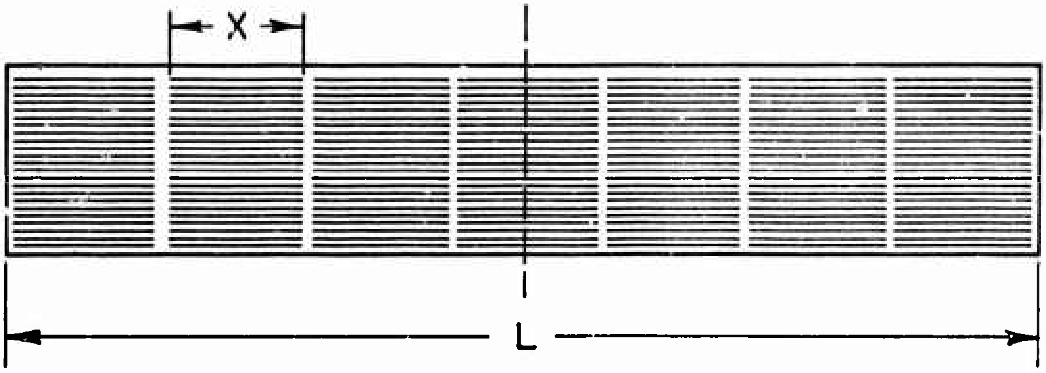


Figure 3. Effect of Spacing on First-Crack Flexural Strength of Fiber-Containing Mortar



Fiber subunits: $U = L/X$

N = total number of fibers

$n = N/U$

Figure 4. Approximation of Fibers Contained in the Fracture Plane of a Flexural Beam

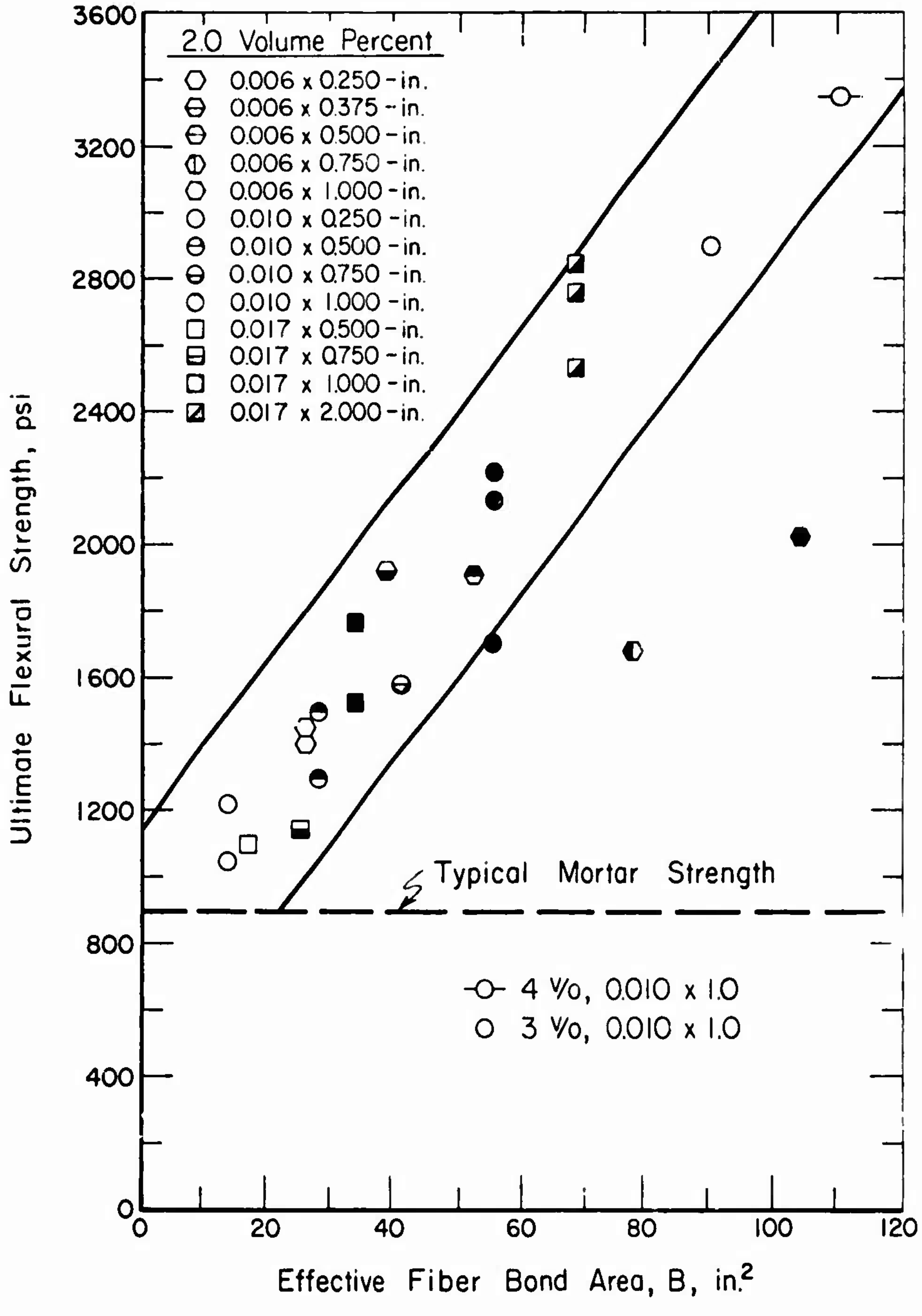


Figure 5. Effect of Effective Fiber Bond Area on the Ultimate Flexural Strength of Steel Fibrous Concrete (1.0 Cement:2.4 Sand Mix)

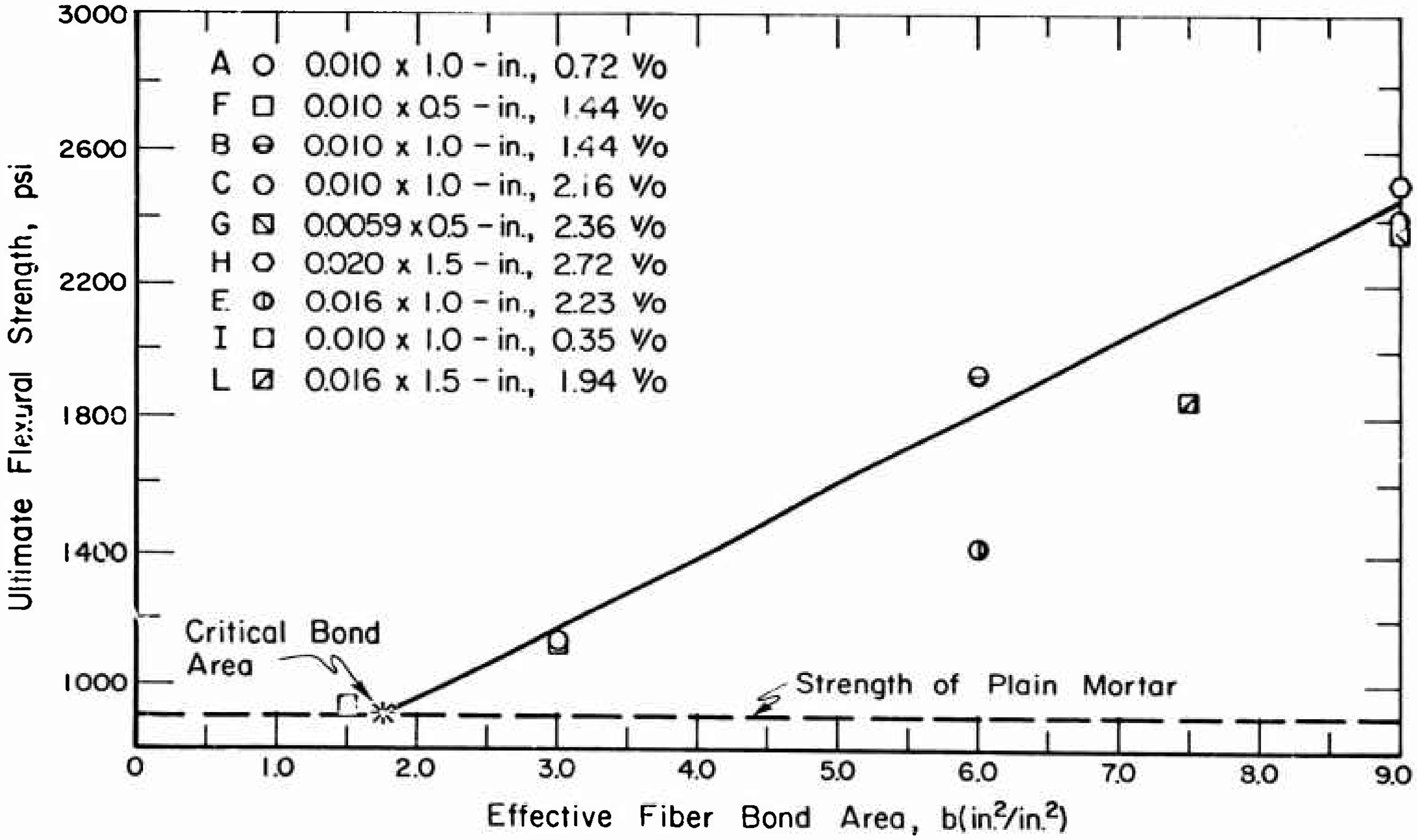


Figure 6. Effect of Fiber Bond Area on the Ultimate Flexural Strength of Steel Fibrous Concrete (1.0 Cement:2.4 Sand) Specimens (2-1/2 by 3 by 16-in.), Center Point Loaded

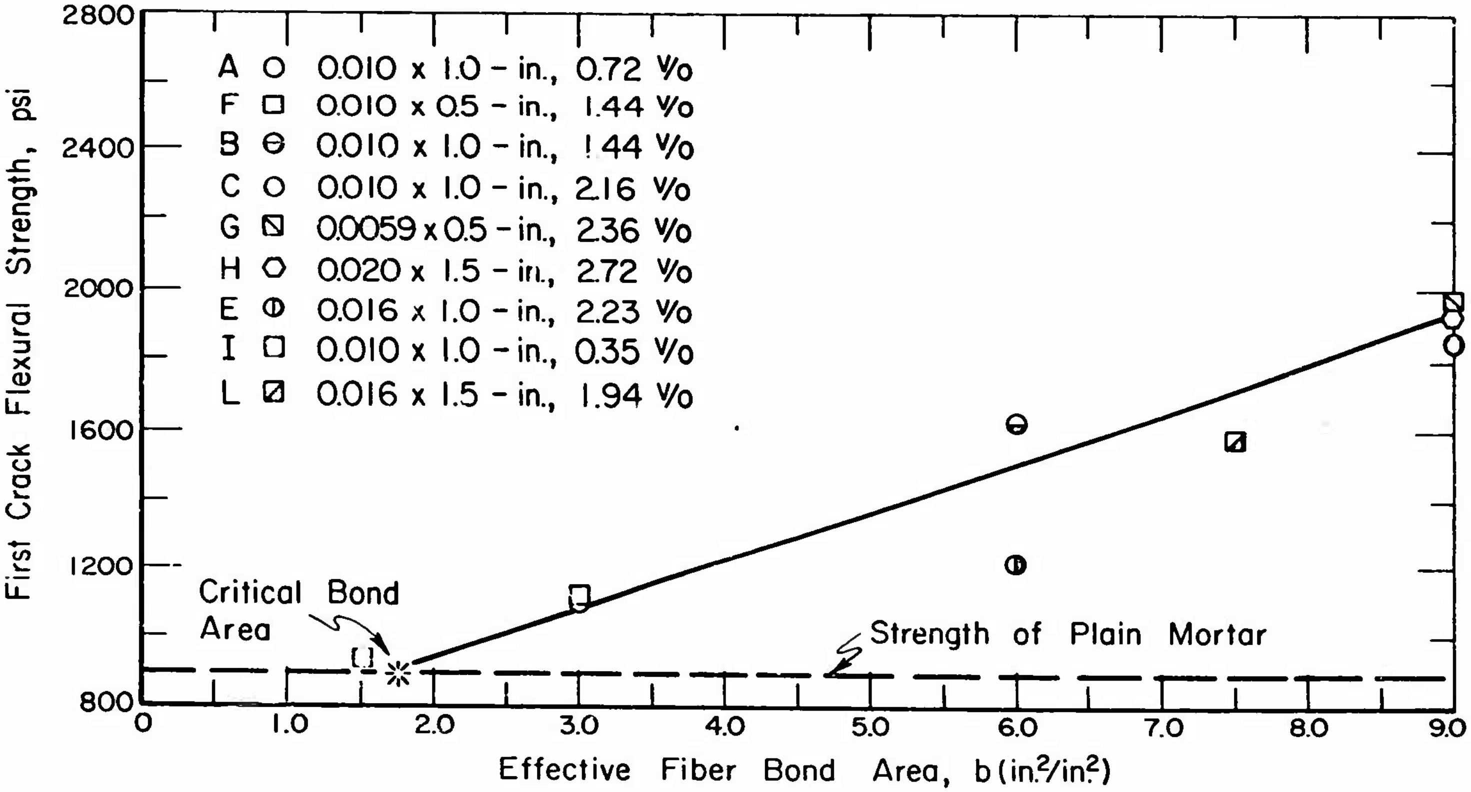


Figure 7. Effect of Fiber Bond Area on the First-Crack Flexural Strength of Steel Fibrous Concrete (1.0 Cement:2.4 Sand) Specimens (2-1/2 by 3 by 16 in.)

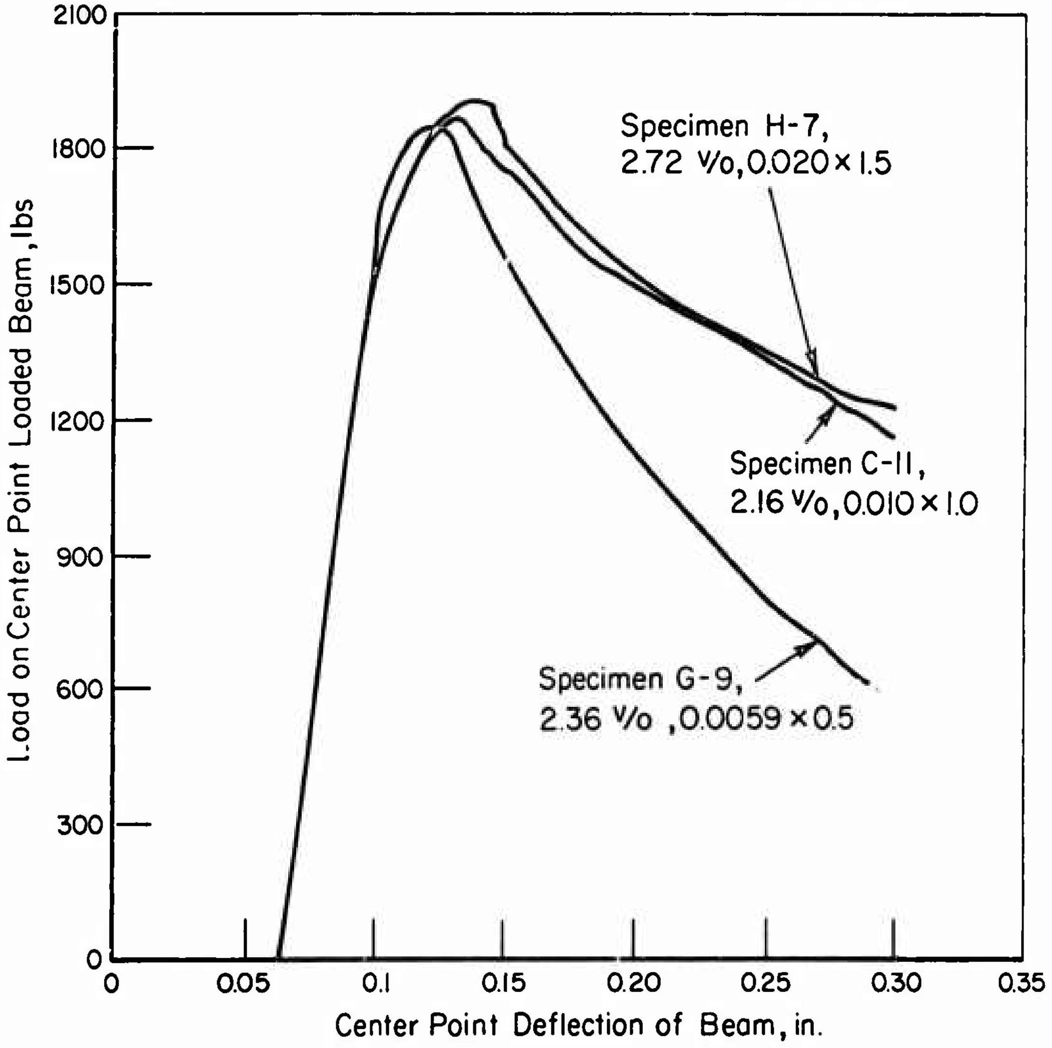


Figure 8. Load-Deflection Behavior of Steel Fibrous Concrete (1.0 Cement:2.4 Sand) with the Same Effective Fiber Bond Area (b = 9.0 in.^{2}/in.^{2})

REFERENCES

1. Romualdi, J. P., and G. B. Batson, "Mechanics of Crack Arrest in Concrete with Closely Spaced Reinforcement," *Proceedings*, ASCE, V. 89, EM3 (June 1963), pp. 147-168.

2. Romualdi, J. P., and G. B. Batson, "Behavior of Reinforced Concrete Beams with Closely Spaced Reinforcement," *ACI Journal*, Proceedings V. 60, No. 6 (June 1963), pp. 775-790.

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

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

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

STEEL FIBER REINFORCED REGULATED-SET CONCRETE

by

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ABSTRACT

This paper contains preliminary results of a study on wire fiber reinforced concrete made with high, very early strength regulated-set cement. This material has been proposed for tunnel linings which are placed by a slipform immediately behind an excavating machine. Regulated-set cement is a new portland cement which can be regulated to set between 2 and 45 minutes. Its long-term properties are similar to conventional portland cement, but the compressive strength of plain mortar can be greater than 1000 psi one and one-half hrs after mixing. With 1-1/2 percent fiber, the corresponding flexural strength is about 300 psi. The strength-time relationship is critically dependent upon the mixing temperature and the dosage of citric acid as a retarder and these relationships are discussed. The many practical difficulties associated with a handling time of 1/2 hr or less are discussed. The future application of this material requires that it be pumpable. Preliminary results of successful laboratory and field pumping tests on wire fiber reinforced concrete made with Type 1 cement are discussed.

STEEL FIBER REGULATED-SET CONCRETE

by

Harvey W. Parker

INTRODUCTION

Steel fiber regulated-set concrete is a combination of two materials--fiber reinforced concrete and regulated-set concrete. This combination of materials was proposed in the fall of 1970 during a search for materials suitable for a continuously-placed tunnel liner. Steel fiber reinforced concrete is the principal subject of this conference so the reader is referred to the many excellent papers describing the material. The fiber used in the studies described in this paper is manufactured by the U.S. Steel Corporation; has a rectangular cross section, 10 mil by 22 mil; and is 1-in. long. Regulated-set cement is a new portland cement patented by the Portland Cement Association.

Practical development of steel fiber regulated-set concrete is presently being conducted by the Civil Engineering Department of the University of Illinois at Urbana-Champaign for the Federal Railroad Administration. Background data leading up to this stage of our research are presented in greater detail in earlier published reports.[1,2] This research includes mix design studies, laboratory and field pumping tests, and large-scale tests on rings 10 ft in diameter, 6-in. thick and 6-ft long to evaluate structural behavior.

SLIPFORMED TUNNEL LINING

Introduction

One of the most promising innovative tunnel support systems appears to be that of thin, high-strength permanent lining continuously extruded behind a tunneling machine. A continuous excavator which can simultaneously place the permanent lining has been a long-standing dream of the tunneling profession and several attempts have been made toward this goal. The Extruded Liner System (ELS) is a new concept to achieve this goal by slipforming a lining composed of a previously untried material. A patent disclosure has been submitted on this system.

This system, which can be adapted to both soil and rock tunnels, has several advantages. The extruded liner provides rapid uniform ground support and permanent lining of the tunnel in a single operation at rates compatible with rapid excavation. Thus, the full mining potential of tunneling machines can be realized in ground which requires immediate support. Rapid advance rates together with the elimination of temporary ground support provides considerable potential for reducing tunneling costs.

Steel fiber regulated-set concrete has properties compatible with rapid slipform construction. It is a reinforced concrete that can be pumped. The set time of the regulated-set cement can be regulated to occur from 2 to 45 minutes by varying several mix conditions. Subsequently, there is a rapid gain of strength to a level of about 1000 psi or greater within one to two hours after mixing. Hence, even with a short slipform, this early strength of the extruded liner is adequate for structural support of the tunnel walls at rates of advance of modern tunneling machines. In the development of this system, there is a strong interaction between operating requirements of the machine and the capabilities of the lining material. There must be some flexibility in the timing of the operating cycle of the machine and in the setting time and rate of hardening of the concrete to allow for minor changes in the rate of advance of the machine. In the event of a stoppage, emergency procedures are necessary to dump previously mixed concrete before it sets. Because of these complications, the tentative criteria proposed for the mix design studies for the concrete require a handling time of 30 minutes and a rate of gain of strength to achieve a compressive strength of 1000 psi one and one-half hours after mixing. Thus our studies have been largely confined to the early behavior of the concrete.

Regulated-Set Concrete

Regulated-set cement is not a mixture of cements or an admixture, but is a portland cement with some new ingredients blended in the kiln. The principal difference between reg-set and ordinary portland cement is that regulated-set cement contains a new ingredient, calcium flouroaluminate, which provides the very high early strength.

Initial and final set occur very soon after mixing for reg-set mixes. The term "handling time" is defined as the maximum time before the concrete must be in its final position. Regulated-set concrete has a controlled handling time which can be varied between 2 and 45 minutes. This regulation can be achieved when the cement is manufactured by blending different proportions of the early strength component, and also in the field by the use of retarding additives or by changing the temperature of the mix.

Even without additives, regulated-set concrete will develop a compressive strength of 1000 psi or more as early as 1-1/2 hrs after mixing.

This early strength is directly proportional to the percentage of calcium flouroaluminate in the cement. An increased percentage of the high early strength component causes a higher early strength and a shorter handling time. The various cement companies which have manufactured reg-set cement have formulated their cement not to any national standard, but to their own specifications. Thus, the behavior and properties of reg-set cement vary according to its source.

Figure 1 shows comparative curves of compressive strength versus logarithm of time for mortars made with Type I, Type III, and regulated-set cements. The regulated-set cement exhibits a rapid gain in strength within one or two hours to a level which is dependent on the percentage of the high early strength component in the cement. The strength development of the calcium flouroaluminate is then nearly complete, and little or no strength gain occurs until the normal silicate hydration becomes effective after about one day. The long term strength, the rate of gain of strength after one day, and other physical properties are then comparable to those of concrete made with Type I and Type III cements.

The relationship of strength and durability to water-cement ratio, and the response to additives are similar to portland cement, however regulated-set cement is considerably more sensitive to variations in these parameters. Regulated-set cement is particularly sensitive to the temperature of the mix and to certain retarders such as citric acid, and these characteristics have important practical significance. The sulfate resistance of reg-set cement is reported to be about the same as Type I cement. Sulfate resistance tests are underway.

The handling time of regulated-set concrete is of considerable practical importance. Handling time increases with: lower temperature, addition of citric acid, higher water-cement ratio, lower cement content and continued mixing. In practice, both temperature and citric acid are used to regulate handling time.

Most problems in the practical use of regulated-set concrete are related to the limited handling time. Regulated set concrete has been mixed in batch-type mixers in the laboratory and has even been mixed in a transit mix truck. However, a continuous auger-type mixer is considered essential to the practical and economic application of regulated-set concrete. To provide as long a handling time as possible, the water for the mix should be added at the last possible moment. Conventional batching is just too slow. Also, mixing, placing, finishing, and the clean up of the equipment must all be accomplished within this short handling time. Since the cement reaction initiates on contact with moisture, preblending of the cement and aggregates requires the latter to be air dry.

Applications of regulated-set cement are varied. Examples are cellular roof decks and patching and resurfacing pavements. Slipforming of tunnel linings is promising. Research on shotcrete made with regulated-set cement presently is being conducted by the Illinois Institute of Technology for the Bureau of Mines.

The cost of regulated-set cement is reported to be double the cost of ordinary portland cement. However, it is a new material and as market trends have not been established, the future cost for production quantities is unknown. Furthermore, the cost of the cement is a small percentage of the total unit cost of the finished product.

Steel Fiber Reg-Set Concrete

Steel fiber reg-set concrete is still in the experimental stage and no field applications are known. It has a controllable set time, high very early tensile and compressive strength properties, and substantial post-crack strength (ductile failure mode). Other physical properties of the concrete are similar to those of conventional steel fiber portland cement concrete. Because of the presence of the fiber, some problems can be anticipated in mixing and placing the material in the relatively short handling time available before the cement sets.

The following test data from a recent preliminary series of tests at the University of Illinois illustrate some of the properties of the material. Basic data regarding these mixes is presented in Table 1. The strengths shown are ultimate strengths, not first crack strengths. The handling times reported were measured from the time water was added to the mix and generally correspond to a slump of about 1 in. All results shown are for steel fiber reg-set containing 1-1/2 percent steel fiber by volume of concrete and are for various different mixes made with reg-set cement manufactured by General Cement Company which has a relatively high calcium flouroaluminate content.

The strength versus logarithm of time of one mix of steel fiber reg-set concrete with 7 bags/cu yd is shown on Figure 2. The compressive strength and the flexural strength appear to develop at about the same rate. The compressive strength and flexural strength at the end of 1-1/2 hrs are about 900 psi and 400 psi, respectively; 4400 psi and 1220 psi after 28 days. Typical post-crack behavior at an early age is illustrated by the load-deflection diagram for a beam shown in Figure 3. Tests on stronger concrete at later ages show a rather pronounced peak early in the load-deflection diagram but considerable post-crack resistance is still evident.

A typical effect of mix water temperature is shown on Figure 4. Colder water produces a longer handling time, and less time available for hydration, thereby reducing the 1-1/2 hr strength. Handling time decreases from 22 to 15 min as the temperature varies from 38 to 75 F. One possible use of this temperature behavior would be to mix the concrete with cold water to extend the handling time. Once the concrete is in the slipform, the concrete might be heated to promote initial gain of strength. Figure 5 shows the effects of one type of retarder, citric acid. It appears that for this particular mix at a given temperature, there may be an optimum

Table 1. Mix Data for Steel Fiber Reg-Set Study

	Quantity/cu yd
Cement	650 - 850 lb
Fly ash	up to 300 lb
Sand	up to 2700 lb
3/8-in. Pea gravel	up to 1300 lb
Steel fiber (10 mil x 22 mil x 1-in. long)	200 lb

dosage of citric acid for strength gain (about .125 to .15 percent by weight of the cement for this mix). Larger doses of citric acid tend to drastically reduce the early strength. For the range of citric acid, the handling time at this temperature (65 F) varies from 15 to 25 min. The data on Figures 4 and 5 are for mixes containing 8-1/2 bags of cement/cu yd.

Pumping of Steel Fiber Reinforced Concrete

Steel fiber reg-set concrete is to be pumped into the ELS slipform. Therefore, both laboratory and field pumping tests have been performed to determine its pumpability. Steel fiber reinforced concrete made with Type I cement, not reg-set cement, was successfully pumped through a 4-in. diameter pumping loop about 100-ft long (including 25 ft of flexible hose) which recirculated the concrete back into the hopper of the pump. Both a piston-type and a squeeze-type pump were used. The results of these pumping tests are summarized in Table 2. The piston-type pump successfully pumped concrete with 1 percent steel fiber by volume. Only the squeeze-type machine pumped 1-1/2 percent and neither was successful in pumping concrete with 2 percent wire. If vibration is applied at critical locations, particularly in the hopper, at the "Y," and at the taper reducer, pumping of concrete with 2 percent steel fiber may be feasible. There was evidence that with these measures and a 5-in. diameter line pumping might be successful in both types of pumps.

A laboratory pumping test has also been utilized in the evaluation of the pumpability of fibrous concrete. The machine is a slump cone with a 4-in. pipe welded to the small end and an 8-in. pipe welded to the large end. Concrete is forced from the large end to the small end with a hydraulic jack and pressure measurements are made. Preliminary results of the lab tests are summarized in Table 3.

