TENSILE PROPERTIES OF PORTLAND CEMENT CONCRETE WITH ALKALI RESISTANT GLASS FIBER REINFORCEMENT

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ABSTRACT

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Submitted to the Departments of Ocean Engineering and Civil Engineering on January 23, 1974, in partial fulfillment of the requirements for the degrees of Master of Science in Ocean Engineering and Master of Science in Civil Engineering.

Successful development in the U.S. and abroad of an alkali-resistant glass fiber has given impetus to the study of the material as a reinforcement for Portland cement paste, mortar, and concrete. This report qualitatively evaluates some of the factors affecting the engineering performance of fiberglass-reinforced Portland cement mortar and suggests the direction future studies might take.

Laboratory tests were undertaken to evaluate the effects of varied mortar or matrix composition, physical orientation of the glass fibers due to forming or compacting of composite samples, and the effect of orientation relative to loading direction of individual fiberglass yarns within the matrix.

The orientation of a given number of fibers in the matrix material was found to be of more significance in determining engineering performance than were small variations in matrix composition. It was indicated that mold configuration and compaction methods affected this orientation.

The mechanics of individual fiberglass yarn failure are shown to be far more complex than those of steel fibers and thus not conducive to the same mathematical analysis. Yarns may fail in various pull-out and/or breaking modes which are controlled both by yarn orientation and matrix properties.

Recommendations made concerning future experimental work with this material are directed toward better understanding of the fiber performance and development of predictable properties for design.

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CHAPTER I

INTRODUCTION

Fiber reinforcement of building materials is an old concept that is being advanced through the use of modern technology and the application of new and often exotic materials. This study attempts to develop qualitative understanding of the behavior of glass-fiber reinforcement in a very common matrix material: Portland cement concrete.

I.1 Historical Background

Fiber reinforcement of construction materials can be traced to such humble beginnings as the straw-clay mixture used in adobe brick or, theoretically, even to the natural fiber-matrix network in sod blocks used by the most primitive peoples for shelter construction. With the relatively low cost and wide-spread use of concrete as a building material, it is only natural to assume fiber reinforcement would have been considered long ago. Such is the case; patents have been granted to Berard (1874), Graham (1911), and Kleinlogel (1920) for various applications of steel-fiber reinforcement to concrete (12).

The desire to improve certain engineering properties or to reduce construction costs has been the impetus for development of fiber reinforcement for concrete. Fibers have been suggested as a means of improving the tensile strength, ductility, impact resistance, and resistance to thermal or flexural cracking (4, 9, 17, 18, 21). The use of fibers to replace conventional reinforcement has been considered as a means of reducing labor costs for construction (23).

Significant experimental effort has taken place in steel-fiber reinforcement of bulk concrete in applications such as pavements, where crack arrest and impact resistance are desirable or for military applications where blast resistance is required (9, 10, 11, 19, 20). A second area of interest has been in the use of asbestos and, more recently, glass fibers in the manufacture of low-cost, two-dimensional materials in sheet or pipe form (21, 23). These are factory-produced materials as opposed to a construction component fabricated on the building site.

I.2 Previous Work

I.2.1 Steel Fibers

A logical beginning to the modern interest in steel-fiber reinforcement might be attributed to the work by Nervi in ferro-cement. The step from conventional reinforcement to ferro-cement concepts is a logical predecessor to the work by Romualdi (14) on closely-spaced wire reinforcement. Romualdi then followed with extensions of these theories to random steel-fiber reinforcement (15) and crack arrest concepts of steel fiber (16). This has been followed by investigation of various aspects of random wire reinforcement and attempts to mathematically model the material's performance. Research in this area has progressed to the point where a steel-fiber reinforced concrete is commercially available and significant full-scale projects have been completed using the material (9, 10, 20).

To date, the limitation on strength development in steel-fiber reinforced concrete has been the inability of the matrix to develop the

full tensile strength of the fiber (10). This is because fiber length is limited by its ability to be incorporated into the matrix without balling or knitting together. Various cross sectional shapes of fiber have been tested in an effort to improve the steel-matrix bond including square, rectangular, and recently a fiber with alternating round and square sections (9). Additionally, work has been done with three-dimensional fiber configurations (12).

1.2.2 Fiberglass Reinforcement

Cement asbestos has been successfully used for some time in sheet or pipe form by the construction industry. When it was found that exposure to the manufacture or use of asbestos was hazardous to the workers' health, a replacement fiber was needed (23). Fiberglass presents an attractive potential replacement, although a basic problem exists. Commercially available glass fiber is chemically attacked by the alkalinity of Portland cement (8, 10, 22). Three approaches have initially been taken to the solution of this problem. Attempts were made to develop durable and impermeable coatings for the yarns which would protect the glass from the surrounding medium. This met with only limited success, particularly in cases where mixing or handling of the mixed material was required. Another approach, taken by researchers in the USSR, was to use a gypsum, high-alumina cement matrix which apparently had little adverse effect on the glass fibers for periods of up to two years (8). While this approach was effective, it was not economically attractive in Western Europe or the United States where most of the cement manufactured is of the Portland type. This led the British

Building Research Station to undertake research leading to a glass which was alkali resistant (21), an approach also followed in the United States. The British product is now commercially available under the trade name Cem-FIL, manufactured by Fibreglass, Ltd., a subsidiary of Pilkington Brothers. In the United States, an alkali-resistant glass fiber has been developed by Owens Corning Fiberglass which they market in a pre-mix (dry) fiber-reinforced mortar form. This fiber was the material used in the following experimental work.

I.3 Future Interest

I.3.1 Material Developments

With the development of an alkali-resistant glass fiber, the major hurdle in the use of glass reinforcement in Portland cement products was cleared. Work with E-glass in a cement paste or mortar matrix had indicated good material performance if the glass degradation problem could be overcome (8).

Various methods have been considered for incorporating the glass fiber into a finished material. In the fabrication of thin, two-dimensional products, use of spray techniques, vacuum molds, and alternating-matrix chopped mat sandwiches have been successfully used (2, 8, 21). Sheet made up using these techniques may then be formed into curved or cylindrical shapes prior to initial setting.

I.3.2 Applications

Much of the interest in a two-dimensional composite of fiberglass and cement mortar is in its application to light-weight, durable, and inexpensive building materials. A material to be used for non-removeable

forms for ordinary reinforced concrete has good potential as a means of reducing labor costs and possibly material costs in building construction. Application of the material to factory prefabricated building partitions is attractive because of reduced weight over other systems, high-quality finish possible, and good fire-resistant properties (10).

Generally, fiber reinforcing has potential application where durability, fatigue resistance, or resistance to dynamic loading are desired. The fibers' ability to act as crack arrestors and to impart a more ductile failure mode to concrete are the major factors of interest.

In addition to building applications, there is interest in fiber-reinforced concrete for marine use (20). Hopefully, fibers can provide crack arrest and impact resistance that would improve the durability of concrete in the splash zone. Also, the ability to form the material to various curved shapes points to the possibility of using it alone or in ferro-cement in ships, other hull-like structures, or storage tanks.

I.3.3 This Study

The work which follows is an initial examination of some of the properties which will affect the use of fiberglass-reinforced mortar as a building material. All work was done on the premise that the glass fiber was truly alkali resistant. No attempt was made to evaluate time effects on the finished composite. The experimental work described here was an attempt to qualitatively illustrate some of the basic mechanisms of fiberglass-cement-mortar composite behavior. No attempt was made, however, to evaluate how this behavior might be affected by various manufacturing techniques.

CHAPTER II

EXPERIMENTAL PROCEDURE

The experimental program for this work consisted of three basic phases. The first utilized tensile specimens to evaluate the sensitivity of the material to changes in various factors of composition such as water-cement ratio, sand-cement ratio, and fiber content. Secondly, tensile specimens of varying geometry and method of molding were used to evaluate causes and effects of fiber orientation within the specimen. Finally, a series of specimens were tested to simulate the action of a single yarn of fibers being pulled from the mortar matrix.

II.1 The Matrix

II.1.1 Composition

The mortar used in all phases of this procedure was made from Type III, high-early-strength, Portland cement and, except where specifically noted, that portion of a standard graded sand (fineness modulus of 2.88) passing a #8 seive. The selection of this sand was arbitrary. As a base mortar having a water-cement ratio of 0.6 and a sand-cement ratio of 1.0 was used. These ratios and the maximum and minimum grain size of the sand were separately varied in Phase One of the tests. The base mortar was used exclusively in the second and third phases.

II.1.2 Mixing

Mixing was accomplished using a commercial type food-mixer having a bucket capacity of approximately 5 gallons. The agitator consisted of a deformed hoop rotating to sweep the entire volume and wetted interior

surface of the bucket. The mixing sequence consisted of mixing the dry sand and cement for approximately two minutes, adding all of the required water, ensuring that the solids were completely incorporated in the mix, and then mixing at low speed for two minutes.

II.2 Glass Fiber

Glass fiber used throughout these experiments was alkali-resistant, chopped yarn manufactured by Owens Corning Fiberglass. All specimens tested used yarns of 1 inch in length. Preliminary experiments had indicated that yarns embedded $\frac{1}{4}$ inch or less would virtually all pull from the mortar, whereas embedded lengths of over $\frac{1}{2}$ inch tended to break the yarn. Since yarn length was not a desired variable, the 1 inch length was chosen and used throughout.

The base for all specimens was the standard mortar mix to which was added fiberglass in the amount of 3% by weight of the sand and cement. The glass content was varied in Phase One and Two. Fibers were sprinkled in the wet mortar mix while the mixer ran, then mixed for two minutes after all had been added.

II.3 Test Specimens

II.3.1 Three-Dimensional Specimens

Samples which will henceforth be referred to as three dimensional, or 3D, were made in a plexiglas mold, as designed by Naaman (13), having a cross section as shown in Figure 1, Appendix A, and a length (perpendicular to the cross section) of about $7\frac{1}{2}$ inches. These samples were subsequently cut with a diamond saw into three, two-inch-thick specimens for testing in Phase One or eight 0.55-inch-thick specimens for Phase Two.

For Phase One, all samples were made by filling the mold from the top with the axis of loading vertical. For Phase Two, alternate samples were made with the axis first vertical and then horizontal by filling from the end.

The 3D molds were filled using a funnel of sufficient capacity to contain the entire charge of mortar. The mold and funnel containing the mortar mix were vibrated externally to cause the mortar to flow into the mold. No rodding or internal vibrating of the mixture was used. The time of vibration varied with the specific mix (1 to 3 minutes) but was continued until the mold had been satisfactorily filled and appeared reasonably free of voids.

II.3.2 Two-Dimensional Specimens

The 2D specimens shown in Figure 3, Appendix A, were made in a sub-divided, five-section mold so that each specimen was cast separately; thickness was maintained uniform by screeding over the complete mold. Each section was individually filled with mortar near the mid-section, then a combination of rolling and external vibrating was used to spread the mortar throughout the mold. In most cases, considerable working of the mortar was required to fill the molds uniformly.

II.3.3 Yarn Pull-Out Specimens

Specimens for these tests were made using the standard mortar mix in one-half of a standard ASTM briquette mold while using a styrofoam sandwich in the other half to locate and expose a measured length of a single fiberglass yarn to embedment. A cardboard-epoxy gripping surface was attached to the free end of the yarn before casting in the

mortar, as illustrated in Figure 5, Appendix A. Testing was accomplished using the upper half of a standard briquette jaw attached to the load cell of the testing machine with a gripper jaw attached to the moveable cross head as shown in Figure 6, Appendix A. Specimens were made using both the basic mortar mix and mortar to which 3% by weight of $\frac{1}{2}$-inch-long glass yarns had been added. The shorter fibers were used to simulate the consistancy and structure of the fiber mix while being compatible with the smaller mold being used. Samples were made for 1/4, 3/8, 1/2, and 3/4 inch embedment with the fibers parallel to the direction of loading ($\phi = 0°$) and for $\frac{1}{2}$-inch embedment with the yarn at 30°, 45°, and 60° ($\phi = 30°$, 45°, or 60°) to the direction of loading. Additionally, single yarn samples were tested to breaking in simple tension.

