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CIVIL ENGINEERING

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Informational Report

JHRP-86/3

THE EFFECT OF STEEL FIBERS ON
THE TOUGHNESS PROPERTIES OF
LARGE AGGREGATE CONCRETE

Stephen Brent Tatro

March 27, 1986

PURDUE UNIVERSITY

Informational Report

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LARGE AGGREGATE CONCRETE

TO: Mr. Paul L. Owens, Chairman
JHRP Advisory Board

March 27, 1986

FROM: Harold L. Michael, Director
Joint Highway Research Project

File: 5-14

The attached report titled "The Effect of Steel Fibers on the Toughness Properties of Large Aggregate Concrete" by Stephen Brent Tatro was recently completed in partial fulfillment of the requirements for the MSCE degree from Purdue University. It is forwarded as an Informational Report to the JHRP Advisory Board members because of its possible interest and value to IDOH through them. As you know this is our long standing practice relative to research directed by JHRP staff but in which IDOH was not a sponsor.

The author was supported in this research by the Walla Walla District Corps of Engineers where he holds an appointment.

The purpose of the study was to evaluate the toughness performance of steel fiber reinforced concrete using aggregate with a maximum size of 1 and 1/2 inches and fibers of varying lengths up to 3 inches. The toughness properties of the concrete were significantly increased by the addition of appropriate length steel fibers. Impact resistance also was found to improve as did fatigue properties.

The report is presented to the Board as information.

Sincerely,

Harold L. Michael
Director

HLM:ms

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Informational Report

THE EFFECT OF STEEL FIBERS ON THE TOUGHNESS PROPERTIES OF
LARGE AGGREGATE CONCRETE

by

Stephen Brent Tatro

Submitted to Purdue University

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ABSTRACT

Tatro, Stephen Brent. M.S.C.E., Purdue University, December 1985. The Effect of Steel Fibers on the Toughness Properties of Large Aggregate Concrete. Major Professor: Charles Scholer.

Traditionally, steel fiber reinforced concrete (FRC) has utilized aggregates not exceeding a maximum size of $3/4$ to 1 inch since early fibers did not exceed 1 inch in length. The purpose of this study was to evaluate the toughness performance of steel FRC mixes containing aggregate with a maximum size of 1 and $1/2$ inches and fibers of varying lengths up to 3 inches.

Mixes were evaluated at two cement contents, three fiber types, and up to three fiber concentrations. Beams were tested in flexure (ASTM C 1018) with load-deflection curves plotted for each. Cylinders were cast to obtain specimens for compressive strength and impact resistance testing. Additional beams were cast for fatigue loading up to 2 million cycles.

The toughness properties of $1-1/2$ -inch maximum size aggregate (MSA) concrete were significantly increased by the addition of appropriate length steel fibers. Better

toughness performance of mixes was observed when the fiber length exceeded the maximum size aggregate diameter than of mixes where the fiber length was less than the maximum size aggregate diameter.

Slow load flexural toughness properties of mixes with the longer hooked and corrugated fibers were excellent at all fiber contents. Most mixes exhibited near ideal elastic-plastic performance. Slow load flexural toughness properties of mixes with short straight fibers were poor for most fiber loadings, although improved performance occurred at extremely high fiber contents.

Impact resistance of specimens significantly increased by the addition of long hooked and corrugated fibers to mixes. Increased fiber contents tended to increase impact resistance. The addition of straight short fibers had little effect on impact resistance except at high fiber contents where impact resistance significantly increased.

The addition of each of the steel fibers types significantly improved the fatigue properties of FRC with 1-1/2-inch MSA when compared to the control specimens.

INTRODUCTION

General

Concrete is considered a brittle material, primarily due to its low tensile strength and low tensile strain capacity prior to fracture. In many applications, poor tensile performance of the concrete is compensated for by incorporating steel reinforcing bars in the tensile zones of the concrete structure to carry the tensile stress. In an attempt to modify concrete to perform in a more ductile manner, the random distribution of steel and other fibers in the mortar/concrete matrix was developed. This resulted in a composite or two-phase system of brittle concrete and ductile steel fibers combined to form an elastic-plastic system. A primary advantage of this system is the post-crack load carrying capacity of concrete members in lieu of catastrophic failure of members at fracture. Other advantages are that the fibers increase precrack tensile strengths of the matrix by restraining the formation of microcracks. Also, fatigue properties, strain capacities, and impact resistance are significantly improved.

History

The addition of fibrous material to a bound matrix is not a new idea. Straw in bricks and animal hair in mortar were used as building materials long before the first use of concrete by the Romans. The first scientific approach to the use of fiber reinforcement in concrete was proposed by Romualdi and Batson in the late 1950's and early 1960's (1). Considerable research activity in FRC followed during the next decade. Study concentrated primarily on small diameter straight steel fibers having lengths less than 1 inch and aspect ratios (length/diameter) up to 100 added to mortar mixes in amounts of 130 to 260 pounds per cubic yard (lbs/cy). The high aspect ratio fibers resulted in decreased workability and a tendency for the fibers to "ball" or tangle in the mix. Research efforts continued and included studies of fibers having lower aspect ratios and to concretes containing coarse aggregates.

Increasing volumes of steel FRC were placed during the 1970's because of the increased usage of larger aggregate in FRC mixes and the development of fibers with lower aspect ratios to reduce balling. Much of this work was pavement overlay and repair, new pavements, and repair of massive concrete structures. Refractory FRC applications developed by the mid-1970's. Other uses developed such as precast construction, shotcrete applications for slope protection and tunnel support, and industrial floor projects.

Prior to the mid-1970's, most steel fibers were primarily a straight fiber, either drawn wire or a slit-sheet, often not exceeding about 1 inch in length. Some fibers were fabricated with surface indentations to enhance pullout resistance. Today, fibers are readily available in a wide variety of materials and in lengths up to 3 inches with very dramatic deformations for end anchorage and pullout resistance.

Statement of Problem

Typical FRC mixes consist of 3/4-inch or 3/8-inch MSA with high cement factors. The high cement factors and relatively high sand content in the mixes are to provide mix workability. Early research (2) concluded that fiber additions to concretes with MSA larger than 3/4 to 1 inch showed much reduced performance. With the use of steel fibers increasing, an increasing number of problems have come to light. FRC mixes are displaying the visible signs of distress that can be expected of concrete with high cement factors. Large thermal volume changes and paste shrinkage generate internal stresses resulting in cracking of thick sections and curling of pavement slabs. In cases where distress is not evident, it is probable that the fibers are restraining volume change, thereby reducing the fiber and composite strain capacity.

