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16. Abstract
This study was conducted to evaluate the physical properties of plastic and hardened fiber reinforced concrete using three basic types of fibers: steel, fiberglass and polypropylene. Fibers have been shown to increase flexural and tensile strength, ductility and toughness of concrete.

In this study, air content and water/cement ratio were varied to keep slump in a workable range (2 to 4 inches) and air contents at 5 percent +/- 1 percent. Mixes with flyash and super plasticizers were also tested. The same cement and aggregate was used for all mixes. When used, flyash and admixture type were the same also. Both 6 and 8 bag mixes were examined.

The results of this evaluation indicate that the addition of steel fibers, especially those with a high aspect ratio, in concrete improves flexural toughness, an indicator of ductility and crack resistance. Steel fibers also increased splitting tensile strength. The addition of super plasticizers enhances these qualities further and also increases compressive and flexural strength which were not increased through the use of fibers alone. With the addition of fibers in concrete, no physical properties were adversely affected but no significant improvements over non fiber reinforced concrete were noted in modulus of elasticity, Poisson's ratio, shrinkage or durability over non fiber reinforced concrete.

A recommendation is made that the department continue to employ the use of fiber in concrete in thin bonded overlays and in structural applications where crack control is desired.

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EVALUATION OF FIBER REINFORCED CONCRETE

FINAL REPORT

By

NICK RABALAIS, P.E.
CONCRETE RESEARCH ENGINEER

REPORT NO. 261

RESEARCH PROJECT NO. 89-1C(B)

Conducted By

LOUISIANA TRANSPORTATION RESEARCH CENTER
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In Cooperation With
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ABSTRACT

This study was conducted to evaluate the physical properties of plastic and hardened fiber reinforced concrete using three basic types of fibers: steel, fiberglass and polypropylene. Fibers have been shown to increase flexural and tensile strength, ductility and toughness of concrete.

In this study, air content and water/cement ratio were varied to keep slump in a workable range (2 to 4 inches) and air content at 5 percent +/- 1 percent. Mixes with flyash and super plasticizers were also tested. The same cement and aggregate was used for all mixes. When used, flyash and admixture type were the same also. Both 6 and 8 bag mixes were examined.

The results of this evaluation indicate that the addition of steel fibers in concrete, especially those with a high aspect ratio, improves flexural toughness, an indicator of ductility and crack resistance. Steel fibers also increased splitting tensile strength. The addition of super plasticizers further enhances these qualities and also increases compressive and flexural strength which were not increased through the use of fibers alone. With the addition of fibers in concrete, no physical properties were adversely affected but no significant improvements over non-fiber reinforced concrete were noted in modulus of elasticity, Poisson's ratio, shrinkage, or durability over non-fiber reinforced concrete.

A recommendation is made that the department continue to employ the use of fiber in concrete in thin bonded overlays and in structural applications where crack control is desired.

IMPLEMENTATION STATEMENT

The results of this study indicate that the addition of fibers to PCC could reduce cracking and rate of crack propagation. Mitchell Fibercon steel fibers have been used on State Project 450-10-84 on a section of Interstate 10 in Baton Rouge, Louisiana in a thin bonded concrete overlay. The construction limits are from Seigen Lane to LA 42.

It is still undergoing evaluation and it remains to be seen whether or not the steel fibers will slow the rate at which cracks widen when they appear. The Pavement Evaluation Unit at LTRC is preparing a report on the evaluation of this overlay. The finished report number will be LTRC 90-1P(B) and will be available in approximately two years.

Another thin bonded concrete overlay, State Project No. 450-11-27, also on Interstate 10, will employ the use of Mitchell Fibercon steel fibers in the same manner. The project limits are from Jct. LA 30 to Jct. LA 22 and it is currently under construction.

METRIC CONVERSION FACTORS*

TO CONVERT FROM	TO	MULTIPLY BY
	LENGTH	
foot	meter (m)	0.3048
inch	millimeter (mm)	25.4
yard	meter (m)	0.9144
mile (statute)	kilometer (km)	1.609
	AREA	
square foot	square meter (m^2)	0.0929
square inch	square centimeter (cm^2)	6.451
square yard	square meter (m^2)	0.8361
	Volume (Capacity)	
cubic foot	cubic meter (m^3)	0.02832
gallon (U.S. liquid)**	cubic meter (m^3)	0.003785
gallon (Can. liquid)**	cubic meter (m^3)	0.004546
ounce (U.S. liquid)	cubic centimeter (m^3)	29.57
	MASS	
ounce-mass (avdp)	gram (g)	28.35
pound-mass (avdp)	kilogram (kg)	0.4536
ton (metric)	kilogram (kg)	1000
ton (short, 2000 lbs)	kilogram (kg)	907.2
	MASS PER VOLUME	
pound-mass/cubic foot	kilogram/cubic meter (kg/m^3)	16.02
pound-mass/cubic yard	kilogram/cubic meter (kg/m^3)	0.5933
pound-mass/gallon (U.S.)**	kilogram/cubic meter (kg/m^3)	119.8
pound-mass/gallon (Can.)**	kilogram/cubic meter (kg/m^3)	99.78
	TEMPERATURE	
deg celsius (C)	kelvin (K)	$t_k=t_c+273.15)$
deg Fahrenheit (F)	kelvin (K)	$t_k=(t_F+459.67)/1.8$
deg Fahrenheit (F)	deg Celsius (C	$t_c=(t_F-32)/1.8$

*The reference source for information on SI units and more exact conversion factors is "Metric Practice Guide" ASTM E 380.
**One U.S. gallon equals 0.8327 Canadian gallon.