II.4 Testing

Following casting, all specimens were stored at 75°F and 100% relative humidity. Samples were removed from their molds within twenty-four hours of casting and cutting, where necessary, was done on the fifth or sixth day. All testing was done on the seventh day after casting.

Specimens were tested on an Instron testing machine using a cross-head speed of 0.05 inches per minute and a recording-chart speed of 2 inches per minute. Tests in Phases One and Two were made using the ten-thousand-pound-capacity-load cell with full-scale reading of 500 or 1000 pounds. Pull-out tests were made with the 50-pound-capacity-load cell and a full-scale reading of 5 pounds.

The Instron machine produces directly a load-versus-elongation plot for each sample. Because the recorded elongation is that of the whole

system and not only the sample, it has no absolute significance but is used here in a comparative manner.

II.5 Additional Experiments

In addition to the primary testing, three experiments to provide supplemental information were performed. First, a sample of 1000, one-inch-long yarns was weighed, heated to 1000°F for $2\frac{1}{2}$ hours, and then re-weighed to determine the weight loss due to burnoff of any coatings or sizing on the yarn. With the actual weight of glass thus determined, a theoretical yarn, cross-sectional area was calculated. These calculations are summarized in Appendix D.

Second, a sample of yarns was weighed, soaked in water, towel-dried, re-weighed, and finally oven-dried and weighed again to determine the water absorption capacity of the fibers. Calculations are summarized in Appendix D.

Lastly, samples were cut from typical 2D and 3D specimens and were then polished and viewed under an optical microscope. These samples were cut to allow viewing of a plane perpendicular to the axis of loading.

CHAPTER III

EXPERIMENTAL RESULTS

The results of the experimental program are presented in this chapter in a qualitative form giving typical curves or, where appropriate, graphs of average data. Raw data and calculations from all tests are tabulated in Appendix B. The significance and limitations of the results will be discussed in Chapter IV.

III.1 Qualitative Evaluation of Experimental Procedures

III.1.1 Mixing and Casting

Within the range of mixes, fiber contents and fiber lengths tested, the mixing procedure used was satisfactory. There was no tendency for the mixer blade to collect fibers or cause segregation. On the basis of observation during mixing, the action of the blade rather appeared to break up lumps of yarn and cause dispersion. The range of water-cement ratios (w/c) and fiber contents examined were at least partially dictated by the mixing procedure. A lower limit of about 0.45 - 0.5 w/c with 3% by weight of glass or an upper limit of about 5% by weight with a w/c of 0.6 was dictated by a combination of mixability with the given equipment and the ability to form satisfactory samples in the molds used. The casting procedure used was adequate for the parameters and equipment being used. This will be discussed further in Chapter IV.

III.1.2 Testing

Tests made on Phase One specimens utilized special wedge-type jaws designed by Naaman(13) for use with the 3D molds. Most specimens tested

with this apparatus gave satisfactory results in that breakage occured in the gage section rather than at the neck or within the jaws.

The same jaws, with spacers to center the specimen, were used where appropriate in Phase Two. One case of suspect data occured here, however: All Phase Two samples made of mortar without fiber failed at the upper neck along a circular arc in the wide section of the sample. This was probably a result of excessive shrinkage (w/c of 0.6) of the unreinforced mortar in a mold where the shape would cause residual tensile stresses. Casting these samples in thinner sections and/or in the horizontal rather than vertical direction might correct this problem.

The 2D samples were tested in jaws with serrated faces, with four bolts on each jaw providing the clamping force. Again, the apparatus was completely satisfactory. No breakage took place in or at the jaws and examination of the sample faces after breaking indicated no slippage of the jaws on the sample.

The test apparatus described previously for the Pull-Out test performed as intended, although some limitations of the test procedure will be discussed in Chapter IV.

III.2 Results of Phase-One Tests

Graphic representations of the results of Phase One tests are shown in Figures 1 through 4, Appendix C. The primary value of these tests, however, lies in the qualitative conclusions regarding workability and the effect the variables may have on workability. Because of the inherent scatter of the results, the limited number of samples, and the uncertainty as to how workability (as reflected in void percentage and

density) affects strength and energy absorption, the test values cannot be assumed reliable either absolutely or on a relative basis.

III.3 Results of Phase-Two Tests

The results of the Phase Two tests are summarized graphically in Figure 5, Appendix C, in the form of comparative, typical load-elongation curves for the four types of specimens. Figures 6 and 7, Appendix C, compare strength and toughness with fiber orientation. The horizontal scale on this graph, relative fiber orientation, is at best a qualitative description of a physical property. Chapter IV will further discuss these results and their significance.

III.4 Results of Pull-Out Tests

Results of the Pull-Out tests are illustrated in Figures 8 through 12, Appendix C, as comparative load-elongation curves and as behavior versus embedded length and versus angle relative to loading. The consistancy of these results, together with the number of specimens tested, indicate this data accurately represents the conditions. Several limitations to this test will be discussed in Chapter IV.

CHAPTER IV

DISCUSSION OF RESULTS

To understand the significance of the test results, a prior understanding of the reinforcing action of the fiber is necessary. Considerable work has been done by others in the study of steel fiber reinforcement. Some basic and significant differences exist, however, in the performance of steel fibers as compared to fiberglass yarns. Evaluation and discussion of the debonding experiments along with a consideration of the test limitations will lead to an understanding of the significance of the Phase One and Two experiments.

IV.1 Pull-Out Experiments

IV.1.1 Test Applicability

The tests used to examine yarn pull-out strength were carefully made to measure the bond strength of a single yarn. The only desired variables were embedded length and relative angle to loading. These tests were very similar to those used by Naaman (13) for steel fibers. The test results indicate that, with a one-inch fiberglass yarn, the expected length of embedment would be $\frac{1}{4}$ inch or less. Results of the tests with plain mortar indicate that most yarns should be pulled from the cracked surface. Actually, however, the fracture surfaces of all test specimens reveal few yarns pulled out intact, and even fewer of as much as $\frac{1}{4}$ inch in length.

The primary weakness in the experimental method lies in the undisturbed condition of the yarn tested. Yarns incorporated in

tensile specimens for Phases One and Two undergo significant deformations in mixing and casting. Samples cut from typical 2D and 3D specimens and examined under the optical microscope indicate that the majority of yarns are not intact, but are in groups of individual fibers separated by from one- to four- or five-fiber diameters. The space between these fibers is subsequently filled with a "matrix" which may or may not resemble the basic mortar. Since this will increase the exposed surface area of glass by a factor of approximately 15, compared to the debonding of the entire yarn as a unit, the critical pull-out length will obviously decrease. Undisturbed fibers, such as those used in the Pull-Out Tests, might accurately compare to yarns used in spray, built-up composites such as those tested by Allen (2) and Grimar (8), but provide only qualitative comparative information with regard to bulk-mixed materials.

The same tests made with a mortar containing yarns in the same amount as the tensile specimens indicate a reduced critical pull-out length as well as a reduced maximum tensile stress on the yarn. It must be kept in mind, however, that in the actual case of a tensile specimen at failure, the yarns in the area of the yarn being examined at the crack tip would also be stressed. While the exact mechanism governing interaction between fibers at the crack tip is not understood, it is likely that stresses in adjacent fibers would have an effect.

IV.1.2 Test Results

Evaluation of the results of tests with yarns at various angles to the direction of loading indicates that the crack surface forms a stress

riser probably in the form of a cutting edge that reduces the maximum tension a yarn may sustain and causes breakage rather than pull out of the yarn. This is in disagreement with the results for steel fibers found by Naaman (13) where the angled crack surface formed a pulley effect causing an increased level of pull-out energy after first cracking of the matrix.

Of major significance in evaluating yarn performance is the variety of modes possible for yarn failure. The fact that yarns may be embedded intact or with fibers dispersed has been mentioned. Yarns examined following the Pull-Out Tests show clearly that an intact yarn may split with any portion of the fibers breaking off while the remainder pull out. Those pulling out may be in contact with other fibers or the surrounding matrix surface. Unless these various modes can be adequately evaluated, predicting the performance of the fiberglass as reinforcement is unlikely.

In their work with steel fiber reinforcement, Romualdi (15, 16), Naaman (13), and Abolitz (1) assumed a uniform or probabilistic distribution and orientation of the fibers in the matrix. With this as a basis, account was taken of the effect of relative orientation to loading by applying a factor between 0.33 and 0.41 to estimate the portion of the total fibers which effectively resist the applied stress. This is possible because the steel wire is uniform and in all cases fails by pulling from the mortar. Since this is a basic assumption made in the derivation of the mathematical models for steel fibers and, further, since it cannot be applied to glass yarn behavior, the direct application of these models to glass yarn reinforcement is not valid.

IV.2 Phase One Experiments

The results of the Phase One experiments are in themselves inconclusive. When these are compared with Phase Two, it may be hypothesized that, within the limits investigated, fiber orientation and mixing are far more significant in the composite behavior than small variations in matrix composition. Conversely, unless each facet of the matrix behavior is understood, the difference between changes having no effect and having two or more compensating effects with no net change cannot be evaluated. More specifically, such changes as removing the fine portion of the sand, increasing the maximum grain size, decreasing the sand-cement ratio (s/c), or increasing the water-cement ratio (w/c) all increase the workability of the mortar-fiber mix. This increase in workability or fluidity of the mortar could be theorized to improve the bond with the yarn by insuring that the fibers are more thoroughly surrounded by matrix. Conversely, it is known that an increased water-cement ratio will start to weaken a given mix beyond an optimum point. Reducing the percentage of fines in the sand may also result in voids or segregation of the mortar, particularly within the yarns where small spaces would be filled with cement paste, water, or remain empty. These factors could have a distinct detrimental effect on yarn matrix bond strength which might mask or negate any benefits of improved workability. In his work with steel fibers, Romualdi (15) recognized that the water-cement ratio was critical, but was primarily concerned with the behavior of the fibers while mixing and compensated by adjusting the water content to achieve some desired workability.

IV.3 Phase Two Experiments

In the Phase Two experiments, an attempt was made to minimize the effects of all variables with the exception of fiber orientation caused by mixing, molding, or vibrating a material of given composition. Specimens were cut where necessary so that all cross sections were a nominal 2 inches by $\frac{1}{2}$ inch to eliminate variable sample geometry.

As mentioned previously, Romualdi (15) and Naaman (13) assumed a random orientation of steel fibers in their analysis and attempted to evaluate fiber effectiveness on that basis. A 30 - 40% effectiveness was calculated. Edgington and Hannant (7) suggested that mold walls, a free surface, or external vibration tend to orient the fibers, making the assumed random distribution suspect. Their experimental work was limited to giving qualitative evidence of their theory regarding the effects of vibration. They assumed that external vibration would tend to orient fibers into a plane or planes perpendicular to the direction of vibration. Thus, in the case of a vibrating table, fibers would tend toward a plane parallel to the table top. Their evidence consisted of fiber-reinforced cubes cast and vibrated on such a table, then split in the directions of the three normal planes. The results indicated a reduced relative strength when split perpendicular to the direction of vibrating.

In the current work, an effort was made to evaluate this theory using the 3D molds. Samples were made from the same mortar-fiber mix, filling molds from the top in one case and from the side with the mold rotated 90° in the other. The first case should theoretically result

in fibers oriented in planes perpendicular to the axis of subsequent loading, while the second case would result in a planar arrangement parallel to the loading direction, simulating a 2D specimen. Concurrent with making these samples, 2D samples were made from the same mix to serve as a measure of comparison.

Several differences in test procedures should be noted at this point. Edgington's work utilized molds having a smallest dimension of 3 to 8 times the length of the fibers used. Also, the molds were filled from the direction of this least dimension which would minimize side wall effects. The present work used molds (3D) having a least dimension of twice the fiber length with filling from the direction of the largest dimension. It must be assumed that the side wall effects were thus significant and also possibly counter to the effects of vibration.