One solution to this problem, which is common in the design of conventional and massive concrete, is to reduce the internal heat generation by lowering the cement contents of the FRC mixes and consequently reducing the potential paste volume shrinkage. Since workability is the overriding factor in present mix formulation, forcing high cementitious contents, increasing the maximum size aggregate and aggregate volume rather than just decreasing cement content is a reasonable approach.

The advent of longer fibers may allow the use of larger coarse aggregate in FRC mixes. Presently, little research and performance data are available for FRC mixes with maximum aggregate sizes greater than $3/4$ to 1 inch and containing the relatively new longer steel fibers. Study and performance data in this area are needed to dispel notions that the upper limit of aggregate size for FRC is still 1 inch.

Methods of measurement of FRC properties are the subject of much debate. Only recently have some of the testing procedures been standardized, while other commonly performed tests have not been standardized. Load-deflection measurement of FRC beams, which fingerprints the elastic-plastic performance of specimens, is presently standardized in ASTM C 1018 (3). Reference 4 provides the background for this new standard as well as the need for further

considerations. No standards presently exist for fatigue testing of FRC specimens, although much fatigue testing has been done on conventional concretes. Impact testing is not yet standardized by the American Society for Testing and Materials (ASTM), but a recommended procedure has been published by the American Concrete Institute (5). Several impact test methods are currently in use although each method presently has significant disadvantages associated with its use (6).

Objectives

The main objective of this study was to show that significant improvement in flexural toughness, impact resistance, and fatigue endurance could be obtained in FRC mixes with 1-1/2-inch MSA. Also, this study would provide documented data on the performance of 1-1/2-inch MSA FRC mixes utilizing several of the commercially available fibers.

Secondary objectives of this study were to establish a simple guideline for proportioning FRC with 1-1/2-inch MSA, to perform load-deflection testing as specified in ASTM C 1018, and to record and analyze data in a cost effective, relatively simple, automated manner.

TESTING PROGRAM

Materials

Aggregates for this project were selected from three separate sources. Coarse aggregates ranging from 1-1/2 inches to 3/4-inch were processed from an alluvial deposit along the Walla Walla River in northeast Oregon. The aggregate can be characterized as almost entirely basaltic, with minor amounts of andesite and traces of weathered basalt. Coarse aggregates ranging from 3/4-inch to No. 4 were taken from an alluvial deposit along the Columbia River in northern Oregon. These aggregates are characterized as mostly basaltic with quartzites, andesites, and granitics. Fine aggregates were taken from an alluvial deposit along the Snake River in south-central Washington. The aggregate can be characterized as mostly basaltic with granitics, intermediate volcanics, and metamorphics. This fine aggregate contains amounts of minus 30 sieve and minus 50 sieve material in excess of that contained in conventional concrete sand. Most producers limit the material in these size fractions when the source is not naturally deficient in these size fractions. Gradations for aggregates used in this study are shown in Appendix A, Table A1.

Lehigh, Type I-II, low alkali cement delivered in 94-pound bags was used. Cement certificates representing the two lots from which cement was used are shown in Appendix A. Potable water was used for mixing and curing of test specimens.

A vinsol resin air entraining admixture (AEA) and an ASTM C 494 Type B and D water reducing admixture (WRA), as supplied by MAC USA, were used.

Three fiber types were used in this project: straight fibers, hooked fibers collated in bundles, and corrugated fibers. The latter two fiber types are collectively termed deformed fibers. The straight fibers are slit-sheet mild steel fibers cut to lengths of 3/4 and 1 inch. The longer 1-inch straight fiber was preferred by the author for this study but the manufacturer recommended the 3/4-inch fiber over the 1-inch fiber and refused to provide the 1-inch fiber. The equivalent fiber diameter is 0.017 inch resulting in an aspect ratio of 45. The hooked fiber is a high strength drawn steel wire fiber having each end crimped. The fiber is 60 mm in length and 0.8 mm in diameter resulting in an aspect ratio of 75. The corrugated fiber is a slit-sheet mild steel fiber supplied at a requested length of 3 inches. The equivalent cross-sectional diameter is 0.032 inch with an aspect ratio of 95. Table 1 summarizes the pertinent information of the three fiber types.

Mix Design

Much work has been done in the area of proportioning FRC mixes containing maximum aggregate sizes up to 1 inch (7,8). FRC mixes are significantly different from conventional concrete mixes in that some of the fine aggregate size fractions of FRC mixes are higher than for conventional concrete. The amount of No. 30 to No. 50 aggregate fractions, as well as cement contents are increased to enhance the workability of the mix. Cement or cement plus flyash contents usually range from 700 to 1,000 lbs/cy for typical mixes. The inordinately high cement contents encourage workability and ease consolidation of the fiber and concrete composite. Otherwise, in the low workability mixtures, the fibers restrain the mix constituents from orienting into a close-packed condition.

Numerical and laboratory methods of aggregate proportioning have been developed for conventional concretes and asphaltic concretes. Several methods were studied for possible use in providing a simple method to combine aggregates up to 1-1/2-inch maximum size for FRC. The author felt that most of the aggregate proportioning methods studied would be difficult to implement for this project since the methods were based on criteria which was not intended for, or applicable to, FRC mixes.

A simple method of combining and proportioning aggregates, cement, water, admixtures, and fibers is available for mixes with MSA up to 1 inch (7). This method, simply stated, blends aggregates in varying proportions until a minimum void condition is achieved. Paste volume relationships have been empirically developed to provide the desired workability level. This procedure has been successfully used in FRC mix proportioning. Similar methods to proportion tremie and pumped concrete mixes to obtain good workability have been used.

Aggregates were combined in a two-step process. Fine aggregate and 3/4-inch to No.4 coarse aggregate were blended in coarse to fine aggregate proportions ranging from 40:60 to 70:30 (coarse:fine percentage). Figure 1 is a plot of the maximum density/minimum void vs. percent fine aggregate. Optimum combination, i.e. minimum void condition, is at 32 percent fine aggregate. To provide adequate mobility of the mix, 3-percent fine aggregate was added to the mixture. This combination was then blended with the 1-1/2-inch to 3/4-inch coarse aggregate to obtain the minimum void combination or, in this case, the maximum density since they occur at the same aggregate proportions. Figure 2 shows the density vs. percent 3/4-inch minus fraction relationship. Fine aggregate modifications and the addition of blend sands did not change the harsh coarse nature of this aggregate combination. It was evident that this

combination was very unsuitable for FRC mixes. Strength testing of concrete mixes using various aggregate combinations showed good compressive strengths at the high coarse:fine aggregate ratios, while flexural strengths were optimized at the more reasonable coarse to fine aggregate ratios of 50/50. This approach to aggregate proportioning was abandoned.