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INTRODUCTION

Fiber reinforced concrete is defined as portland cement concrete containing discontinuous discrete fibers. Continuous meshes, woven fabrics, and long rods are not considered to be discrete fiber reinforcement(1).

A numerical parameter describing a fiber is its aspect ratio. This is defined as the fiber length divided by an equivalent fiber diameter. Typical aspect ratios range from about 30 to 150 for fiber lengths of 0.25 inches to 3 inches.

The addition of fibers in concrete has been shown to increase the tensile strength of concrete. They also improve the toughness and durability of concrete. Although they don't chemically affect shrinkage properties of concrete or effect the hydration of portland cement, they have been reported to reduce cracking and crack propagation associated with shrinkage by possibly increasing concrete's tensile and flexural strength.

The use of fibers in concrete can be compared to the use of straw for reinforcement of sunbaked clay bricks in ancient times(2). However, its use by the transportation industry is still being investigated and could be called experimental.

This study was undertaken to provide information on the physical properties of both plastic and hardened fiber reinforced concrete using three basic types of fibers: steel, fiberglass, and polypropylene.

PURPOSE AND SCOPE

The specific purpose of this study is to: 1) Evaluate the ability of fibers to enhance portland cement concrete characteristics to such a degree that it would be beneficial in roadways and structures to reduce cracking and to improve strength and 2) Optimize field slump specifications for fiber reinforced concrete.

The study's scope is limited to standard laboratory testing and comparison of test results concerning workability, strength, ductility, toughness and durability. Variables considered were cement content, water/cement ratio, admixture dosages and fiber addition rates. The same type of cement and aggregate was used for each mix.

METHODOLOGY

The methodology used in this study was designed to enable a comparison between control or reference mixes (RF) and experimental mixes. The following physical properties of plastic and hardened concrete were measured:

Slump	ASTM C-143
Air content	ASTM C-148
Unit weight	ASTM C-148
Compressive strength: 7, 28 and 56 days	ASTM C-39
Flexural strength: 7, 28 and 56 days	ASTM C-78
Flexural Overlay	
Static Modulus of Elasticity	ASTM C-469
Poisson's Ratio	ASTM C-469
Resistance to Rapid Freeze/Thaw	ASTM C-666
Length Change	ASTM C-157
Splitting Tensile Strength	ASTM C-496

In addition, one theoretical test, a modified version of Flexural toughness index, ASTM C-1018, was performed.

MATERIALS

The cement used in this project was Magnolia Brand Type 1 manufactured by Blue Circle Cement, Inc. of Birmingham, Alabama. The coarse aggregate used was chert gravel from Louisiana Industries and came from a borrow pit in Baywood, Louisiana. The fine aggregate used was silica sand and it came from the same source. Aggregate gradation is presented in Table 1. The flyash was Type C supplied by Bayou Ash, Inc. in Erwinville, Louisiana. It was "manufactured" by Big Cajun Power Plant in New Roads, La. Air entrainment used in all mixes except those with super water reducers was "Gifford Hill Air-tite" by Cormix, Inc. In mixes containing super plasticizer, the air entrainment used was "Daravair" from W.R. Grace and Company. The super plasticizer used was "Daracem 100", also from W.R. Grace and Company.

TABLE 1

AGGREGATE GRADATION

Coarse Aggregate (Chert Gravel)		Fine Aggregate (Sand)	
Size	% Passing	Sieve Size	% Passing
3/4 inch	100	3/8 inch	100
1/2 inch	55	No. 4	99
No. 8	0	No. 16	78
		No. 50	13
		No. 100	1
		No. 200	0

FIBER TYPES

The fibers used in this study include:

1) Mitchell Fibercon (FN) deformed steel fibers (Figure 1)

2) Ribtec (RC) corrugated steel fibers (Figure 2)

3) Dramix (DX) hooked end steel fibers (Figure 3)

4) ARG fiberglass fibers (Figure 4)

5) Grace (GE) polypropylene (Figure 5)

The physical properties and manufacturer's specifications of these fibers are presented in Appendix D.

Figure 1. Mitchell Fibercon deformed steel fibers (FN)

Figure 2. Ribtec Corrugated steel fibers (RC)

Figure 3. Dramix Hooked End Steel Fibers (DX)

Figure 4. ARG Fiberglass Fibers (ARG)

Figure 5. Grace Polypropylene Fibers (GE)

MIX DESIGN

For workability considerations, mixes were developed to achieve a slump of 2 to 4 inches and an air content of 5 +/- 1 percent as per Louisiana DOTD Standard Specifications for Roads and Bridges. Specimens were cured according to ASTM test method C-192-88.

Reference and fiber mixes containing 6 and 8 bags of cement per cubic yard were batched according to the following mix proportions:

a) Reference mix (RF): 6 bags cement per cubic yard with air entraining agent; 50/50 ratio of fine (sand) to coarse aggregate (chert gravel); one-half inch maximum size coarse aggregate.

b) Same as (a) but with the addition of fibers. Fine aggregate quantities were adjusted (by volume) to compensate for the addition of fibers.

c) Same mix as (b) with the substitution of 20 percent (by weight) flyash for cement and accordingly adjusted fine aggregate by volume.

d) Reference mix (RF): 8 bags cement with air entraining agent; 50/50 ratio of fine to coarse aggregate; one-half inch maximum size coarse aggregate.

e) Same as (d) but with the addition of fibers. Fine aggregate quantities were adjusted (by volume) to compensate for the addition of fibers.

f) Same mix as (e) with the substitution of 15 percent (by weight) flyash for cement and accordingly adjusted fine aggregate by volume.

g) Same mix as (e) with super plasticizers.