The fibers used in this study were comparable in aspect ratio to those used by Edgington, the glass aspect ratio being 90 versus 50 and 100 for the steel. A significant difference exists in the specific gravities, however, with the glass only about 2.5 while the steel is approximately 7.8. The vertical force acting on fibers during vibration would therefore be more significant with the steel than with glass.

Results of the Phase Two tests, nevertheless, consistantly indicate both increased tensile strength and toughness for the samples cast horizontally over those cast vertically. Further increases in strength are noted in the case of the 2D samples. The 2D samples may only be qualitatively compared with the 3D specimens, however, since their size and the method of casting assure a high degree of orientation.

Microscopic examination of samples cut from 3D (vertical) and 2D specimens provide qualitative support for these results. In the 3D sample, a significant number of fibers are seen to be in or near the cutting plane (perpendicular to the axis of loading) while very few normal cross sections are visible. The 2D sample on the other hand exhibits a majority of fibers cut close to right angles with very few at a large angle to the axis of loading.

IV.4 Summary

The results of the various tests conducted indicate that the behavior of fiberglass-reinforced concrete or mortar will generally follow that of wire-reinforced concrete. It has also been shown, however, that the mathematical analysis that has been developed for steel fibers probably does not apply to glass yarns. Of major significance among these results are the factors indicating behavior that is unique to glass yarns and suggesting the complexity of their strengthening mechanisms. The indication is that fiberglass-reinforced concrete will not become an all-encompassing construction material, but will have to be carefully designed in each case to develop the required combination of strength and toughness.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

V.1 Conclusions

1) The most significant factor affecting the tensile strength of concrete-glass-fiber composites is fiber allignment. This property is basically a factor relating the amount of fiber alligned to effectively resist the applied load to the total fiber content. For a given fiber content, the allignment is affected by the relative size and shape of the mold used, the aspect ratio of the fiber, the method of placing the mixture in the mold, and the methods used for distributing and compacting the mixture.

2) The performance of the glass fibers after initial cracking of the matrix controls the engineering properties of the composite. The combination of fiber pull out and fiber breakage achieved at the crack surface will determine the relative strength and toughness of the material. An increased amount of fiber breakage will generally relate to increased tensile strength while toughness is proportional to the amount of fiber pull out.

3) Fiberglass yarns will fail by breaking either at the crack surface or within the surrounding mortar, pulling intact from the matrix or splitting, which results in some fibers breaking and some pulling out. The failure mode is a function of bond strength which is controlled by fiber and matrix properties. The significant fiber properties are length, ultimate tensile strength of yarn and the individual fibers,

and the final configuration of the yarn, i.e. the amount of separation between individual fibers and degree of influx of matrix. The strength and ability to surround the fibers (a combination of fluidity and grain size) are the significant properties of the matrix.

4) The mathematical analysis that has been done for steel fibers in a concrete matrix has as its basis the assumption that all fibers will pull out and none will be stressed to failure in tension. Because the failure mode of the fiberglass yarns is much more complex, involving both pull out and breakage as well as glass-matrix bond, glass-glass friction, and variable yarn cross sections, the analysis of steel fibers cannot be applied directly.

V.2 Recommendations

1) Rather than attempting to apply previously developed theories to the analysis of glass-fiber reinforcement, effort should be made toward developing empirical solutions which would allow rational performance predictions. Testing with emphasis on isolating as much as possible the individual variables, sufficient data to minimize uncertainty due to inherent scatter and test inaccuracy, and a co-ordinated program of microscopic examination of the samples should be undertaken.

2) In order to apply the analytical results to a practical construction material, a parallel effort should be made to determine mix properties and fabricating techniques that will allow predictable design and reasonable reproducibility of engineering properties.

BIBLIOGRAPHY

1. Abolitz, A. L., Agbim, C. C., Untrauer, R. E., Works, R. E., "Discussion of Paper on Tensile Strength of Concrete Affected by Uniformly Distributed and Closely Spaced Short Lengths of Wire Reinforcement," American Concrete Institute Journal, Dec. 1964, p. 1651.

2. Allen, H. G., "Stiffness and Strength of Two Glass-Fiber Reinforced Laminates," Journal of Composite Materials, Vol. 5, April 1971, p. 103.

3. Allen, H. G., "Tensile Properties of Seven Asbestoes Cements," Composites, June 1971, p. 103.

4. Brown, J. H., "The Failure of Glass-Fiber-Reinforced Notched Beams in Flexure," Magazine of Concrete Research, Vol. 25, No. 82, March 1973, p. 31.

5. De Vekey, R. C., Majumdar, A. J., "Determining Bond Strength in Fiber-Reinforced Composites," Magazine of Concrete Research, Vol. 20, No. 65, Dec. 1968, p. 229.

6. Dixon, J., Mayfield, B., "Concrete Reinforced with Fiberous Wire," Concrete, March 1971, p. 73.

7. Edgington, J., Hannant, D. J., "Steel Fiber Reinforced Concrete. The Effect on Fiber Orientation of Compaction by Vibration," RILEM, Materianx et Constructions, Vol. 5, No. 25, 1972, p. 41.

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

9. Lankard, D. R., "Steel Fibers in Mortar and Concrete," Composites, Vol. 3, No. 2, March 1972, p. 65.

10. McCurrich, L. H., Adams, M. A. J., "Fibers in Cement and Concrete," Concrete, Vol. 7, No. 4, April 1973, p. 51.

11. Monfore, G. E., "A Review of Fiber Reinforcement of Portland Cement, Paste, Mortar, and Concrete," Journal, Portland Cement Association Research and Development Laboratories, Vol. 10, No. 3, Sept. 1968, p. 36.

12. Naaman, A. E., McGarry, F. J., Sultan, J. N., "Developments in Fiber-Reinforcement for Concrete," M.I.T. Civil Engineering Department Report R72-28, May 1972.

13. Naaman, A. E., "A Statistical Theory of Strength for Fiber-Reinforced Concrete," Ph.D. Thesis, Massachusetts Institute of Technology, Cambridge, Massachusetts, Sept. 1972.

14. Romualdi, J. P., Batson. G. B., "Behavior of Reinforced Concrete Beams with Closely Spaced Reinforcement," Journal of the American Concrete Institute, Vol. 60, No. 6, June 1963, p. 147.

15. Romualdi, J. P., Mandel, J. A., "Tensile Strength of Concrete Affected by Uniformly Distributed and Closely Spaced Short Lengths of Wire Reinforcement," Journal of the American Concrete Institute, Vol. 61, No. 6, June 1964, p. 657.

16. Romualdi, J. P., Ramey, M., Sanday, S. C., "Prevention and Control of Cracking by Use of Short Random Fibers," Paper No. 10, Special Publication No. 20, American Concrete Institute, 1968.

17. Shah, S. P., Rangan, B. V., "Fiber-Reinforced Concrete Properties," Journal of the American Concrete Institute, Vol. 68, No. 2, Feb. 1971, p. 126.

18. Snyder, M. J., Lankard, D. R., "Factors Affecting the Flexural Strength of Steel Fiberous Concrete," Journal of the American Concrete Institute, Vol. 69, No. 2, Feb. 1972, p. 96.

19. Sridhara, S., Jumar, S., Sinare, M. A., "Fiber Reinforced Concrete," Indian Concrete Journal, October 1971, p. 428.

20. "State-of-the-Art Report on Fiber Reinforced Concrete," ACI Committee 544 Report, American Concrete Institute Journal, Nov. 1973, p. 729.