A more basic mix proportioning approach was adopted. Data from existing field proven gradation curves used for 1-inch MSA FRC mixes were extrapolated to provide a 1-1/2-inch MSA combination. Coupled with gradation curves for 1-1/2-inch MSA tremie and pumped concrete mixes, a visually acceptable gradation band for 1-1/2-inch MSA FRC was developed as shown in Figure 3. A typical 3/4 inch FRC gradation curve is also shown as reference on Figure 3. Available aggregates were proportioned in quantities to nearly match the proposed gradation curve. Density/void values of this combination were determined by dry rodding of aggregates.

An iterative process of mix design and trial batching was performed to establish paste volume requirements for the aggregate combination. Several factors were held constant for all trial mixes and later specimen fabrication. The water/cement ratio was fixed at 0.4, slump at 4 to 5 inches prior to the addition of fibers, and the air content fixed

at 5 percent. No batch quantity adjustments were made for differing fiber quantity additions since steel volumes constituted less than 1.5 percent of the total mix volume. Appendix B details the mix design procedure used for this study.

The limiting factor in cement content determinations was the minimum batch water required to wet and mix aggregates. Generally, 250 to 270 lbs/cy of water were necessary to attain the required workability at reasonable WRA dosages. This required a minimum of 650 lbs/cy of cement to maintain a water/cement ratio of 0.4. The first set of load-deflection beams, designated as Mix 1, was cast using this mix. Table 2 contains a listing of the mix proportions.

To reduce the cement content, the fine aggregate content was increased 2 percent and the WRA dosage was increased. This reduced the water demand and permitted a lower cement content of 575 lbs/cy. The remaining test specimens were cast using this mix design. Table 2 also contains a listing of this mix design.

Test Specimens

Aggregates were stockpiled in three separate size groups. The fine aggregate stockpile was kept covered to

maintain a nearly uniform moisture content in the stockpile. Prior to batching aggregates, surface moisture of the coarse and fine aggregates was determined and batch weight adjustments made. Bagged cement was stored in sealed plastic drums to avoid moisture related problems. Since specimen casting was performed during the winter months, admixtures were stored in a temperature controlled location in the laboratory.

Aggregates, cement, and fibers were manually batched in plastic 5-gallon buckets on a platform balance. The water was batched in two parts, one part containing the WRA, and the other part containing the AEA. Mixing was done in a 4-1/2-cubic-foot rotating drum mixer powered by a small electric motor. The drum was first coated with a mortar mix similar to the mortar fraction of the FRC mix. The following sequence of batching and mixing was used.

While the drum was rotating:

1. Batch all 1-1/2-inch aggregate
2. Batch 1/2 of the fine aggregate
3. Batch 1/2 of the 3/4-inch aggregate
4. Batch 1/2 of the water with AEA
5. Batch 1/2 of the cement
6. Batch 1/2 of the 3/4-inch aggregate
7. Batch 1/2 of the water with WRA
8. Batch 1/2 of the cement

9. Batch 1/2 of the fine aggregate
10. Batch fibers (sprinkle into mix by hand, slowly)
11. Mix for 3 minutes (time starts at step 9)
12. Stop mixer for 3 minutes
13. Mix for 3 minutes (increased for collated fibers)
14. Discharge and fabricate specimens.

All beams (6x6x21 inches) and cylinders (6x12 inches) were made in molds placed on a vibrating table. The table was a modified "Vebe Consistometer." The vibrational frequency of the table with beam mold was approximately 4,500 hertz. Vibrational amplitude was not determined. Each steel beam mold was set on the Vebe table and filled halfway with the mix. The mold and mix were vibrated for 20 seconds. This time corresponded to the time when entrapped air bubbles were visually observed to cease rising to the surface of the FRC. The beam molds were then filled and vibrated for an additional 20 seconds. The surfaces were finished with a steel trowel. Cylinders, fabricated in plastic molds on the vibrating table, were filled in thirds and vibrated for 20 seconds after each lift.

Generally, beams and cylinders were stripped after 2 days and placed in standard curing tanks. Several beam sets were stripped at 1, 3, and 4 days of age. All specimens were continuously immersed in 70 to 75 degree F water until testing.

Testing Procedures

Load-Deflection Testing

Beams, 6x6x21 inches, spanning 18 inches, were tested in flexure in pairs at 7, 14, and 28 days. Schedule conflicts necessitated some testing being performed at times other than stated. During the flexure test, concurrent load on and deflection of the beam were recorded to establish the load-deflection history. This testing was done as outlined in ASTM C 1018. Appendix C contains a detailed description of the flexural test equipment and the data acquisition and recording equipment.

As shown in Figure E1, three bars were banded to the underside of the beam at the third points and at the center point to serve as reference points to measure beam deflection. The beam was then centered on a steel reaction frame which provided rotational freedom of the beam but not translational freedom for the beam. A similar frame was fabricated to apply load to the third points at the top of the beam. A similar load frame is described in ASTM C 78. Two banks of three linear voltage differential transducers (LVDT) were positioned on either side of the beam to track the vertical deflection of the bars under the beam during loading. Readings from the six LVDT's and a pressure transducer indicating applied load were collected by a microcomputer equipped with an analog-to-digital interface board. Application of load was performed manually, while

data aquisition was done automatically every 3 seconds.

Beams were loaded at a constant rate of third point deflection of approximately .02 inch per minute. The deflection rate was tracked with a 0.0001-inch incremental dial indicator mounted on the testing machine platen.

Compressive Strength Testing

Cylinders, 6x12 inches, were tested in pairs at 7, 14, and 28 days of age to determine the ultimate compressive strength. After continuous immersion curing, cylinders were capped with a sulphur capping compound and loaded in compression as specified in ASTM C 39.

Impact Resistance Testing

Impact resistance testing was performed on specimens sawn from cylinders cast with the compressive strength cylinders. Impact specimens measured 2-5/8-inches thick by 6 inches in diameter. They were obtained by sawing three each from 6x12-inch cylinders. A set of three specimens each was tested at 7, 14, and 28 days. A description of the test equipment and procedure is contained in Reference 5.