Table 2. Summary of Field Pumping Tests on Steel Fiber Reinforced Concrete

Steel Fiber (% by volume)	Slump (in.)	Remarks
1	3	Pumped by piston-type pump
1-1/2	7	Piston-type pump unsuccessful; squeeze-type pump was successful
2	6	Neither piston nor squeeze-type pumps were able to pump concrete

Note:

1. Mix data per cu yd = cement - 7 bags
   fly ash - 230 lb
   aggregate - 50% sand, 50% 3/8-in. max
2. Percentage of fiber shown is by total volume of concrete (1% = 132 lb/cu yd). Fiber is 10 mil by 22 mil by 1-in. long.
3. Pumping loop = 4-in. diameter line about 100-ft long.

Table 3. Summary of Laboratory Pumping Tests on Steel Fiber Reinforced Concrete

Steel Fiber (% by vol)	Slump (in.)	3/8-in Pea Gravel (% of total aggregate)	Remarks
1	7	47	Pumped
1-1/2	5	55	Did not pump
1-1/2	5	40	Pumped
1-1-1/2	2-1/2	20	Pumped

Note:

1 percent fiber = 132 lb/cu yd. Fiber is 10 mil by 22 mil by 1-in. long.

The following conclusions can be made from the field and laboratory evaluation of pumping. Design for reg-set mixes should be based on a pumping time of about 30 min. The maximum size aggregate should be 3/8 in. and the percentage of aggregate should be about 25 percent of the total weight of aggregate. One and one-half percent steel fiber can be pumped, but 2 percent is a very harsh mix and will require special measures to pump. Some commercial pumping aids seem promising, but their effect on strength, corrosion of fibers and handling time of the reg-set cement must be evaluated for each case.

ACKNOWLEDGMENTS

This research was performed by the Department of Civil Engineering of the University of Illinois at Urbana-Champaign, Urbana, Illinois. Professor C. E. Kesler contributed his time, experience and advice generously. The basic idea of the material and the Extruded Liner System was developed by Mr. Robert M. Semple. The author gratefully acknowledges Mr. Kai Wong and Mr. Ralph Boirum for their enthusiastic work in the lab and in the field. The project was sponsored by the Federal Railroad Administration, through Contract No. DOT FR 20020, under the technical direction of Mr. William N. Lucke.

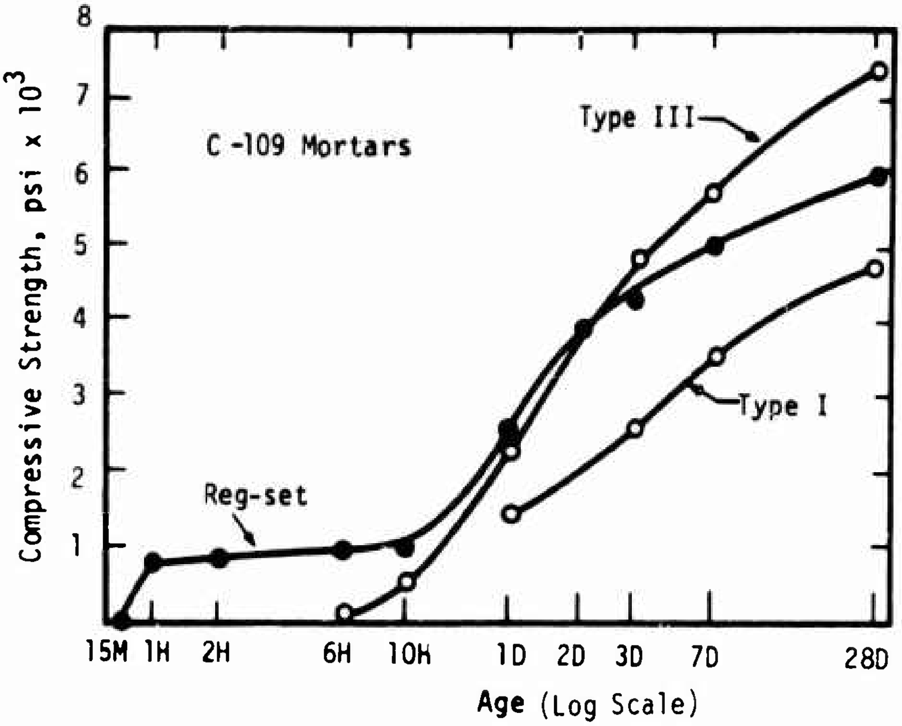


Figure 1. Compressive Strength-Age Relation for Reg-Set and Normal Portland Cement Mortars (after PCA)

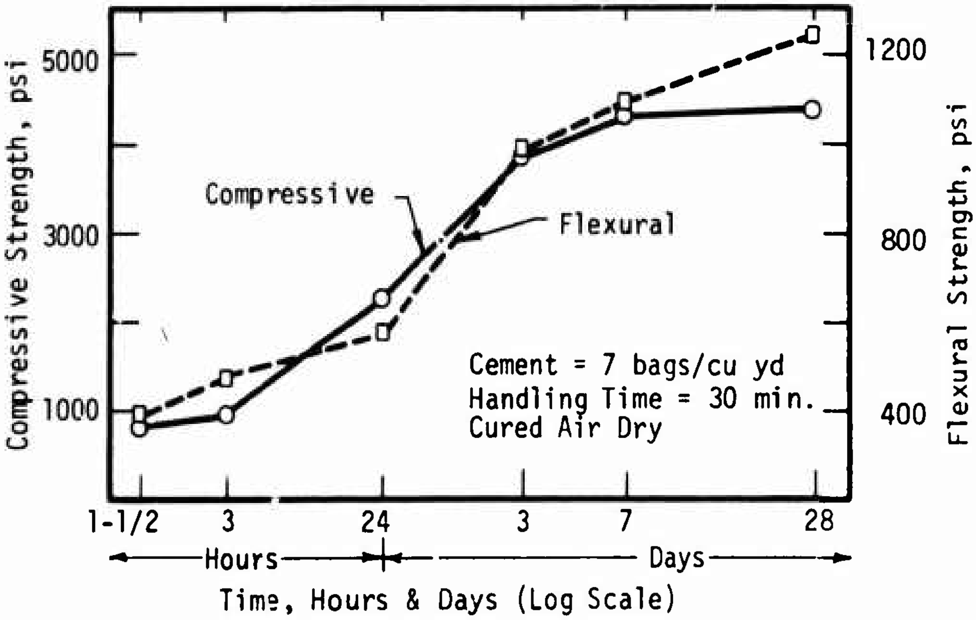
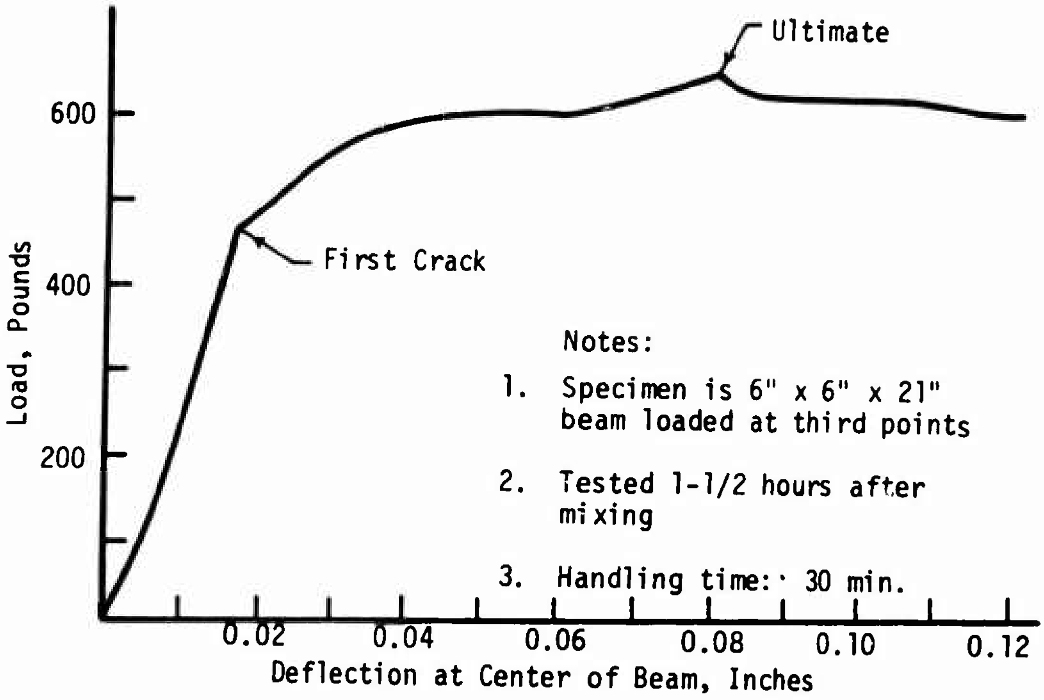


Figure 2. Typical Compressive and Flexural Strength Versus Age Relations for Steel Fiber Reg-Set Concrete



Notes:

1. Specimen is 6" x 6" x 21" beam loaded at third points
2. Tested 1-1/2 hours after mixing
3. Handling time: 30 min.

Figure 3. Typical Load-Deflection Curve at Early Age for Steel Fiber Reg-Set Concrete Beam with 1-1/2 Percent Steel Fiber

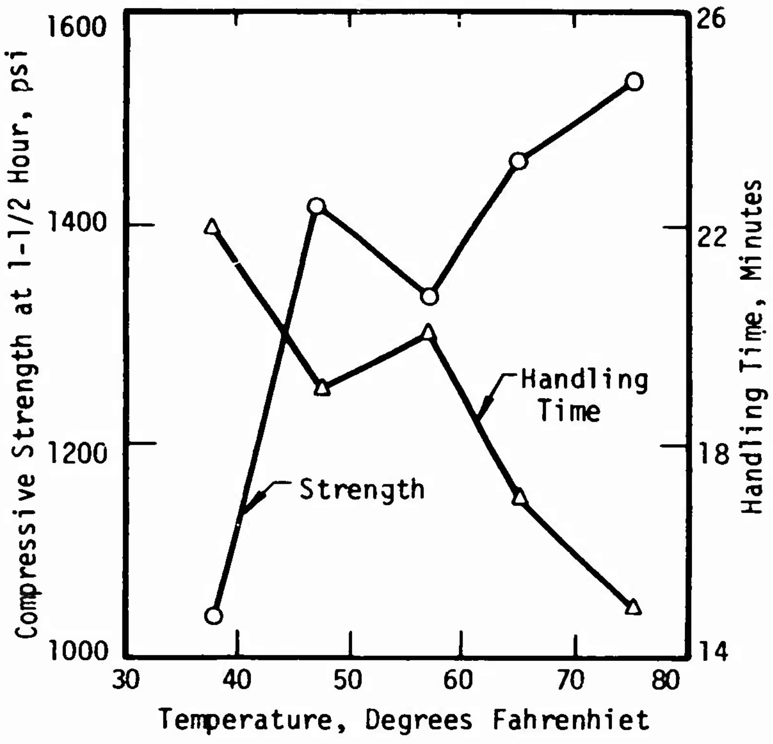


Figure 4. Typical Effect of Mix Water Temperature on Handling Time and Early Strength of Steel Fiber Reg-Set Concrete

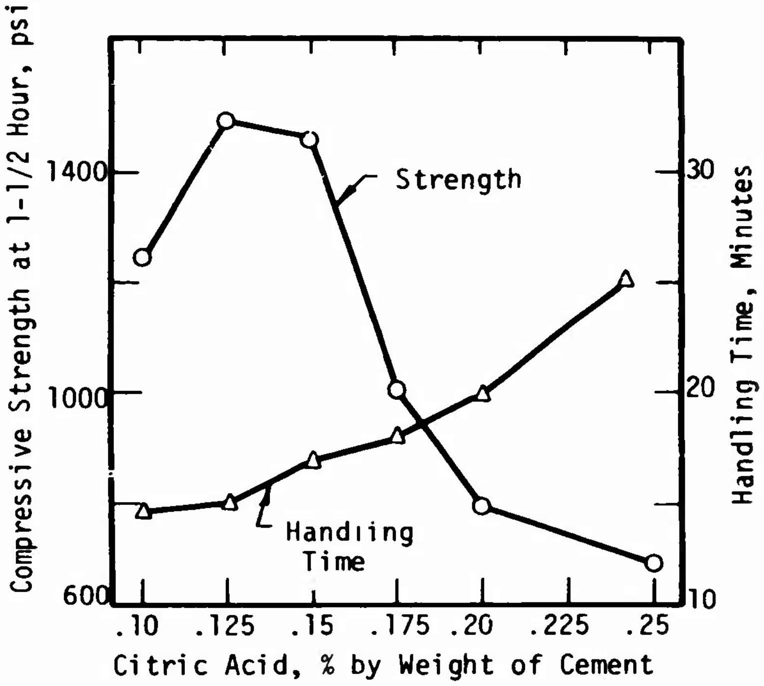


Figure 5. Typical Effect of Citric Acid on Steel Fiber Reg-Set Concrete

REFERENCES

1. Parker, H. W., Semple, R. M., Rokshar, A., Febres-Cordero, E., Deere, D. U. and Peck, R. B., "Innovations in Tunnel Support Systems," Report No. FRA-RT-72-17, May 1971, Office of High Speed Ground Transportation, Federal Railroad Administration (NTIS Catalog No., PB-204 437).

2. Parker, H. W., Deere, D. U., Peck, R. B., Semple, R. M. and Febres-Cordero, E., "Program for Large-Scale Tests on Prototype Tunnel Supports," Report No. FRA-RT-72-26, November 1971, Office of High Speed Ground Transportation, Federal Railroad Administration.

PAVEMENT APPLICATIONS OF FIBROUS CONCRETE

by

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Presented at
CERL Fibrous Concrete Conference:
"Fibrous Concrete--Construction Material for the Seventies"
May 1972

ABSTRACT

The potential applications of fibrous concrete in the paving field are discussed. Its use as an overlay on existing highway and airport pavements is examined. The use of a thin fibrous concrete overlay under bridges for maintaining proper clearance where headroom is limited would be of particular interest to highway departments and the concrete paving industry. The research needed to determine its performance under traffic is briefly discussed. Research items which we felt need study are thickness requirements for highway loadings, maximum length of slab that will perform under different bond conditions, and type of joint system needed for fibrous concrete.

PAVEMENT APPLICATIONS OF FIBROUS CONCRETE

by

William A. Yrjanson

INTRODUCTION

The American Concrete Paving Association has followed the development of fiber reinforced concrete with considerable interest during the past few years, and some of our members have actively participated in its development and installation of field research projects. Field installations have been observed and the heavy load tests (C-5A gear) of fiber reinforced panels by the Corps of Engineers at Vicksburg, Mississippi, have been followed with keen interest. Performance of both the fibrous concrete overlay and the 5-in. slab placed directly on a weak subgrade in this test program indicates that this material has potential advantages for certain applications in the paving field. In order to determine practical uses and the proper installation of this material, we feel that several items need examination. Among these are: Where can it be used to advantage? What further field and laboratory research is needed? What are the costs involved? What are the construction problems? Each of these items will be discussed later.

WHY ARE WE INTERESTED?

There are several instances where fiber reinforced concrete could be used to good advantage. Let's consider some of the possible applications.

RESURFACING

Resurfacing of existing highway pavements would be a large potential market provided the total annual cost is competitive with other designs, or it results in a significant reduction in traffic interference due to pavement maintenance. The total annual cost of any pavement structure is not only dependent upon first cost but other considerations such as service life, maintenance costs, traffic control costs, and other items associated with this type of project.

In resurfacing of urban expressways where vertical clearance at bridges is limited, the use of a thin fibrous overlay would be particularly beneficial. This could eliminate removal and reconstruction of pavement and thus minimize traffic interruption or raising of bridges and adjustments to adjacent roadways.

Resurfacing of airport pavements to increase load capacity to meet the requirements for the jumbo jets could also be a possible use for fibrous concrete. The performance of the thin (4-in.) fibrous overlay on the shattered pavement at the Vicksburg test site suggests that with proper engineering consideration, this type of material could be used as a direct overlay on airport pavements which are structurally damaged due to overload or to increase load carrying capacity of existing pavements.

The use of fibrous concrete on new full depth construction instead of regular plain concrete or conventionally reinforced concrete would have to be analyzed from the cost standpoint. At the current cost of the fibers, the thickness would have to be reduced considerably to bring the material cost more in line with other designs. With the thinner pavements possible with this material, the subbase design becomes important due to the higher deflections in the thinner sections.

Although not directly connected with pavements, the use of a fibrous concrete in bridge decks should be of benefit.

RESEARCH NEEDED IN PAVING FIELD

Laboratory research and field installations such as the heavy load tests at Vicksburg have given us some indication of the performance to be expected of this material. Laboratory research into the physical properties of fibrous concrete indicates the great increase in flexural and tensile strength, fatigue endurance, spall resistance and ductility that can be effected with this material. All these properties can be used to good advantage in pavement structures.

Among the items we feel need further research are:

Thickness Requirements--What are the thickness requirements of fibrous concrete resurfacing of existing pavements for highway loadings? What are the thickness requirements for new full-depth construction using fibrous concrete for highway-type loading? What type of subbase is needed?

Fiber Content--What is the optimum fiber content considering strength requirements, cost considerations, and performance? Field research projects are needed in lower fiber contents below 1-1/2 percent by volume.

Aggregates--What is the maximum size coarse aggregate best suited for fiber reinforced paving mixtures? The normal top size aggregate used in most paving concrete is in the 1 to 1-1/2-in. range. Most experimental field work with fibrous concrete has been with much smaller aggregate (3/8 in.) except for the Tampa overlay project which had a top size aggregate of 3/4 in. From the cost standpoint, aggregates in the 3/4 to 1-in. top size range would probably be best suited for the thicker pavement sections with a smaller size, 3/8 to 1/2 in. used for thicknesses less than about 3 in. Use of the larger size aggregate would permit a reduction in cement requirements and the use of less water in the mix with a resulting reduction in shrinkage. Improved mix designs for this type of concrete will evolve as it becomes more widely used.

Jointing--What are the jointing requirements for fibrous concrete pavements? It would be of tremendous benefit if all joints except construction joints could be eliminated. The load testing conducted to date has been on panels with limited length. Where long sections have been placed, they have developed cracks at 250 to 300-ft intervals. While this type of pavement will accommodate some shrinkage stress through closely spaced microcracks, it may be necessary to use some type of jointing to keep shrinkage stresses within tolerable limits. Can joints be sawed or formed at 200-ft intervals? Proper joint spacing may depend upon whether the project is full-depth construction or overlay. Proper jointing in thin overlays will require some engineering judgment. In the case of overlaying existing concrete pavements, any jointing pattern in the overlay could be offset from the existing joints. This would provide excellent load transfer and strengthen the pavement structure throughout.

COST

The cost of fibrous concrete will, of course, influence its use in the paving field. The cost of materials for a typical cubic yard of paving concrete is in the neighborhood of $10 to $12. This includes cost of cement (5.5 to 6 bag mix), sand, and coarse aggregates. This cost could be higher or lower depending upon cost of cement and aggregates.

To determine the total cost per square yard or cubic yard of concrete in place, additional costs are added to cover: job overhead, mixing, hauling, finegrading, placing, curing, jointing, steel reinforcement if used, office overhead, insurance, and profit. These costs are influenced by labor rates, production rates, and material costs of reinforcement, jointing system, and other materials used. These additional costs could double or triple the basic material costs depending upon the complexity of the project and the design of the pavement.

A potential use of fibrous concrete could be in resurfacing of heavily traveled urban expressways. Performance is of prime importance on these routes. The cost of maintenance and protection of traffic can be a major cost item with up to 20 to 25 percent of total contract cost involved in this item. In-place costs are higher due to scheduling, production, and delivery problems usually associated with these projects. In situations such as this, the initial cost of pavement materials does not assume as large a role as in normal pavement construction where production and scheduling is not affected by these problems. Research is needed on the proper thickness of resurfacing for this type of facility.

Fiber content has a big influence on the cost of this type of concrete. Field installations have been placed with fiber contents of 1-1/2 percent by volume or approximately 200 lbs/cu yd of concrete. If fiber costs were $.15/lb, this would amount to $30/cu yd of concrete. Any reduction in fiber content or price of fibers will have a tremendous effect on the cost of this material. The thickness used will also have a great effect on cost. The material costs are about $1.15/sq yd in. using the cost figures quoted above. Reducing the fiber content to 100 lbs/cu yd would result in a cost of $.72/sq yd in. for materials. This cost will require efficient use of this material in pavement applications.

CONSTRUCTION

A recent fiber reinforced concrete overlay placed on a main taxiway at Tampa International Airport demonstrated that this type of concrete can be mixed, hauled, and placed using high production mainline paving equipment.

I will not discuss the project at this time since it will be reported on later in the session by Frazier Parker of the Corps of Engineers. The only comment I would make is that there were no problems in obtaining good fiber distribution in the large central mix plant and no great problems were experienced in hauling, placing, and finishing the pavement.

A method of bulk handling the fibers must be developed to meet the production capacity of modern mixing and placing equipment. The fibers on the Tampa project were shipped in 40-lb boxes. A typical 9-yd batch would require 1,800 lbs of fibers with a fiber content of 1-1/2 percent of volume. Normal charging time for a mixer is in the neighborhood of 20 seconds with mixing time in the order of 50 to 75 seconds. With these production rates, bulk handling is a necessity.

Preblending of materials on the belt feeding the mixer is required for a uniform mix at these production rates. Fibers should be preblended with the aggregates on the belt feed for proper distribution with this type of plant. This should result in good fiber distribution with a minimum of mixing time.

Some increase in charging and mixing time could be tolerated since the square yards placed will require much less material than is normally used. If thickness requirements are reduced by one-half, an equivalent reduction in concrete production will still result in the same number of square yards placed and finishing costs would be about the same. We would, of course, prefer to see bulk handling facilities for fibers which would more nearly meet plant production capacity.

SUMMARY

Laboratory research indicates that fiber reinforced concrete exhibits the physical properties which would make it an excellent paving material. Field research confirms the laboratory findings.

ACPA is currently cooperating in the planning of future field research that should help find answers to some of the unanswered questions on practical applications of fibrous concrete in highway and airport paving. We hope to have additional information to report in the near future.

PAVEMENT PERFORMANCE INVESTIGATION

by

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Presented at
CERL Fibrous Concrete Conference:
"Fibrous Concrete--Construction Material for the Seventies"
Champaign, Illinois
May 1972

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ABSTRACT

Two controlled traffic test sections have been conducted by CERL in recent months and the preliminary results are remarkable. Traffic simulating operations of the C-5A cargo aircraft have been applied to a 6-in. thick fibrous concrete slab on grade and a 4-in. thick fibrous concrete overlay of a 10-in. thick plain concrete slab. The fibrous concrete thickness represents approximately one-half the design thickness of plain concrete necessary to sustain about 4000 simulated repetitions of the C-5A before significant structural damage to the slab occurs. To date about 8700 repetitions have been applied to the 6-in. thick slab on grade and 6900 repetitions have been applied to the 4-in. thick overlay pavement. After this volume of traffic, testing was suspended and the only distress evident was a number of hairline width cracks. These cracks would not interfere with normal aircraft operations on an in-use pavement.

PAVEMENT PERFORMANCE INVESTIGATION

by

Bobby H. Gray and John L. Rice

INTRODUCTION

Pavements constructed to serve aircraft and roadway vehicles represent a sizeable investment of funds. Pavement and materials researchers are continually striving to improve pavement performance by exploiting more effective materials for initial construction, strengthening of existing pavement, and maintenance repair.

Fibrous concrete exhibits highly desirable behavior properties for pavement applications. High first crack strength, ability to carry load after cracking, ability to arrest cracks and high spall resistance and ductility are some of the advantages offered by fibrous concrete over conventional concrete.

TEST METHOD

The U. S. Army Construction Engineering Research Laboratory (CERL) is actively engaged in a feasibility study of two pavement applications of fibrous concrete. These two applications consist of a fibrous concrete slab on grade and a fibrous concrete overlay of a failure plain concrete pavement.

Both the slab on grade and the overlay pavement were subjected to simulated C-5A traffic. With a gross weight of 750,000 lbs, the C-5A is designed with flotation which permits it to be used on medium-load airfields. The airplane has three landing gears with 12 wheels on each of two main gears, and four wheels on the nose gear (Figure 1). The CERL tests were performed with the U. S. Army Engineers Waterways Experiment Station (WES) loading apparatus simulating one 12-wheel gear loading with 30,000 lbs per wheel (Figure 2). To simulate a reasonable distribution of traffic, loads were applied sequentially along five evenly-spaced parallel lines, across an area 200-in. wide. The C-5A traffic concentrated on the southern half of the test pavement.

At the conclusion of the C-5A traffic, the northern half of the test section was utilized for simulated twin tandem assembly traffic. The twin tandem assembly was loaded to 41,500 lbs per wheel and loads were applied sequentially along five parallel lines across an area 120-in. wide. The twin tandem traffic represents an approximation of the Boeing 747 aircarft traffic.

TEST ITEMS

The construction of the two fibrous concrete test sections as well as several plain concrete sections was accomplished using manual techniques because of the small size of the placements. The concrete was supplied by a ready-mix plant and was transit mixed. Mix design information is shown in Table 1. The steel fibers were blended with the aggregates by manually feeding the fibers onto the aggregate conveyor belt. The ready-mix trucks were then charged in the conventional manner. To insure adequate mixing, the trucks were loaded to approximately 70 percent capacity for transit mixing. Hand placement techniques were used at the job site. Laborers were used to distribute the fibrous concrete and an electrically powered surface vibrator was used to consolidate the material and screed the surface. The surface was then hand floated. No attempt was made to texture the surface after floating. The test sections were moist cured using wet burlap for 7 days and then covered with a polyethylene sheet for 21 days.

Table 1. Fibrous Concrete Mix Design and Strength Properties

Property	Slab	Overlay	Units
Cement Factor (Type I)	9	9	Bag/cu yd
Water-Cement Ratio	0.50	0.46	by wt
Fine-Coarse Aggregate Ratio	3	3	-
Maximum Size Coarse Aggregate	3/8	3/8	in.
Fiber Content	2	2	by vol
Fiber Type	Steel	Steel	-
Fiber Cross Section	0.016	0.010x0.022	in.
Fiber Length	1.0	1.0	in.
Test Age	73	28	days
Flexure Strength	940	1140	psi
Mod. of Elast. (flexure)	5.30	5.28	psi x 10^6
Compressive Strength	5760	6960	psi
Tensile Strength	760	870	psi
Air Content	5.5	5.9	%
Slump	5	3-1/4	in.

The fibrous concrete slab on grade is located at the east end of a 320 ft long test track. The slab is 25-ft long and 50-ft wide and rests on a 4-in. thick sand filler course having a modulus of subgrade reaction of 52 pci. The slab is 6-in. thick with the transverse edges thickened to 9 in. The thickened edge was provided by a uniform taper over a 30-in.

length to reduce the free edge stress to an acceptable level. No provision for transfer of load from the fibrous concrete slab to another slab was possible due to space and geometry limitations. The slab is instrumented with strain, deflection, pressure, and temperature transducers to monitor slab and subgrade responses during trafficking. Prior to trafficking, static loads were applied to the test slab with single, twin tandem and 12-wheel assemblies to determine slab response to various wheel configurations and to provide an instrumentation check out.

The plain concrete nonreinforced test section used for making comparisons of performance between the plain and fibrous concrete pavement was constructed by the WES to investigate the effects of multiple-wheel heavy gear loading (C-5A) on various types of pavement construction joints. The plain concrete test item is 50 by 50-ft and is formed by four 25 by 25-ft slabs resting on a 4-in. thick sand filter course having a modulus of subgrade reaction of 125 pci.

The fibrous concrete overlay consists of a 4-in thick overlay placed over the 10-in. thick plain concrete base pavement described above. Prior to overlaying, the base pavement was subjected to 950 loadings of simulated C-5A traffic and was in a shatter condition. Major structural cracks were present and the cracks had spalled severely. The overlay was of the partial bond type, i.e , the base pavement was cleaned and moistened prior to overlaying, but no concentrated effort was made to achieve bond. The spalled areas were cleaned of loose debris but were not filled prior to overlaying. The overlay was cast monolithically over the entire 50 by 50-ft base pavement.