21. Thomas, J. A. G., "Glass-Fiber-Reinforced Cement," Composites, Vol 2, No. 2, June 1971, p. 95.

22. Thomas, J. A. G., "Fiber-Air-Entrained Concrete," Composites, Vol 3, No. 2, March 1972, p. 71.

23. Thomas, J. A. G., "Fiber Composites as Construction Materials," Composites, Vol 3, No. 2, March 1972, p. 62.

APPENDIX A

ILLUSTRATION OF TEST SPECIMENS AND APPARATUS

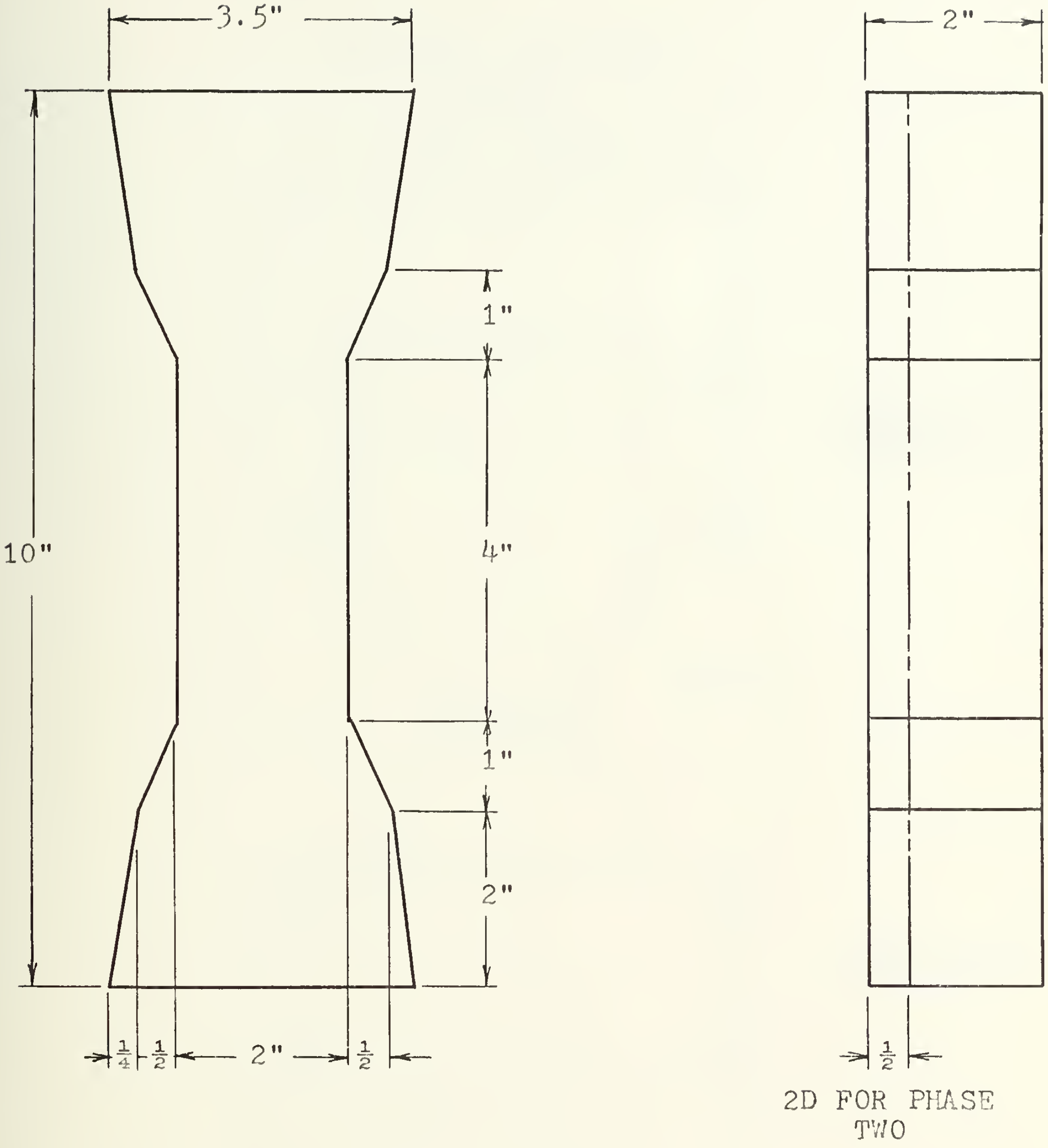

FIG. 1 3D TENSILE SPECIMEN

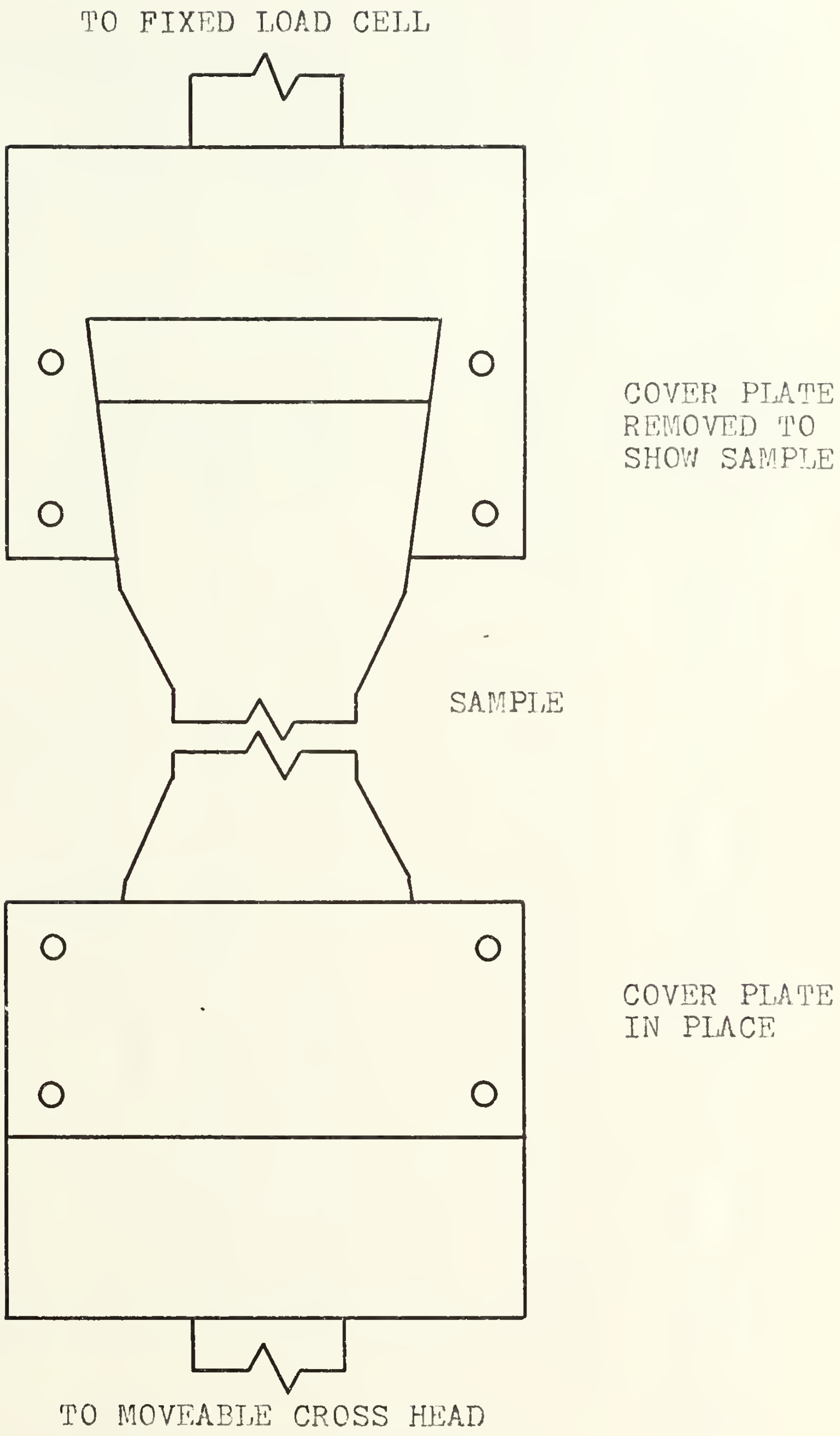

FIG. 2 3D TEST APPARATUS

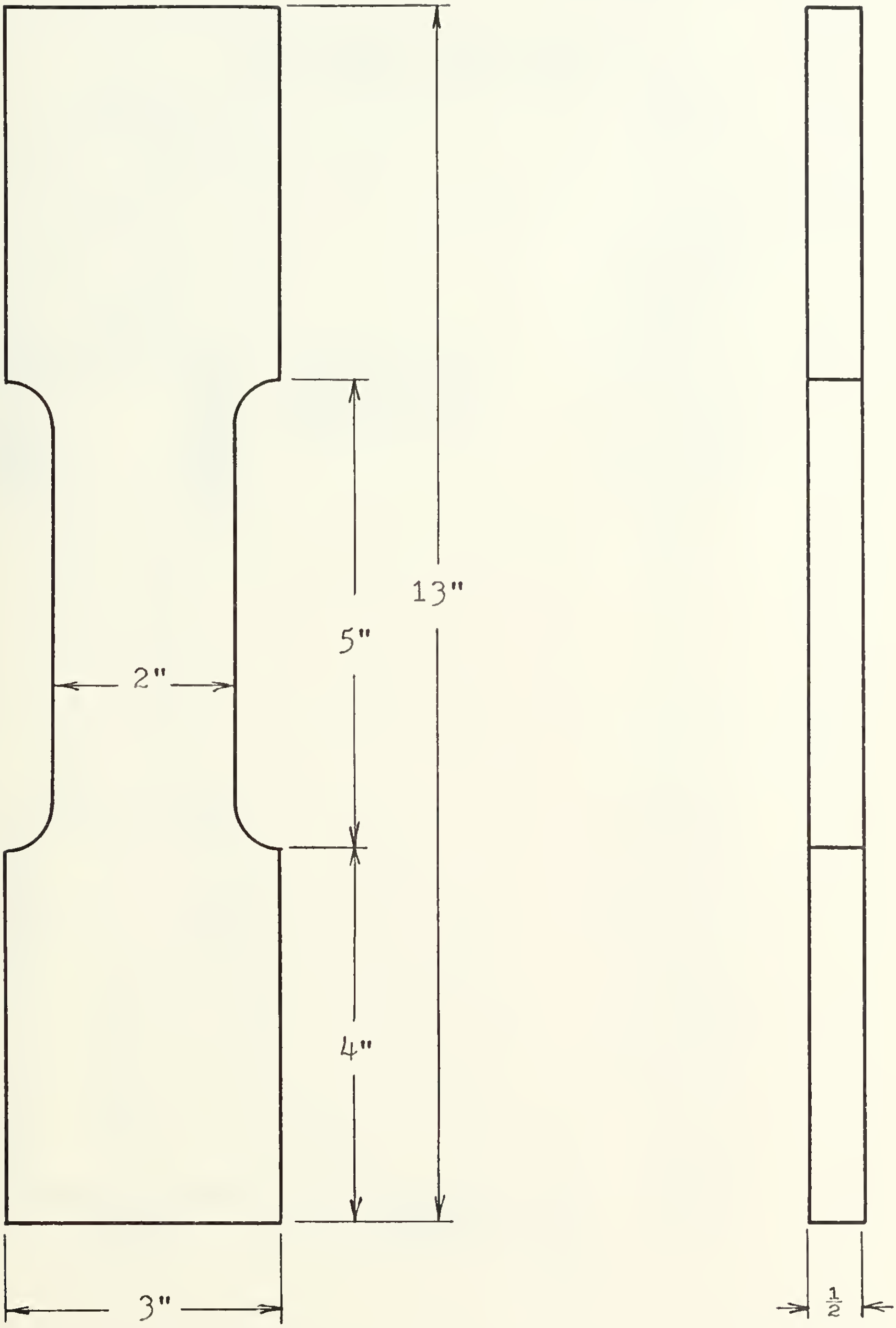

FIG. 3 2D TENSILE SPECIMEN

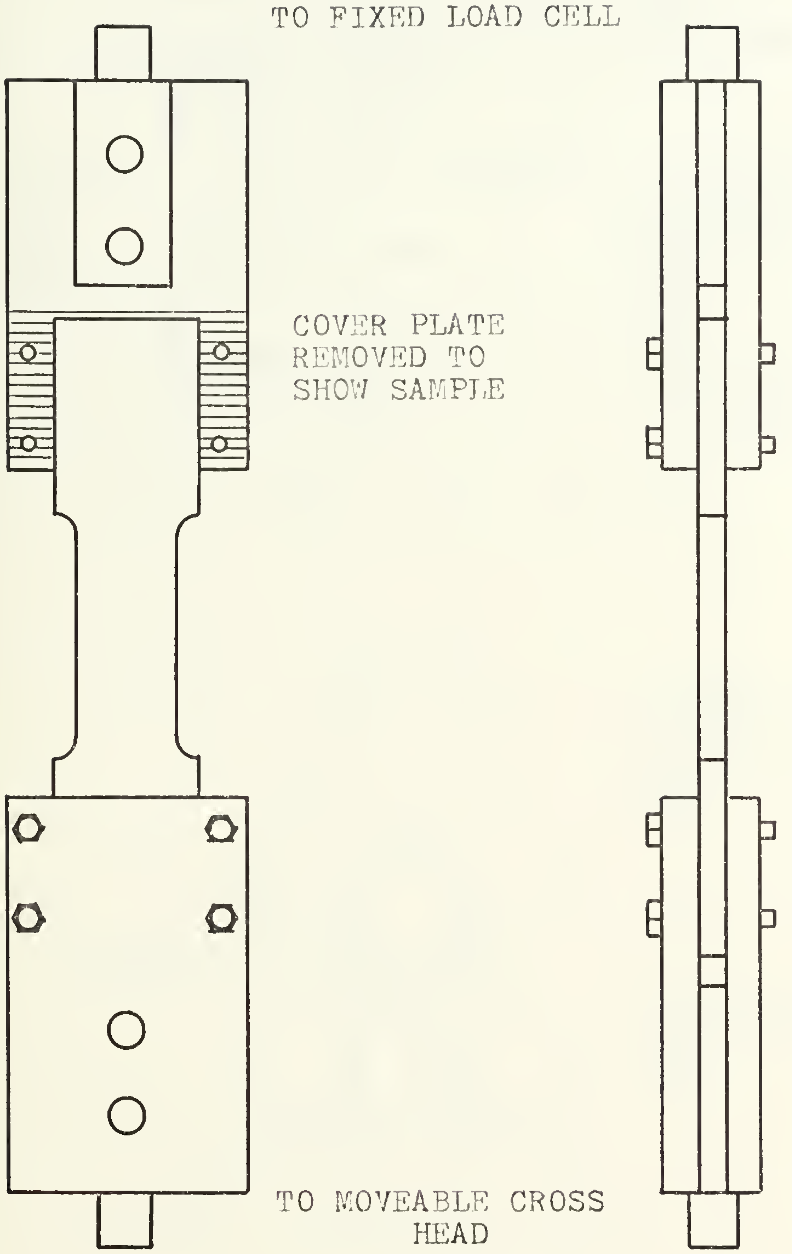

FIG. 4 2D TENSILE TEST APPARATUS

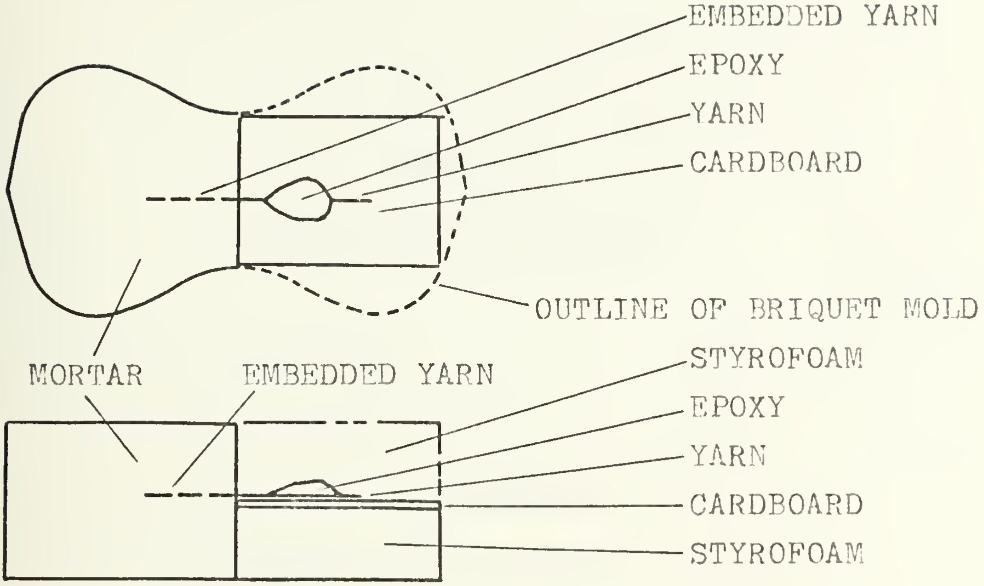

FIG.5 PULL OUT TEST SPECIMEN

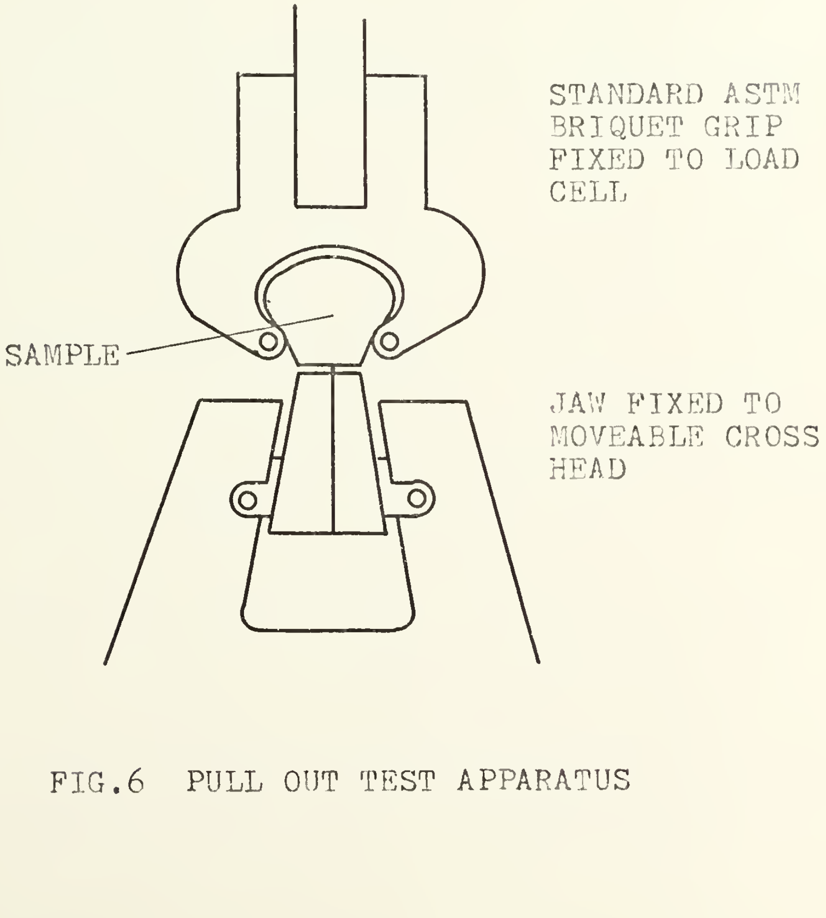

FIG.6 PULL OUT TEST APPARATUS

APPENDIX B

TABULATION OF TEST RESULTS

Phase One Experiments

Phase Two Experiments

Pull-Out Experiments (Plain Matrix)

Pull-Out Experiments (Fiber Matrix)

PHASE ONE EXPERIMENTS

Sample	W/C	S/C	Fiberglass	Maximum Stress	E_{tot}	Remarks
11	.6	1.0	3% by wt	342.1	45.89	
12	.6	1.0	3% by wt	407.9	58.91	
21	.6	1.0	3% by wt	368.4	73.88	Sand Pass #20
22	.6	1.0	3% by wt	296.0	56.82	
23	.6	1.0	3% by wt	342.0	87.82	
31	.6	1.0	3% by wt	414.5	61.20	
32	.6	1.0	3% by wt	302.6	37.00	Sand Pass #8
33	.6	1.0	3% by wt	342.0	46.18	
41	.6	1.0	3% by wt			Broke in Grips
42	.6	1.0	3% by wt	335.0	46.31	Sand Pass #4
43	.6	1.0	3% by wt	361.0	70.77	
61	.6	1.5	3% by wt	355.0	76.68	Sand Pass #8
62	.6	1.5	3% by wt			Broke in Grips
63	.6	1.5	3% by wt	263.0	34.19	Sand Pass #8

PHASE ONE EXPERIMENTS

Sample	W/C	S/C	Fiberglass	Maximum Stress	E_{tot}	Remarks
71	.6	1.22	3% by wt	236.0	33.19	
72	.6	1.22	3% by wt	289.0	61.71	Sand Pass #8
73	.6	1.22	3% by wt	329.0		
81	.6	.66	3% by wt	118.0	19.52	
82	.6	.66	3% by wt	184.0	23.64	Sand Pass #8
83	.6	.66	3% by wt	210.0	29.28	
91	.6	.43	3% by wt	197.0		
92	.6	.43	3% by wt	199.0	56.13	Sand Pass #8
93	.6	.43	3% by wt	118.0	33.45	
111	.5	1.0	3% by wt	289.0	73.54	Sand Pass #8
112	.5	1.0	3% by wt	342.0	56.37	Cracking in Jaws
113	.5	1.0	3% by wt			Broke in Jaws

PHASE ONE EXPERIMENTS

Sample	W/C	S/C	Fiberglass	Maximum Stress	E_{tot}	Remarks
121	.55	1.0	3% by wt	316.0	62.09	Sand Pass #8
122	.55	1.0	3% by wt			Cracking in Jaws
123	.55	1.0	3% by wt	197.0	48.18	Sand Pass #8
131	.65	1.0	3% by wt	329.0	65.80	
132	.65	1.0	3% by wt	335.0	68.66	Sand Pass #8
133	.65	1.0	3% by wt	230.0	41.85	
141	.6	1.0	4% by wt	303.0	45.87	
142	.6	1.0	4% by wt	289.0	44.25	Sand Pass #8
143	.6	1.0	4% by wt	289.0	45.43	
151	.6	1.0	5% by wt	197.0	27.71	Sand Pass #8
152	.6	1.0	5% by wt	270.0	46.93	
153	.6	1.0	5% by wt	276.0	36.72	Broke in Grips

PHASE ONE EXPERIMENTS

Sample	W/C	S/C	Fiberglass	Maximum Stress	E_{tot}	Remarks