The impact specimen was centered on a flat steel plate with a hardened steel ball placed on top of the specimen center. A framework holds the ball in place while a hammer applies blows to the top of the ball. A shop fabricated

impact hammer, similar to the ASTM D 1557 drop hammer, was used to drop a weight of 10.5 pounds from a height of 18 inches. The number of blows to the specimen causing the first visible crack and ultimate failure was recorded. Ultimate failure is apparent when the specimen deforms to a diameter of 6-3/8 inches, at which time it contacts the framework supports of the test device. Testing was terminated after 500 blows if failure had not yet occurred.

Fatigue Testing

Beams for fatigue testing were immersion cured for approximately 70 to 90 days prior to the start of testing. Since fatigue testing spanned a period of 2 months, testing of specimens at ages greater than 60 days reduced variability in results which at earlier ages may have significantly affected the results. Once fatigue testing commenced, further moist curing was not done. Four sets of 12 beams each were fabricated for testing. The four sets consisted of the control mix (beams C1-C12), the hooked fiber mix (beams B1-B12), the corrugated fiber (beams R1-R12), and the straight fiber (beams F1-F12). The mix proportions used in casting the fatigue beams are listed in Table 2.

A minimum of two beams from each set were tested in static flexure to establish the ultimate strength value for each set. Additional beams were tested in static flexure if

results were highly variable or questionable. Beams were then tested at varying percentages of the ultimate strength to establish the load at which the beam could tolerate 2 million nonreversed cycles of the applied load. It is not practical to continue testing past 2 million cycles for reasons of time and expense. After two beams verified the value of the endurance limit for the beam set, the remaining beams were tested in static flexure to provide more data to better establish the ultimate strength values.

RESULTS AND DISCUSSION

Mix Design

Proportioning mixes for steel FRC is generally done with workability being the primary consideration. Using this approach, strength requirements will almost always be exceeded since excess cement is used to provide mix mobility and the water/cement ratio can be kept low.

An easily conceptualized and implemented approach to mix proportioning is the void-density approach discussed above. However, this method did not optimize flexural strength performance for the materials available for this project. Maximum density-minimum void aggregate proportions resulted in a very coarse mixture completely unsuitable for FRC mixes. In fact, increased density may be realized with even coarser aggregate blends, but testing was discontinued since results were out of acceptable ranges.

The "fit the aggregates to the gradation curve" approach resulted in a good blend of aggregates while also being easy to implement. The 1-1/2-inch MSA gradation curve (Figure 3) provided good workable mixes while attaining respectable strength and performance levels. Sufficient

large aggregate was available in the mix to be truly a 1-1/2-inch MSA mix while providing enough fine aggregate for workability. The increased fine aggregate content provided better strength parameters as well as reduced cement content. The enhanced workability seemed to allow better consolidation of the mix. Figure 4 compares the flexural strength gain of mix designs designated C1 and C2. Additional trial batching using different gradations within the theoretical gradation band (Figure B1) was not done.

The resultant paste volumes were determined by an iterative process of mix design and trial batching. A summary of the recommended mix design procedure for 1-1/2-inch MSA FRC mixes is contained in Appendix B. This procedure does not preclude the trial batching procedure; it only establishes a reasonable starting point for mix design.

The sequence of batching materials, described earlier, provided a very uniform mixture. Studies (8) performed on the effect of batching sequence on mix uniformity indicate that various batch sequences had little effect on uniformity. However, poor mixing of collated hooked fibers was observed when only fibers, water, and coarse aggregates were premixed.

Mixing was done with a portable 4.5-cubic-foot rotating drum mixer. Mixing times were established at 3 minutes of

initial mixing, 3 minutes of still time, and 3 minutes of final mixing. This procedure worked well for all mixes except the collated hooked fiber mixes. Additional mixing time was required to adequately soften the glue and mechanically separate the individual fibers.

Studies (9) have concluded that best performance of FRC mixes, measured by strength testing, is achieved by casting beam specimens in a horizontal position and consolidating by using external vibration. No data were provided on recommended vibration frequency and amplitude. Beam specimens for this study were cast in this manner. Sawn sections through the beams and cylinders show few entrapped air voids, with only a minor amount of voids at specimen surfaces. Given the fixed vibrational frequency and amplitude, the applied vibration during the casting of specimens was considered sufficient except for the corrugated fiber mixes. Additional vibration time for these mixes would probably significantly increase the mix performance properties above those shown in this study.

Load-Deflection Testing

Load-deflection curves are a standardized method of quantifying the energy a beam absorbs during its load induced flexural deflection history. The area under the curve represents the energy absorbed by the composite

material. Several means of numerically communicating the data have been proposed, but only recently has one been shown to be superior.

Briefly, toughness index (ASTM C 1018) is a dimensionless parameter which defines or fingerprints the shape of the load-deflection curve. Indexes have been defined on the basis of three service levels, identified as multiples of the first-crack deflection. The index is computed by dividing the total area under the load-deflection curve up to the given service level deflection by the area under the same curve up to the first-crack deflection. I5 is the toughness index at three times the first crack deflection. Likewise, I10 and I30 are the indexes up to 5.5 and 15.5 times the first-crack deflection, respectively.

A controversy exists in the industry on whether the area under the curve up to first-crack deflection for the actual FRC beam should be the denominator, or the area under the curve up to first-crack deflection of a companion beam with the same mix proportions but containing no fibers. The primary benefit of adding steel fibers to concrete is to enhance post-crack behavior. The fact that first-crack load capacity is increased by the addition of fibers is not significant to the desired post-crack performance. This is reason alone to use the area to first-crack of the actual

FRC beam of index computations. Control mixes containing no fibers will generally provide lower first-crack areas and result in higher numerical values for indexes. Secondly, the intent of using nonfiber mixes is to include the pre-first-crack performance in the index value, but the fallacy is that nonfiber mixes should be proportioned differently as would be done for conventional concrete. At this point one is comparing apples to oranges.

Figure 5 portrays the ideal elastic-plastic performance of a beam in flexure. Note that the listed ideal indexes and ratios correspond to the index name. For example, ideal elastic-plastic behavior up to three times the first-crack deflection is designated I5 and equal to 5. Measured index values below 5 indicate a decreasing elastic-plastic performance, while index values above 5 indicate increasing energy absorption (6).

The automated method of accumulating load-deflection data proved very satisfactory for this study. Although six transducers (LVDT's) were used to record beam deflection at the beam center and third points, the third point data were not used in plotting curves and calculation of toughness indices. The third point data showed that the beams were subject to a slight torsional load which was due to a slightly misaligned load frame, forcing the beam to twist. Many of the beams displayed a center crack which was

slightly skewed across the base, indicating a torsional loading and consequent shear stress between third points. Stress computations show that the added torsional load had little effect on elements in the stress field and, consequently, less effect on the load-deflection curves and subsequent toughness indices.