PERFORMANCE

A discussion of the performance will be limited to what has been observed under simulated C-5A traffic. The 6-in. thick fibrous concrete slab on a weak subgrade is about half the design thickness of the 10-in. thick plain concrete slab on a medium strength subgrade. The 6-in. thick fibrous concrete slab developed the first visible crack at 350 traffic loadings and the second visible crack at 700 traffic loadings. The 10-in. thick plain concrete slab developed the first crack at less than 40 traffic loadings and was in a shatter condition after 700 traffic loadings. A comparison of the condition after 200 traffic loadings of the plain and fibrous slabs is shown in Figures 3 and 4. After 950 traffic loadings the plain concrete slab was considered failed due to major structural cracking, and the crack spalled severely (see Figures 5 and 6). The progression of cracking in the fibrous slab was gradual (Figures 7 and 8) until at the end of the simulated C-5A traffic, 8735 traffic loadings, many hairline-width cracks had developed. During the early portion of the trafficking, the adjacent maneuver area failed and had to be excavated to effect repair. The initial crack was probably precipitated by the maneuver area failure or repair process. It was semi-circular in shape and occurred at the same point where the maneuver area failure occurred. Only one crack could be classified as a working crack; it is in a longitudinal position close to the center of the slab. Also a small spall (about 6-in. diameter) is beginning to develop in the traffic area but the action of the steel fiber reinforcement is such that the material within the spalled area cannot be ejected because the fibers hold the material in place.

The 4-in. thick overlay pavement has been subjected to 6900 repetitions of simulated C-5A traffic and has developed several hairline cracks and only one working crack. The first crack formed at 900 traffic loadings, the second crack after 1400 loadings and the third after 2600 loadings (Figure 9). These repetitions do not include the 950 traffic loadings which were placed on the base pavement. The first crack was obviously a reflection of the longitudinal joint in the base pavement at the east end and the second crack was generally semi-circular and was located near the east end of the test item. The east end of the test item had exhibited a considerable amount of pumping during the traffic which was applied prior to overlaying. The cracking which initially appeared at the east end was probably due to loss of subgrade support through pumping. The semi-circular shaped crack tends to validate this conclusion. Other cracks tended to form gradually under traffic and were reflections of major structural cracks in the base pavement. At the end of the simulated C-5A traffic, 6900 traffic loadings (Figure 10), only one crack is classified as a working crack; it is in a longitudinal position at the center of the traffic lane.

Although the reduction of instrumentation data are not complete as of this writing, a few observations have been made from available data. The fibrous concrete slab on grade exerts between 10 and 12 psi on the sand filter course under the simulated C-5A traffic. The slab deflects on the order of 0.2 in. maximum under a static application of the C-5A assembly. The strains measured in the fibrous concrete seem to seek a level of about 60 μin./in. during simulated traffic. Strain readings much larger than 60 were observed but were of short duration and tended to reduce under more traffic.

CONCLUSIONS

The performance of the two feasibility test sections described herein indicates that fibrous concrete will function extremely well as a paving material. The performance verified laboratory tests which indicated the applicability of this material to pavements.

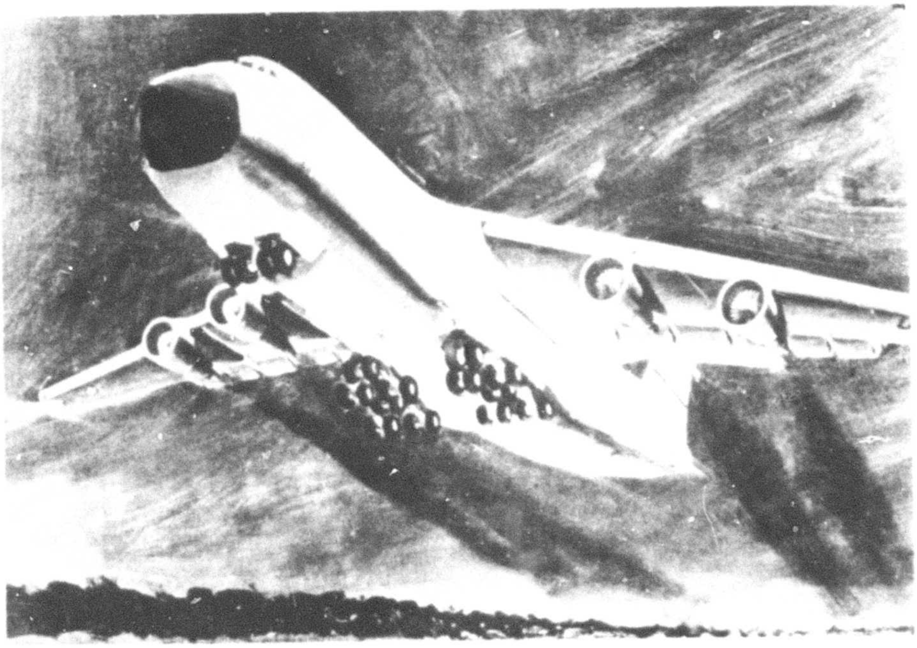

Figure 1. Artist's Rendering of C-5A Showing Landing Gear Complex

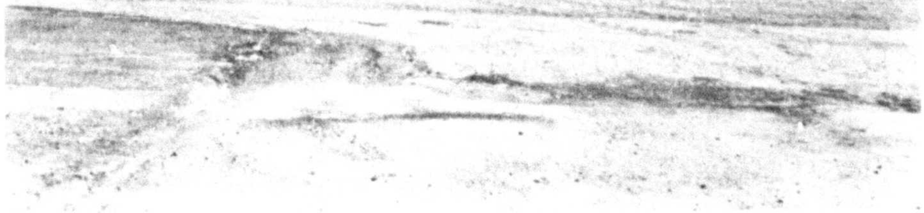

Figure 2. Loading Apparatus Used to Simulate C-5A Traffic

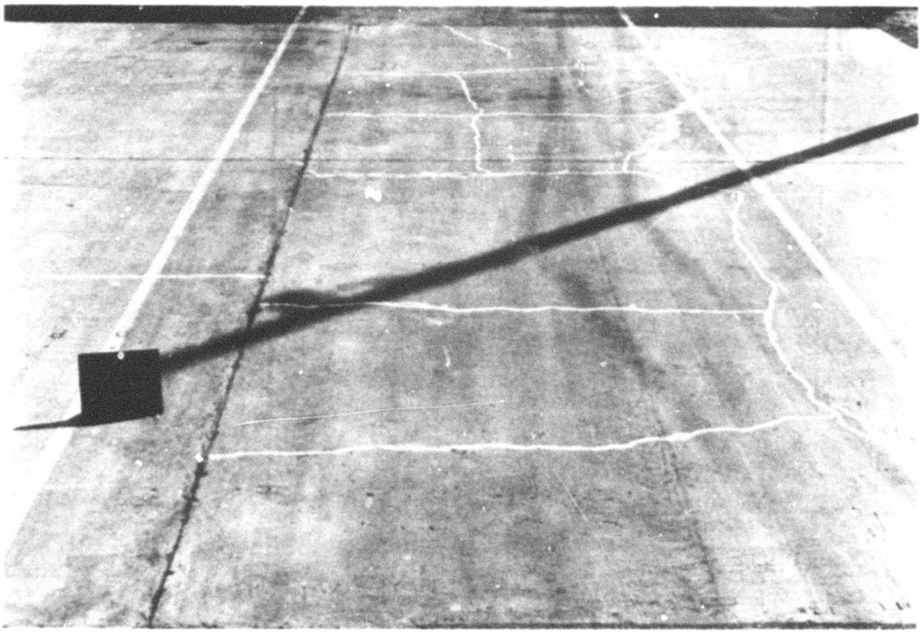

Figure 3. Condition of 10-in. Plain Concrete Test Item After 200 Traffic Loadings

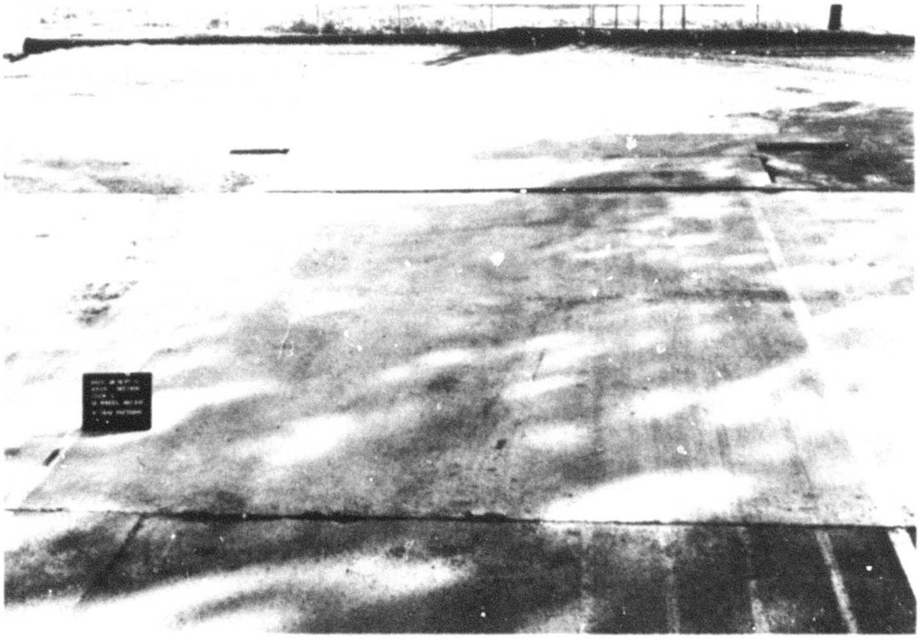

Figure 4. Condition of 6-in. Fibrous Concrete Test Item After 200 Traffic Loadings

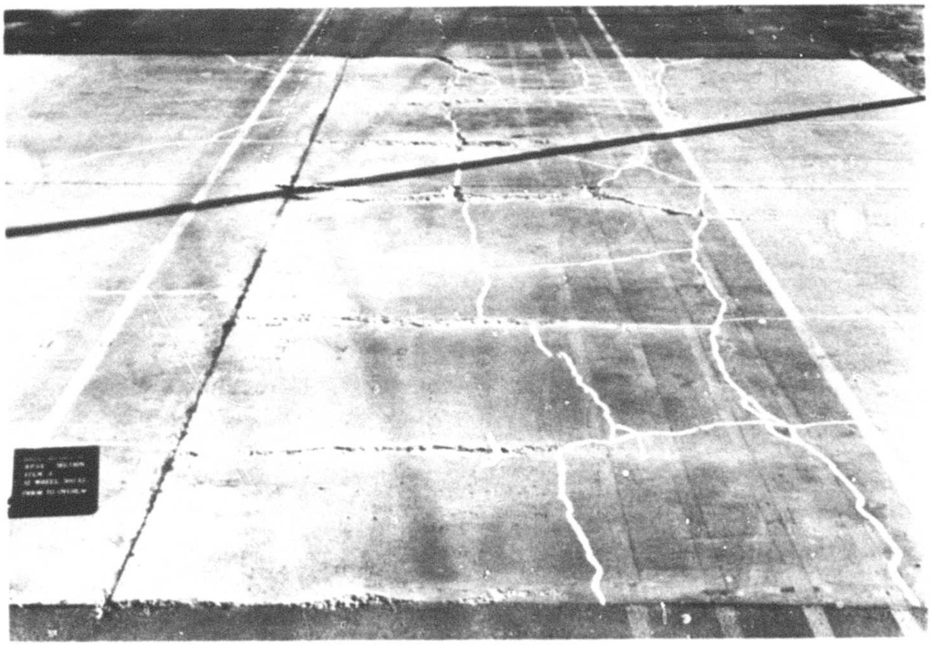

Figure 5. Condition of 10-in. Plain Concrete Test Item After 950 Traffic Loadings. Item has been cleaned and was overlaid at this point with a 4-in. fibrous concrete overlay

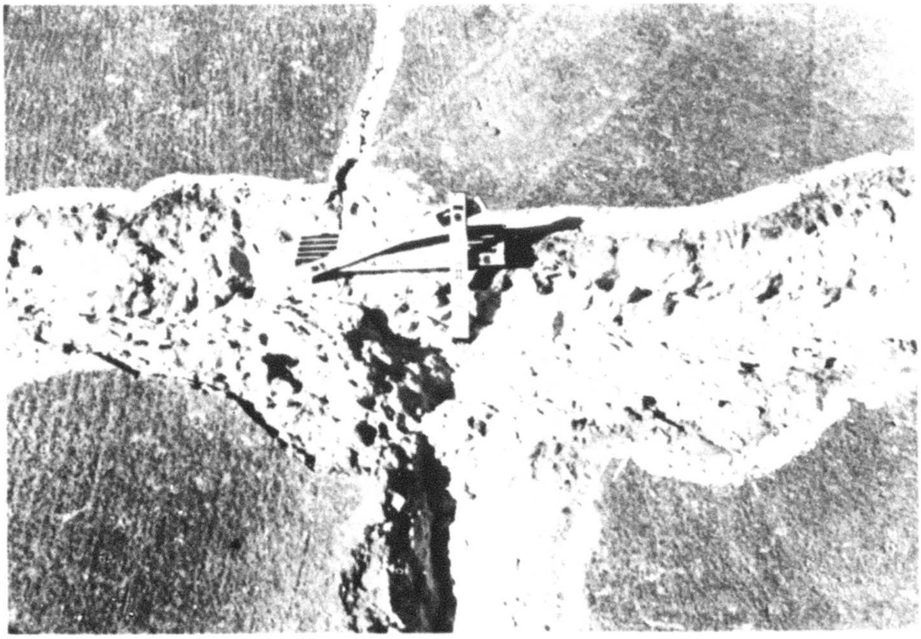

Figure 6. Close up of a Spalled Crack in 10-in. Thick Plain Concrete Item Shown Above in Figure 5

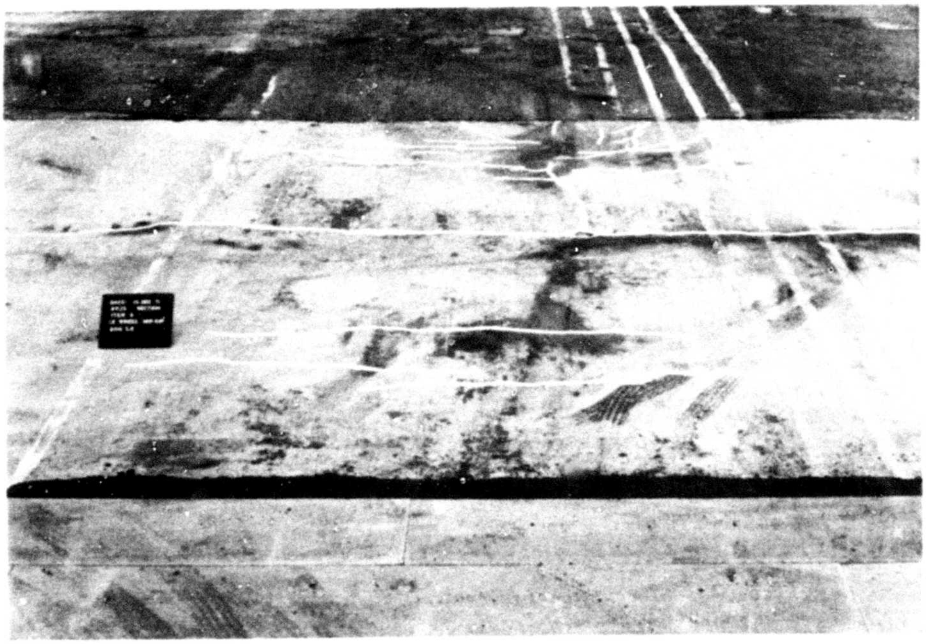

Figure 7. Condition of 6-in. Fibrous Concrete Test Item After 4400 Traffic Loadings

Figure 8. Condition of 6-in. Fibrous Concrete Test Item After 8735 Traffic Loadings

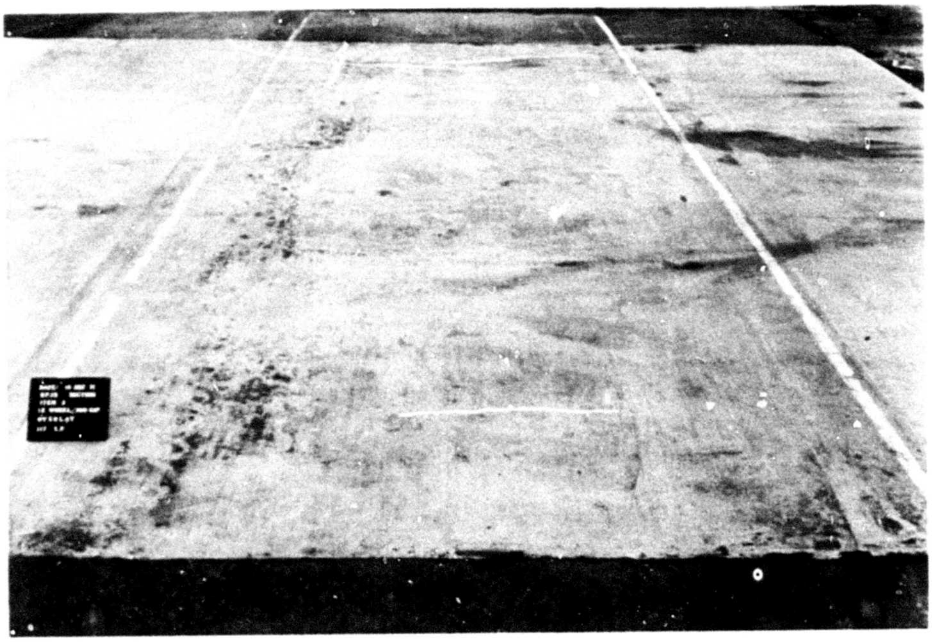

Figure 9. Condition of 4-in. Thick Fibrous Concrete Overlay After 2575 Traffic Loadings. NOTE: These loadings do not include the 950 loadings placed on the 10-in. plain concrete base slab

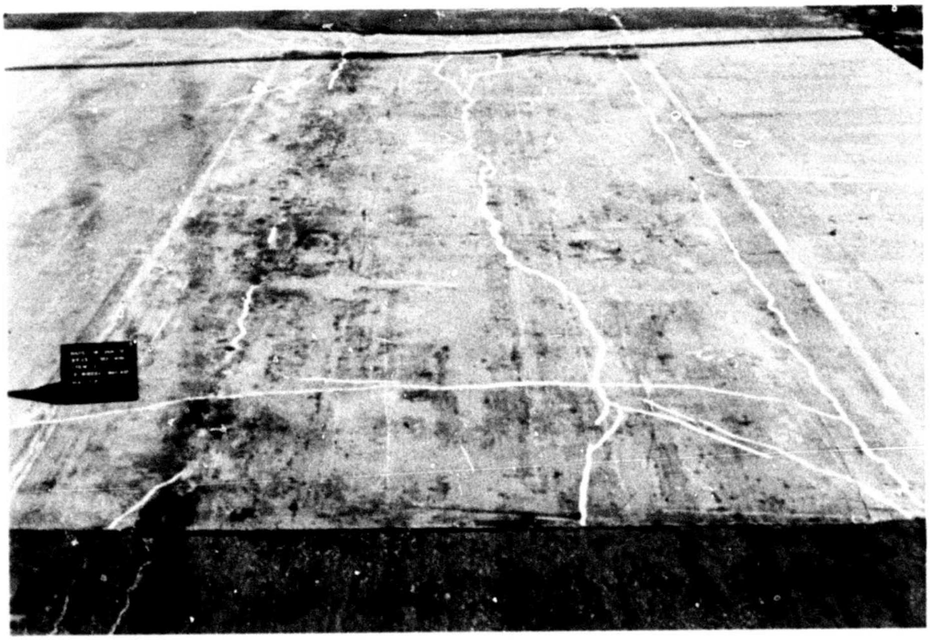

Figure 10. Condition of a 4-in. Thick Fibrous Concrete Overlay After 6900 Traffic Loadings. See above note

PAVEMENT DESIGN CONSIDERATIONS

by

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Presented at
CERL Fibrous Concrete Conference:
"Fibrous Concrete--Construction Material for the Seventies"
Champaign, Illinois
May 1972

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ABSTRACT

This report presents recommended design criteria for fibrous concrete pavements for airfields. It provides recommended design procedures for slabs on grade and overlays together with an illustrative example of an airfield pavement design. These procedures are based on the Corps of Engineers standard practice for pavement design. References are provided for information on mix design, batching and handling.

PAVEMENT DESIGN CONSIDERATIONS

by

J. L. Rice

INTRODUCTION

Purpose and Scope

This report presents guidance for the design of fibrous concrete airfield pavements using the current Corps of Engineers design methods modified appropriately to account for the particular properties of fibrous concrete. It is intended as a guide for the design of future fibrous concrete pavements.

This report is limited to the design phase of fibrous concrete pavements. Information on mix design, batching, and handling is available from other sources.

Background

Fibrous concrete contains the same materials used for conventional portland cement concrete plus short steel fibers dispersed in the concrete matrix. Coarse aggregates are smaller; the ratio of coarse-to-fine aggregate is smaller; and the cement factor is higher. The steel fibers are nominally 1 -in. long and from 10 to 16 mils in diameter. The steel fibers are introduced to achieve, as nearly as possible, a random distribution of fiber throughout the mixture. The fiber reinforces the concrete matrix in all directions, at all points, when a true random distribution is obtained. Additional strength is derived from the bond between the cement paste and the fibers.

The engineering properties of fibrous concrete are ideally suited to pavement applications. Laboratory research and test sections demonstrate high first crack strength, an ability to support substantial loads after cracking, an ability to arrest cracks, a high spall resistance, and improved ductility.

The Corps of Engineers has been conducting studies of fibrous concrete for nine years. These studies were primarily concerned with blast-resistant materials. Trial field placements and laboratory studies have led to guidelines for the mixing and placing of fibrous concrete.[1] Most of these guidelines have a direct application to fibrous concrete pavements. Field tests[2] of the material demonstrate that improved performance can be anticipated from relatively thin fibrous concrete pavements. The material has been used as a slab on grade and as an overlay of a distressed, conventional portland cement concrete pavement. Both applications provided superior performance under simulated aircraft traffic.

DESIGN PROCEDURES FOR SLABS ON GRADE

General

The recommended design procedure for slabs on grade involves three considerations:

1. Flexural stress and strength,

2. Elastic deflection, and

3. Foundation stress and strength.

The slab must be of sufficient thickness to accommodate the flexural stresses imposed by traffic or other loadings. Since traffic-induced stresses are repetitive and cyclic, a reasonable working stress for the fibrous concrete must be established to insure performance under fatigue loadings.

A fibrous concrete slab will be relatively flexible in comparison to conventional concrete slabs because of its reduced thickness and the more ductile nature of fibrous concrete. The magnitude of anticipated elastic deflection must be correctly predicted, since the danger of pumping the supporting materials from beneath the slab increases as elastic deflections increase.

Stresses developed within the supporting material should be examined. The stresses in the underlying layers must be low enough to preclude the possibility of introducing permanent deformation in the supporting materials. Excessive permanent deformation can result in a rough riding pavement or it can precipitate structural failure in the pavement slabs. These three considerations in the design procedure as outlined above are amplified in the subsequent sections. A design example is included at the end of this chapter.

Flexural Stresses

To resist the same loading, the pavement thickness required for fibrous concrete will be on the order of seven-tenths of that required for conventional concrete pavements. The fatigue properties of fibrous concrete are such that the selection of a working stress at 80 percent of the stress which induces a first crack will assure satisfactory pavement performance for a 5000 coverage design life. During its design life, the pavement will exhibit cracks but the cracks will be held tightly closed and will not spall. The computation of stress by the current Corps of Engineers method, i.e., the Westergaard analysis[3] of an edge-loaded slab, will yield reasonable results. A thickness rule-of-thumb for fibrous concrete pavements is based on the strength properties of fibrous concrete and the stress computation formulas given by Westergaard.

The first crack strength of fibrous concrete is approximately twice the flexural strength of conventional concrete. The allowable working stress of fibrous concrete is 80 percent of the first crack strength; for conventional concrete it is 75 percent of the flexural strength. This assumes a 5000 coverage design life for both materials. The ratio of working stress for fibrous concrete pavements to working stress for conventional concrete pavements can be expressed by

$$\frac{S_P}{S_F} = \frac{.75\ R_P}{.80\ R_F} \qquad (1)$$

where S_P = working stress for plain concrete pavements

S_F = working stress for fibrous concrete pavements

R_P = flexural strength of plain concrete

R_F = first crack strength of fibrous concrete

Nominal values for R_P and R_F yield a working stress ratio of 0.48.

The stress computation formulas developed by Westergaard show that stress is approximately proportional to the inverse of the square of the pavement thickness. The pavement thickness enters at several points in the formula; however the inverse of the square is the main driving factor in the formula. The ratio of thickness of fibrous concrete pavement to plain concrete can be approximated by:

$$\frac{t_F}{t_P} \approx 0.7 \sqrt{\frac{S_P}{S_F}} \qquad (2)$$

where

t_F = thickness of fibrous concrete pavement

t_P = thickness of plain concrete pavement

S_P and S_F are as above

The ratio of thicknesses of fibrous to plain concrete is approximately 0.48 for a working stress ratio of 0.48.

It is recommended that the thickness of plain concrete pavement be determined for the given load and for a flexural strength of 600 psi. One-half of the plain concrete pavement thickness should then be used to begin flexural stress computations for fibrous concrete pavements.

If load transfer devices are provided at joints, an assumption of 25 percent load transfer across the joint is applicable. If no load transfer is provided across a joint, a thickened edge is recommended. The edge thickening should provide a 15 percent increase in thickness at the free edge over a uniform taper with a 1:10 slope(Figure 1). The design process is then a trial-and-error procedure of selecting various pavement thicknesses and computing maximum flexural stresses. The current Corps of Engineers design process involves the use of thickness design charts such as Figure 2. The flexural stress determination can also be made using the influence charts developed by Pickett and Ray[4] or by computer techniques developed by Kreger.[5] The use of the formulas developed by Westergaard is not recommended as the solutions are quite laborious for landing gears with more than one tire.

Elastic Deflections

The design of a fibrous concrete pavement on grade should include, as previously mentioned, an analysis of the anticipated elastic deflections. Elastic deflections themselves are not harmful to pavement structures. However, excessive elastic deflections can aggravate pavement pumping or blowing. Based on field experience,[2] a maximum static deflection 0.15 in. is recommended to guard against pavement pumping. The recommended method for the computation of elastic deflection is the influence chart technique of Pickett and Ray.[4]

The 0.15 in. maximum value is based on a 5000 coverage design life. Unfortunately, adequate data are not available to establish permissible values for other coverage level designs. In the absence of specific performance data on the local soil, the designer is advised to use a maximum 0.15 in. elastic deflection value for 5000 coverages or less and a maximum value of 0.10 in. for 5000 to 25000 coverage designs.

Foundation Stresses

The use of fibrous concrete as a pavement slab will increase the stresses transmitted to the foundation. Thinner slabs, having greater flexibility, do not distribute normal forces over as large an area as thicker, stiffer conventional concrete pavements. Precautions should be taken to prevent the foundation stresses from becoming excessive and introducing permanent deformation into the foundation materials.

The recommended method of determining foundation stresses is the use of a computer program based on an elastic layered structure.[6,7] An inherent problem in using an elastic layered code is the assignment of a value for the modulus of elasticity and Poisson's ratio to a soil layer. Reasonable results are obtained by using 1500 times the California Bearing Ratio (CBR) value of the layer for the modulus of elasticity of the layer. Values for Poisson's ratio can be obtained experimentally or estimated. The effect of Poisson's ratio on the vertical subgrade stress is relatively small so that some error in estimating a value is not critical.

The allowable vertical stress which can be imposed on a subgrade soil is a function of the strength of the subgrade soil. The relationship between subgrade soil CBR and permissible vertical stress developed by Peattie[8] is shown in Figure 3. This curve was developed by computing the required pavement thickness for soils with various CBRs and then determining the theoretical vertical stress developed under them. This curve represents the approximate endurance limit of the pavement. Multiple applications of vertical stresses of these magnitudes have very little cumulative effect.