161	.6	1.0	3% by wt	368.0	53.93	
162	.6	1.0	3% by wt	329.0	46.30	Sand Pass #8 Retained on #50
163	.6	1.0	3% by wt	223.0	43.85	
171	.6	1.0	3% by wt	303.0	45.56	Sand Pass #8 Retained on #30
172	.6	1.0	3% by wt	264.0		Broke in Grips
173	.6	1.0	3% by wt	381.0	60.00	Sand Pass #8 Retained on #30
181	.6	1.0	4% by wt	329.0	40.98	
182	.6	1.0	4% by wt	402.0	66.80	Sand Pass #8 Retained on #30
183	.6	1.0	4% by wt	381.0	68.48	
191	.6	1.0	5% by wt	316.0	59.20	
192	.6	1.0	5% by wt	369.0	80.00	Sand Pass #8 Retained on #30
193	.6	1.0	5% by wt	316.0	60.00	

PHASE TWO EXPERIMENTS

Sample	W/C	S/C	Fiberglass	Maximum Stress	E_{tot}	Remarks
201	.6	1.0	3% by wt	259.0	9.69	
202	.6	1.0	3% by wt	277.0	12.42	
203	.6	1.0	3% by wt	380.0	11.81	
204	.6	1.0	3% by wt	276.0	12.97	Cast Vertical - 3D
205	.6	1.0	3% by wt	269.0	11.04	
206	.6	1.0	3% by wt	345.0	17.50	
207	.6	1.0	3% by wt	282.0	11.72	
208	.6	1.0	3% by wt	232.0	6.50	
211	.6	1.0	3% by wt	227.0	9.03	
212	.6	1.0	3% by wt	292.0	12.83	
213	.6	1.0	3% by wt	264.0	11.97	
214	.6	1.0	3% by wt	395.0	21.01	Cast Horizontal - 3D
215	.6	1.0	3% by wt	397.0	18.70	
216	.6	1.0	3% by wt	450.0	24.27	

PHASE TWO EXPERIMENTS

Sample	W/C	S/C	Fiberglass	Maximum Stress	E_{tot}	Remarks
217	.6	1.0	3% by wt	500.0	25.24	Cast Horizontal - 3D
218	.6	1.0	3% by wt	470.0	27.69	
221	.6	1.0	3% by wt	440.0	9.16	
222	.6	1.0	3% by wt	492.0	9.37	
223	.6	1.0	3% by wt	496.0	11.53	Cast Horizontal - 2D
224	.6	1.0	3% by wt	538.0	9.68	
225	.6	1.0	3% by wt	546.0	10.28	
231	.6	1.0	0% by wt	254.0		Broke in Jaw
232	.6	1.0	0% by wt	212.0		
233	.6	1.0	0% by wt			Broke in Jaw
234	.6	1.0	0% by wt	232.00		Cast Vertical - 3D
235	.6	1.0	0% by wt	273.00		
236	.6	1.0	0% by wt	236.0		

PHASE TWO EXPERIMENTS

Sample	W/C	S/C	Fiberglass	Maximum Stress	E_{tot}	Remarks
237	.6	1.0	0% by wt	227.0		Cast Vertical - 3D
238	.6	1.0	0% by wt	214.0		
241	.6	1.0	4% by wt	341.0	14.67	Cast Horizontal - 3D
242	.6	1.0	4% by wt	326.0	18.38	
243	.6	1.0	4% by wt	379.0	22.68	
244	.6	1.0	4% by wt	277.0	14.05	
245	.6	1.0	4% by wt	380.0	15.64	
246	.6	1.0	4% by wt	373.0	18.22	
247	.6	1.0	4% by wt	441.0	19.92	
248	.6	1.0	4% by wt	336.0	12.26	
251	.6	1.0	4% by wt	258.0	8.21	Cast Vertical - 3D
252	.6	1.0	4% by wt	168.0	9.01	
253	.6	1.0	4% by wt	305.0	13.82	

PHASE TWO EXPERIMENTS

Sample	W/C	S/C	Fiberglass	Maximum Stress	E_{tot}	Remarks
254	.6	1.0	4% by wt	186.0	8.59	
255	.6	1.0	4% by wt	218.0	12.82	
256	.6	1.0	4% by wt	191.0	9.59	Cast Vertical - 3D
257	.6	1.0	4% by wt	239.0	8.23	
258	.6	1.0	4% by wt	263.0	8.84	
261	.6	1.0	4% by wt			Broke before test
262	.6	1.0	4% by wt	605.0	9.39	
263	.6	1.0	4% by wt	533.0	12.01	Cast Horizontal - 2D
264	.6	1.0	4% by wt	492.0	10.66	
265	.6	1.0	4% by wt	653.0	11.20	

PULL OUT EXPERIMENT (PLAIN MATRIX)