Mixing procedures followed ASTM test method C-192 for mixing times. Manufacturer's recommendations were followed for fiber addition rates and mixing methods to prevent balling and clumping of fibers.

DISCUSSION OF RESULTS

PHYSICAL PROPERTIES OF PLASTIC CONCRETE

Six-bag fiber mixes had water/cement ratios of approximately 0.48 (0.47 to 0.49) as shown in Table 2. Air contents ranged from 5.0 percent to 5.8 percent with the exception of Mitchell Fibercon(FN) which showed 7.0 percent. Slumps ranged from 2.25 to 5.25 inches. FN and (Ribtec)RC mixes fell marginally out of the acceptable slump range of 2 to 4 inches at the upper end.

In 6 bag mixes with 20 percent flyash, the water/cement ratio averaged 0.44, ranging from 0.41 to 0.45, an average of .04 less than non- flyash mixes. All air contents fell within acceptable limits. Slumps for Dramix(DX) and FN mixes were out of acceptable range at 5 and 1.5 inches, respectively. All other fiber mixes had slumps within acceptable ranges.

In 8 bag mixes, the reference mix had a water/cement ratio of 0.37. The range of water/cement ratios in the fiber mixes was from 0.38 to 0.41 (Table 3). Only DX fiber mixes fell out of slump specifications at 4.50 inches. All other fiber mixes met all specifications.

In 8 bag mixes with 15 percent flyash, the reference mix water/cement ratio was 0.35 and the range for the fiber mixes is from 0.36 to 0.39. Air contents and slumps fell in the acceptable range for all mixes except Grace(GE) fiber mixes with values of 6.4 percent and 4.75 inches, respectively.

In 8 bag fiber mixes with super plasticizers, water/cement ratios ranged from 0.30 to 0.32. Slumps were in the acceptable range for all mixes except ARG glass fiber mixes with 4.25 inches. Air contents fell within the acceptable range for all fiber mixes. Unit weights and temperatures for all mixes were considered normal and did not affect test results in any adverse way.

COMPRESSIVE STRENGTH

In 6 bag mixes, GE showed the highest strength at all ages tested (Table 4 and Figure 6). The reference mix showed a higher strength than all fiber mixes at all test ages except GE at 56 days. RC mixes showed the lowest strength at 7 and 28 days. ARG mixes showed higher strengths than RC and FN mixes at all test ages except for the 28 day strength of FN. RC mixes had the greatest total percentage increase in strength from 7 to 56 days of all mixes and DX the lowest.

In 6 bag mixes with flyash, FN showed the highest strength of the fiber mixes at all ages tested (Table 5 and Figure 7). ARG mixes showed the highest 28 day and 56 day strengths of all fiber mixes except FN. At all test ages, the reference mix showed higher strengths than any of the fiber mixes. The combination of 20 percent flyash and a lower water/cement ratio generally produced higher strengths at all test ages than non-flyash mixes in all but 3 mixes; DX at 7 and 56 days and GE at 56 days.

In 8 bag mixes, the reference mix showed the highest strength of all mixes at all ages tested (Table 6 and Figure 8). It should be noted, however, that the water/cement ratio was 0.01 to 0.04 lower than any of the fiber mixes. FN mixes showed the highest strengths of all fiber mixes at all ages tested but the lowest percentage increase in strength from 7 to 56 days. ARG showed the lowest strength at all ages tested and the greatest total percentage increase in strength from 7 to 28 days. GE mixes showed higher strengths at all ages tested than DX and RC steel fiber mixes.

In mixes with 15 percent flyash, FN mixes showed the highest strength at all ages tested except 56 day where ARG mixes showed the highest (Table 7 and Figure 9). Only GE mixes showed lower strengths at all ages tested than the reference mix. All mixes except FN showed lower 7 day strengths than the reference mix but

all except GE showed higher 56-day strengths. ARG mixes showed the highest percentage strength gain of all mixes. When compared to non-flyash mixes with higher water/cement ratios, flyash mixes produced higher 28-day strengths. All mixes met the previously mentioned minimum strength requirements.

In 8 bag mixes with super plasticizers, FN had the highest strength at all test ages of all mixes (Table 8 and Figure 10). All steel fiber mixes had higher ultimate strengths than non-steel fiber mixes. DX showed the greatest overall percentage strength increase. Steel fiber mixes showed a greater percentage strength increase than non-steel. Mixes with super plasticizers and a lower water/cement ratio had much higher strengths than both flyash and non-flyash fiber mixes.

An analysis of variance was performed on compressive strength test results to determine if ther was significant difference between fibers within each test group, i.e. 6 bag mixes with flyash at 7 days. Only specimens from the same test group were compared. That is, specimens that were the same age, had the same cement content, and the same additives (flyash or super plasticizers) or no additives. Each group consisted of 18 specimens, 3 made using each fiber and 3 reference mixes. The results show that:

1) Steel fibers mixes do not necessarily or consistently produce higher strengths than non-steel fiber mixes. In some groups steel fiber mixes produced higher strengths and in some groups non-steel fiber mixes did. In some groups, the strengths of the two were dispersed equally from high to low.

2) In all test groups except one, reference mix strengths were higher than fiber mix strengths. The only notable exception was 8 bag mixes with flyash, where ARG and FN produced higher strengths than the reference mix at all test ages.

FLEXURAL STRENGTH

In 6 bag mixes, DX had the highest strength at all ages tested (Table 9 and Figure 11). The reference mix showed higher strength at 28 and 56 days than all mixes except DX. GE mixes produced higher strengths than ARG and RC mixes at all ages tested. LADOTD has no specifications for minimum flexural strengths at the present time. The non-steel fibers had a much smaller percentage strength increase than steel fiber mixes.