Tables D1 and D2 in Appendix D summarize the results of all the load-deflection testing. The effect of fiber type and concentration on ultimate load, load at first crack, toughness indices, and toughness ratios are shown here. Visual observation of beams after testing shows a high variability in the fiber distribution. Because of the length of the fibers, the large aggregate, and the relative mold dimensions, this variability can be expected. Fiber counts of selected beams which displayed out-of-the-ordinary ultimate strength values showed high fiber concentrations or extreme fiber alignment in the tensile zone of the beam. Low ultimate strength values resulted from low fiber concentrations or nonpreferential alignment of fibers in the beam tensile zone. Because of large load capacity of fibers, small changes in concentration can result in large variations in beam load capacities.

In Tables D1 and D2 of Appendix D, it is not difficult to select which specimens contained abnormal fiber distribution. This does not prevent sound conclusions being

drawn from this data, though conclusions may not be as specific as hoped.

Maximum flexural loads carried by the control mixes, C1 and C2, are contained on Figure 4. Data interpolation provides typical 28-day load capacities for mix C1 of 6,500 to 7,000 pounds, and typical 28-day load capacities for mix C2 of 7,500 to 8,000 pounds. In most cases, the addition of fibers significantly increased the ultimate flexural load capacity of the beams. The addition of fibers increased first-crack load capacity in mix 1 over control mixes, while mix 2 showed little improvement. A summary of the increases as a percentage of the load capacity of the control mix is shown in Table 3.

The addition of hooked fibers and corrugated fibers significantly increased ultimate load capacity of beams at all fiber loadings, but most notably at the higher 100 lbs/cy range. Little data were produced for fiber loadings of 80 lbs/cy, but it appears that the greatest increase is after the fiber loading exceeds 80 lbs/cy. The addition of straight fibers showed minor increases in ultimate load capacity for fiber loadings up to 120 lbs/cy, with the highest increase being at the 200 lbs/cy loading. Figures 8 and 9 show this clearly.

Review of the toughness data shows that no correlation between toughness values and the age of the specimen at time of loading can be made. This is not surprising since toughness is a relation of areas under the load-deflection curve. To ease the assimilation of data, the indexes for a set of beams have been averaged and rounded to the appropriate level of significance. These data are contained in Table 4.

The toughness performance of the hooked fiber equaled or exceeded the ideal elastic-plastic performance limits as earlier defined. The B1 mix at 60 lbs/cy loading fell below the ideal level at the I30 index level. Nearly ideal load-deflection curve slopes were maintained through the I10 level for all mixes. From I10 to I30 levels, the B1 mixes showed a decline in the load-deflection curve indicated by the I30/I10 ratio less than 3.0. The B2 mixes performed in a good "plastic manner." Although the original data exhibit some variability, the B1 and B2 mixes performed alike until large deflections (15.5 x first-crack deflection) were realized, whereas the B2 mixes showed better performance. Better performance of the B2 mixes is attributed to higher workability promoting better consolidation.

All the corrugated fiber mixes exceeded the ideal elastic-plastic performance limits as indicated in Table 5.

The R1 mix at the 60 lbs/cy loading did not perform quite as well as the others. Sudden deflections were observed during loading when a fiber would fail. These are seen as inverted spikes on the load-deflection curves.

Load and deflection data were recorded at 3-second intervals, producing accurate results when rate of deflection was low or constant during the 3-second period. When large deflections occurred during only a part of the 3-second period, artificially high areas under the load-deflection curve would result. Load-deflection curves for several of the F1 and F2 beams were affected in this way. Based on visual observation of the beam deflection history, the plotted curves have been adjusted to reflect the actual load-deflection history. Toughness indices and ratios in Table 5 and Tables D1 and D2 in Appendix D also reflect these adjustments. Although the accuracy of the adjusted data may be subject to some error, it is much nearer to reality than the data as originally collected.

Compressive Strength Testing

The compressive strength test results are contained in Table 5, and a bar chart showing a comparison of the mixes is contained in Figure 6. As expected, the control mix achieved good compressive strength at the three age levels. The addition of 60 and 200 lbs/cy of straight steel fibers

to the control mix increased the 28-day compressive strength by 21 and 25 percent, respectively, while the addition of 120 lbs/cy of straight fibers decreased the 28-day compressive strength by 2 percent. The addition of 60, 80, and 100 lbs/cy of hooked fibers to the control mix increased the 28-day compressive strength by 17, 27, and 25 percent, respectively. The addition of 60, 80 and 100 lbs/cy of corrugated fibers to the control mix increased the 28-day compressive strength by -2, 6, and 6 percent, respectively.

Mixes F2-120, R2-60, R2-80, and R2-100 exhibited lower compressive strengths than expected at all age levels. It is not known why these mixes performed below normal but it is significant that the four mixes were batched at the same time and cured together. The relative strength values of the four mixes indicate that whatever factor caused the poor performance, it affected the entire set. Relative performance of the remaining fiber mixes shows consistent and similar results. These four mixes were cast at the time when a new cement batch was used. These mixes and all subsequent trial batches contained cement from the second cement shipment. It is possible that the characteristics of the cement shipments were significantly different which affected the mix performance. Because of similar performance in the F2-120 mix and the R2 mixes, it can be assumed that errors during the batching of materials did not occur since the same error would have to be repeated four times.

In spite of the anomalies, the addition of fibers does increase compressive strength of cylinders at all the age levels. Although the data show a tendency for higher compressive strength values for mixes with higher fiber concentrations at all age levels and fiber types, the compressive strength is not sensitive to these factors. Rather, the addition of fibers increases the compressive strength to the point where further fiber additions have a minimal effect in the range of fiber loadings considered. A more comprehensive study of the effect of these materials and fiber loadings on compressive strength is warranted.

Impact Resistance Testing

Table 6 is a summary of the impact resistance test results, and Figure 7 provides a comparison of average impact test results in bar chart form.

Three impact specimens tested at each age and for each mix were sawn from a single 6x12-inch cylinder. The three specimens were sawn starting from the cylinder bottom, designated A, B, and C, and tested in the same order. In almost all cases, the A specimens required higher blow counts for first-crack and failure than did the B or C specimens. One factor which may have produced the higher blow counts of the A specimen is the greater mix consolidation at the lower portion of the cylinders because of longer duration of vibration. This is exemplified by the

higher blow counts of the A specimens compared to the B and C specimens of the C2 mix which contained no fibers. More significant is the fiber alignment induced by the mold surfaces at the base of the cylinder mold which produced the abnormal blow count values for the A specimens. Consequently, the blow counts from the A specimens were not included in the averaged results in Table 6.