Sample	Embedded Length	Matrix	ϕ	T Max.	Energy	Remarks
1	1/4	Mortar	0°	3.92	.2688	Pulled out intact
2	1/4	Mortar	0°	1.55	.1865	Pulled out intact
3	1/4	Mortar	0°	4.65	.1065	Yarn broke off
4	1/4	Mortar	0°	1.94		Yarn split
5	1/4	Mortar	0°	1.75	.0847	Yarn pulled out
6	1/4	Mortar	0°	1.96	.0970	Yarn split
7	3/8	Mortar	0°	1.76		Pulled from epoxy
8	3/8	Mortar	0°	1.48	.1554	Yarn pulled out
9	3/8	Mortar	0°	2.75	.1648	Yarn pulled out
10	3/8	Mortar	0°	2.87	.1476	Yarn split
11	3/8	Mortar	0°	3.30	.1395	Yarn pulled out
12	3/8	Mortar	0°	2.60	.1079	Yarn broke

PULL OUT EXPERIMENT (PLAIN MATRIX)

Sample	Embedded Length	Matrix	ϕ	T Max.	Energy	Remarks
13	1/2	Mortar	0°	1.49	.0835	Yarn pulled out
14	1/2	Mortar	0°	3.17	.0537	Yarn broke
15	1/2	Mortar	0°	3.24		Pulled from epoxy
16	1/2	Mortar	0°	3.10	.0440	Yarn broke
17	1/2	Mortar	0°	2.75		Broke in epoxy
18	1/2	Mortar	0°	4.15	.0722	Yarn broke
19	3/4	Mortar	0°	3.18	.1121	Yarn broke in mortar
20	3/4	Mortar	0°	3.05		Pulled from epoxy
21	3/4	Mortar	0°	1.67		Broke in epoxy
22	3/4	Mortar	0°	2.07		Broke in epoxy
23	3/4	Mortar	0°	3.37		Pulled from epoxy
24	3/4	Mortar	0°	3.04		Pulled from epoxy

PULL OUT EXPERIMENT (PLAIN MATRIX)

Sample	Embedded Length	Matrix	ϕ	T Max.	Energy	Remarks
25	1/2	Mortar	30°	1.85		Broke in epoxy
26	1/2	Mortar	30°	3.50	.1238	Yarn broke in mortar
27	1/2	Mortar	30°	1.00		Broke in epoxy
28	1/2	Mortar	30°	2.52	.0544	Yarn broke
29	1/2	Mortar	30°	3.60	.1735	Broke in mortar
30	1/2	Mortar	30°	2.34	.0714	Yarn broke
31	1/2	Mortar	45°	1.37	.0441	Yarn broke
32	1/2	Mortar	45°	1.30	.0303	Yarn split
33	1/2	Mortar	45°	1.63	.0697	Yarn broke
34	1/2	Mortar	45°	1.22		Broke in epoxy
35	1/2	Mortar	45°	2.04	.0453	Yarn broke
36	1/2	Mortar	45°	2.03	.0487	Yarn broke

PULL OUT EXPERIMENT (PLAIN MATRIX)

Sample	Embedded Length	Matrix	ϕ	T Max.	Energy	Remarks
37	1/2	Mortar	60^o	.75	.0275	Yarn broke
38	1/2	Mortar	60^o	.26	.0153	Yarn broke
39	1/2	Mortar	60^o	.46	.0150	Yarn broke
40	1/2	Mortar	60^o	.48	.0267	Yarn broke
41	1/2	Mortar	60^o	.62		Pulled from epoxy
42	1/2	Mortar	60^o	.42	.024	Yarn broke

PULL OUT EXPERIMENT (FIBER MATRIX)

Sample	Embedded Length	Matrix	ϕ	T Max.	Energy	Remarks
1	1/4	M w/fibers	0°	1.00	.0532	Yarn broke in mortar
2	1/4	M w/fibers	0°	1.65	.0454	Yarn broke
3	1/4	M w/fibers	0°	1.52		Pulled from epoxy
4	1/4	M w/fibers	0°	1.40	.0505	Yarn broke
5	1/4	M w/fibers	0°	1.37	.0451	Yarn broke
6	1/4	M w/fibers	0°	.90	.0743	Yarn split
7	3/8	M w/fibers	0°	1.75	.0659	Yarn broke
8	3/8	M w/fibers	0°	1.90	.0534	Yarn split
9	3/8	M w/fibers	0°	1.62	.0306	Yarn broke
10	3/8	M w/fibers	0°	1.35	.0725	Yarn split
11	3/8	M w/fibers	0°	1.62	.0221	Yarn split
12	3/8	M w/fibers	0°	1.38	.0429	Yarn split

PULL OUT EXPERIMENT (FIBER MATRIX)

Sample	Embedded Length	Matrix	ϕ	T Max.	Energy	Remarks
13	1/2	M w/fibers	0°	1.51	.0239	Yarn broke
14	1/2	M w/fibers	0°	2.45	.0278	Yarn broke
15	1/2	M w/fibers	0°	1.78	.0219	Yarn split
16	1/2	M w/fibers	0°	1.78	.0562	Yarn split
17	1/2	M w/fibers	0°	1.78	.0244	Yarn broke
18	1/2	M w/fibers	0°	1.98	.0334	Yarn broke
19	3/4	M w/fibers	0°	1.98		Pulled from epoxy
20	3/4	M w/fibers	0°	2.51		Broke in epoxy
21	3/4	M w/fibers	0°	2.71	.0379	Yarn broke
22	3/4	M w/fibers	0°	2.00	.0348	Yarn broke
23	3/4	M w/fibers	0°	2.00	.0417	Yarn broke
24	3/4	M w/fibers	0°	2.13	.0456	Yarn broke

PULL OUT EXPERIMENT (FIBER MATRIX)

Sample	Embedded Length	Matrix	ϕ	T Max.	Energy	Remarks
25	1/2	M w/fibers	30°	1.23	.0626	Yarn broke
26	1/2	M w/fibers	30°	.61	.0138	Yarn broke
27	1/2	M w/fibers	30°	1.32		Pulled from epoxy
28	1/2	M w/fibers	30°	1.92	.0923	Yarn broke
29	1/2	M w/fibers	30°	1.07		Pulled from epoxy
30	1/2	M w/fibers	30°	.80	.0237	Yarn broke