This relationship is too conservative for airfield pavements constructed of fibrous concrete. Peattie's curve was derived from flexible highway pavement data; highway pavements are subjected to several times as many traffic loadings as airfield pavements. Additionally, materials used in flexible pavements have little or no capacity for bridging. One principal difference between flexible and rigid pavements is the ability of a rigid pavement to bridge over weak supporting materials. Considering the above-mentioned factors, the allowable foundations stresses shown in Figure 3 can be at least doubled for CBR values of 10 percent or below. This recommendation has been verified by field tests[12] of fibrous concrete pavements in which vertical stresses on a subgrade CBR of 4 percent were about 10 psi over a 6000 coverage life. The designer should bear in mind that Peattie's relationship is applicable only if the materials are compacted to reasonably high densities such as 90-95 percent of CE 55 for cohesive soils and 95-100 percent of CE 55 for noncohesive soils.

The designer is cautioned to be suspect of widely spread, heavy loads or poorly compacted soil layers when considering foundation stresses. The designer is also advised to exercise great care and judgment in assigning modulus of elasticity values to soil layers. For example, if a soil layer such as a nonstabilized base course is incapable of withstanding tensile stresses, the subgrade analysis must be carefully checked to insure that such layers are not required to resist tension forces that are significant. The designer should also consider that, in a layered pavement system,an increase in the modulus of elasticity of more than double the modulus of the underlying layer is extremely difficult to obtain without a stabilizing agent.

Design Example

The following example is included to illustrate the recommended design procedure for fibrous concrete pavements on grade.

A fibrous concrete pavement is to be designed for a tricycle gear aircraft (medium load design)[9] having a gear configuration consisting of twin wheels spaced 37 in. center to center and each tire with a 267 square in. contact area. The design life is for 5000 coverages at a 100,000 lb gear load. The subgrade is composed of a clay material which has a CBR value of 5 percent. A filter course material is available with a CBR value of 10 percent. The subgrade modulus of the foundation system using a 4 in. thick filter course over the clay subgrade is 150 lb per cu in. The allowable working stress for the fibrous concrete in flexure is 1200 psi.

Flexural Stress Computation--The thickness of a conventional concrete pavement necessary to support the given loading conditions is determined by using Figure 2. The design chart is entered on the left ordinate with a flexural strength of 600 psi. A horizontal projection is made to a subgrade modulus of 150 psi. A vertical projection is then made to the B traffic area line (5000 coverages). From the intersection of the vertical projection and the B traffic area line, a horizontal projection is made to the right ordinate and the required thickness of plain concrete is read as 17 in. Therefore a tentative flexural stress computation should be performed for a fibrous concrete pavement on the range of 7 to 9 in. in thickness. A tabulation of results obtained using the computerized edge-loading Westergaard analysis (see Ref. 5) with an allowance for 25 percent load transfer at the joints follows:

Thickness (Inches)	Stress (psi)
7	1590
7.5	1450
8	1330
8.5	1225
9	1130

Noting that the allowable working stress for the fibrous concrete is 1200 psi, therefore, the 8.5 or 9-in. thickness should be used for further analysis.

Elastic Deflection Determination--The influence charts developed by Pickett and Ray,[4] are used to compute the elastic deflection of the twin wheels spaced 37 in. center to center along a jointed edge allowing for 25 percent load transfer for an 8.5 in. thick pavement.

Wheel 1	0.076 in.
Wheel 2	0.009 in.
Total	0.085 in.

For 5000 coverages, the permissible deflection is 0.10 in., therefore, the 8.5-in. thick pavement provides an acceptable level of elastic deflection.

Foundation Stress Computation--The permissible vertical stresses for the filter course and subgrade are determined from the given CBR data using Figure 3, and doubling the values for vertical stresses as previously discussed. In this particular design example, the filter course material can tolerate a vertical stress of 17 psi and the subgrade a vertical stress of 7 psi. An analysis of the layered structure in this instance shows that the subgrade stresses control the design. For a 4-in. thick filter course, the following foundation stresses were computed:

Pavement Thickness (Inches)	Filter Course Stress (psi)	Subgrade Stress (psi)
8	11.5	10.0
8.5	10.4	9.1
9	9.5	8.3
9.5	8.7	7.7
10.0	8.1	7.0

In this particular instance, a pavement thickness of 10 in. over a 4-in. filter course would be recommended. Another acceptable alternative which could be considered is a 9-in. thick fibrous concrete pavement over a 12-in. thick filter course. Local conditions would dictate which cross section is more economical.

DESIGN DETAILS FOR SLABS ON GRADE

The use of fibrous concrete for pavements located on grade does not present any unique problems in design or construction. There are, however, some precautions which should be emphasized for the design and construction of fibrous concrete pavements.

Subsurface Drainage

A free draining filter course is essential beneath a fibrous concrete pavement. The fibrous concrete pavement will deflect more than a conventional concrete pavement under the same load and is thus more susceptible to pumping or blowing. The filter course must be at least 4-in. thick and provide positive drainage across the entire pavement cross section. The allowable elastic deflections, discussed above, are still applicable even though a free-draining filter course is required. This is essential since the possibility still exists of either blowing the finer fraction of the filter course or pumping subgrade materials up into the filter course. Abrupt changes in grade, such as intersections with conventional concrete pavements, will require careful attention to prevent a ponding condition beneath the pavement.

Joints

Construction--Construction joints are required as with conventional concrete pavement construction. These joints are placed between adjacent paving lanes at the end of a day's placement, and at other locations where concrete placement will be interrupted for one hour or more. Load transfer devices or thickened-edge joints are recommended to avoid high stresses at the free edge of a pavement. Shear transfer can be accomplished by using a doweled or keyed joint. Although doweled joints are preferred, keyed joints are acceptable for slabs greater than 9 in. in thickness if the design is for medium or light loading. Pavements which will be subjected to C-5A or 747 aircraft should be designed with doweled construction joints or thickened edge joints. For details concerning dowel size and spacing, see TM 5-824-3.

Contraction--Contraction joints are required in fibrous concrete pavement to control cracking from concrete shrinkage. Contraction joints are normally perpendicular to the direction of paving and should be the dummy groove joints in which a weakened plane is formed either by sawing a groove, or by placing an insert in the plastic concrete. The spacing of contraction joints is a function of the coefficient of friction between the slab and foundation, the percentage of steel reinforcement, and the unit weight of concrete. Experience with fibrous concrete pavement indicates that slab lengths of 100 ft are acceptable for pavements using conventional or high, early-strength cements. The use of shrinkage-compensating cements may permit slab lengths in excess of 100 ft; however, no data are available to indicate a limiting value.

Grooving of Plastic Concrete

Satisfactory grooves which may be necessary to eliminate hydroplaning can be formed in fibrous concrete in the plastic state with a wire combing device. The wire comb should be constructed to press the grooves in the concrete using the force of the spring steel tines of the comb. The comb should be positioned so that the tines are not perpendicular to the surface but are inclined toward the direction of motion. Best results are obtained by using a comb with curved tines and forming the groove with the convex side of the tine.

Other Placement Considerations

Placement considerations such as surface texturing, slump control, and curving have been adequately covered by Gray.[1]

DESIGN PROCEDURE FOR FIBROUS CONCRETE OVERLAY PAVEMENTS

General

The design of a fibrous concrete overlay pavement follows the general procedures for conventional rigid overlay pavements. Three types of fibrous concrete overlay pavements are considered: nonbonded, partially bonded, and fully bonded. The discussion presented here is applicable to fibrous concrete overlays of existing rigid pavements. Fibrous concrete overlays of existing flexible pavements should be treated as slabs on grade. The overlay pavement srructure equivalence to a single thickness of rigid pavement is influenced by the condition of the base slab, the degree of bond between the slab and overlay, as well as the thicknesses of the base pavement and overlay.

Even though modern day computerized techniques are available to solve layered-structure problems, the single slab equivalence method is recommended for fibrous concrete overlays. The boundary conditions affecting overlay pavements are too complex to solve economically by computer methods.

Nonbonded

The use of a nonbonded overlay is recommended for applications where the base pavement is in poor structural condition and rather large increases in structural capacity are desired.

The existing Corps of Engineers design procedure for nonbonded overlays should be used[9] where conditions are such that a leveling or bond-breaking course between the overlay and the concrete is necessary, or where an all-bituminous overlay of less than 4 in. is in place. The thickness of the overlay will be determined from the no-bond formula as follows:

$$h_o = \sqrt{h_d^2 - Ch^2} \qquad (3)$$

where

h_o = thickness of overlay pavement

h = thickness of existing pavement

h_d = design thickness of plain rigid pavement

C = condition factor

The following values of C should be used:

$C = 1.00$ Existing pavement in good condition

$C = 0.75$ Existing pavement with initial cracks due to loading, but no progressive cracks

$C = 0.35$ Existing pavement badly cracked or crushed

In the above formula h_d will be determined from the appropriate design chart for the particular pavement feature in question. The thickness thus determined should be reduced by one-half or a nonbonded fibrous concrete overlay. The one half reduction in required thickness is not due solely to differences in flexural strength but is also the result of postcrack behavior of fibrous concrete.

Partially Bonded

The use of partially-bonded overlays is recommended for applications where an increase in load carrying capacity is required and the base pavement is in fair condition.

As with nonbonded overlays, the current Corps of Engineers thickness design method should be used and then reduced by one-half for partially bonded fibrous concrete overlays. Rigid pavement overlays to be placed directly on the existing rigid base pavement will be designed using the partial bond formula as follows:

$$h_o = \sqrt[1.4]{h_d^{1.4} - Ch^{1.4}} \qquad (4)$$

where

h_o, h_d, C, and h are as before.

Bonded

Several disadvantages are apparent when using fully bonded overlays: the elaborate surface preparation required, positioning of load transfer devices across joints, positioning of the fibrous concrete in the compressive zone of the slab, and the high cost of surface preparation. Generally, the fully bonded overlay is used where a problem with grades exists or only surface defects are to be corrected with little or no increases in load carrying capacity. The structural condition of the base pavement has to be quite good in order to utilize a fully bonded overlay effectively.

Bonded overlays produce a thicker monolithic pavement slab. When a perfect bond is achieved the base pavement and overlay will act as a single slab. In this instance, if identical materials are used for the base pavement and overlay, the strain distribution will be linear and the neutral axis will be at the mid-depth of the combined thicknesses. If a different material, such as fibrous concrete, is used for the overlay pavement, some shift in the neutral axis will occur. In this instance, the full potential of fibrous concrete cannot be realized since the material is used in the compressive stress zone of the cross section. The equation recommended to determine the thickness of fibrous concrete overlay required for a bonded condition is given below:

$$h_o = 0.9 (h_d - h) \qquad (5)$$

where

h_o = thickness of fibrous concrete overlay

h_d = thickness of plain pavement desired as determined from rigid pavement design chart

h = thickness of base pavement

A more detailed discussion of the current overlay design procedure has been presented by Hutchinson.[10]

CONSTRUCTION DETAILS FOR FIBROUS CONCRETE OVERLAYS

The use of fibrous concrete for the construction of overlay pavements requires little modification to existing overlay pavement practices. The modifications only concern jointing of the overlay pavement.

Jointing

Due to the high crack-resistant properties of fibrous concrete, it is necessary to match the base pavement jointing scheme only when using a bonded overlay; partially bonded and nonbonded overlays will not require matching jointing schemes. Load transfer devices will be required only for nonbonded overlays.

Other Considerations

Considerations such as surface preparation and form setting should be performed in accordance with TM 5-824-3.[9] Curing of overlay pavements, texturing, etc., are to be performed in accordance with recommendations made by Gray.[1]

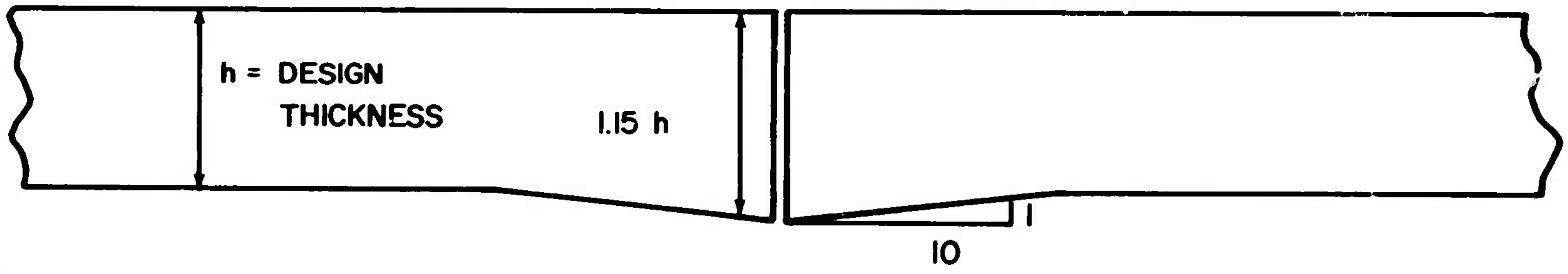
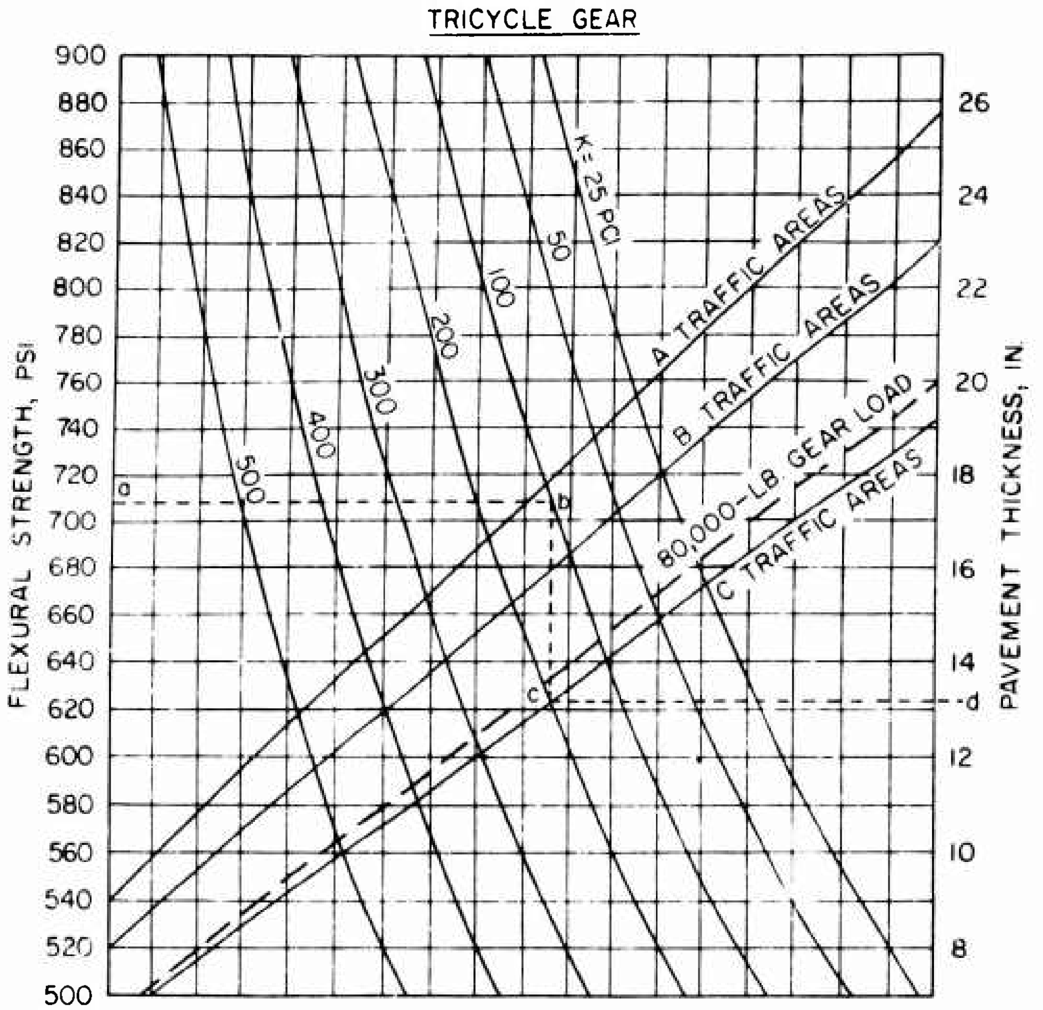


Figure 1. Detail of Thickened Edge Construction Joint

From TM 5-824-3/AFM 88-6, Chap. 3



MEDIUM-LOAD DESIGN CURVES
FOR CONCRETE AIRFIELD PAVEMENTS

TWIN WHEELS SPACED 37 IN. C.C.
267 SQ. IN. CONTACT AREA EACH WHEEL
100,000-LB. GEAR LOAD

1267 A25B5C575

Figure 2. Medium-Load Design Curves for Concrete Airfield Pavements

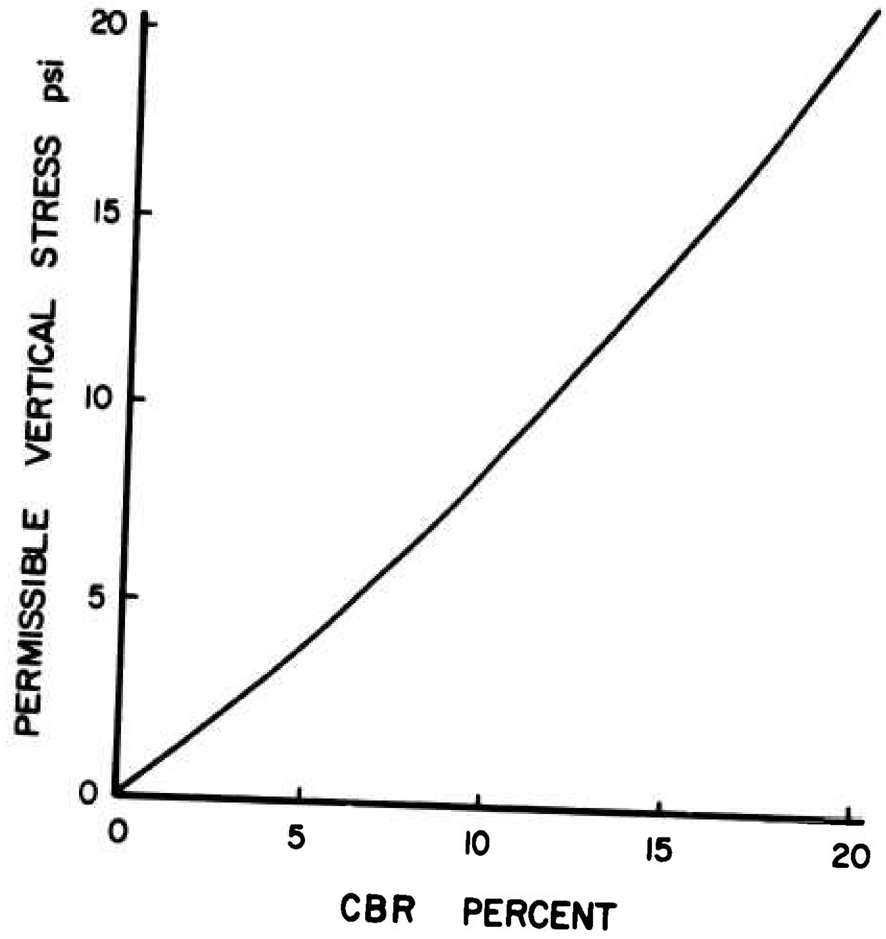


Figure 3. California Bearing Ratio Vs Permissible Vertical Stress(by Peattie)

REFERENCES

1. Gray, B. H., "Fiber Reinforced Concrete: A General Discussion of Field Problems and Applications," Construction Engineering Research Laboratory, U. S. Army Corps of Engineers, Technical Manuscript M-12, April 1972.

2. Gray, B. H., and J. L. Rice, "Fibrous Concrete for Pavement Applications," Construction Engineering Research Laboratory, U. S. Army Corps of Engineers, Technical Report M-13, April 1972.

3. Westergaard, H. M., "New Formulas for Stresses in Concrete Pavements of Airfields," *Transactions,* American Society of Civil Engineers, 1948.

4. Pickett, G. and G. Ray, "Influence Charts for Rigid Pavements," *Transactions,* American Society of Civil Engineers, 1951.

5. Kreger, W., "Computerized Aircraft Ground Flotation Analysis-Edge Loaded Rigid Pavement," General Dynamics, Fort Worth Division, Report No. ERR-FW-572, January 1967.

6. Peutz, M., A. Jones, and H. van Kempten, "Layered Systems Under Normal Surface Loads," Computer Program, Koninklijke/Shell Laboratorium, Amsterdam, Holland.

7. Michelow, J., "Analysis of Stresses and Displacement in an N-Layered Elastic System Under a Load Uniformly Distributed on a Circular Area," Computer Program, California Research Corporation, Richmond, CA; September 1963.

8. Peattie, K. R., "A Fundamental Approach to the Design of Flexible Pavements," *Proceedings,* International Conference on the Structural Design of Asphalt Pavements, August 1962.

9. Rigid Pavements for Airfields Other Than Army, TM 5-824-3, AFM 88-6 Chapter 3, Department of the Army and Department of the Air Force, December 1970.

10. Hutchinson, R., "Basis for Rigid Pavement Design for Military Airfields," Misc. Paper 5-7, Department of the Army, Ohio River Division Laboratories, Corps of Engineers, May 1966.

CONSTRUCTION OF FIBROUS CONCRETE OVERLAY TAMPA INTERNATIONAL AIRPORT

by

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Presented at
CERL Fibrous Concrete Conference:
"Fibrous Concrete--Construction Material for the Seventies"
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ABSTRACT

Two fibrous reinforced concrete overlay test sections were constructed on a taxiway at Tampa International Airport. One test section was 6-in. thick, 75-ft wide, and 175-ft long. This section was constructed by paving three 25-ft wide paving lanes. The only joints present were the two longitudinal construction joints. The second test section was 4-in. thick, 50-ft long, and 50-ft wide. This section was constructed by paving two 25-ft wide paving lanes. The only joint was the longitudinal construction joint. A CMI slipform paver was used to construct the overlays. The overlays were placed directly on the base pavement with no provisions made for bonding or stress relief. The base pavement consisted of 12-in. thick, 25 by 25-ft slabs. The base pavement, especially in the center slabs, was badly cracked with severe spalling at many of the cracks. A Rex central mix plant was used to produce the fibrous reinforced concrete. A fly ash concrete was used containing 5.1 percent fibers by weight. The fibers were 10 by 20 mil rectangular sheared fibers, 1-in. length. Although some extra effort was necessary to introduce the fibers into the batching operation, no particular problems were encountered in mixing and placing. The handling characteristics of the fibrous reinforced concrete were very similar to plain concrete.

CONSTRUCTION OF FIBROUS CONCRETE OVERLAY
TAMPA INTERNATIONAL AIRPORT

by

Dr. Frazier Parker, Jr.

INTRODUCTION

The Systems Research and Development Service of the Federal Aviation Administration has requested that the Waterways Experiment Station produce design criteria for the use of fibrous reinforced concrete as an airfield paving material.

Prior research on this material indicates that it has properties that may be superior to plain or reinforced concrete when used as a paving material. Among these properties are increased flexural strength, increased fatigue endurance limit, and an increased resistance to spalling. This may result in thinner pavements and reduction in foreign object damage to aircraft engines due to ingestion of loose concrete particles. The fibers inhibit the propagation of cracks in the pavement and restrict the width of cracks that do form. In addition, the joint spacing can be increased, thereby reducing the maintenance problems associated with joints.

Before proceeding with controlled testing to establish design criteria, it was necessary to determine if conventional mixing and paving equipment could be used to produce and place fibrous concrete. To obtain this information, two fibrous concrete overlay test sections were constructed at Tampa International Airport, Tampa, Florida, in February 1972.

ORIGINAL PAVEMENT

The east parallel taxiway to runway 18R-36L was opened to traffic in January 1966. The original pavement system is composed of 12 in. of plain concrete, 3 in. of crushed limestone base, and a minimum of 28 in. of E-3 material. The slabs are 25 by 25 ft. Longitudinal construction joints are keyed and tied, and transverse expansion and contraction joints are doweled.

Pavement distress began to appear in December 1966 in the form of longitudinal cracks in the center slabs. Deterioration has continued under an increasing volume of jet aircraft traffic. Figures 1 and 2 illustrate typical deterioration of the pavement.

OVERLAY DESCRIPTION

The two test items were constructed on the east parallel taxiway to runway 18R-36L. The approximate locations are shown in Figure 3.

Item 1 is 6-in. thick, 175-ft long, and 75-ft wide. This item was constructed by paving three 25-ft wide lanes. The only joints formed were two longitudinal construction joints, which were sawed and sealed with bituminous joint sealer.

Item 2 is 4-in. thick, 50-ft long, and 50-ft wide. This item was constructed by paving two 25-ft wide lanes. No joints were formed except the longitudinal construction joint, which was sawed and sealed with bituminous joint sealer.

The layout for the test sections shown in Figure 4 gives the relative positions of the joints in the original pavement and the joints in the overlay. In the 6-in. section, longitudinal construction joints were matched, and the transverse contraction and expansion joints in the original pavement were spanned by the overlay. In the 4-in. section, two longitudinal construction joints and one transverse contraction joint in the original pavement were spanned by the overlay.

OVERLAY CONSTRUCTION

Three steps were involved in the construction of the overlays: preparation of the surface of the original pavement, batching and mixing of the fibrous concrete, and construction of the pavement. The surface preparation was minimal. It consisted of chipping loose material from the cracks and removing any joint sealant that protruded above the pavement surface. These operations are illustrated in Figures 5 and 6. The loose material was swept from the surface, and the surface was kept wet for two hours prior to placing the overlay. No special effort was made to achieve or to destroy bond between the original and overlay pavements.

Concrete was batched and mixed in 8-cu yd batches in the Rex Central Mix Plant shown in Figure 7. Fibers were introduced by hand, dumping 40-lb boxes of fibers onto a conveyer belt that discharged onto the aggregate charging belt of the central mix plant. Figure 8 illustrates this operation. The addition of the conveyer belt was the only modification necessary for introduction of the fibers into the batching process.

The mix design used is given in Table 1. This mix resulted in an average 7-day flexural strength of 765 psi, an average 28-day flexural strength of 827 psi, and an average 90-day flexural strength of 1007 psi. The aggregate used was the controlling factor in the strength obtained. This aggregate was a very low-strength crushed limestone, but is the only aggregate that is commercially available in the Tampa area. Seven-day beam breaks result in fracture of almost all of the aggregate across the failure plane. Slump of the concrete at the paving site ranged from 1/2 to 4-1/2 in., but with the majority of the 8-cu yd batches having slumps between 1 and 2 in.

The overlays were constructed in 25-ft wide paving lanes. Item 1 was constructed by slipforming the outer lanes on 23 February and filling in the center lane on 28 February. The west lane of Item 2 was slipformed on 24 February and the east lane placed adjacent to the west lane on 28 February.

Figures 9 to 12 illustrate the construction procedure. Concrete was hauled to the paving site in side dump trucks. A Maxon spreader was used to spread the concrete across the paving lane for the two outer lanes of the 6-in. section. For the center lane of the 6-in. section and for the 4-in. section, concrete was dumped directly onto the base pavement and spread with a front end loader. A CMI slipform paver consolidated the concrete and formed the pavement section. A self propelled tube float was used to locate irregularities in the surface and for final surface finishing. Hand finishing was kept to a minimum and was usually only necessary adjacent to headers. The paving equipment handled the fibrous concrete satisfactorily. The equipment operators indicated that the fibrous concrete handled essentially like plain concrete. For dry batches, vibration was required for dumping the fibrous concrete from the side dump trucks into the spreader. The paver operator stated that the paver required more power for forward movement than was required for plain concrete.

Several methods for application of surface texture were tried. A burlap drag was unsuccessful because it pulled fibers from the concrete and caused tearing of the surface. Transverse brooming with a wire comb worked satisfactorily, but the texture was very irregular due to the uneven drying of the surface. The most successful method was hand brooming with a stiff bristle brush. This resulted in very uniform surface texture with very little displacement of the fibers.

Figure 13 shows Item 1 immediately after completion of the center lane. Bituminous transition sections were constructed on both ends of the two test items, which were opened to traffic on 6 March 1972.