In 6 bag mixes with 20 percent flyash, FN produced the highest strength at all ages tested (Table 10 and Figure 12). The reference mix produced higher strengths at all test ages than any other mix except FN and 28 day-strength RC. The possible reason the other two steel fibers produced lower strengths than FN may be that they dispersed less uniformly in the mix because of their greater length and the presence of flyash. No trends could be detected that would indicate that steel fibers, with the exception of FN, have higher strength than non-steel fiber mixes.

In 8 bag mixes, FN showed the highest strength at all ages tested of all fiber mixes (Table 11 and Figure 13). The reference mix showed the second highest strengths. GE mixes had higher strengths than the other two steel fiber mixes. ARG mixes showed the lowest strengths but the greatest percentage strength increase over all test age intervals.

In 8 bag mixes with 15 percent flyash, FN had the highest strength at all ages tested (Table 12 and Figure 14). ARG and RC mixes produced very similar strengths at 7 and 28 days, but ARG had the higher 56-day strength of the two. The lower water/cement ratio and flyash produced only marginally higher strengths in DX mixes when compared to non-flyash mixes and similar or even lower strengths in the reference and other fiber mixes. The percentage increase in strengths over time was greatest in the reference mix followed by DX and ARG mixes.

In 8 bag mixes with super plasticizers, RC had the highest 56-day strength, but both other steel fiber mixes had higher 7 and 28 day strengths (Table 13 and Figure 15). Both ARG and GE mixes had lower strengths at all ages than any of the steel fiber mixes. ARG mixes showed the highest overall percentage strength increase. The combination of super plasticizers and lower water/cement ratios than flyash mixes produced the highest strengths of all 8 bag fiber mixes. Also, steel fiber mixes with super plasticizers showed higher strengths at all ages tested than non-steel fiber mixes with super plasticizers.

FLEXURAL OVERLAY TESTING

The intent of this test is to simulate a thin-bonded concrete overlay on a roadway. An 8 bag reference mix was used to construct half of the 6" x 6" x 20" specimen. The other half was constructed using the same mix with the addition of fibers. The composite specimens are tested in flexure according to ASTM C-78 at 28 days.

Results are then compared to specimens constructed entirely of fiber-reinforced concrete.

ARG mixes had the highest strength of all specimens and exceeded the strength of the specimen constructed entirely of ARG fiber-reinforced concrete (Table 14). All other specimens strengths were less than that of their all fiber counterparts. Specimen strengths were less than those of non-fiber reinforced concrete.

When cracks extended into the fiber reinforced section of the beam, it was held together by fibers such that the crack width in the non-reinforced section was extended to over 1 inch before complete failure occurred. Figure 16 illustrates the crack mitigation properties of fiber-reinforced concrete.

TABLE 14

FLEXURAL OVERLAY STRENGTHS

FIBER	FLEX. OVERLAY (PSI)	ALL FIBER (PSI) SPECIMENS	REF. (PSI) 792
GE	519	717	
DX	528	683	
RC	550	800	
ARG	581	567	

Figure 16. Flexural overlay specimen after testing.

MODULUS OF ELASTICITY

Modulus of elasticity is a measure of the slope of the stress strain curve of cylinders tested in compression up to first crack strength at 28 days. It is essentially linear up to that point. The steeper the slope (thus, the higher the value), the less deformation occurs.

In 6 bag mixes, ARG had the highest value of all mixes, including the reference mix, at 5.8 million psi, 22 percent higher than any of the remaining fiber mixes (See Table 15). The reference mix showed a higher value than all fiber mixes except ARG. Values for the other fiber mixes ranged from 4.31 to 4.76 million psi. A value of 4 million psi is considered an acceptable value in non-fiber reinforced concrete(2).

TABLE 15
MODULUS OF ELASTICITY VALUES (PSI)
6 BAG MIXES

RF	GE	DX	RC	ARG	FN
5252278	4655980	4762246	4683281	5798486	4309780

In 6 bag mixes with 20 percent flyash, FN showed the highest value of the fiber mixes at 5.53 million psi, followed by ARG mixes at 5.31 million psi (Table 16). DX mixes had the lowest value with 4.76 million psi. Values ranged from 4.24 to 5.55 million psi. The reference mix showed a higher value than any of the fiber mixes. Only two fiber mixes had lower values than their non-flyash counterparts with higher water/cement ratios: DX and ARG.

TABLE 16
MODULUS OF ELASTICITY VALUES (PSI)
6 BAG MIXES WITH FLYASH

RF	GE	DX	RC	ARG	FN
5827718	4780466	4240268	5064091	5314660	5548435

In 8 bag mixes, the reference mix had the highest value (Table 17). The range of values was from 5.00 to 5.37 million psi in the fiber mixes. FN showed the highest value of the fiber mixes. Both non-steel fiber mixes showed higher values than every steel fiber mix except FN. In 8 bag mixes with 15 percent flyash, values ranged from 5.02 (ARG) to 5.69 (DX) million psi (Table 18). In these mixes, non - steel fibers had lower values than steel fiber mixes and lower than the reference mix (5.53 million psi).

TABLE 17

MODULUS OF ELASTICITY VALUE (PSI)

8 BAG MIXES

RF	GE	DX	RC	ARG	FN
5574909	5179728	5004987	5033797	4075287	5372612

TABLE 18

MODULUS OF ELASTICITY VALUES (PSI)

8 BAG MIXES WITH FLYASH

RF	GE	DX	RC	ARG	FN
5525852	5265216	5692345	5534093	5024224	5683491

In 8 bag mixes with super plasticizers, values ranged from 5.88 to 6.28 million psi (Table 19). These were higher than 8 bag mixes with flyash and a higher water/cement ratio. DX had the highest value and FN the lowest. Both non-steel fibers showed higher values than FN.