APPENDIX C

GRAPHICAL PRESENTATION OF TEST RESULTS

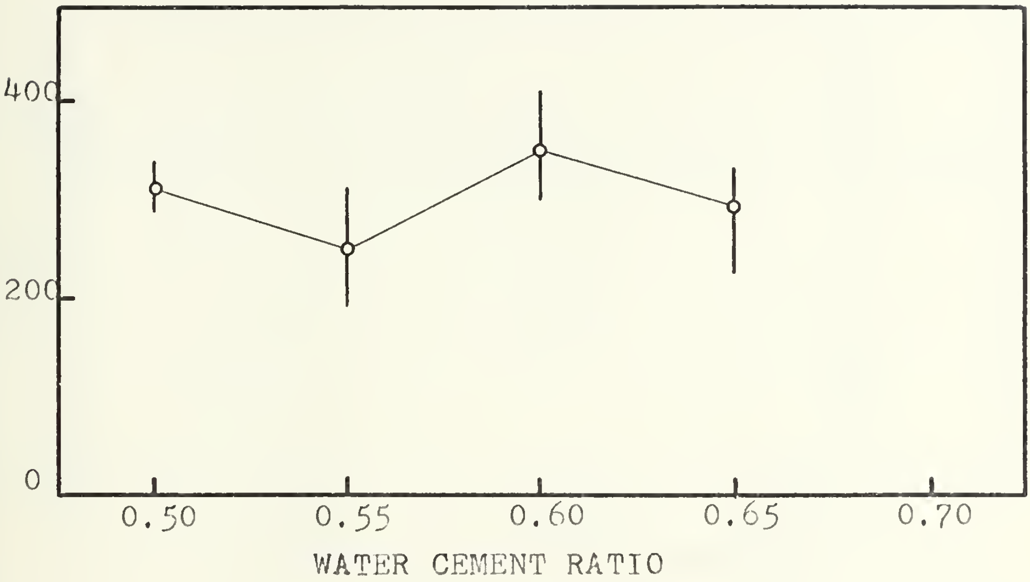

FIG. 1 INFLUENCE OF WATER CEMENT RATIO ON TENSILE STRENGTH

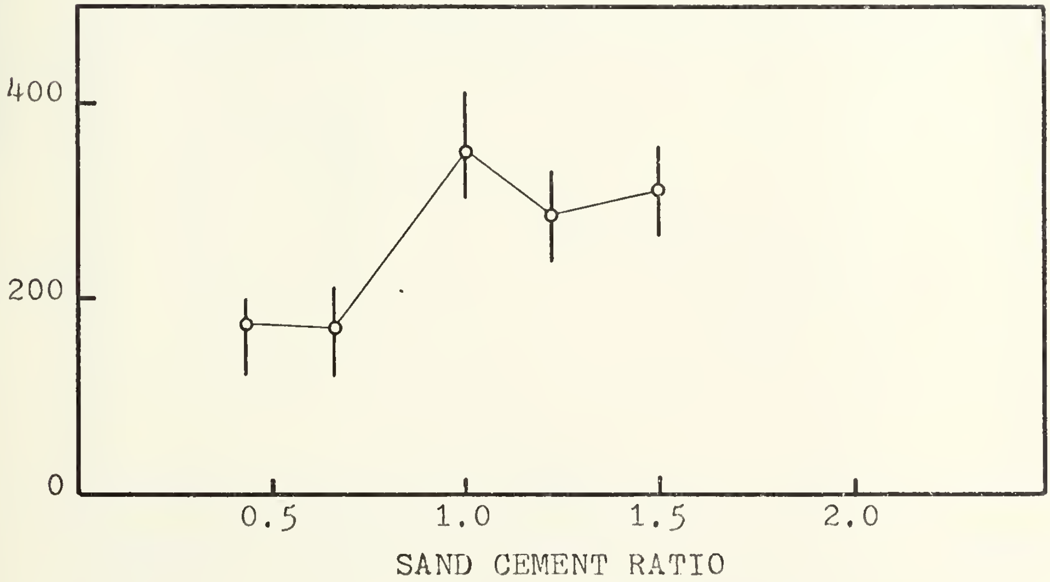

FIG. 2 INFLUENCE OF SAND CEMENT RATIO ON TENSILE STRENGTH

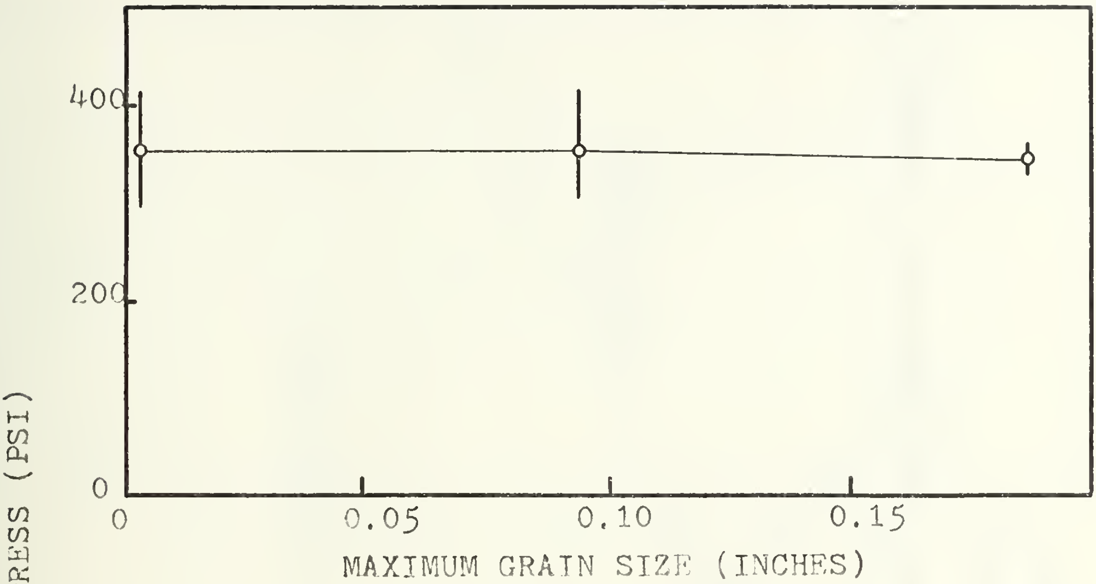

FIG. 3 INFLUENCE OF MAXIMUM GRAIN SIZE ON TENSILE STRENGTH

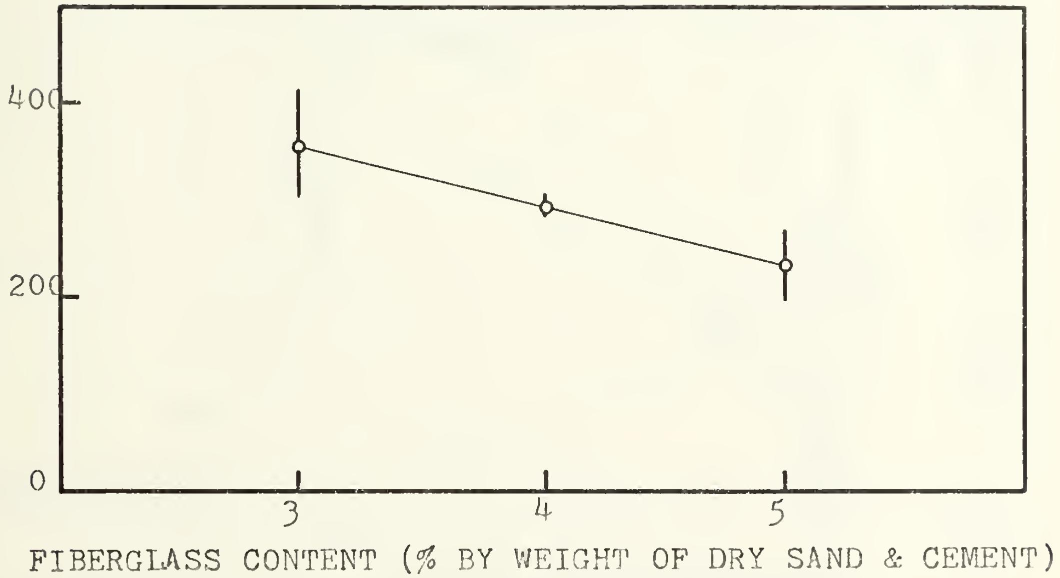

FIG. 4 INFLUENCE OF FIBER CONTENT ON TENSILE STRENGTH

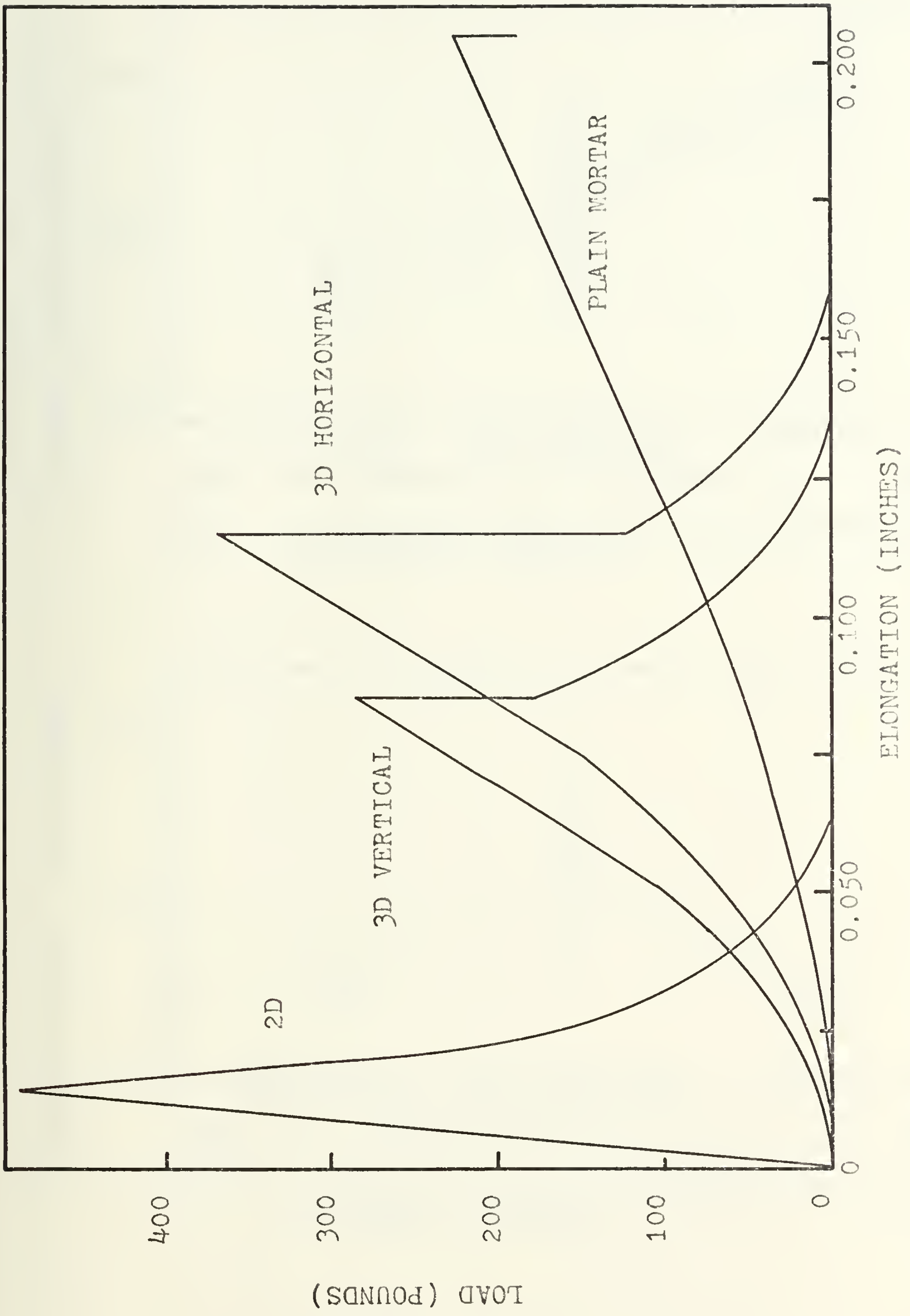

FIG. 5 TYPICAL LOAD VS. ELONGATION CURVES

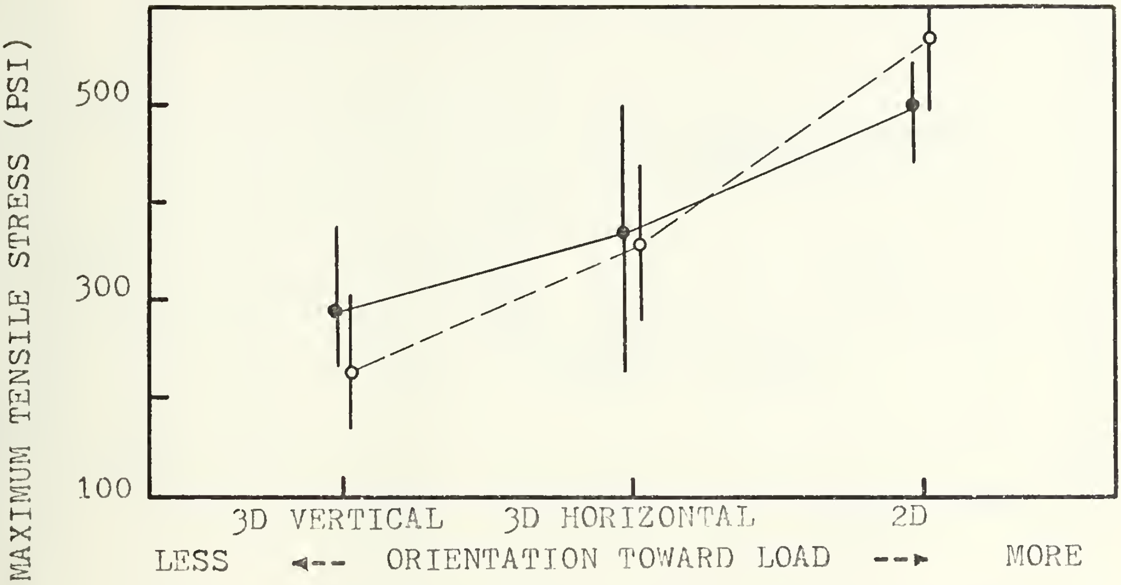

FIG. 6 INFLUENCE OF RELATIVE FIBER ORIENTATION ON TENSILE STRENGTH

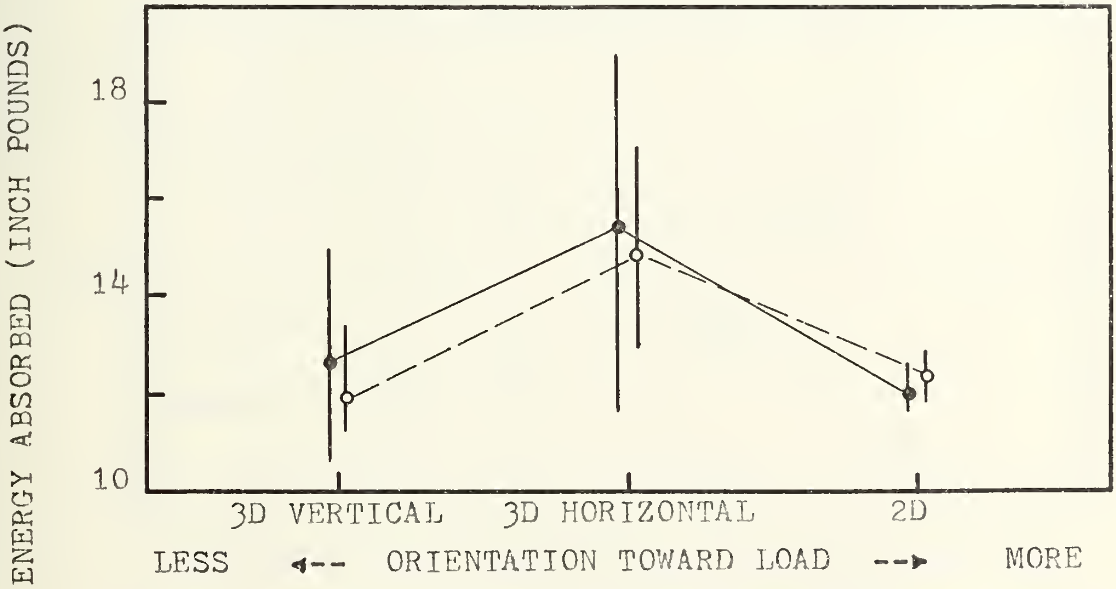

FIG. 7 INFLUENCE OF RELATIVE FIBER ORIENTATION ON ENERGY ABSORBED

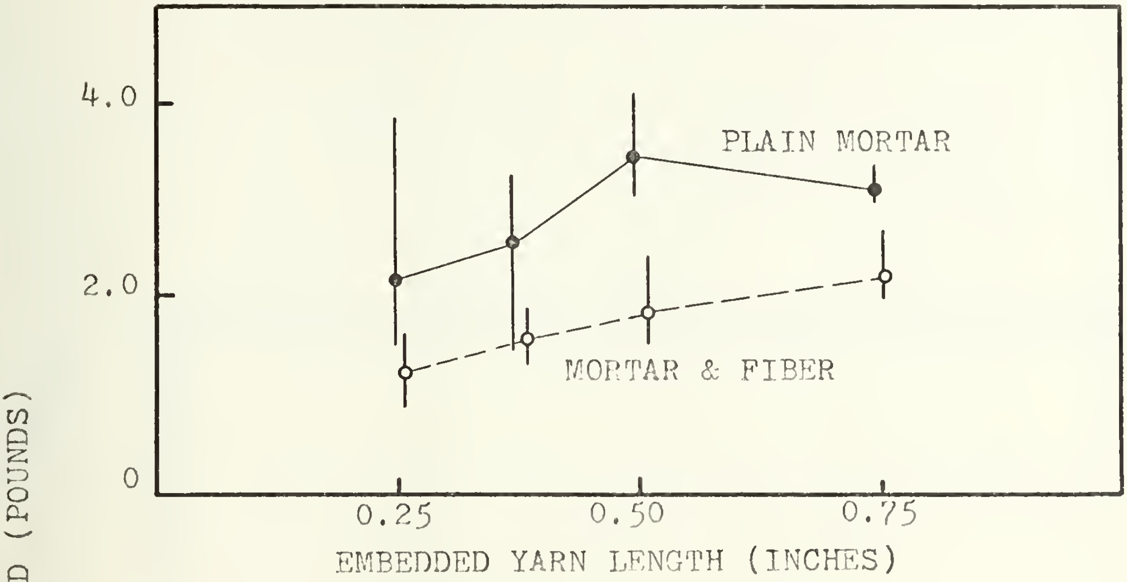

FIG. 8 INFLUENCE OF EMBEDDED LENGTH ON TENSILE STRENGTH

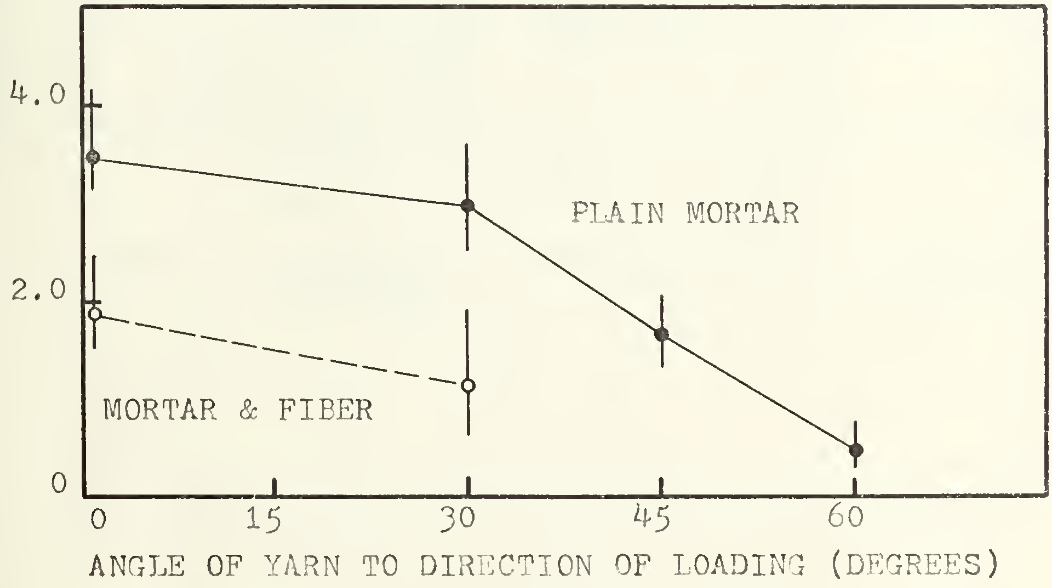

FIG. 9 INFLUENCE OF YARN ORIENTATION ON TENSILE STRENGTH

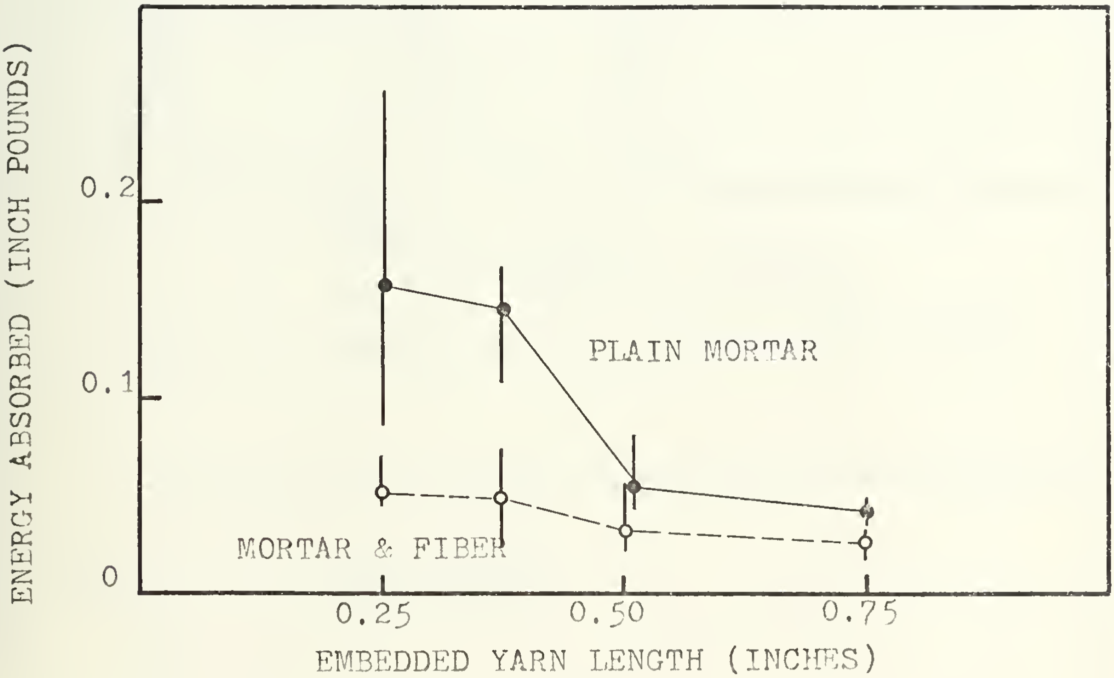

FIG. 10 INFLUENCE OF EMBEDDED LENGTH ON ENERGY ABSORBED

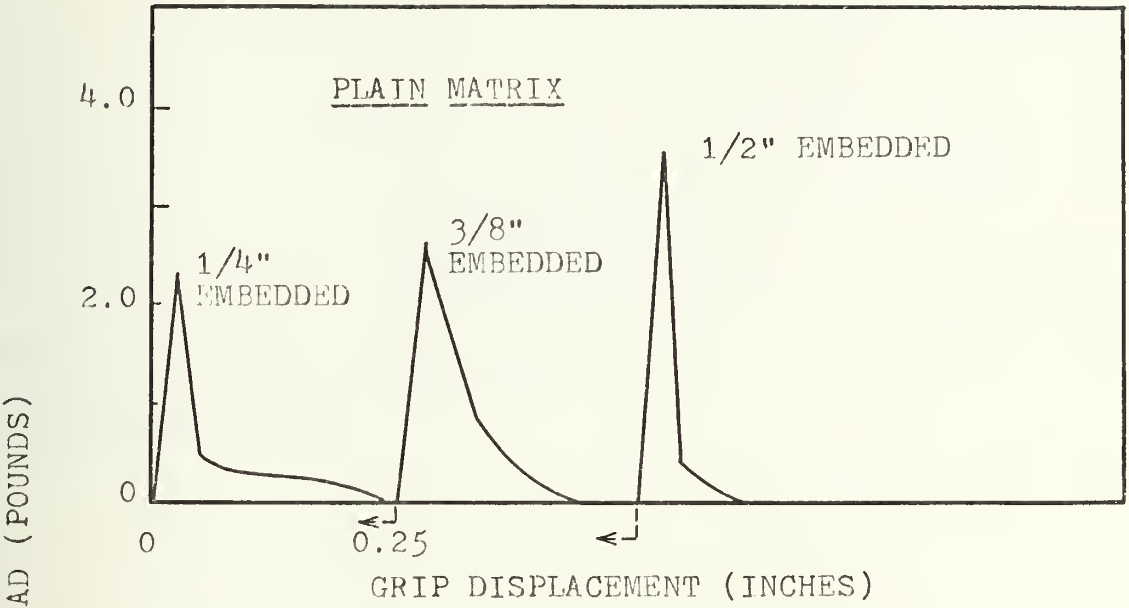

FIG. 11 TYPICAL LOAD VS. DISPLACEMENT CURVES

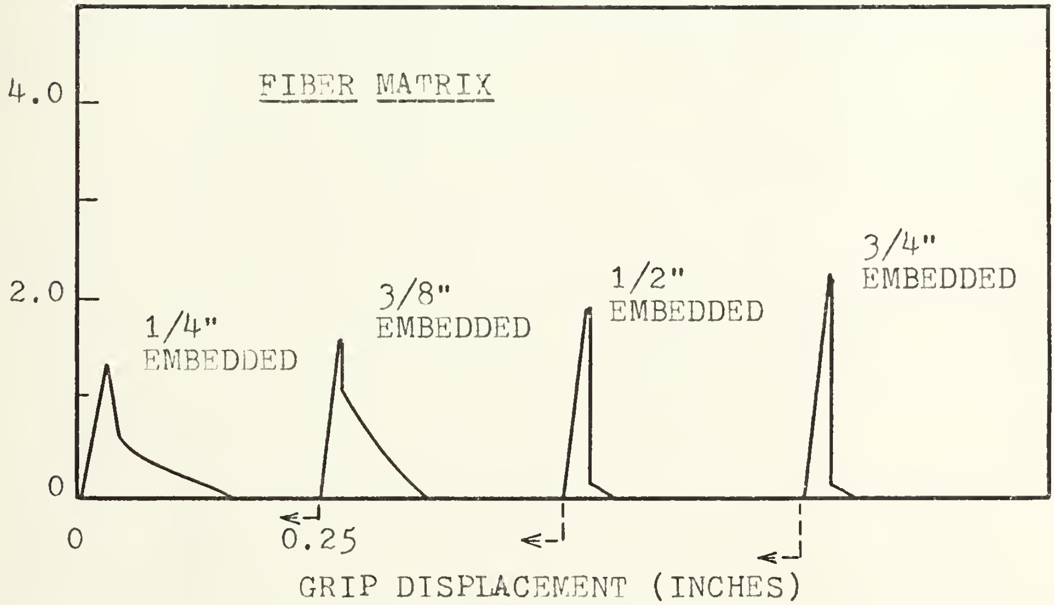

FIG. 12 TYPICAL LOAD VS. DISPLACEMENT CURVES

APPENDIX D

CALCULATED DATA

Theoretical Yarn Cross-Sectional Area

Water Absorption Capacity

APPENDIX D

CALCULATED DATA

A. Theoretical Yarn Cross-Sectional Area