TABLE 1. MIX DESIGN

	Weight Per cu yd
Cement (5.5 sacks/cu yd	517 lb
Fly Ash (3 sacks/cu yd)	225 lb
Fibers (rectangular 0.02 by 0.01 in., by 1-in. length)	200 lb
Coarse Aggregate (3/4-in. max. size)	1200 lb
Fine Aggregate	1525 lb
Water (33 gal/cu yd)	275 lb
Air In (0.6 oz/sack)	3.3 oz
HP-SR (7 oz/sack)	38.5 oz

PERFORMANCE EVALUATION

In addition to providing information on the handling and placing characteristics of fibrous concrete, the test sections will be utilized to study the performance of fibrous concrete pavement when subjected to actual aircraft traffic and environmental conditions. Visual observations of the pavement condition will be made periodically, and used in conjunction with actual traffic volumes to assess the performance of the overlays. The aircraft weights used will be only approximations, but they should be sufficient to evaluate the overlay performance.

The overlays were inspected on 12 March 1972. This inspection revealed that no cracking had occurred in the 6-in. section, and that longitudinal cracks had developed in the 4-in. section along the center line of both of the 25-ft wide slabs. These cracks are located directly above the longitudinal construction joints in the old pavement. They are narrow and no evidence was found to indicate that they had started working. In addition, a hairline crack had developed in the east slab near the longitudinal construction joint. This crack was very narrow and ran parallel to the longitudinal construction joint at a distance varying from about 2 ft to about 6 in. The location of this crack coincides with a badly spalled crack in the old pavement.

The early cracking of the 4-in. section was probably caused by the combined effects of several factors. First, and probably the most important, is the fact that a longitudinal construction joint in the old pavement was spanned by the overlay. Secondly, the quality of the concrete in the 4-in. section was poor. One of the two 8-cu yd loads used in the west lane had a slump of 4-1/2 in. One of the two 8-cu yd loads used in the east lane had a 1/2-in. slump which made consolidation difficult. Thirdly, the overlays were opened to traffic after the east lane had cured for only 7 days.

CONCLUSIONS

The construction of these two overlay pavements demonstrated that fibrous concrete can be satisfactorily produced in central mix plants and can be placed with slipform paving equipment. Initial observations of the overlays indicate that cracks will occur when longitudinal construction joints are spanned, and that for similar conditions, a joint spacing greater than 175 ft may be permissible.

ACKNOWLEDGEMENTS

A number of agencies contributed to the success of this project. Funds for the construction were furnished by the Federal Aviation Administration and Hillsborough County Aviation Authority. Technical supervision was provided by personnel of J. E. Greiner Company, Inc., Waterways Experiment Station, and Construction Engineering Research Laboratory. Concrete Pavers, Inc. constructed the pavement, and Florida Testing Laboratories provided laboratory facilities for control testing. The steel fibers were furnished by U. S. Steel, the cement by General Portland Cement, Co., and the aggregate and fly ash by Florida Mining and Material Corporation.

Figure 1. Typical Crack Pattern in Base Pavement

Figure 2. Example of Severe Spalling in Base Pavement

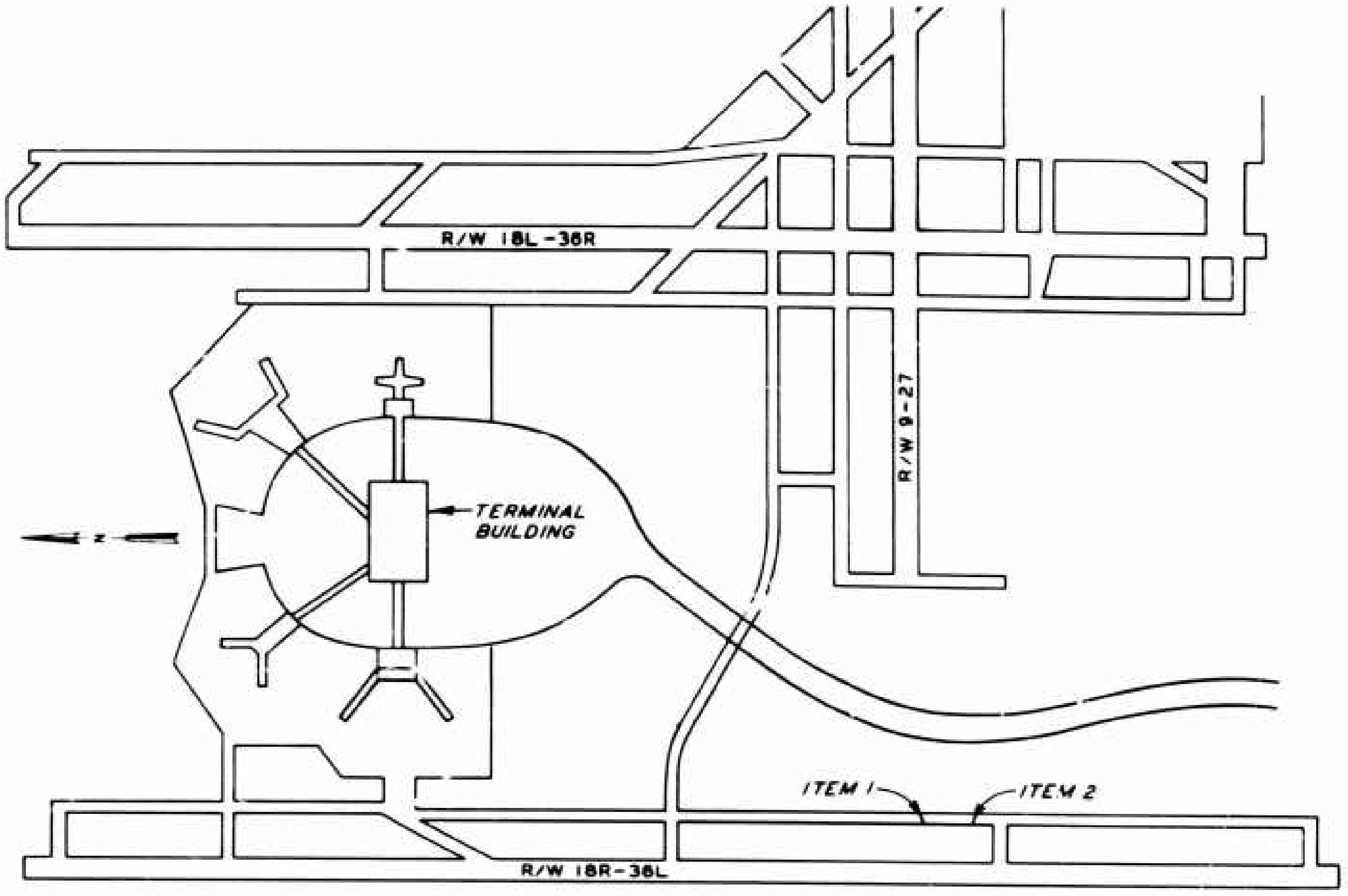
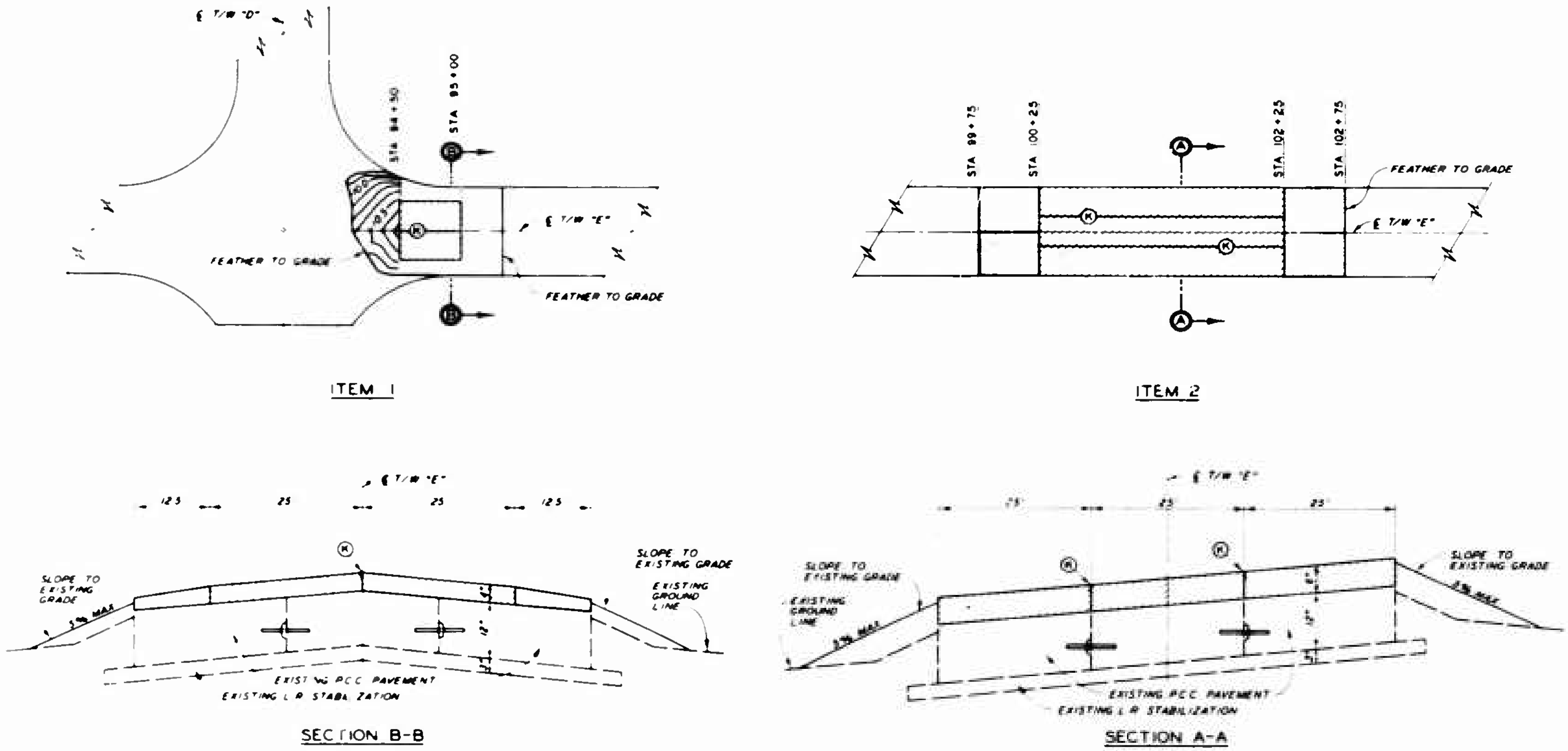


Figure 3. Location of Test Items at Tampa International Airport



NOTE THE SURFACES WILL BE CLEANED OF ALL LOOSE MATERIAL AND DIRT. JOINT SEALING MATERIAL EXTENDING ABOVE THE SLAB SURFACE WILL ALSO BE REMOVED.

PRIOR TO PLACEMENT OF THE CONCRETE OVERLAY, THE EXISTING SURFACE SHALL BE IN A DAMP CONDITION. THIS SHALL BE ACHIEVED BY SOAKING THE SURFACE WITH WATER FOR A PERIOD OF AT LEAST 24 HOURS AT THE START OF THE OVERLAY OPERATIONS. ANY FREE STANDING WATER SHALL BE REMOVED.

THE Ⓚ JOINT ON THE 4 IN-THICK CONCRETE OVERLAY WILL BE SAWED TO A DEPTH OF 1/2 IN INSTEAD OF 2 IN.

LEGEND

☐ PCC OVERLAY (STEEL WIRE ADDITIVE)
☐ BITUMINOUS OVERLAY TRANSITION

Figure 4. Layout of Test Items

Figure 5. Surface Preparation - Chipping Loose Material From Cracks

Figure 6. Surface Preparation - Removing Joint Sealer From Joints

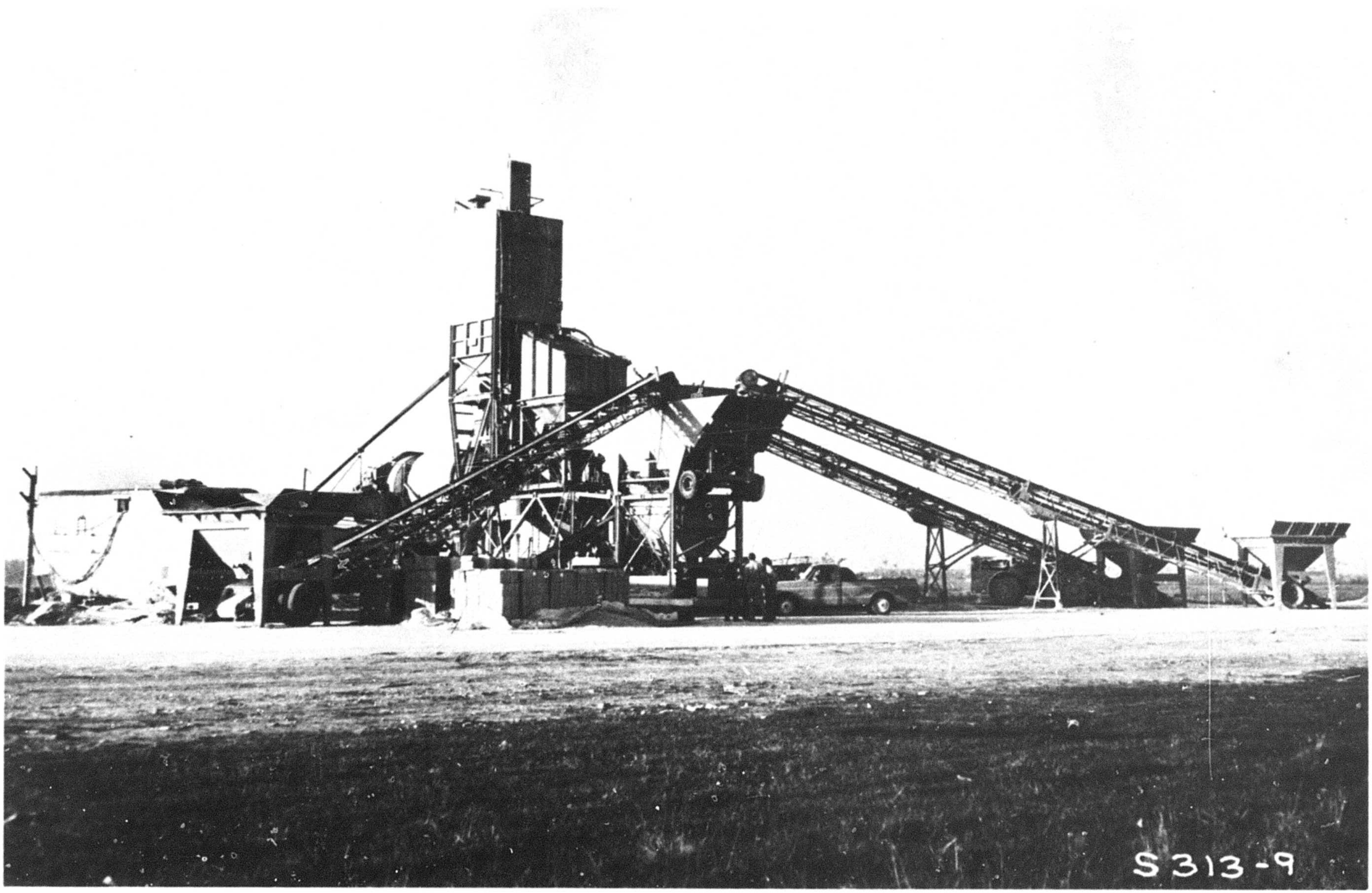


Figure 7. Rex Central Mix Plant Used for Production of Fibrous Concrete

Figure 8. Method for Introducing Fibers

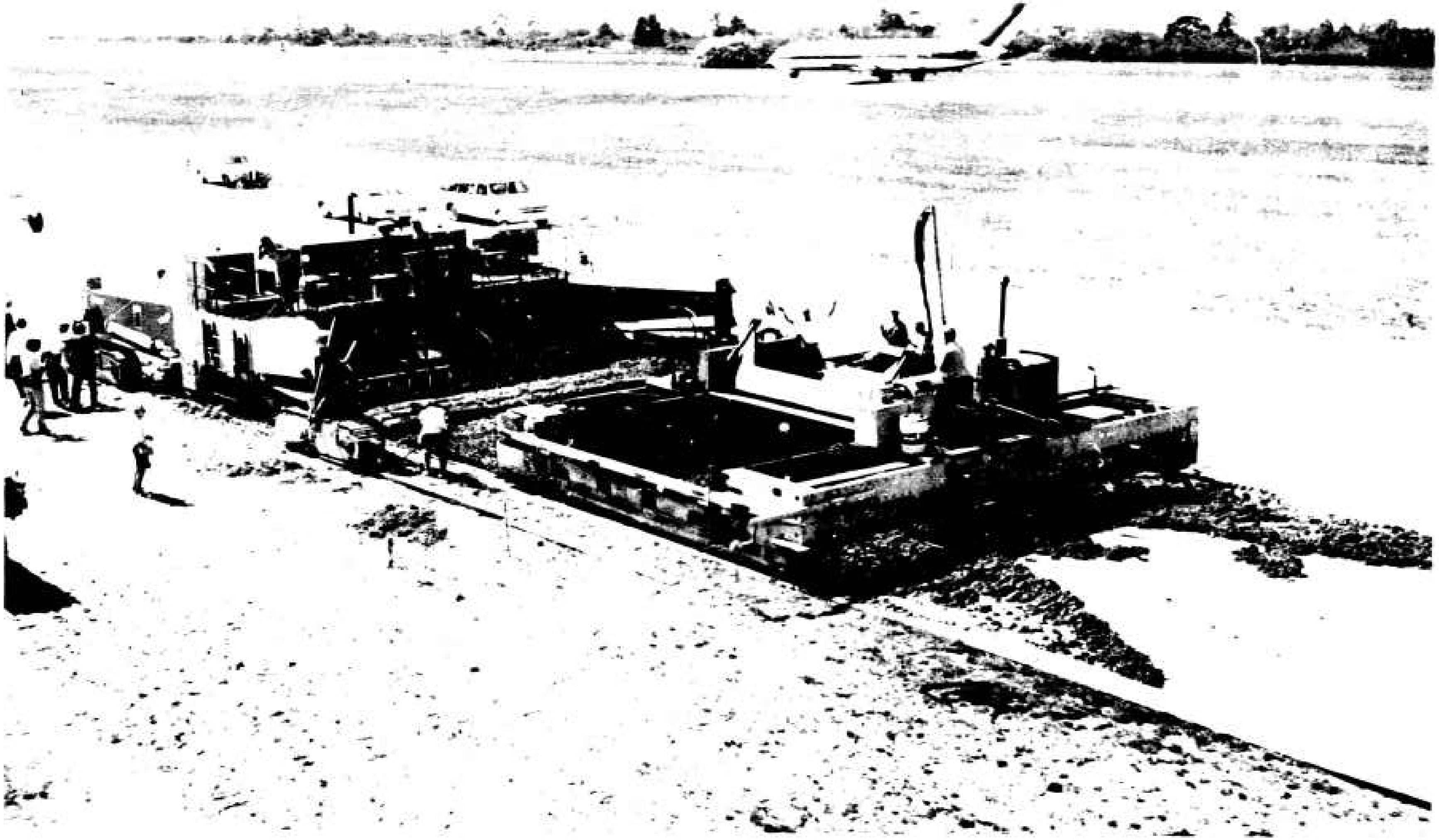


Figure 9. Maxon Spreader and CMI Slipform Paver Spreading and Forming Fibrous Concrete