Past impact resistance testing has provided highly variable results (10). Unfortunately, no better practical test is presently available, although other methods are available. In this study, the use of large aggregate and long fibers added to the variability of the results. The test does provide an economical measure of specimen performance relative to control specimen performance in an impact environment.

The following comments are generalizations although isolated data points can be selected to dispute such generalizations. The addition of straight steel fibers in the quantities used does not significantly affect the impact resistance of the mix except at the early age of 7 days and at high fiber loadings of 200 lbs/cy. The addition of hooked fibers did significantly increase impact resistance of the mix, with the most increase observed at the higher fiber loadings of 80 and 100 lbs/cy. The addition of corrugated fibers to the mix increased impact resistance although the

effect of fiber loading was not pronounced. Again, the internal resistance of the mix to consolidation probably affected the performance of the specimens in this test.

Fatigue Testing

Fatigue data are generally displayed as an S-N curve, (stress ratio vs. number of loadings) where the stress ratio is the actual loading stress as a percentage of the modulus of rupture. Since beam sizes are nearly constant for all specimens in this study, the load values will be presented as pounds rather than stress or stress ratio. Figures 10 through 13 show load vs. number of loadings for the four mixes tested in fatigue. The endurance load is the maximum load at which the beam will perform through an infinite number of loadings. Two million loadings is the practical limit set for this study. The endurance limit will be calculated as the ratio of endurance load to ultimate static load for the same beam set, and the ratio of the endurance load to the ultimate static load for the control beam set which contains no fibers.

From Figures 10 through 13 it is apparent that the data are highly variable. Data, representative of the beam set, were determined by visual observation of fiber distribution and fiber number in the tensile zone on the fractured faces.

The ultimate static load of the control mixes was measured at 6,900 pounds with an endurance load of 4,000 pounds after 2 million cycles. The S-N curve for the control mix is shown on Figure 10. The endurance limit is calculated to be 57 percent, which compares favorably with fatigue testing performed by others (10) on conventional concretes.

Ultimate static load capacities for the hooked fiber mixes ranged from 7,500 to 17,075 pounds. Highly variable fiber distribution and fiber alignment along beam mold surfaces caused such a load range. After visual observation of the fractured faces of the beams, the value of 10,000 pounds was determined to be representative of the ultimate static load capacity for this beam set. The endurance load was 6,500 pounds, resulting in a within-set endurance limit of 65 percent. The endurance limit as a percentage of the control ultimate static load capacity is 94 percent.

Likewise, the corrugated fiber mixes displayed significant variability as seen on Figure 12. The use of large aggregate with long fibers and relatively small specimen dimensions is the cause of this variability. The ultimate static load capacity was determined to be 10,250 pounds, while the endurance load for this beam set was 6,000 pounds. The within-set endurance limit for this beam set is 59 percent, and the endurance limit as a percentage of the

control ultimate static load capacity is 87 percent.

The straight fiber mixes exhibited an average ultimate static load capacity of 11,800 pounds and an endurance load of 6,500 pounds. The within-set endurance limit for this beam set is 53 percent and the endurance limit as a percentage of the control ultimate static load capacity is 94 percent.

Table 7 summarizes the load capacities and endurance limits. In general, with the fiber types and fiber concentrations used, the addition of fibers increased the endurance load from 4,000 pounds to 6,000 to 6,500 pounds or 50 to 60 percent over the control mix endurance load. The within-set endurance limits for the corrugated (59 percent) and straight (53 percent) beam sets did not significantly change from that of the control beam (57 percent) set, while the hooked fiber set was only slightly higher at 69 percent. The addition of fibers increased ultimate static strengths as well as the endurance load capacities, netting only minor percentage increases. This is why endurance limits of the FRC beam sets are not significantly higher than the endurance limit for the control mix. The addition of fibers significantly improved fatigue performance of control mixes, although little within-set improvement was observed. These tests on large aggregate mixes show much less effect of the fibers on the fatigue properties than do fatigue studies by

others which have shown within-set endurance limits as high as 90 to 95 percent for FRC mixes with 3/4-inch MSA.

CONCLUSIONS

The toughness properties of 1-1/2-inch MSA concrete were significantly increased by the addition of appropriate length steel fibers. Better toughness performance of mixes was observed when the fiber length exceeded the maximum size aggregate diameter than in mixes where the fiber length was less than the maximum size aggregate diameter.

The simple mix design method, documented in Appendix B, is useful in establishing initial mix proportions for FRC with a 1-1/2-inch MSA.

Slow load flexural toughness properties of mixes with hooked fibers (Dramix ZP 60/.80) were excellent at all fiber contents. Most mixes exhibited near ideal elastic-plastic performance. The addition of hooked fibers to control mixes increased the first-crack load and ultimate load capacities.

Slow load flexural toughness properties of FRC mixes with corrugated fibers (Xorex 3-inch) were excellent at all the fiber contents. The fibrous concrete exhibited near ideal elastic-plastic performance. The addition of corrugated fibers to control mixes increased the first-crack

load capacities and ultimate load capacities.

Slow load flexural toughness properties of mixes with short straight fibers (Fibercon 3/4-inch) were poor for most fiber loadings, although improved performance occurred at extremely high fiber contents. The addition of short straight fibers to control mixes increased the first-crack load and ultimate load capacities.

The addition of steel fibers to 1-1/2-inch MSA control mixes tended to increase the compressive strength of 6x12-inch cylinder specimens. Compressive strength values were not sensitive to the fiber type or to fiber loading, although minor increases in compressive strengths were observed at very high fiber contents.

Impact resistance of specimens is significantly increased by the addition of long hooked and corrugated fibers to mixes. Increased fiber contents tend to increase impact resistance. The addition of straight short fibers had little effect on impact resistance except at high fiber contents where impact resistance significantly increased.

The addition of steel fibers significantly improved the fatigue properties of FRC with 1-1/2-inch MSA when compared against the control specimens. Endurance limits of FRC mixes when compared to control mixes were increased 87 to 94

percent by the addition of steel fibers, while little percentage change was observed in the within-set endurance limits.

RECOMMENDATIONS FOR FURTHER STUDY

The use of steel fibers with mixes containing large maximum sized aggregate and lower cement contents should be encouraged. More study is needed to establish performance limits for each fiber type.