TABLE 19

MODULUS OF ELASTICITY VALUES (PSI)

8 BAG MIXES WITH SUPER PLASTICIZERS

GE	DX	RC	ARG	FN
6085773	6276643	6226607	6124831	5878139

No trends could be established to indicate that one type of fiber produced higher values than another within comparable mixes. In 8 bag mixes with flyash, fiber mixes did not show values any higher than that of the reference mix. Eight bag mixes containing super plasticizers showed greater values than 8 bag flyash mixes with higher water/cement ratios.

POISSON'S RATIO

Poisson's Ratio is a ratio of lateral expansion to longitudinal shortening under compressive loads for specimens 28 days old. The lower the values, the less the deformation. The average is 0.16.(3)

In 6 bag mixes, the lowest value observed was in GE mixes for values of all mixes(Table 20). The highest was RC. Both ARG and DX had lower values than any of the steel fiber mixes. The reference mix value was lower than that of DX, FN, and RC and was equal to the average value of 0.16. Because of the larger aspect ratio of polypropylene and fiberglass, many more fibers are dispersed throughout a mix. This may account for the lesser lateral expansion and longitudinal shortening of these specimens.

TABLE 20
POISSON'S RATIO VALUES
6 BAG MIXES

RF	GE	DX	RC	ARG	FN
0.1600000	0.1045752	0.1615385	0.1850746	0.1447368	0.1721311

In 6 bag mixes with 20 percent flyash, ARG showed the lowest value and RC showed the highest (Table 21). The reference mix had a lower value than any fiber mix except ARG and was also lower than its non-flyash counterpart despite the lower water/cement ratio. Both RC and FN mixes showed lower values than GE mixes. With the exception of DX mixes all 6 bag flyash mixes showed higher values than non-flyash mixes with higher water/cement ratios.

TABLE 21
POISSON'S RATIO VALUES
6 BAG MIXES WITH FLYASH

RF	GE	DX	RC	ARG	FN
0.132500	0.1506849	0.1671733	0.1428751	0.1243243	0.1382979

In 8 bag mixes, DX produced the lowest values and GE the highest of the fiber mixes (Table 22). The reference mix actually showed lower values than any of the fiber mixes. Only one steel fiber mix, RC, had higher values than either of the non-steel fibers.

TABLE 22
POISSON'S RATIO VALUES
8 BAG MIXES

RF	GE	DX	RC	ARG	FN
0.1311475	0.2095808	0.1589595	0.1951780	0.1829268	0.1590909

In 8 bag mixes with 15 percent flyash, DX had the lowest value (Table 23). ARG had an almost identical value. RC mixes had the highest value (0.22). The reference mix had a value close to that of ARG and DX (0.16). GE mixes had a value of 0.19 and FN a value of 0.16.

TABLE 23

POISSON'S RATIO VALUES

8 BAG MIXES WITH FLYASH

RF	GE	DX	RC	ARG	FN
0.1592357	0.1871166	0.1569560	0.2179487	0.1569767	0.1626506

In 8 bag mixes with super plasticizers, RC had the lowest value and DX the highest (Table 24). The range of values was from 0.15 to 0.19. The fact that this mix had a lower water/cement ratio than 8 bag flyash mixes did not contribute to lower values except in RC mixes.

TABLE 24

POISSON'S RATIO VALUES

8 BAG MIXES WITH SUPER PLASTICIZERS

GE	DX	RC	ARG	FN
0.1813472	0.1901235	0.1543689	0.1757576	0.1587983

Six bag mixes had about the same range of values as 8 bag mixes and in some cases lower values than 8 bag mixes. Fiber mixes do not seem to produce significantly lower values than non-fiber mixes despite the difference in water/cement ratios. Nor does the addition of flyash or super plasticizers in like mixes produce significantly different values.

FREEZE THAW RESISTANCE

In this test, as described in ASTM Test Method C-666, Procedure B, Young's Modulus is obtained from beam specimens using a sonometer. Young's Modulus of concrete is a function of the frequency obtained using the sonometer on a given specimen. Beams are then alternately frozen in air at 0 degrees F for 1.5 hours and then thawed in water at 40 degrees F for 1.5 hours. This constitutes one freeze-thaw cycle.

After approximately ten cycles, Young's Modulus is again obtained and a ratio of new Young's Modulus to initial is obtained. The whole procedure is repeated until the ratio approaches 60 percent or 300 cycles are performed (whichever comes first). Freeze-Thaw testing then stops. A durability factor is then calculated as a function of Young's Modulus and the number of cycles.

There are no established criteria for acceptance or rejection of concrete in terms of durability factors; however, durability factors and the number of cycles of freeze and thaw are values that can be used to compare the different types of concretes, aggregates or other mix properties. A value (durability factor) above 60 is probably satisfactory.(2)

In 6 bag mixes, ARG showed the lowest durability factor with a value of 41.3, and RC had the highest of all mixes at 87.3 (Table 25). GE showed a marginally acceptable value of 52.1. DX showed an unacceptable value of 43.6. The reference mix had a higher value than GE, DX, and ARG.

TABLE 25
DURABILITY FACTORS
6 BAG MIXES

RF	GE	DX	RC	ARG	FN
73.0	52.1	43.6	87.3	41.3	80.9

In 6 bag mixes with flyash, DX showed the highest durability factor with 91.7 and ARG showed the lowest at 34.2 (Table 26). GE had a value of 65.3; FN had a value if 75.3; and RC a value of 79.0. The reference mix showed a lower value than any of the fiber mixes except ARG. Only 2 mixes showed better performance than their non-flyash counterparts, despite the lower water/cement ratio of the flyash mixes. They were GE and DX. However, in mixes with flyash, steel fiber mixes had higher durability factors than non-steel.