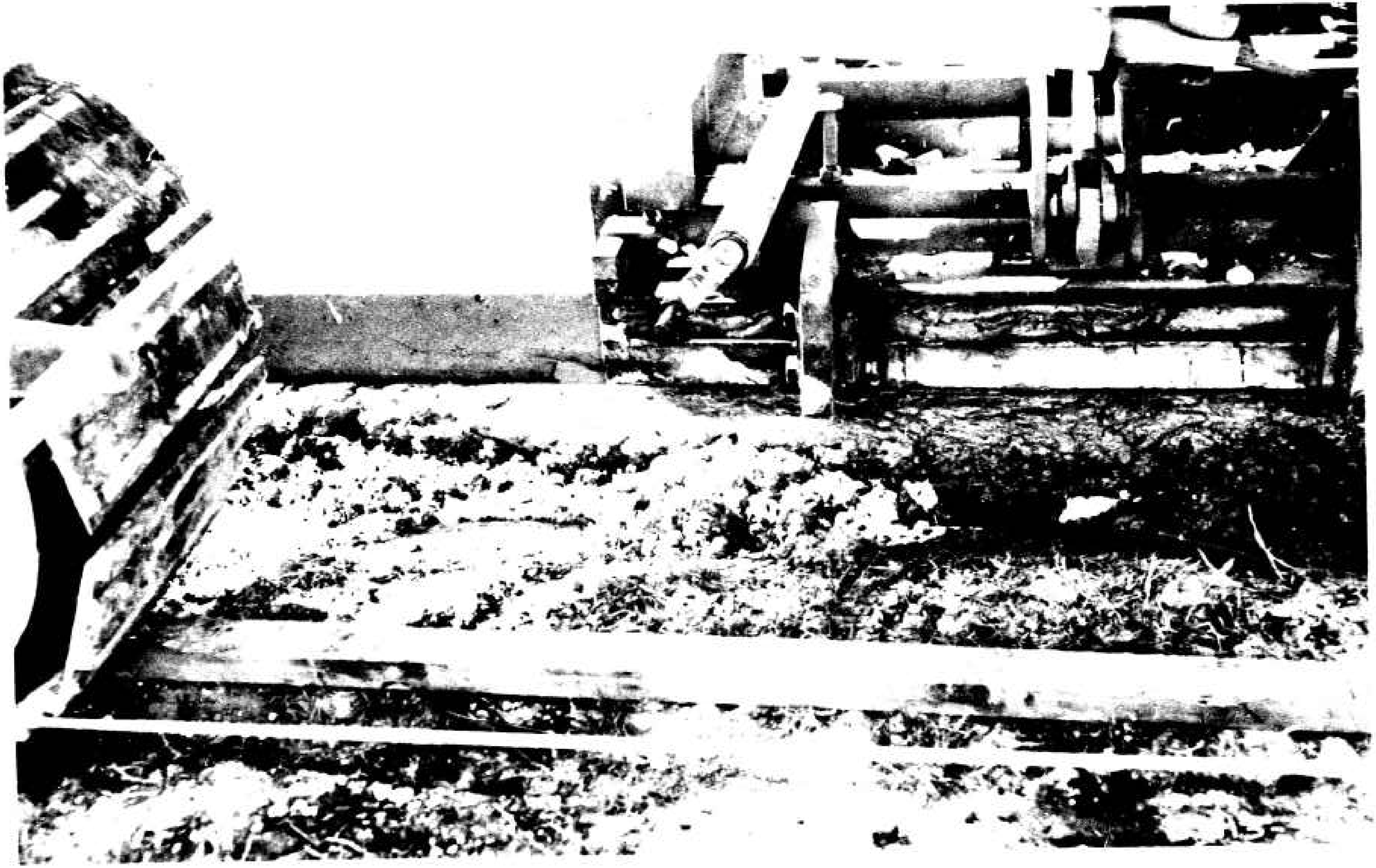


Figure 10. Edge of 6-in. Fibrous Concrete Pavement as Formed

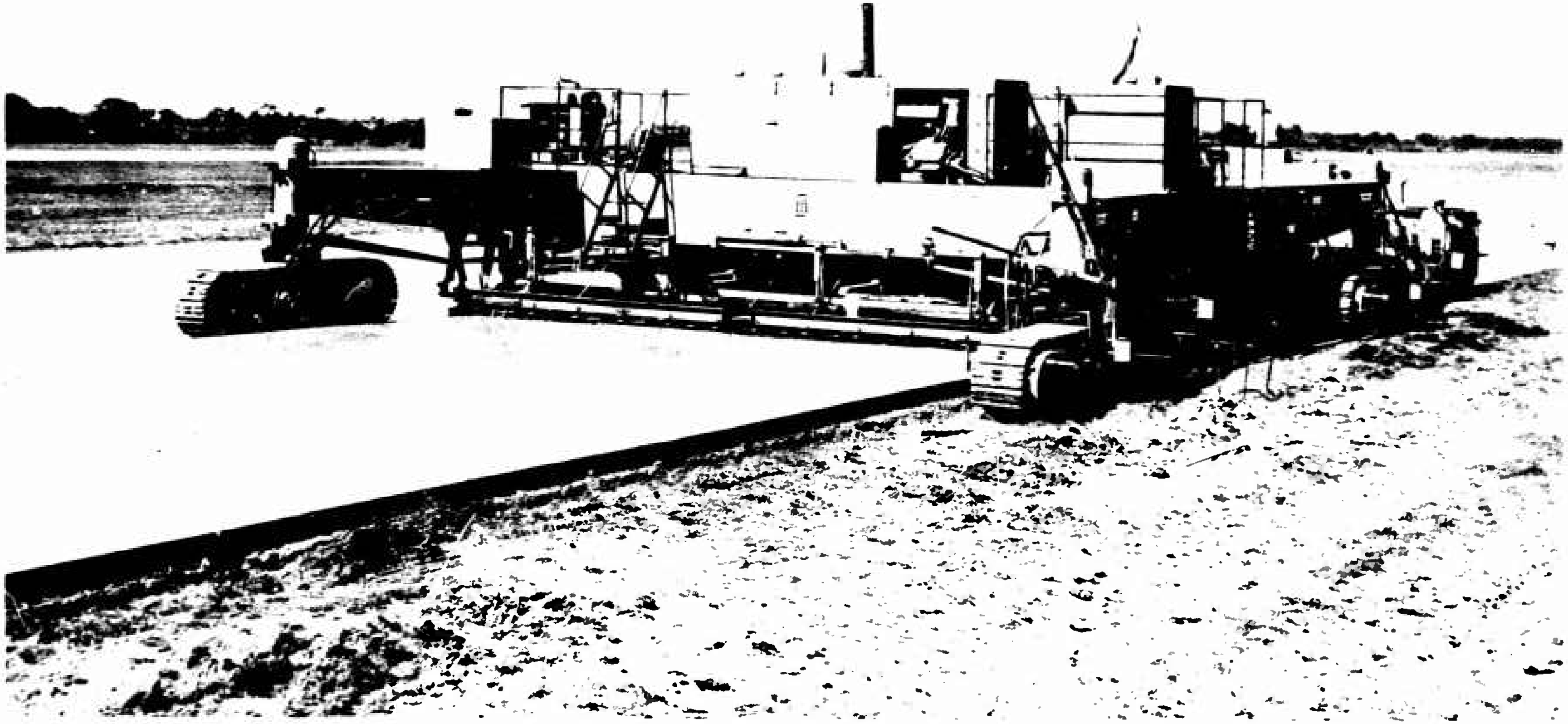


Figure 11. Paving Lane as Formed by Slipform Paver

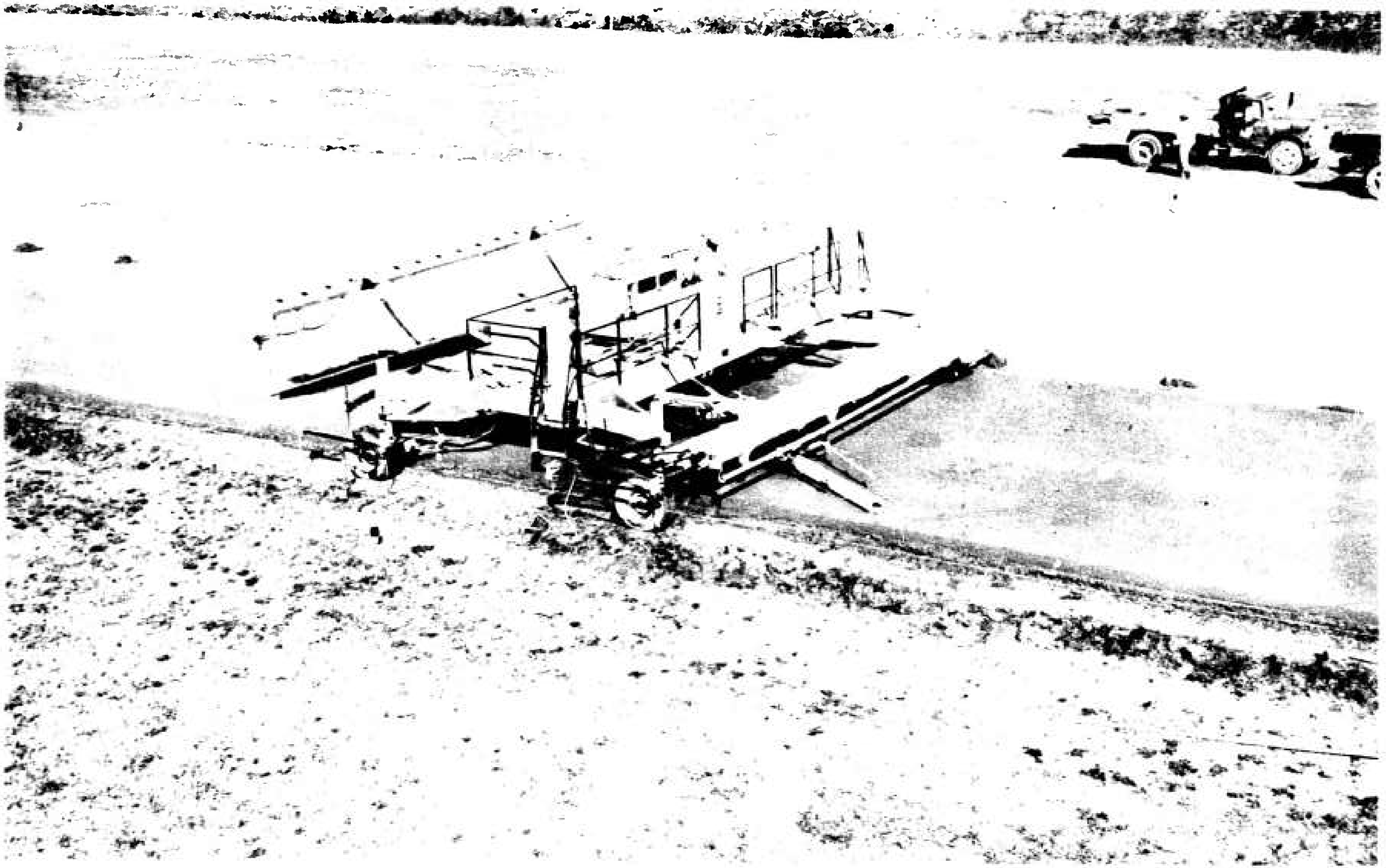


Figure 12. Tube Float Finishing Surface of Pavement

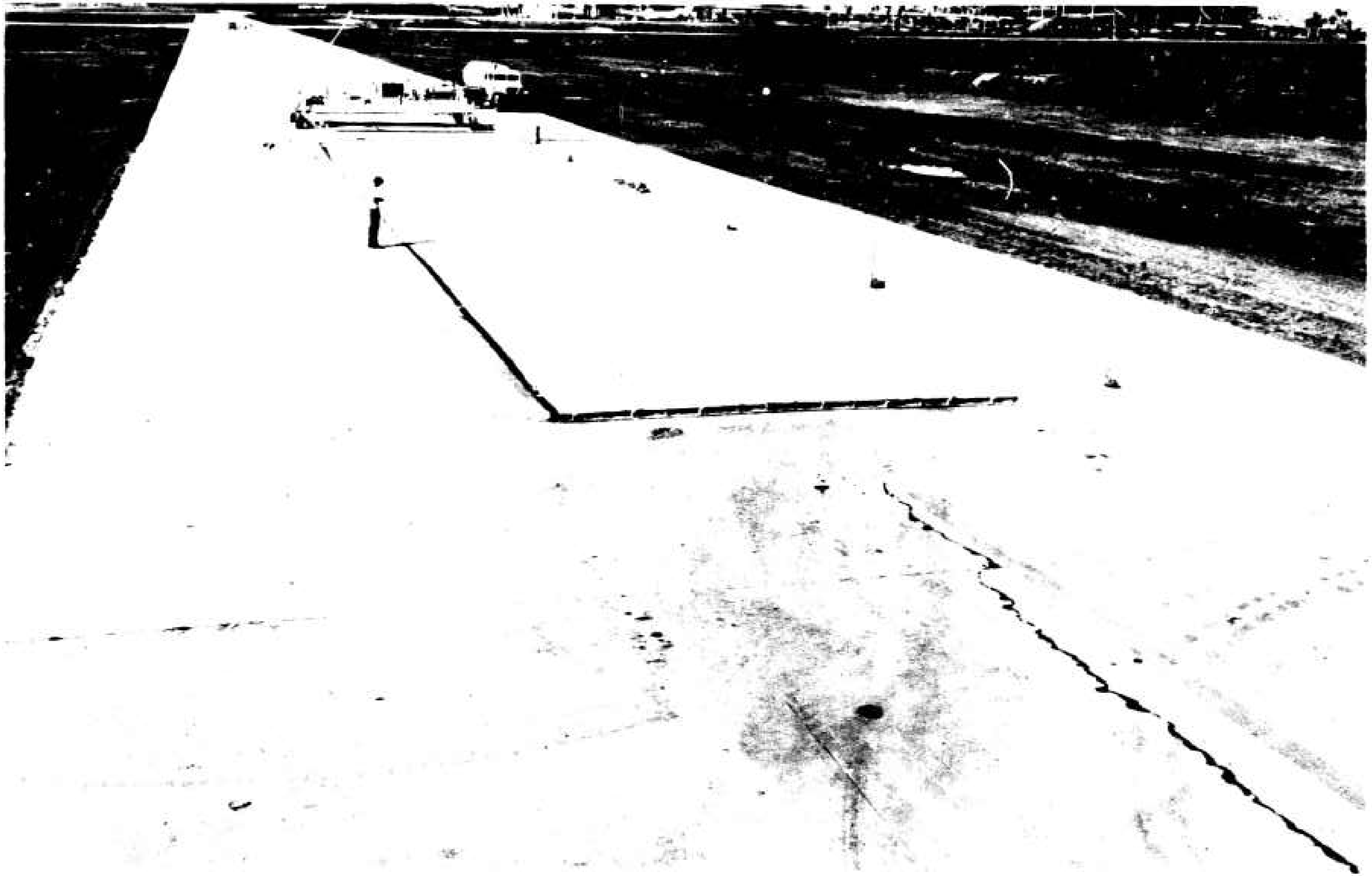


Figure 13. Item 1 Immediately After Completion of Center Lane

DRIVEWAY, ROAD, AND AIRPORT SLABS

by

Clare E. Luke
Wirand Concrete Coordinator
National-Standard Company
Niles, Michigan

Presented at
CERL Fibrous Concrete Conference:
"Fibrous Concrete--Construction Material for the Seventies"
Champaign, Illinois
May 1972

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ABSTRACT

A discussion of the fiber wire reinforced concrete field placements is presented. Road placements of different thicknesses using varying sizes and types of fibers, road overlays on different substrates, industrial floors and overlays, and airport apron and runway patching are all presented and briefly discussed.

A new road patching concept, future fiber wire reinforced concrete, and its economics are presented.

DRIVEWAY, ROAD, AND AIRPORT SLABS

by

Clare E. Luke

For many years National-Standard has produced many sizes and types of specialty wire. These wires are sold and used by our customers in their products at their own discretion. When the opportunity for the promotion of fiber wires for reinforcing concrete arose, it was found that we had to promote a total concept, a new material, rather than just wire to be used in a commercial product.

Since laboratory work showed a marked improvement in the physical properties of this new material over conventional concrete when N-S Fiber Wires were used as a reinforcement, it was decided to apply this information to applications that had great production potential.

The application selected first was a 70 ft, no expansion joint road section compared to a similar no expansion joint section of conventional concrete. In addition to comparing these two placements, it was also desired to gain experience in handling N-S Fiber Wires under conventional concrete mixing methods as well as to observe the aging of the pavement.

A traffic count was made of truck traffic entering National-Standard Company, Machinery Division, Niles, Michigan. From this the probably projected number of axles during the design life of the concrete road was determined. A conventional concrete placement was then designed to meet standard highway road construction specifications. An N-S Fiber Wire reinforced concrete slab was then designed to be equal in strength with this conventional placement.

Thus, on September 27, 1968, a section of N-S Fiber Wire reinforced concrete was laid on the left lane of a road into our National-Standard Machinery Division (Figure 1). This section was 4-in. thick. The right lane of conventional concrete of 7-1/2 in. thickness had been previously poured. Conventional methods were used in the mixing and placing of the fiber wire reinforced concrete with 1 in. by 0.012 in. both flat and round fiber wires being added with the aggregate.

After three years and seven months, the conventionally reinforced concrete road section has three transverse cracks across the complete width of the pavement which were first recorded in June 1969. The N-S Fiber Wire reinforced concrete section has no cracks even though the trucks cut the corners of this 4-in. thick lane. Our first test application gave us experience on handling fiber wire reinforcement, and gives continually today, an example of what can be accomplished.

The Rock Island Arsenal in Rock Island, Illinois constructed a building for testing helicopters and weapons. In this building a room was designed that could operate at temperatures between -100 F to +200 F for testing the firing of guns under different conditions. The walls and the ceiling were of poured concrete and were insulated from the temperatures of the room by 16 in. of insulating materials. Since the floor could not be protected in this manner it was decided to use a material that would withstand use under these temperature extremes.

The U. S. Army Corps of Engineers designed and developed specifications for this application which called for the use of fiber wire reinforced concrete. National-Standard Company was designated as a source for fiber wire, and was contracted to supply N-S Fiber Wires for this application. In addition, National-Standard furnished personnel with experience in handling N-S Fiber Wires to assist in the floor placement as well as in the testing of sample beams.

On May 7, 1969, 13-1/2 yds of 1 in. to 0.010 in. by 0.022 in. flat fiber wire reinforced concrete were poured in the Rock Island Arsenal building (Figure 2). No difficulties were encountered in the mixing or pouring of this material. This building floor is functioning satisfactorily at this time.

Wirand concrete is a normal concrete mix to which relatively short small diameter wire fibers have been added. Battelle Development Corporation holds the patents and has registered Wirand as a trademark for this material. To evaluate Wirand concrete of various thicknesses and overlays compared to conventional concrete, a road 12-ft wide by 160-ft long was placed coming out of a readimix concrete plant in Niles, Michigan (Figure 3). This road was broken down into 11 20-ft long test sections of different thicknesses, different wire reinforcements, different laminations and overlays. This work was done during June 1970. Fifty thousand pound readimix concrete trucks pass over these sections each day.

Sections were poured 4-in., 3-in., and 2-in. thick; 1 in. Wirand with 2 in. of conventional 5-1/2 bg 6AA topping; 2-in. blacktop with a 2-in. Wirand topping; 1-1/2 in. Wirand overlay over old concrete. These sections were a nine bag mix with 25 percent 3/8 in. maximum aggregate, 75 percent sand and 200 lbs of fibers per cubic yard.

A 3-in. thick section with no fibers broke up within a few days. However, the Wirand concrete sections still look excellent by comparison. There are corner cracks on the 2-in. Wirand over 2-in. blacktop. The blacktop section was only hand compacted and is the first section crossed coming into the plant area. The 2-in. Wirand section dished on curing causing flexing and pumping. There was some corner cracking in a little over a year. The 2 in. 5-1/2 bag mix Wirand broke up within a few months. A 1-1/2 in. conventional concrete section overlayed over conventional concrete (6 in. total) cracked in a few months, while the 1-1/2 in. Wirand concrete overlay over conventional concrete has no visible cracks today. Trucks were put over this overlay 64 hrs after placement.

On October 7, 1970 eleven small patches were made along the key joint on a runway used by 747's at a major airport in Illinois (Figure 4). The runway is 12-in. thick and has cracks across it about every 5 ft. This runway is reinforced with rebar about every 6 in. in both directions at a depth of 6 in. The patches were cut out with a saw and an air hammer was used to remove the material. The patches were about 1-ft wide by from 3 to 6-in. deep and 3 to 11-ft long. They were blown out with air, wetted, and filled with Wirand concrete using 1 in. by 0.016 in. round fibers.

Similar patchwork was done with epoxy 2 years ago along this same key joint. Some of this had to be cut out as it was not the full answer. Epoxy costs about $500/cu yd. It is our understanding that the Wirand patches still look good after two winters.

On July 15, 1971, we installed an apron slab at a major airport in Michigan (Figure 5). One of the problems at this airport was the drain boxes around which normal concrete continues to crack providing a repetitive repair problem. The particular drain area repaired, in a gate area which 747's use, was 20 by 30 ft. The thickness of the surrounding slab was approximately 12 in. The 20 by 30 ft slab was prepared for 8 in. of Wirand by building up the original base. Holes were drilled into the surrounding slab and rebar reinforcing rods were placed into the holes and allowed to protrude into the Wirand placement area. Twenty yards of Wirand concrete reinforced 1 in. by 0.016 in. round fiber wires were used for this placement. Recent observation shows satisfactory conditions exist.

A number of industrial patches and floors have been placed around the country. In September, 1971, a 4-in. patch was placed in front of a copper smelting furnace in St. Louis, Missouri. This floor is not only exposed to heavy loads, but to high temperatures and changes in temperature. Though covered by a roof the furnace area is open to the weather on the sides. Molten copper is poured from the furnace, and is sometimes spilled on the floor causing severe spalling. It is estimated the metal temperature is 2000 F. It was reported this floor section, though only used 30 percent of the time, had to be replaced every six months. The Wirand patch has been in place over six months and was recently reported to look very good. There was one small spot that had spalled, but nothing of a problem compared to previous floors.

Precast Wirand patches 3-in. thick were placed in the truck route in the Queens Tunnel in New York. Trucks were running over these repairs within three hours time. Some state highways are using 6-in. precast slabs for this type of patchwork. There is a continuing demand for airports and highways to get repair patchwork done and get traffic over it in as short a time as possible. We would like to submit a new concept for this type of application. The following briefly outlines what preliminary tests show would be possible.

1. Cut and dig out the broken up area;
2. Prepare the areas with reinforcing rods or tubes, if needed, to tie the patch to the old sound sections;
3. Use High Early Cement and 200 lbs of fibers in a Wirand mix and pour in prepared area;
4. Allow traffic after 24 hrs.

Laboratory work indicates the following flexural test results (Table 1) are obtained with this Wirand mix after noted elapsed time.

Table 1

	First Crack*	Ultimate
24 hours	765 psi	831 psi
48 hours	936 psi	1122 psi
72 hours	984 psi	1140 psi

* Stress at which load-deflection curve deviates from linearity.

Indications are that highway specifications require 525 psi flexural strength to put traffic over it. It would seem with this simple repair method that the shutdown time on the road would be no greater than the presently used precast patch method. The road could be opened to traffic in 24 hrs and the cost would be considerably less. For example, the fibers used in a 6-in. section would cost approximately $6.30/sq yd. This, added to the concrete costs of $3 to $4/sq yd, illustrates the cost advantage of using Wirand. The 6-in. thick precast patch used by some states costs about $50/sq yd for the complete job.

When a new concept like Wirand concrete is introduced to the market, extra precautions are taken, so that failures are nonexistant. A safety factor is added to a safety factor. N-S started recommending 265 lbs of fibers/cu yd in a 9 bag mortar mix. After some experience and additional testing this was dropped back to 150 lbs to 200 lbs of fibers/cu yd and 7 to 8 bag mix with 25 percent 3/8-in. aggregate. Our laboratory work now indicates we can go to 25 percent 3/4 in. aggregate and still obtain excellent strengths. Others have done work using 5-1/2 bag mix in combination with fly ash and report good properties.

Wirand concrete field work has been designed to 1,100 to 1,200 psi first crack flexural, with a minimum of 1,000 psi as placed. N-S laboratory work indicates that with the right fiber we can meet these requirements with 80 to 100 lbs of fibers/cu yd. Thus this concept allows one to use one-half the quantity of concrete by pouring half the thickness, eliminate the normal reinforcements, and put this savings into fiber wire. This concept gives an economically feasible placement plus one that would have many advantages over regular concrete.

We do not have all the answers but we know that as Wirand concrete usage spreads it will find many more applications.

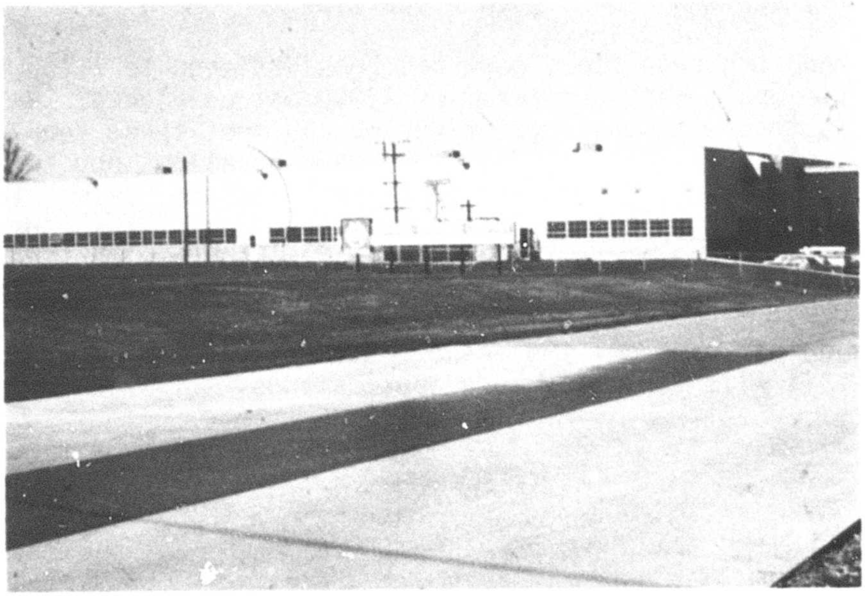

Figure 1. Four Inch Wirand Concrete Roadway Into National-Standard Machinery Division

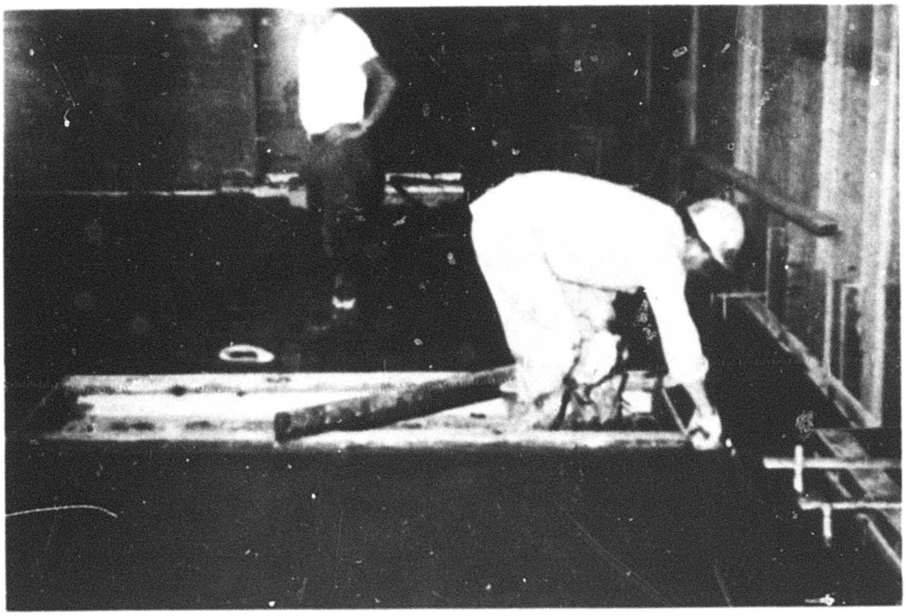

Figure 2. Six Inch Wirand Floor In Rock Island Arsenal Building

Figure 3. Wirand Concrete Roadway Coming Out of a Ready Mix Plant in Niles, Michigan. Roadway Made Up of Eleven Different Test Sections

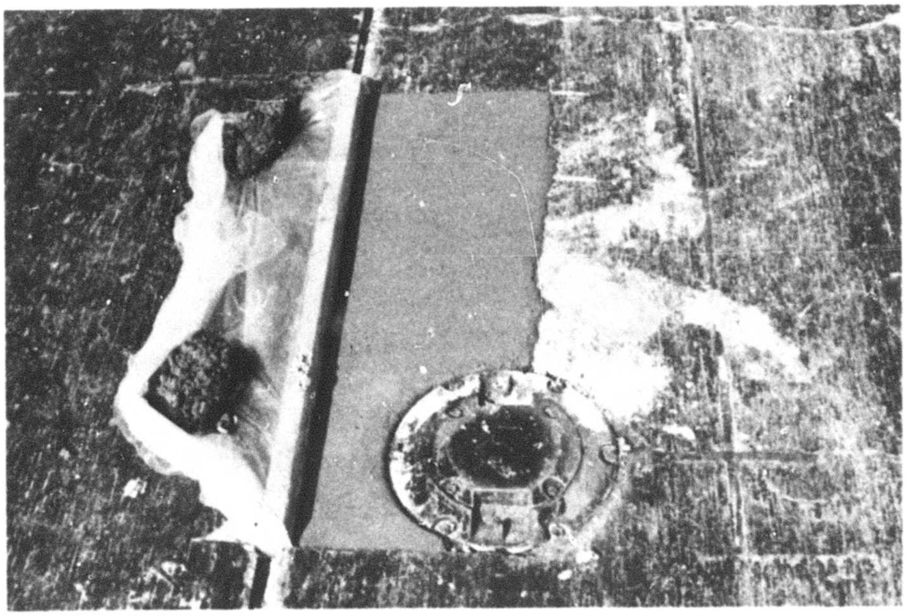

Figure 4. Wirand Concrete Patch Work Along Key Joint on a Runway at Major Airport

Figure 5. Wirand Concrete Placement Around Drain Box on Apron Slab at Gate Area

WIRAND CONCRETE PAVEMENT TRIALS

by

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Champaign, Illinois
May 1972

WIRAND CONCRETE PAVEMENT TRIALS

by

A. R. McDonald

BACKGROUND

A number of test stretches of highway pavement have been laid in the U.S.A. using Wirand concrete and indications so far are that these pavements are much more durable and damage resistant than conventional 8 in. reinforced slabs designed in accordance with the requirements of various highway authorities.

A typical example of this was the placement of comparative Wirand and conventional concrete pavements for the National-Standard Company at Niles, Michigan, U.S.A. (1968).

In this experiment, two pavements were placed. Serving as an entrance, a conventionally reinforced concrete pavement 7-1/2 in. in depth was placed, covering an area 12 ft wide by 70 ft long. Serving as an express route, a Wirand concrete pavement was placed, 4 in. in depth, covering an area 12 ft wide by 70 ft long. The conventional pavement was jointed at the transverse center line. The Wirand pavement had no joints.

The mix design for the conventional concrete was from the standard specifications of the Michigan State Highway Department.

An inspection of the two pavements was made in January 1970. At that time, the 4 in. thick Wirand slab was completely free of any cracking. The 7-1/2 in. thick, conventionally reinforced concrete slab had two major transverse cracks and a third crack had also started. The performance of the Wirand slab to date suggests the use of Wirand concrete in thicknesses less than 4 in. for paving applications.

TESTS AT WAKEFIELD

Recognizing that some form of field exposure was desirable for pavements of varying thicknesses of 4 in. and less, a test layout (Table 1 and Figures 1 and 2) was produced for approximately 1,500 yds of the existing Works area at Spencer Wire Company in Wakefield. Another important

Table 1.

Pavement Layout Details

Section Reference	Approximate Length, ft	Section Thickness, in.	Wire Content lbs/yc %	Date Laid
A	104	4	200 - 5% wt	15/12/70
B	90	4	120 - 3% wt	14/12/70
C	70	2	200 - 5% wt	18/12/70 *
D	70	3	200 - 5% wt	21/12/70
E	60	4	160 - 4% wt	21/12/70
F	200	4	120 - 3% wt	16/12/70
G	28	2	200 - 5% wt	12/12/70
H	145	2	120 - 3% wt	11/12/70
J	26	1	200 - 5% wt	12/12/70*
K	6	1	160 - 4% wt	21/12/70*
L	6	6	200 - 5% wt	12/12/70*
M	210	4	120 - 3% wt	17/12/70
N	130	3	120 - 3% wt	23/12/70
O	120	4	200 - 5% wt	19/12/70
P	Conventional Concrete			

* Hand laid

aspect of the test program was to gain first hand knowledge of laying Wirand concrete using a slipform paver.

Variations in slab thickness range from 1 in. to 4 in. and the range of varying wire contents is 3 percent, 4 percent and 5 percent by weight (Figure 4). All wire used in the trials was 0.010 in. diameter by 1 in. long.

SLIPFORM PAVING MACHINE

The C.P.P. 60 Paving Machine (Figures 3 and 4) used to lay part of the wet lean concrete, the majority of the Wirand concrete pavements, is a British-designed slipform paver of the extrusion of conforming plate type. Designed initially with smaller road works in mind, the construction of the C.P.P. 60 allows the basic machine frame to be adjusted to various paving widths (at the Wirand concrete pavement trials at Wakefield the width of the lanes was fixed 9 ft).

No difficulties were experienced using Wirand concrete with the slipform paving machine; in fact, it was laid with the same ease as which the wet lean concrete was laid.

The exercise at Wakefield enabled the machine to demonstrated the variations in laying methods; single width slabs were laid, "odd-legging" for adjacent bays was carried out, and infill runs were also laid by the paver.

WET LEAN CONCRETE

After all the necessary excavations, backfilling and general leveling had taken place, the whole experimental pavement area received a 6 in. average thickness of compacted store hardcore.

Wet lean concrete was then placed with the slipform paving machine and by hand on all areas that were to receive Wirand concrete pavements, i.e., Lanes 1 to 7 (with the exception of the two small areas noted on the wet lean concrete layout). Tables 2 and 3 provide mix details and strength values for the wet lean concrete. Table 4 and Figure 5 provide layout details.

Table 2.

Wet Lean Concrete Mix Details

	Dry Weights lbs/yc	Aggregate Moisture Contents	Adjusted-wts lbs/yc
O.P.C	240		240
N. Yorkshire Sand	1405	8%	1560
3/4 in. Limestone	2105	2%	2145

Table 3.

Compression Tests

Age	Strength
7 days	750 psi
7 days	500 psi
28 days	950 psi
28 days	850 psi

Table 4.

Layout Details

Cold Joint Reference Layout	Distance From Datum
A	7' 6"
B	185' 6"
C	140' 0"
D	7' 6"
E	188' 0"
F	104' 0"
G	169' 6"
H	199' 6"
J	9' 6"
K	190' 6"
L	199' 6"
M	100' 6"
N	172' 0"
O	128' 0"
P	207' 0"

Section Reference Number		Date Laid
1		5/12/70
2	Laid by paver	4/12/70
3		7/12/70
4		8/12/70
5		7/12/70
6		4/12/70
7	Laid by paver	3/12/70
8		7/12/70
9		7/12/70
10		8/12/70
11		9/12/70
12	Hardcore	
13		3/12/70
14	Laid by paver	2/12/70
15		4/12/70
16		5/12/70
17	Hardcore	
18		9/12/70
19		8/12/70
20		7/12/70
21	Laid by paver	4/12/70
22		5/12/70

WIRAND CONCRETE MIX DETAILS

Initial Mix Proportions (Dry Weights)

		lbs/yc
Mix A	Quartzite sand	1,860
	3/8 in. Quartz	630
	O.P.C.	780
	Water	345
	A.E.A. (Cemtair)*	7 fl oz

Mix Proportions After Allowances for Moisture Contents of Aggregates

Quartzite sand	5 percent M.C.	2.60 S.G.
3/8 in. Quartz	2 percent M.C.	2.60 S.G.

		lbs/yc	
Mix B	Quartzite sand	1,955	3 in. Slump
	3/8 in. Quartzite	645	
	O.P.C.	780	
	Water (added)	240	
	A.E.A. (Cemtair)*	7 fl oz	

* According to manufacturers instructions and technical information the air content due to the addition of Cemtair should have been 4 percent. A check carried out at the Readymix plant however resulted in a 6 percent air content.

The three variations of wire content added to Mix B were as follows:

1. "3 percent by weight" - 120 lbs
2. "4 percent by weight" - 160 lbs
3. "5 percent by weight" - 200 lbs

After completing the first run on Lane 4H, there was a discrepancy between the theoretical quantity required and the actual volume of concrete received. This occurrence repeated itself on the second main paver run in run in Lane 1B and thus a check was instigated on the mixer output and materials. It was found that the S.G.'s used for determining the original mix proportions were slightly lower than the actuals (actual S.G. for quartzite sand and 3/8 in. quartz, 2.65).