Weight of sample (1000 one-inch-long yarns): 1.8079 grams
Weight of sample after heating (1000°F; $2\frac{1}{2}$ hrs): 1.7705 grams
Change in weight (weight of coatings): 0.0374 grams

Weight of coatings (per cent of weight of glass): 2.07%

Weight of glass = Volume of glass x density of glass

Volume = $(\text{length})(\pi/4)(\text{diameter})^2$ (1000 yarns)
Density of glass = (2.54) gm/cc
Length = 1 inch
Weight = 1.7705 grams

In compatible units, solving for diameter:

Calculated equivalent yarn diameter: 0.0117 inches
Calculated yarn cross-sectional area: 1.081×10^{-4} sq in

For yarn of 204 fibers (assumed):

Calculated fiber cross-sectional area: 5.31×10^{-7} sq in
Calculated fiber diameter: 8.22×10^{-4} sq in

Calculated surface area of $\frac{1}{2}$-inch length of equivalent yarn: 0.0184 sq in
Calculated surface area of $\frac{1}{2}$-inch length of 204 individual fibers: 0.264 sq in
Surface area of fibers/surface area of yarns: approx. 15

B. Water Absorption Capacity

Weight of glass yarn sample: 1.6758 grams
Sample soaked in water 20 minutes
Sample towel-dried
Weight of towel-dried sample: 2.0270 grams
Sample oven-dried (2 hrs at 110°F)
Weight of oven-dried sample: 1.6706 grams
Weight of retained water: 0.3512 grams
Calculated absorption capacity of glass yarns (per cent of weight of glass) 21%

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