TABLE 26
DURABILITY FACTORS
6 BAG MIXES WITH FLYASH

RF	GE	DX	RC	ARG	FN
57.0	65.3	91.7	79.0	34.2	75.3

In 8 bag mixes, FN showed the highest value at 90.7 and ARG showed the lowest at 52.9 (Table 27). Values for other fiber mixes were acceptable, but none of the non-steel fiber mixes performed as well as the steel fiber mixes.

TABLE 27
DURABILITY FACTORS
8 BAG MIXES

RF	GE	DX	RC	ARG	FN
86.7	60.4	82.0	82.3	52.9	90.7

In 8 bag mixes with flyash, the reference mix produced the lowest value at 32.9, followed by ARG at 35.5 (Table 28). FN showed a value of 76.7. GE had a marginally acceptable value of 57.5. Here again, steel fiber mixes showed higher values than non-steel. Without exception, flyash mixes did not show values as high as non flyash mixes despite having a lower water/cement ratio.

TABLE 28

DURABILITY FACTORS

8 BAG MIXES WITH FLYASH

RF	GE	DX	RC	ARG	FN
32.9	57.5	71.0	72.3	35.5	76.7

In 8 bag mixes with super plasticizers, the lowest value observed was in ARG mixes at 77.7; the highest was in RC at 98.3 (Table 29). All other values were well above the accepted minimum. The values were much higher than those of flyash mixes with higher water/cement ratios.

TABLE 29

DURABILITY FACTORS

8 BAG MIXES WITH SUPER PLASTICIZERS

GE	DX	RC	ARG	FN
89.3	83.7	98.3	77.7	97.0

Eight bag mixes did not show appreciably higher durability factors than 6 bag mixes with the exception of 8 bag mixes containing super plasticizers.

Overall, Freeze-Thaw durability of concrete is dependent on aggregate type, gradation, and air void content. Fibers seem to do very little to affect it.

LENGTH CHANGE

This is the change in length due to shrinkage from 24 hours to 28 days expressed as a percentage of 24-hour length.

In 6 bag mixes, both DX and ARG showed the lowest percentage change at 0.015 percent (Table 30). RC had the highest at 0.036 percent. GE showed a value of 0.026 percent as did the reference mix and FN showed a value of 0.020 percent.

TABLE 30
PERCENTAGE LENGTH CHANGE
6 BAG MIXES

RF	GE	DX	RC	ARG	FN
0.026	0.026	0.015	0.036	0.015	0.020

In 6 bag mixes with flyash, RC showed the lowest change with a value of 0.024 percent (Table 31). DX had the highest value with 0.040 percent. The reference mix value was 0.028 percent, lower than GE and DX. In all cases except with RC fiber mixes, flyash mixes with lower water/cement ratios showed a greater percentage change in length than non-flyash mixes.

TABLE 31
PERCENTAGE LENGTH CHANGE
6 BAG MIXES WITH FLYASH

RF	GE	DX	RC	ARG	FN
0.028	0.033	0.040	0.024	0.026	0.027

In 8 bag mixes, ARG had the lowest percentage change in length at 0.021 percent and RC had the highest at 0.026 percent (Table 32). The reference mix value was 0.024 percent. Values were very close to each other.

TABLE 32
PERCENTAGE LENGTH CHANGE
8 BAG MIXES

RF	GE	DX	RC	ARG	FN
0.024	0.024	0.022	0.026	0.021	0.022

In 8 bag mixes with flyash, the reference mix showed a lower value than any of the fiber mixes at 0.013 percent (Table 33). ARG had the lowest value of any of the fiber mixes at 0.020 percent and GE had the highest at 0.036 percent. With GE, DX, and RC, values were higher than in non-flyash mixes despite having lower water/cement ratios. With ARG and FN, they were almost identical (to non-flyash mixes).

TABLE 33
PERCENTAGE LENGTH CHANGE
8 BAG MIXES WITH FLYASH

RF	GE	DX	RC	ARG	FN
0.013	0.036	0.028	0.033	0.020	0.021

In 8 bag mixes with super plasticizers, RC had the lowest value at 0.012 percent followed by FN at 0.013 percent (Table 34). Both non-steel fiber mixes had values higher than those of steel fiber mixes.

TABLE 34

PERCENTAGE LENGTH CHANGE
8 BAG MIXES WITH SUPER PLASTICIZERS

GE	DX	RC	ARG	FN
0.028	0.026	0.012	0.019	0.013

No trend was seen that would indicate one type of fiber produced lower values than another, except in the case of 8 bag super plasticizer mixes where steel fiber mixes produced lower values than non-steel. No appreciable differences were noted between 6 bag mix values and 8 bag. Super plasticizer mixes (8 bag) produced lower values than 8 bag flyash mixes with higher water/cement ratios. The largest value observed constitutes a change in length of approximately 1/200-inch in a 12-inch cylinder. This would be equal to 1/10-inch (longitudinally) in a 20-foot concrete slab.

The ability of fibers to reduce shrinkage cracking in the first few hours after placement was not investigated in this project.

SPLITTING TENSILE STRENGTH

Specimens were tested at 28 days. DX and the reference mix, almost identical, showed the highest strength in 6 bag mixes, followed by RC mixes (Table 35 and Figure 17). GE fiber showed lower strength than all steel fiber mixes except FN. ARG mixes showed the lowest strength.