Calculations for volume output:

Mix A

	lbs/yc	Based on S.G.	Volume in F.C.
Quartzite sand	1,860	2.65	11.2
3/8 in. Quartz	630	2.65	3.8
O.P.C.	780	3.12	4.0
Water (added)	240	1.00	5.5
Water (in Aggs.)	105	1.00	
A.E.A. Cemtair	(4%)		1.08
			25.58 cu ft

At this point the mix quantities increased by 5 percent which resulted in the following mix proportions (including adjustments for the moisture contents in the aggregates).

Mix C

	lbs/yc
Quartzite sand	2,050
3/8 in. Quartz	675
O.P.C.	815
Water (added)	252
A.E.A. (Cemtair)	7-1/4 fl oz

Conversion into metric quantities for the Readymix plant and "rounding off" the quantities to the nearest 5 kgs was as follows:

Mix C (Metric)

	kgs/yc
Quartzite sand	930
3/8 in. Quartz	305
O.P.C.	370
Water (added)	116 liters
A.E.A. Cemtair	205 milliters

The wire content variations remained the same at:

1. "3 percent by weight" - 120 lbs   54.4 kgs
2. "4 percent by weight" - 160 lbs   72.6 kgs
3. "5 percent by weight" - 200 lbs   90.7 kgs

MIXING METHOD FOR WIRAND CONCRETE

1. Quartzite sand and 3/8 in. quartz into mixer (via conveyor belt) simultaneously
2. Dispensation of wire into mixer began when the first aggregates were in the mixer
3. Cement discharged into mixer
4. Water added at the same time as cement
5. A.E.A. introduced into mixer
6. Wire continues to be dispensed throughout operations 3 to 5 and after, until requisite wire content into mixer
7. Batch (all 1 yd batches) discharged into truck mixer

Mix cycle then repeats until 4 or 6 yd batch complete. Concrete transported to site (8 miles--20 minutes) agitated on site and then discharged into slipform paving machine.

INSTRUMENTATION AND JOINT DETAILS

In conjunction with Sheffield University, all of the seven lanes of paving have been fully instrumented (Figure 6) with stainless steel bolts (to check expansion and contraction) and two types of strain gauges, viz., R.R.L. Vibrating Acoustic Wire Gauges, on 900 c/s and 800 c/s; the 800 c/s gauges being more suitable for measuring stresses in the tensile zones of the pavements.

All the strain gauges, with the exception of one, are placed in a longitudinal direction (direction of greatest stress and movements), and all stainless steel bolts are placed equidistant from the edges of the 9 ft wide machine runs. Samples of the results are shown in Figures 7, 8, and 9.

All joints between the different "trial runs and sections" are simple butt joints. The one exception being the load transfer joint between Sections A and B in Lane 1.

Another "joint" worthy of mention is the "floating end" of Section N in Lane 6 (Figure 10). Here the direct substitution of the lean mix concrete (under all of the other Wirand concrete pavement) with compacted sand will induce a cantilever action and an area of maximum tensile stress on the surface of the pavement whenever a vehicle passes over it.

As can be seen from the section through this detail, a 800 c/s strain gauge has been put near the surface of the pavement at this point, and a counting device has also been installed to count the number of times the end of the slab deflects.

PAVING SEQUENCE

11 December 1970; Section H, Lane 4. This section was the first Wirand concrete pavement to be laid using the slipform paving machine (see Figure 11).

The mix used for this section was Mix B with a wire content of 120 lbs/yc (i.e., 3.3 percent by weight of all mix ingredients). At the Readymix concrete plant, 3 number 6 in. cubes were taken from the first batch and 3 from the second. The pavement was started approximately 170 ft from the datum end of Lane 4, with the intention of a continuous 170 ft long slab at 2 in. thick. The discrepancy between the theoretical quantity required and the actual volume of concrete received (see notes on mix details) meant that this ended 28 ft from datum.

The surface finish of the slab is as left by the slipform paver.

Instrumentation in this section consists of 3 number 900 c/s strain gauges and 2 stainless steel bolts.

12 December 1970; Section G, Lane 4. This small section, 28 ft long, was laid by the slipform paving machine. It is 2 in. thick and the mix used was Mix B with a wire content of 200 lbs/yc (i.e., 5.5 percent by weight of all mix ingredients).

The section is not instrumented and the surface finish is as left by the paving machine.

12 December 1970; Section J, Lane 4. This 24 ft long section was hand placed at 1 in. thick with the same mix as used in Section G. (N.B. Attempts were made to lay Section J with the slipform paver and had this section been longer it would have been successful). This section could not

be instrumented because of the thickness and the pavement surface has a steel float finish.

12 December 1970; Section L, Lane 4. This small tapering section, approximately 6 ft long, was hand laid; the subbase being hardcore.

The mix used was as Section G, with a steel float finish.

14 December 1970; Section B, Lane 1. Section B is 4 in. thick and approximately 85 ft long. The section is not instrumented.

The mix used was Mix B with a wire content of 120 lbs/yc. (i.e., 3.3 percent by weight of all mix ingredients).

It should be noted that at the tapering end of the slab, hand laid concrete has been placed and merged into the main run laid by the paving machine. The slab has a "nonskid" brushed finish.

15 December 1970; Section A, Lane 1. This section of Wirand concrete pavement was the first to be laid with the revised Mix C. The wire content selected for this section was 200 lbs/yc (i.e., 5-1/4 percent by weight).

The pavement is 104 ft long and 4 in. thick. Instrumentation in this section consists of 2 number 900 c/s strain gauges and 2 stainless steel bolts. N.B. Section A is separated from Section B in Lane 1 by a "minature" Cromwell Mk. IV load transfer joint assembly.

16 December 1970; Section F, Lane 3. Section F, is the second longest continuous length of pavement. The slab is 4 in. thick and Mix C was used, with a wire content of 120 lbs/yc (i.e., 3.15 percent by weight of all mix ingredients). The slab length was 200 ft.

The slab was laid by "odd-legging" the paving machine tracks (one on the Wirand Concrete pavements in Lane 4 and the other on the wet lean concrete in Lane 2).

This pavement was the one chosen for the demonstration that was held and was viewed by members of the Cement and Concrete Association, the British Airport Authority, the Department of Environment and various Company Officials representing consulting engineers and contractors.

The section is instrumented with 3 number 900 c/s strain gauges and 3 stainless steel bolts, as shown on the instrumentation layout.

Three beams (20 in. by 4 in. by 4 in.) were cast from this section and modules of rupture tests in accordance with B.S. 1881 will be carried out at 28 days.

As with the majority of remaining sections the pavement has a brushed finish.

17 December 1970; Section M. Lane 5. This section, the longest continuous pavement (210 ft) is also 4 in. thick with a wire content of 120 lbs/yc using Mix 'C.'

As in Section F in Lane 3 the slipform paving machine was "odd-legged" while laying the pavement.

Instrumentation of this section consists of 2 number 800 c/s strain gauges and 1 number 900 c/s strain gauge in a longitudinal direction, 1 number 800 c/s strain gauge in the transverse direction and 3 stainless steel bolts.

18 December 1970; Section C, Lane 2. This is the longest (70 ft) hand laid section of Wirand concrete pavement. It is 2 in. thick and the mix used was Mix C with a wire content of 200 lbs/yc (i.e., 5-1/4 percent by weight of all mix ingredients).

The section is not instrumented and has a "tamped" finish.

(N.B. It was not the original intention to hand lay this section; an electrical fault developed with the slipform paving machine just before the Wirand concrete arrived on site.)

19 December 1970; Section O, Lane 7. This section, adjacent to the conventional concrete, is 120 ft long, 4 in. thick and 9 ft wide.

The mix used for this run was Mix C with a wire content of 200 lbs/yc (i.e., 5-1/4 percent by weight of all mix ingredients).

The pavement has 2 number 800 c/s strain gauges and 2 stainless steel bolts set into the Wirand concrete as shown on the layout.

Four 20 in. by 4 in. by 4 in. beams were cast from this section for modulus of rupture tests, to be performed when 28 days old.

21 December 1970; Section D, Lane 2. One of the two sections in the pavement trials with a thickness of 3 in. This section is approximately 70 ft long and the mix used was Mix C with a wire content of 200 lbs/yc.

Two stainless steel bolts have been set into the pavement and an 800 c/s strain gauge is situated in the center, lying in a longitudinal direction.

21 December 1970; Section E, Lane 2. To complete Lane 2 an area of pavement, approximately 60 ft long and 4 in. thick, was laid by the slipform paving machine.

Mix C with a wire content of 160 lbs/yc was used (i.e., 4.2 percent by weight of all mix ingredients) and the slab was instrumented with an 800 c/s strain gauge and two stainless steel bolts.

21 December 1970; Section K, Lane 4. One of the smallest areas of land laid in Wirand concrete, it is 6 ft long, 1 in. thick and consists of the same mix as detailed in Section E, Lane 2 above.

23 December 1970; Section O, Lane 6. This section completed the Wirand concrete paving. It is approximately 130 ft long, 3 in. thick and incorporates Mix C with a wire content of 120 lbs/yc (i.e., 3.15 percent by weight of all mix ingredients).

The end of the slab nearest datum includes the "cantilever floating" joint arrangement detailed earlier in this report.

The 300 c/s strain gauges positioned at this joint detail is one of two that are included in the full length, as can be seen from the instrumentation layout. A brush finish was applied to the surface.

WIRAND CONCRETE TEST RESULTS

Compression Tests. Compression tests were conducted in accordance with B.S. 1881, 1970. Tests were of Mix B with a wire content of 120 lbs/yc (concrete laid in Section H, Lane 4). The 7 day results were 4350 psi and 5070 psi. The 28 day results were 6280 psi and 6530 psi. The other cubes cast at the same time will be "sawn" in half as a check on the wire distribution. Average density of the above 6 in. cubes is 139 lbs/cu ft.

Washout Tests. In an effort to check the distribution of the wire within the mixed concrete, two washout tests were carried out.

Test 1: 15 December 1970--sample from Section A, Lane 1. Theoretical wire content was 5.25 percent by weight of all mix ingredients.

Weight of sample was 1,786 gms. Weight of wire retained after washing was 92 gms. Wire content as percent of weight of sample was 5.14 percent.

Test 2: 17 December 1970--sample from Section M, Lane 5. Theoretical wire content was 3.15 percent by weight of all mix ingredients. Weight of sample was 2,234 gms. Weight of wire retained after washing was 67 gms. Wire content as percent of weight of sample was 3 percent.

Flexural Strength Tests. Twenty in. by four in. by four in. beam specimens subjected to 3rd point loading at 28 days (all specimens cured in field).

Wirand Concrete--3 percent

M.O.R.	545 lbs/in.^{2}	Average 565 lbs/in.^{2}
Cast 16/12/70	615 lbs/in.^{2}	
Tested 13/1/71	555 lbs/in.^{2}	
	545 lbs/in.^{2}	

Wirand Concrete--5 percent

M.O.R.	675 lbs/in.^{2}	Average 680 lbs/in.^{2}
Cast 19/12/70	705 lbs/in.^{2}	
Tested 15/1/71	655 lbs/in.^{2}	
	695 lbs/in.^{2}	

Wet Lean Concrete

Compression tests in accordance with B.S. 1881, 1970.

7 days	750 psi
7 days	500 psi
28 days	950 psi
28 days	850 psi

CONVENTIONAL CONCRETE

As a performance check for the Wirand concrete pavements, an area of hand laid, conventionally reinforced concrete pavement was placed.

This was placed in 8 ft wide lanes, the maximum length being approximately 90 ft and there were no transverse joints.

Mix Design (design strength 4000 lbs/in.^{2} at 28 days)

	Dry wts lbs/yc	Aggregate Moisture Contents	Adjusted Weights lbs/yc
N. Yorkshire Sand	1080	6%	1145
N. Yorkshire 3/4 in. to 3/16 in. gravel	2090	3%	2150
Water	250	--	125
A.E.A (Cemtair)	5 fl oz	--	5 fl oz
O.P.C.	580	--	580

Mesh Reinforcement

Spencer Wire Co. Ltd., Ref A.252 (Square Mesh) main and cross wires 8 mm diameter at 200 mm pitch.

Flexural Strength Tests

M.O.R.	335 lbs/in.^{2}	Cast 22/12/70
	420 lbs/in.^{2}	Tested 19/1/71

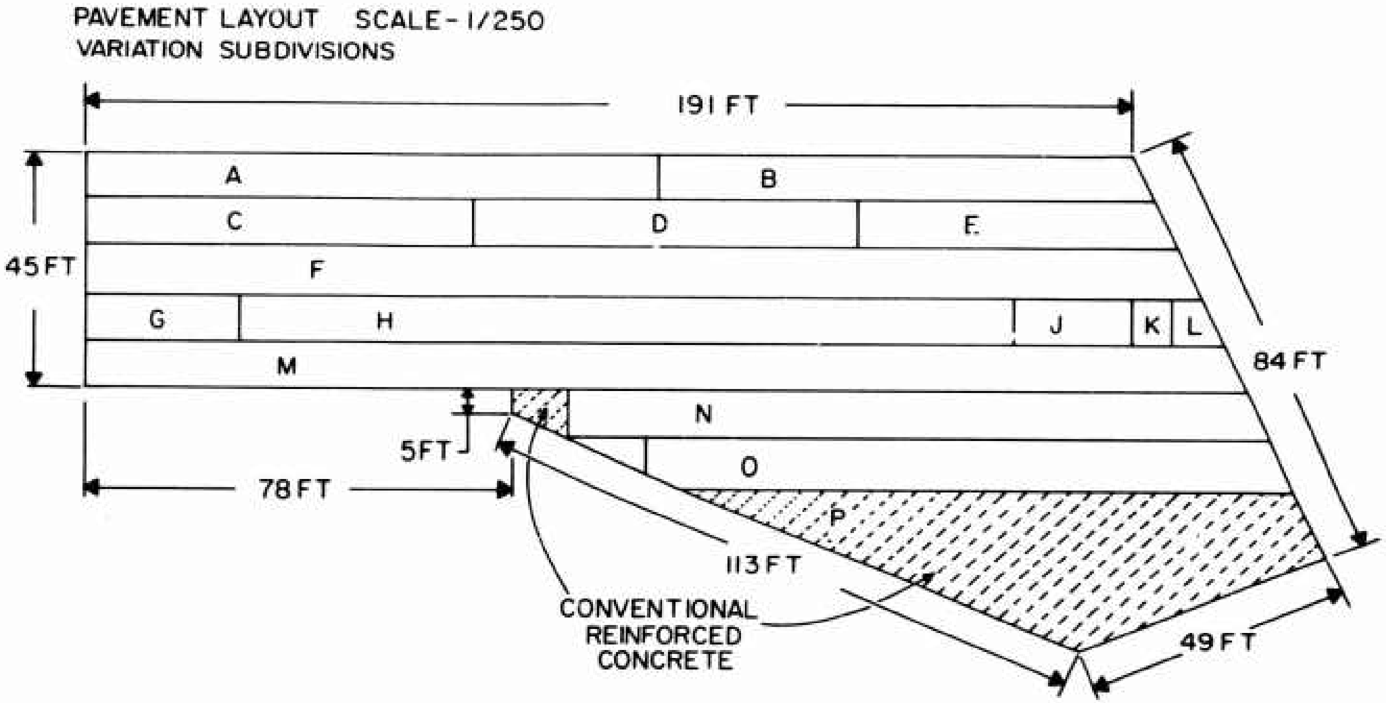


Figure 1. Variation Subdivisions of Pavement Layout

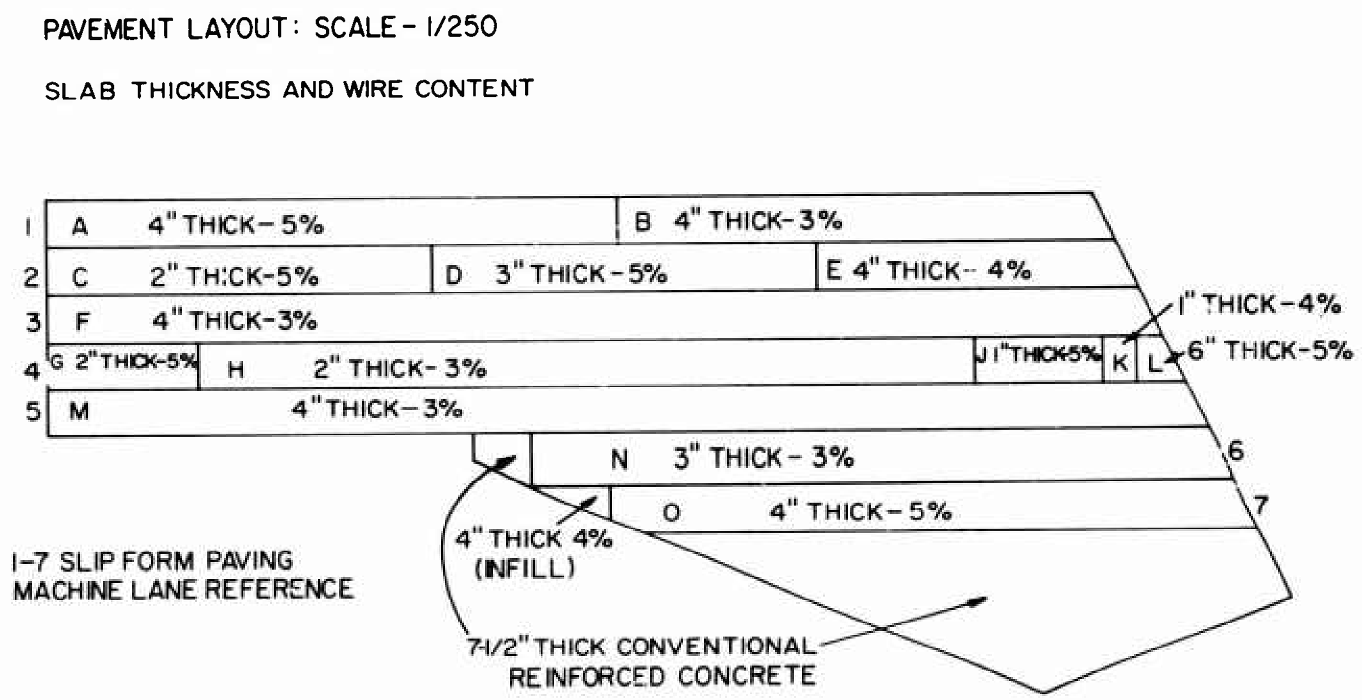


Figure 2. Pavement Layout of Slab Thickness and Wire Content

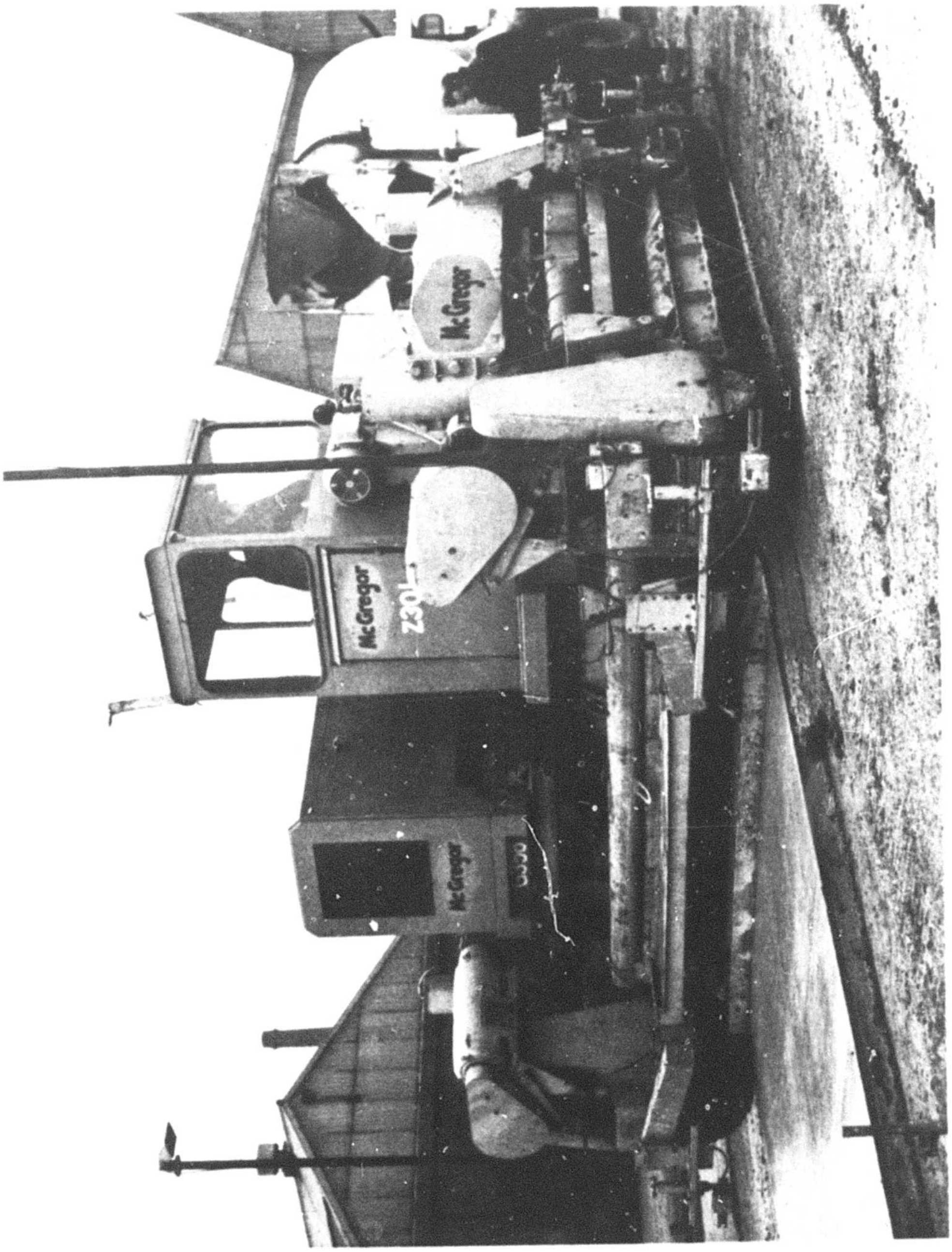


Figure 3. C.P.P. 60 Paving Machine

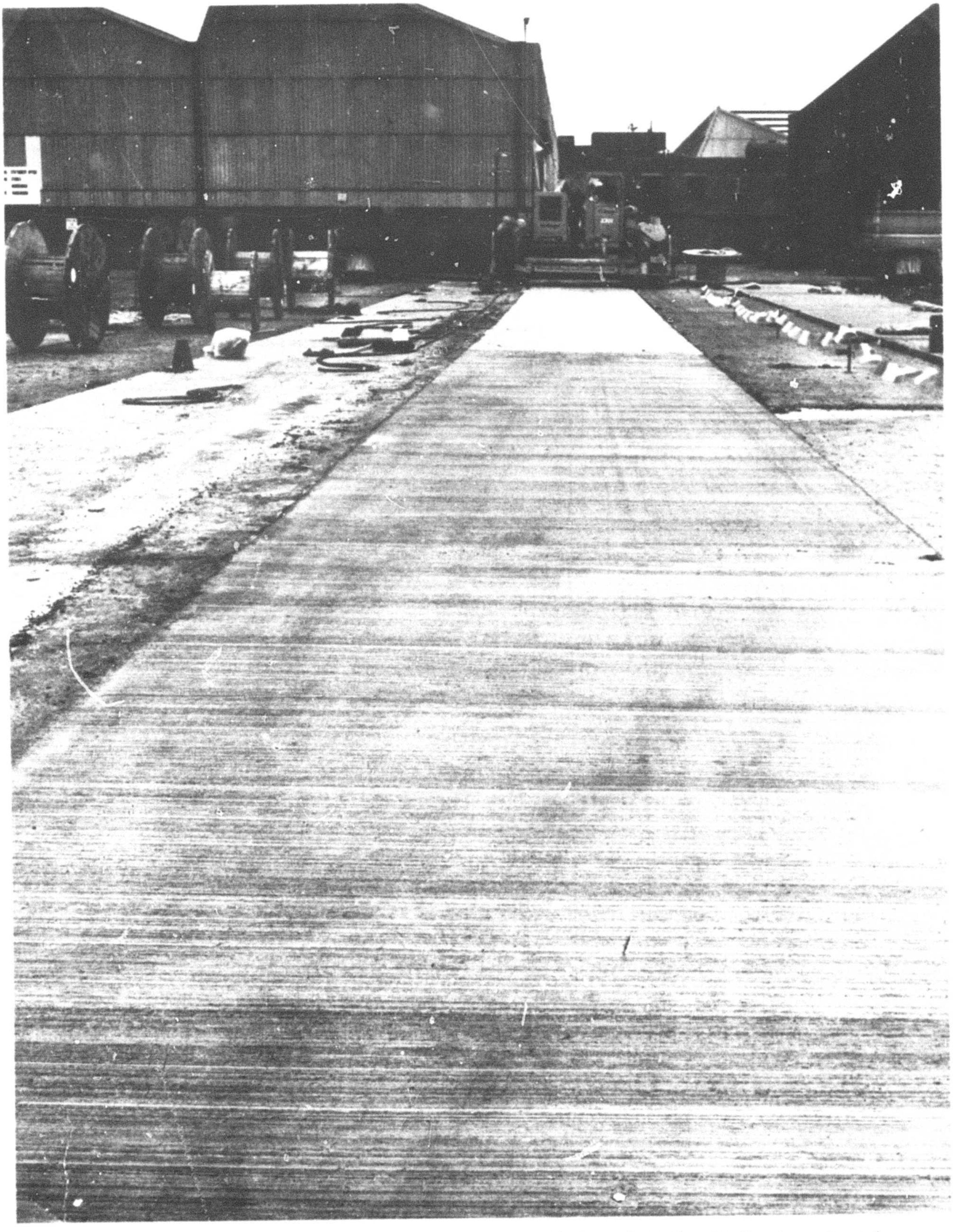
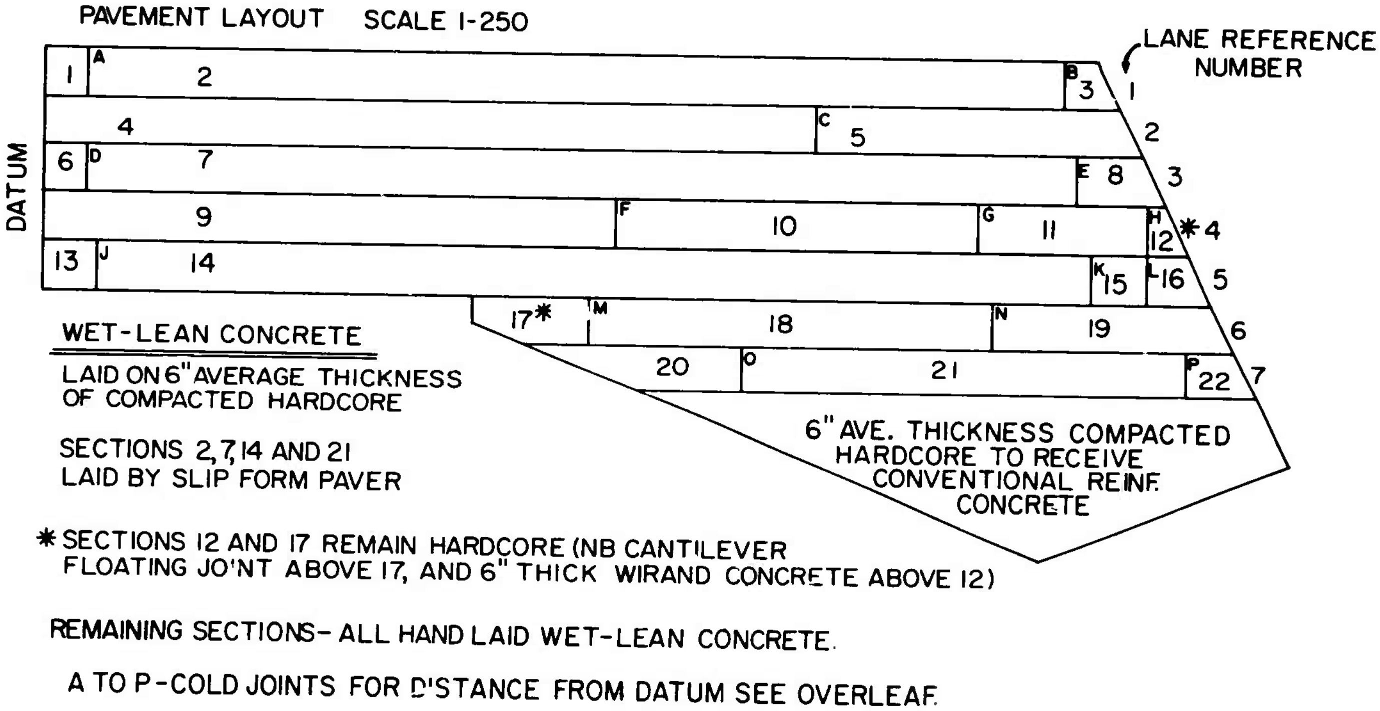


Figure 4. View of Slab After Placement With a C.P.P. 60 Paving Machine



WET-LEAN CONCRETE

LAID ON 6" AVERAGE THICKNESS OF COMPACTED HARDCORE

SECTIONS 2, 7, 14 AND 21 LAID BY SLIP FORM PAVER

* SECTIONS 12 AND 17 REMAIN HARDCORE (NB CANTILEVER FLOATING JOINT ABOVE 17, AND 6" THICK WIRAND CONCRETE ABOVE 12)

REMAINING SECTIONS- ALL HAND LAID WET-LEAN CONCRETE.