The effect of high frequency fatigue loadings on the endurance limits of FRC specimens should be studied to determine if the inertial effects of the testing bias the results.

Additional standardization of load-deflection testing methods and equipment is needed to provide more realistic comparison of toughness data for various size specimens and to minimize measurement error due to equipment deformations.

Additional data are necessary for fatigue endurance limits of FRC mixes containing large maximum sized aggregate. With these data, correlations between endurance limits, impact resistance, toughness properties, and other properties may be possible. Say endurance limits of FRC can be correlated with slow load flexural toughness, materials can be more easily specified and tested at much less expense.

Table 1 - Summary of Steel Fiber Data

Fiber Type	Hooked	Corrugated	Straight
Fiber Title	Dramix ZP 60/.80	Xorex - 3 inch	Fibercon - 3/4 inch
Manufacturer	Bekaert Steel Wire Corporation	Ribbon Technology	Mitchell Fibercon
Material	Carbon Steel	Carbon Steel	Carbon Steel
Yield Str.	170 ksi	140 ksi	55 ksi
Process	Drawn Wire	slit sheet	slit sheet
Length	60 mm (2.4 in)	76 mm (3 in)	19 mm (.75 in)
Diameter (equivalent)	.8 mm (.03 in)	.8 mm (.03 in)	.4 mm (.017 in)
Aspect ratio	75	95	45
Mechanical Anchorage	hooked ends	corrugated shape	none

Table 2 - Mix Design Summary

	Mix C1		Mix C2		Fatigue Specimens	
	<u>lbs/cy</u>	<u>kg/m3</u>	<u>lbs/cy</u>	<u>kg/m3</u>	<u>lbs/cy</u>	<u>kg/m3</u>
Cement	637	378	575	341	597	354
Water	255	151	230	136	229	136
Coarse Aggregate	778	462	709	421	707	419
1-1/2-inch						
Coarse Aggregate	1246	739	1162	689	1157	686
3/4-inch						
Fine Aggregate	1091	647	1354	803	1348	800
Fibers						
hooked	**	**	**	**	80	47
corrugated	**	**	**	**	80	47
straight	**	**	**	**	200	119
	<u>oz/cy</u>	<u>ml/m3</u>	<u>oz/cy</u>	<u>ml/m3</u>	<u>oz/cy</u>	<u>ml/m3</u>
Air Entraining	4.6	178	4.6	178	4.6	178
Admixture *						
Water Reducing	18.3	707	29.0	1120	29.0	1120
Admixture						

* Air content adjusted to 5 percent $\pm$.5 percent.

** Fiber content varied depending on the mix.

Table 3 - Ultimate Load Capacity as a Percent of Control

MIX TYPE	FIBER LOADING IN LBS/CY				
	60	80	100	120	200
B1	169	167	256	—	—
B2	129	—	260	—	—
R1	197	—	230	—	—
R2	159	—	239	—	—
F1	126	—	—	146	—
F2	104	—	—	—	146

Table 4 - Load-Deflection Toughness Index Summary

Mix	I5	I10	I30	I10/I5	I30/I10
B1-60	5	10	25	2.0	2.5
B1-80	5	12	32	2.2	2.7
B1-100	7	15	40	2.3	2.6
B2-60	5	13	41	2.3	3.2
B2-100	7	17	56	2.5	3.4
R1-60	6	12	35	2.2	2.8
R1-100	6	14	43	2.2	3.0
R2-60	6	13	40	2.3	2.9
R2-100	6	14	42	2.3	3.0
F1-60	1	2	*	1.0	*
F1-120	3	4	*	1.3	*
F2-60	4	6	*	1.4	*
F2-200	6	11	23	1.9	2.1

Table 5 - Compressive Strength Summary

Mix		7 Day		14 Day		28 Day	
		Each	Ave.	Each	Ave.	Each	Ave.
C2	A	3245		4571		5385	
	B	3325	3285	4545	4558	5261	5323
F2-60	A	4041		5411		6419	
	B	4023	4032	5500	5455	6446	6433
F2-120	A	3077		4266		5199	
	B	3024	3051	4306	4266	5199	5199
F2-200	A	4280		5827		6799	
	B	4067	4174	5615	5721	6552	6676
B2-60	A	4218		5402		6340	
	B	4165	4194	5270	5336	6083	6211
B2-80	A	4386		5924		6667	
	B	4315	4350	5827	5875	6808	6738
B2-100	A	4430		5977		6799	
	B	4642	4540	5809	5893	6525	6662
R2-60	A	3201		4333		5199	
	B	3130	3165	4297	4315	5181	5190
R2-80	A	3554		4907		5712	
	B	3563	3559	4775	4841	5588	5650
R2-100	A	3210		4545		5570	
	B	3263	3237	4642	4593	5721	5646

Table 6 - Impact Resistance Testing Summary

		<u>C2</u>	<u>F2-60</u>	<u>F2-120</u>	<u>F2-200</u>	<u>B2-60</u>	<u>B2-80</u>	<u>B2-100</u>	<u>F2-60</u>	<u>B2-80</u>	<u>B2-100</u>
7 DAY RESULTS											
A.	For	14	15	60	61	50	17	85	48	19	32
	Fail	15	23	92	125	239	397	325	133	149	362
B.	For	7	121	15	15	34	21	24	15	18	19
	Fail	7	130	44	41	135	183	160	113	96	235
C.	For	6	8	30	40	24	25	11	9	11	15
	Fail	7	14	43	71	123	276	165	42	86	154
Ave.	For	6	64	22	28	29	23	18	12	14	17
	Fail	7	72	44	56	129	229	162	78	91	194
.....											
14 DAY RESULTS											
A.	For	61	50	164	21	98	—	—	84	—	—
	Fail	70	75	210	130	487	—	—	149	—	—
B.	For	45	17	46	44	—	94	125	66	—	—
	Fail	49	34	74	101	—	240	468	124	—	—
C.	For	13	11	24	55	35	48	—	14	—	—
	Fail	18	33	68	104	235	575	—	186	—	—
Ave.	For	29	14	35	50	35	71	125	40	—	—
	Fail	34	34	71	102	235	408	468	155	—	—
.....											
28 DAY RESULTS											
A.	For	82	37	66	87	—	—	—	—	—	112
	Fail	96	49	97	115	—	—	—	—	—	348
B.	For	11	22	41	238	70	221	319	56	119	60
	Fail	15	38	56	297	391	500+	500+	305	236	239
C.	For	32	14	24	31	43	69	167	30	19	60
	Fail	43	29	56	63	144	500+	500+	101	281	116
Ave.	For	22	18	32	134	56	145	243	43	69	60
	Fail	29	34	56	180	268	500+	500+	203	258	178