In 6 bag mixes with 20 percent flyash, DX showed the highest strength followed by RC and FN mixes (Table 36 and Figure 18). ARG mixes had the lowest strength. The reference mix showed a higher strength than all fiber mixes except DX. The hooked end configuration and length of DX fibers may increase resistance to shear because of its bonding capabilities to the concrete mortar; hence, they enhance splitting tensile strength.

In 8 bag mixes, DX again had the highest strength of all fiber mixes (Table 37 and Figure 19). All steel fiber mixes and the reference mix showed higher strengths than non-steel fiber mixes, though the reference mix strength was lower than that of any of the steel fiber mixes.

In 8 bag mixes with 15 percent flyash, DX produced the highest strength and ARG produced the lowest (Table 38 and Figure 20). Steel fiber mixes again showed higher strengths than non-steel. The reference mix had a lower strength than any of the fiber mixes. Despite containing flyash and having a lower water/cement ratio, strengths were only marginally higher than in non-flyash mixes. In RC mixes, the flyash mix strength was actually lower than the non-flyash mix strength.

In 8 bag mixes with super plasticizers, RC fiber mixes showed the highest strengths followed by DX (Table 39 and Figure 21). ARG mixes showed a higher strength than FN. GE mixes had the lowest strength. Mixes with super plasticizers and a lower water/cement ratio produced higher strengths than flyash fiber mixes.

Steel fiber mixes showed greater strengths than similar non-steel fiber mixes or reference mixes with lower water/cement ratios. The addition of flyash and lower water/cement ratios than non-flyash mixes produced slightly higher strengths with only the aforementioned exceptions. Super plasticizer mixes produced the highest strengths of all. So, fibers did enhance splitting tensile strength in 8 bag mixes. Figure 22 illustrates a specimen undergoing a splitting tensile strength test.

Figure 22. Specimen Undergoing Splitting Tensile Strength Test

FLEXURAL TOUGHNESS INDEX

Flexural Toughness is defined as the area under the load deflection curve for flexural testing of beams. The test method used for determining the flexural toughness index in this study is a modified version of ASTM test method C-1018. In this study in the toughness index will be defined as the entire area under the load deflection curve (Area 1) divided by the area under the curve up to the first crack strength (Area 2). See Figure 23.

The toughness index is a measure of ductility of concrete, hence resistance to cracking and crack propagation. When fibers are present in concrete, cracks cannot extend through them without stretching and or debonding them. As a result, additional energy is necessary before complete fracture occurs. The toughness index is an indicator of this additional energy.(1)

If the slope of the load deflection curve up to first crack strength is large (steep), this indicates a brittle material. Given the same first crack strength, the material with the greater slope will have a smaller area under the curve, increasing the likelihood of a larger toughness index. The index is also dependent on the shape of the load deflection curve after first crack strength is reached. Concretes with different fibers may behave in a different fashion after first crack strength is reached. That is, some may exhibit more ductility after first crack strength is reached than other fibers. If the curve (after first crack strength is reached) extends more horizontally than vertically, or descends gradually rather than abruptly vertically, this will increase the area under the curve, hence increasing the toughness index.

Appendix A, B, and C contain load deflection curves for DX, RC and FN.

Though two specimens (beams) were tested for each mix and test age, the variation between specimens from the same mix and test age in deflection values, areas under the load deflection curve, and toughness index was such that only the "better" of the two was selected. The better specimen was the one that deflected the most before separating completely. This did not necessarily give the higher toughness index nor was it the specimen that showed the highest strength.

However, if the values of the two specimens from the same mix and test age were close enough based on engineering judgement, they were averaged.

Polypropylene and fiberglass fibers did nothing to improve the toughness index. The toughness index for these specimens is equal to 1, as are the reference mix toughness indices. After the first crack occurred, specimens failed completely through, unlike the steel fiber specimens, which resist cracking completely through with continued loading.

In 6 bag mixes, FN showed the lowest index of the three steel fibers at all test ages (Table 40). It also remained relatively constant through all test ages. RC mixes generally showed the next highest index, followed by DX. At 28 and 56 days, the difference between the indices of the two is very slight.

TABLE 40

TOUGHNESS INDEX OF 6 BAG MIXES

FIBER	7 DAY	28 DAY	56DAY
Dramix	107.92	34.91 avg.	12.11 avg.
Ribtec	50.12	34.82	11.30 avg.
Fibercon	1.96 avg.	2.15 avg.	2.19 avg.

In 6 bag mixes with flyash, DX produced the highest index at all test ages tested except 56 days, where RC mix had the highest index (Table 41). FN had the lowest index at all ages tested. Its index increased with each successive test age. DX showed an increase from 7 to 28 days but a decrease from 28 to 56 days. RC showed the greatest percentage increase at all test age intervals. In mixes containing flyash and a lower water/cement ratio, significant increases over non flyash mix indices were observed in only 2 instances: 28 day DX and 56 day RC, where they doubled and tripled, respectively.

TABLE 41

TOUGHNESS INDICES OF 6 BAG MIXES WITH FLY ASH

FIBER	7 DAY	28 DAY	56 DAY
Dramix	22.21	64.36	9.84
Ribtec	2.73	16.87	34.66
Fibercon	2.42	2.65 avg.	3.91

In 8 bag mixes, DX had the highest index at all test ages except 56 days, where RC showed a slightly higher index (Table 42). The index actually decreased in FN mixes with each successive test age. The DX index increased from 7 to 28 days but decreased from 28 to 56 days. With RC, a decrease was noted from 7 to 28 days , but an increase in index occurred from 28 to 56 days.