A TO P-COLD JOINTS FOR DISTANCE FROM DATUM SEE OVERLEAF.

Figure 5. Pavement Layout of Wet Lean Concrete

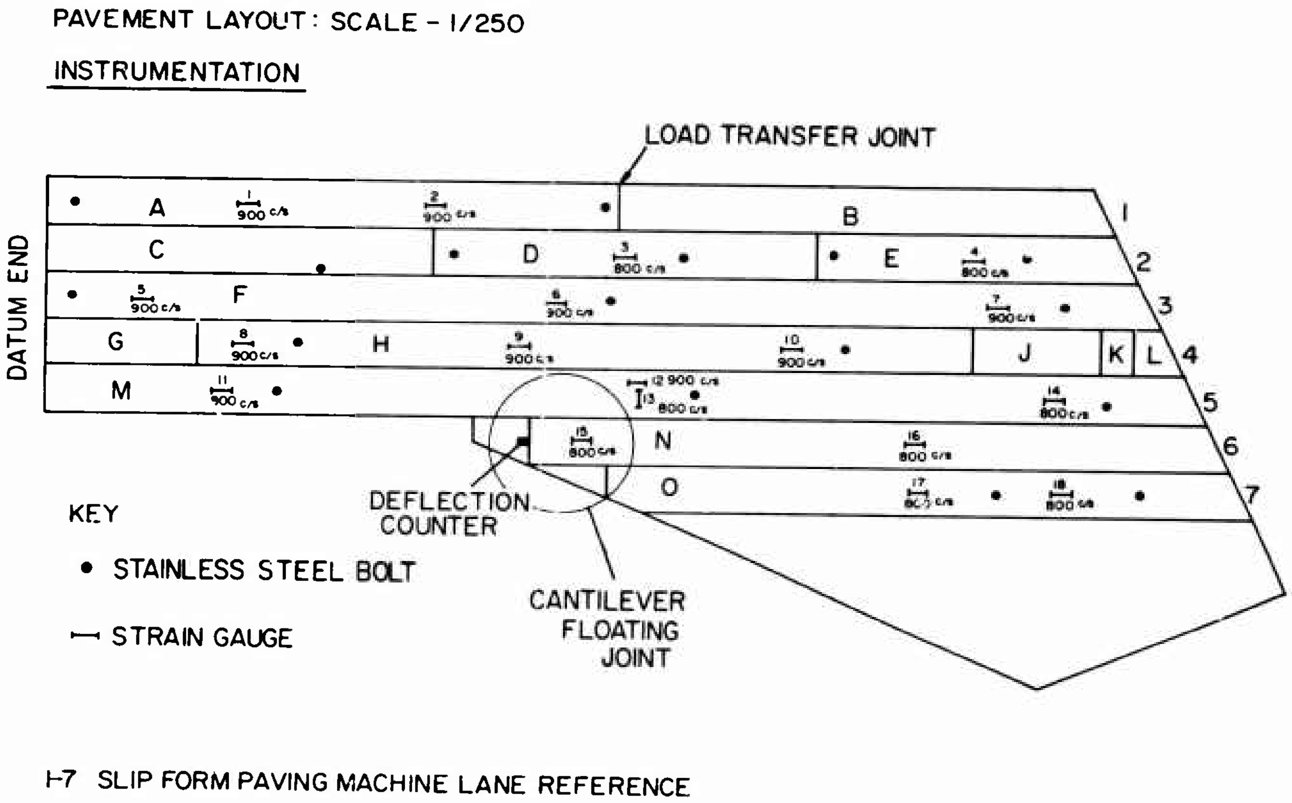


Figure 6. Pavement Layout for Instrumentation

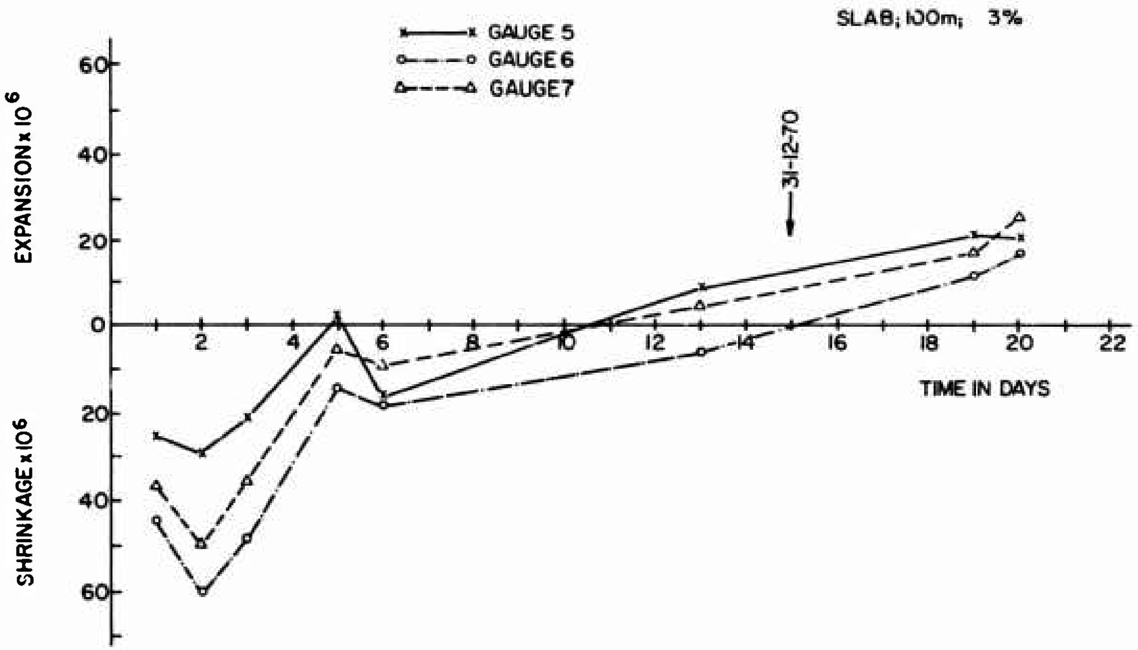


Figure 7. Instrumentation Results of Gauges 5, 6, and 7

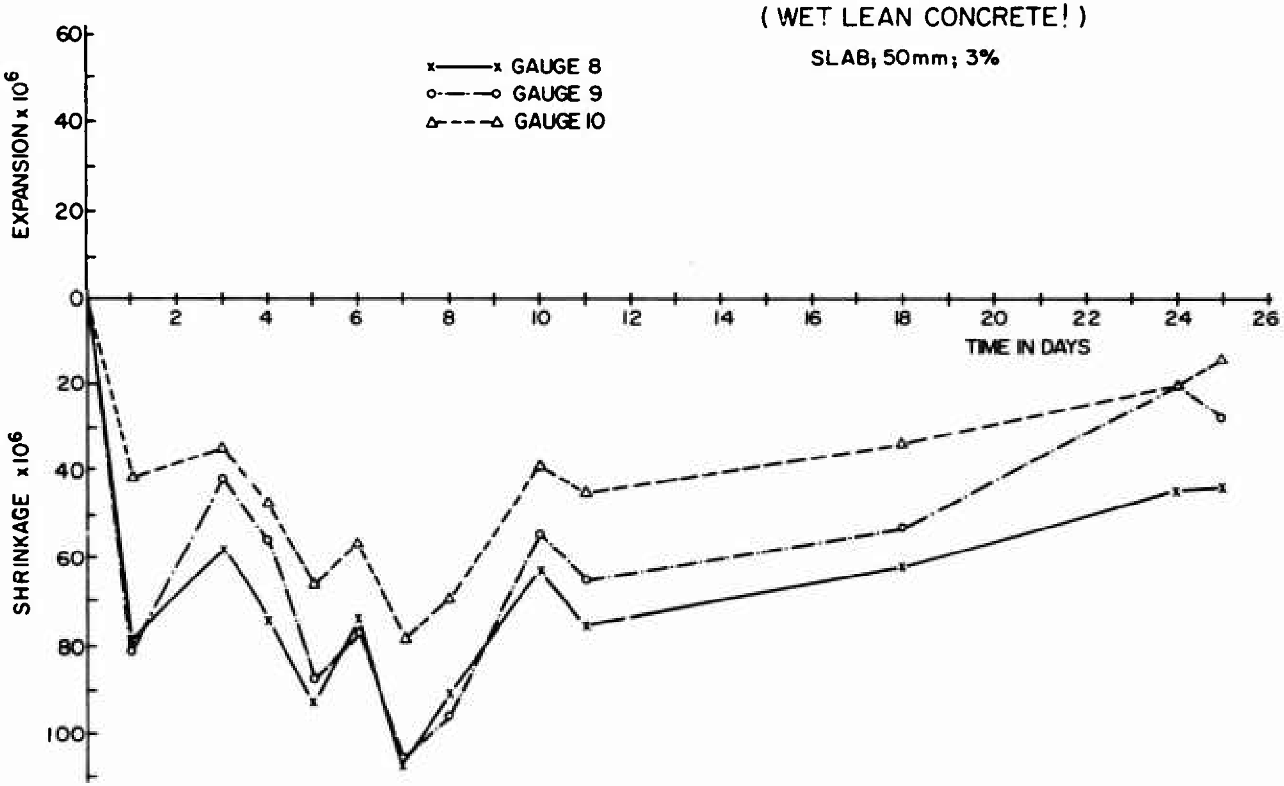


Figure 8. Instrumentation Results of Gauges 8, 9, and 10

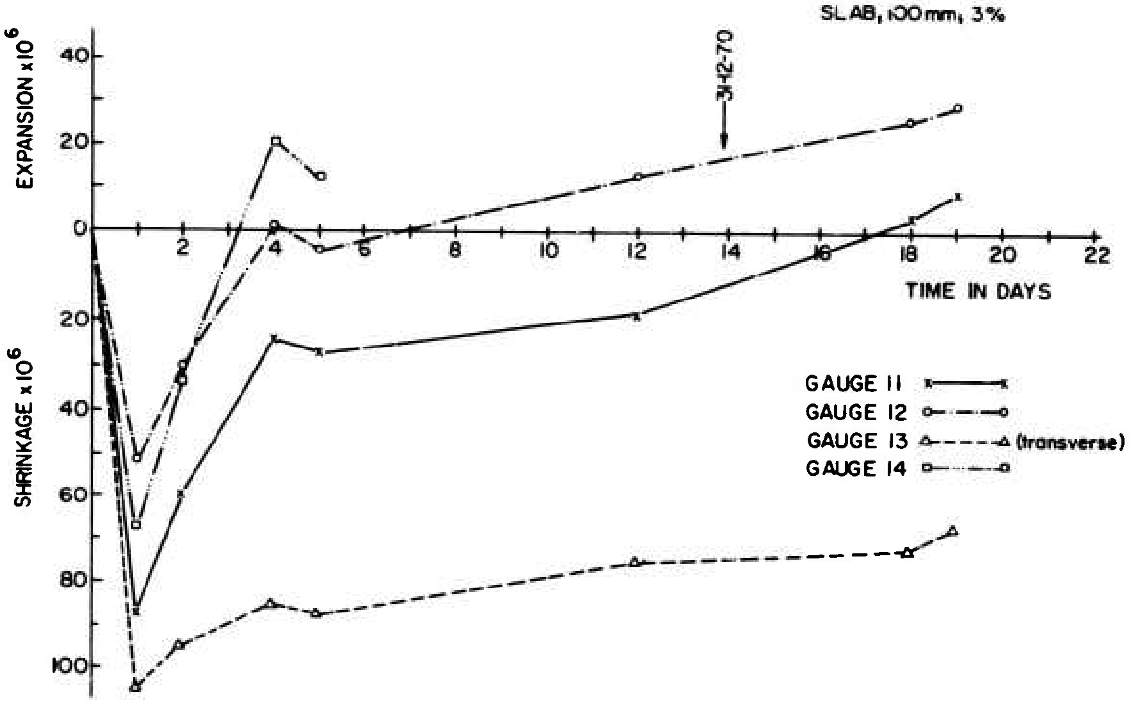


Figure 9. Instrumentation Results of Gauges 11, 12, 13, and 14

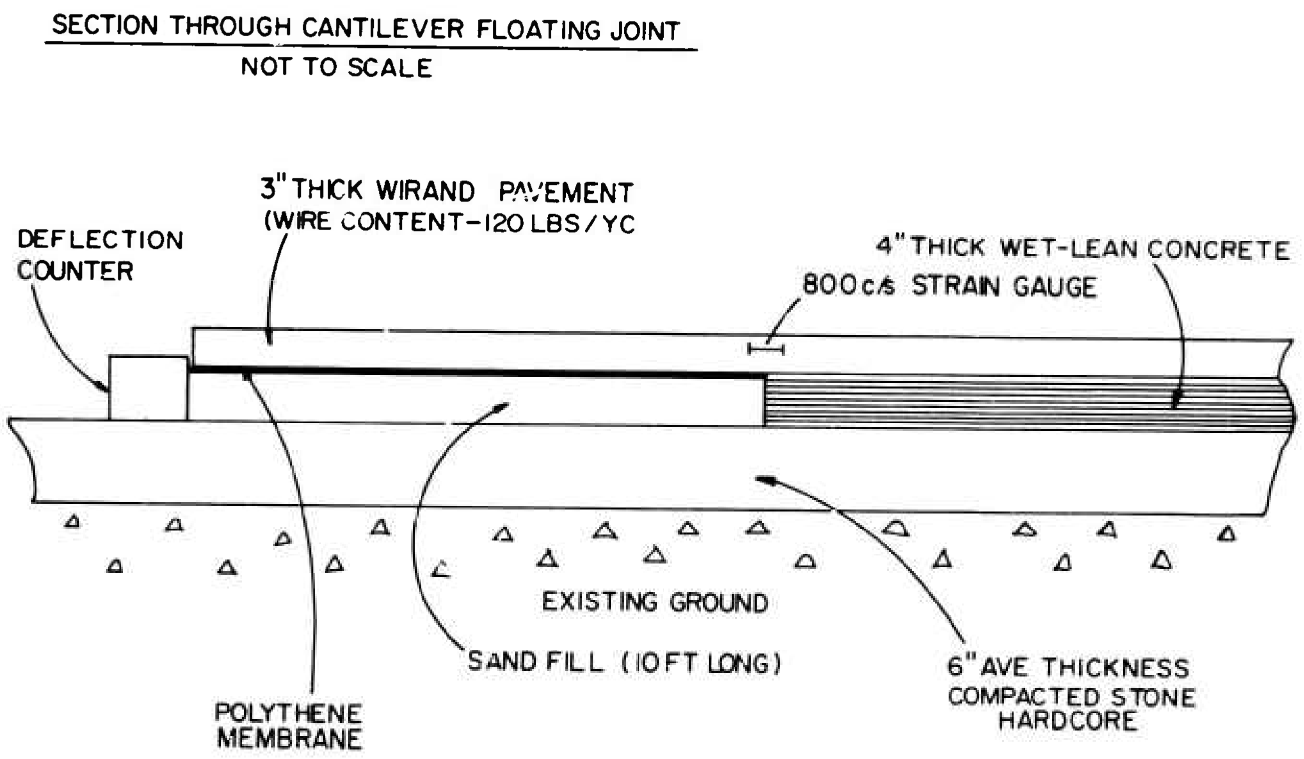


Figure 10. Section Through Cantilever Floating Joint

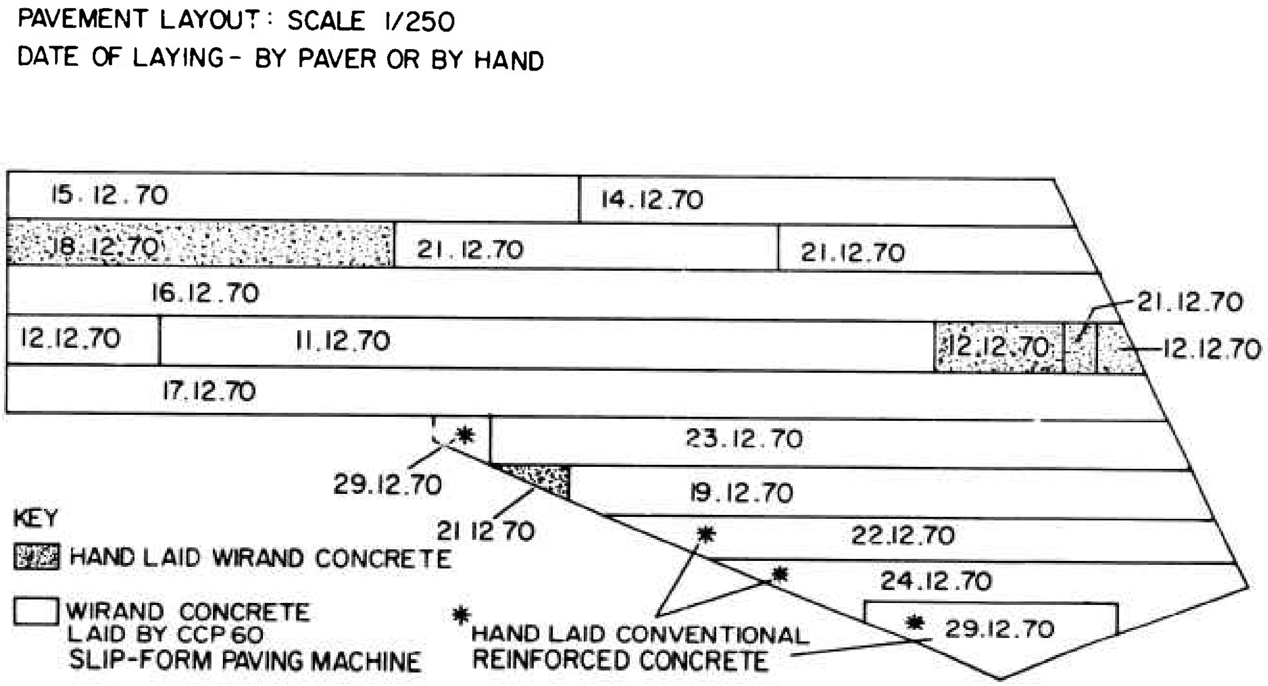


Figure 11. Paving Sequence and Type

CONFERENCE PHOTOGRAPHS

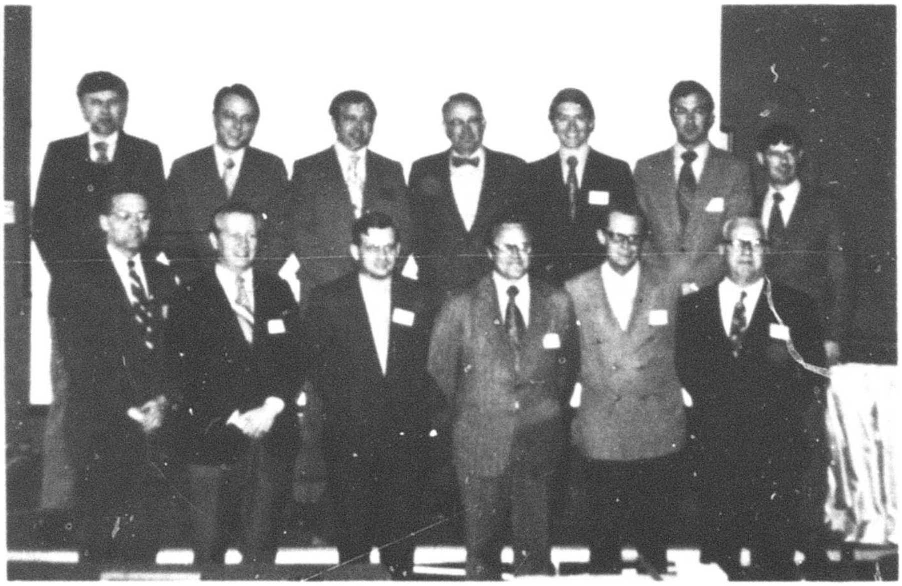


Figure 1. Conference Speakers. Bottom row, left to right: Henry Marsh, Bruce Waterhouse, Gordon Batson, William Yrjanson, Clare Luke, Alan McDonald; top row, James Lott, John Rice, Bobby Gray, Clyde Kesler, David Lankard, Frazier Parker, Harvey Parker. Not pictured: Alan Schwarz.

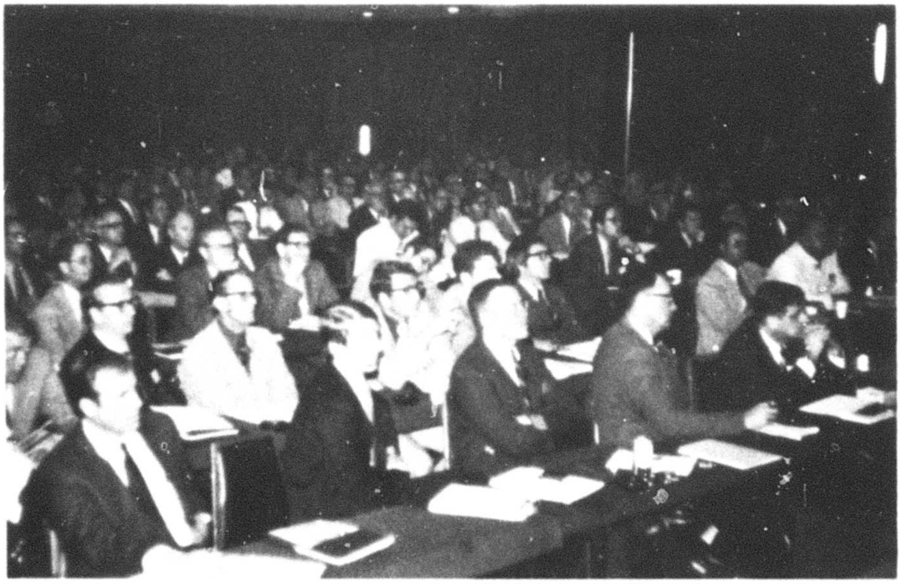


Figure 2. Conference in Session. Attendees from diverse backgrounds verified the fulfillment of the conference objective to provide the current state-of-the-art of fibrous concrete to the concrete industry.

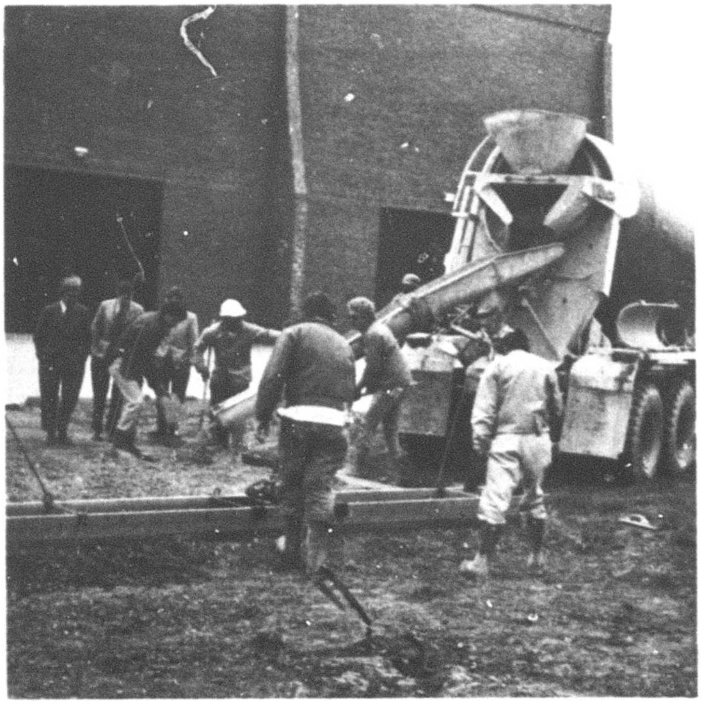


Figure 3. Highlight of the conference visit to CERL was the opportunity to view an actual placement of a 3-in. thick, 35 x 50-ft parking slab constructed on grade with ready-mix fibrous concrete.

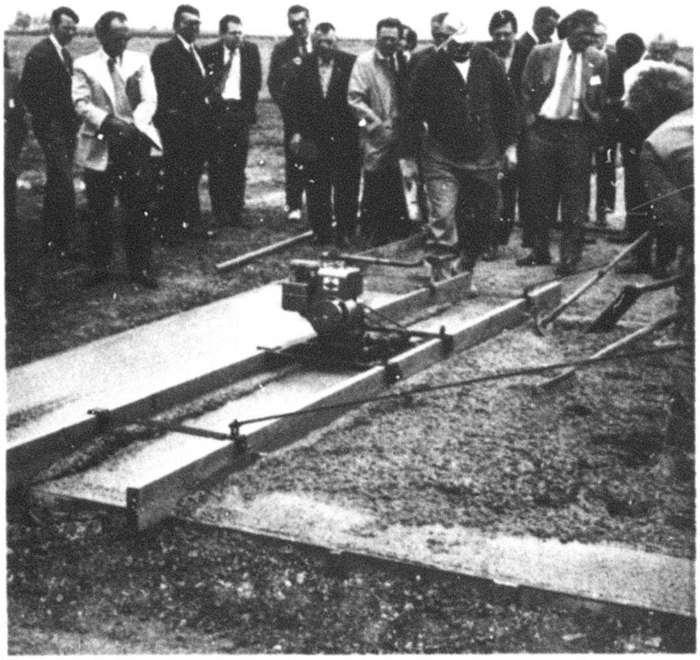


Figure 4. Conference attendees also viewed the demonstration of a semi-manual technique of consolidating and striking-off the fibrous concrete. Fibrous concrete material was provided courtesy of U.S. Steel Corporation and National Standard Company.

Figure 5. Several conference attendees view one of the many displays demonstrating various aspects of fiber characteristics. Display courtesy of U.S. Steel Corporation.

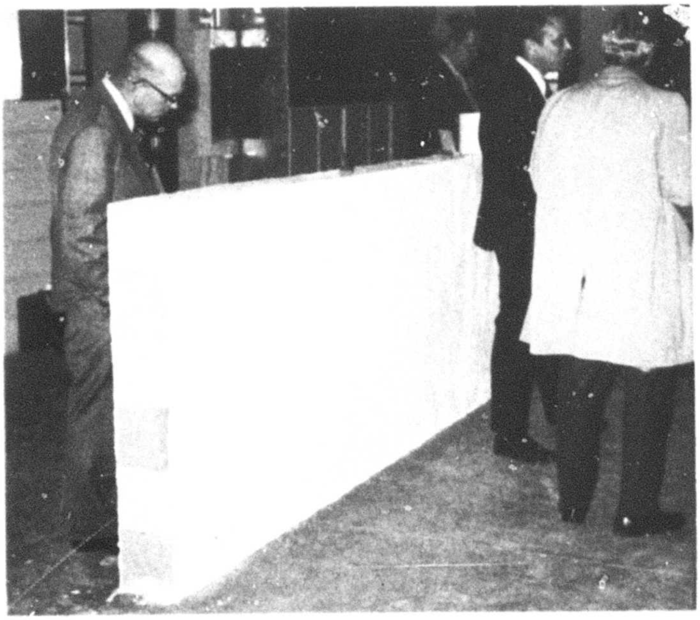


Figure 6. On display was a masonry block wall surface bonded (no mortar between the blocks) with a glass fiber reinforced cement paste. The surface bonding material is "Block Bond," provided by the Owens-Corning Fiberglas Corporation. Display courtesy of Owens-Corning Fiberglas Corporation.