For = First visible crack in specimen

Fail = Failure of specimen

+ = Specimen not tested beyond 500 blows

Table 7 - Fatigue Endurance Limit Summary

Beam Set	Maximum Static Load-lbs	Endurance Load lbs	Endurance Limit Percentage	
			Within Set	Above Control
Control	6800	3900	57	—
Hooked	10000	6900	69	101
Corrugated	10250	5700	56	84
Straight	11800	6200	53	91

Figure 1 - Density and Void Volume vs. Percent Fine Aggregate

Figure 2 - Density vs. Percent $\frac{3}{4}$ Minus Blend

Figure 3 - Recommended Gradation Curve for 1-1/2 inch MSA
Fiber Reinforced Concrete

Figure 4 - Ultimate Flexural Strength Capacity of Control Mixes

Area Basis	Index Designation	Deflection Criterion	Values of Toughness Indices	
			Plain Concrete Material	Elastic - Plastic
OACD	I_s	3δ	1.0	5.0
OAEF	I_{10}	5.5δ	1.0	10.0
OAGH	I_{30}	15.5δ	1.0	30.0

Figure 5 - Idealized Load-Deflection Curve for Elastic-Plastic Material

Figure 6 - Average Compressive Strength Bar Chart

Figure 7 - Average Impact Resistance Bar Chart

Figure 8 - Average First Crack Load and Ultimate Load Capacity Bar Chart - Mix 1

Figure 9 - Average First Crack Load and Ultimate Load Capacity Bar Chart - Mix 2

Figure 10 - Load vs. Loading Cycles for Endurance Limit of Control Mix

Figure 11 - Load vs. Loading Cycles for Endurance Limit of Hooked Fiber Mix

Figure 12 - Load vs. Loading Cycles for Endurance Limit of Corrugated Fiber Mix

Figure 13 - Load vs. Loading Cycles for Endurance Limit of Straight Fiber Mix

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*These appendices are omitted from this JHRP report. They may be obtained for the cost of reproduction from JHRP, School of Civil Engineering, Purdue University, West Lafayette, IN 47907.

APPENDICES

Appendix B - Mix Design Procedure

MIX DESIGN PROCEDURE

* Proportioning Aggregates

Various proportions of aggregate A (1-1/2 to 3/4-inch), aggregate B (3/4-inch to No.4), and aggregate C (3/8-inch to No. 200) were blended to obtain a combined gradation that fits, or most nearly fits, the recommended gradation curve for 1-1/2-inch MSA FRC mixes. A sample of the blending computation follows for 22 percent A, 36 percent B, and 42 percent C aggregates.

Sieve Size	% Passing			22%	36%	42%	Total
	A	B	C	A	B	C	
2.0	100.0	100.0	100.0	22.0	36.0	42.0	100.0
1.5	99.2	100.0	100.0	21.8	36.0	42.0	99.8
1.0	71.8	100.0	100.0	15.8	36.0	42.0	93.8
.75	17.3	95.2	100.0	3.8	34.3	42.0	80.1
.50	1.0	64.7	100.0	.2	23.3	42.0	65.5
.38	.6	39.8	100.0	.1	14.3	42.0	56.4
No 4	.4	6.9	98.8	.1	2.5	41.5	44.1
No 8		2.8	87.3		1.0	36.7	37.7
No 16			72.8			30.6	30.6
No 30			56.5			23.7	23.7
No 50			26.1			11.0	11.0
No 100			6.5			2.7	2.7
No 200			.8			.3	.3

* Aggregate Unit Weight

After establishing the percentages of available aggregates necessary to best meet the recommended gradation curve, the unit weight value of the blend was required. The aggregates were batched in the required proportions and thoroughly mixed. The mixture was then compacted by rodding the blend into a .32-cubic-foot container in three equal lifts. Rodding was done with a square oak rod having an end area of .56 square inch. Each lift was rodded 50 times. The top surface was screeded level and the container and contents weighed. The unit weight computation follows.

Total weight -	72.12	lbs
Tare weight -	28.31	lbs

Net weight -	43.81	lbs
Container Volume	.3245	ft3

Unit weight = $43.81 / .3245 = 135.0 \text{ lbs/ft}^3$

* Void Volume

It was necessary to compute the volume of the voids in a 1-cubic-foot volume of blended aggregate. This computation was easily done by converting proportional aggregate weights into volumes, summing the volumes, and subtracting the total from 1 cubic foot.

Aggregate	Specific Gravity	Weight	Volume

A	2.79	31.05	0.178
B	2.72	49.95	0.294
C	2.69	54.00	0.322
		-----	-----
		135.00 lbs	0.794 ft3

Void Volume = $1.00 - 0.794 = 0.206 \text{ ft}^3$

It would require .206 cubic foot of water, cement, and air to fill the voids in 1 cubic foot of blended aggregate in a saturated surface dry condition. Additional water, cement, and air were required to increase the workability to a level suitable for FRC mixes. This, in effect, spread the aggregate to allow paste to mobilize the mix.

For mixes containing a water reducing admixture and 5-percent entrained air, the appropriate void volume adjustment factor was 1.43. This increase of 43 percent in the void volume provided the desired workability level which was 4 to 5 inches of slump prior to the addition of fibers and assumed a normal range of water/cement ratios (.35 to .5).

Adjusted Volumes

Void Volume	0.206×1.43	=	0.295 ft3
Aggregate Volume	$1.00 - 0.295$	=	0.705 ft3

			1.000 ft3

* Mix Proportions

Aggregates were proportioned to fill the .0705-cubic-foot volume while cement, water, and air were proportioned to fill the .295-cubic-foot volume. Water cement ratio was set at .40, which was not unreasonable when a water reducing admixture was used. The following table shows the mix proportions.

	Volume	Weight
	-----	-----
Aggregate A (22%)	.155	27.00
Aggregate B (36%)	.254	43.10
Aggregate C (42%)	.296	49.73
	-----	-----
	.705 .705	
Cement (w/c = .4)	.108	21.23
Water	.137	8.55
Air (5%)	.05	---
	-----	-----
	.295 1.00	149.61

* Trial Mixing

The final step in the process was to perform trial mixes. Adjustments to the mix were required to refine the desired level of performance for the available materials. The values computed in this exercise apply to specific materials and do not necessarily apply to all materials.

Figure B1 - Recommended Gradation Band for 1-1/2 inch MSA Fiber Reinforced Concrete

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