TABLE 42

TOUGHNESS INDICES OF 8 BAG MIXES

FIBER	7 DAY	28 DAY	56 DAY
Dramix	16.90	30.48	17.56
Ribtec	15.23	14.38	21.12
Fibercon	1.50 avg.	1.37	1.00

In 8 bag mixes with flyash, DX had the highest index for all test ages, followed by RC and FN (Table 43). At 28 and 56 days, the FN specimen failed completely through after first crack strength was reached (index = 1). In general, flyash mixes showed lesser values or roughly the same as comparable non-flyash mixes with higher water/cement ratios.

TABLE 43
TOUGHNESS INDICES OF 8 BAG MIXES WITH FLY ASH

FIBER	7 DAY	28 DAY	56 DAY
Dramix	23.24	28.66	14.25 avg.
Ribtec	9.83	4.83	10.71 avg.
Fibercon	1.76 avg.	1.00	1.50

In 8 bag mixes with super plasticizers, DX showed the highest index at 7 and 56 days, but RC had a higher index at 28 days (Table 44). FN showed the lowest index at all ages tested and also showed decreasing values with each successive test age.

TABLE 44
TOUGHNESS INDICES OF 8 BAG MIXES WITH SUPERPLASTICIZERS

FIBER	7 DAY	28 DAY	56 DAY
Dramix	20.23	3.78	38.22
Ribtec	5.04	10.03	5.87 avg.
Fibercon	1.60 avg.	1.59	1.00

Some specimens' indices increased during a given time interval and others' did not. At 7 days, no super plasticizer mixes showed higher indices than flyash mixes despite having lower water/cement ratios. At 28 days, RC with super plasticizers showed a higher index than its flyash mix and DX did the same at 56 days. In all other cases, indices were either equal to or less than their flyash mix counterparts with higher water/cement ratios.

In summation, reference mixes and non-steel fiber specimens had an index of 1 (one). They failed completely through upon reaching first crack strength. The longer steel fiber reinforced specimens had the higher indices. FN is the shortest of the steel fibers. Its mixes consistently had the lowest indices of all steel fiber specimens. In 6 bag mixes with flyash and a lower water/cement ratio, toughness indices were not significantly higher than those of non-flyash mixes with the few exceptions noted in the discussion of results. The same was found to be true in 8 bag flyash and super plasticizer mixes when compared to non-additive mixes. RC was the only fiber mix whose index increased with age, but DX produced the most consistently high indices.

CONCLUSIONS

1) Fiber reinforced concrete mixes can be made that meet current La. D.O.T.D. specifications for slump and approach, meet, or exceed performance characteristics of non-fiber reinforced concrete.

2) The addition of fibers to concrete did not appreciably improve compressive or flexural strength as expected when compared to the reference mix (non-fiber reinforced concrete). In many cases, strengths for fiber reinforced specimens were lower than those of the the refernce mix. However, the non-fiber reinforced "reference" mixes had slightly lower water/cement ratios. In 8 bag mixes with flyash, only one fiber mix, DX, showed higher flexural strengths at all test ages than the reference.

   No trends could be detected to show that one type of fiber (steel, fiberglass, or polypropylene) consistently produced higher strengths than another. In some test groups, steel fiber mixes did. In others, non-steel fiber mixes did. In others, steel and non-steel were randomly grouped from high to low. The only exception was in 56 day old 8 bag mixes where superplasticizers were used. In these mixes, steel fiber mix strengths were higher than non-steel.

   In both 6 and 8 bag fiber mixes containing flyash, compressive strengths and flexural strengths were generally only slightly higher than non-flyash mixes having a higher water/cement ratio.

   Fibers in concrete seem to influence the strength gain rate less than the addition of flyash and super plasticizers.

3) The splitting tensile strength of fiber mixes was increased over reference mix strength, despite the reference mix's lower water/cement ratio in some instances, by using steel fibers. This may be due to the fact that the longer (of the three tested) steel fibers better resist debonding from the concrete matrix than non-steel. In the 8 bag mixes with flyash, the reference mix showed a lower strength than any of the fiber mixes. Mixes with super plasticizers and lower water/cement ratios (than flyash mixes) showed the highest strengths of all.

4) The addition of steel fibers increases the toughness index. The non-steel fiber specimens as well as the reference mix specimens all had a toughness index of 1 (one). The longer steel fibers (of the three tested) had much larger indices, some over 100. Though no value has been established as being a "good" toughness index, it is the opinion of the author that values are relative to one another. That is, a value of 100 indicates a greater resistance to cracking and crack propagation than a value of 20. This is illustrated in the flexural overlay test specimens where cracking was slowed once it reached the fiber reinforced portion. Flyash mixes did not show consistently higher indices than non-flyash mixes. The same was true between mixes containing super plasticizers and those that did not.

5) Modulus of elasticity, shrinkage resistance, Poisson's Ratio and freeze-thaw durability were not enhanced appreciably through the use of fibers in concrete.

   Fibers were not found to produce higher moduli than non-fiber mixes and no trends were observed to indicate one fiber's superiority to another.

   The addition of super plasticizers and flyash did not significantly lower Poisson's Ratio.

No one fiber was seen as producing a lesser length change within any one mix group, except in 8 bag super plasticizer mixes where steel fiber mixes outperformed non-steel. In freeze-thaw durability, 8 bag mixes did not show appreciably higher durability factors than 6 bag mixes. Steel fibers did show slightly higher durability factors than non steel and non fiber reinforced concrete.

RECOMMENDATIONS

1) This concept has been used in a thin bonded fiber reinforced concrete overlay on Interstate 10 in Baton Rouge, Louisiana and is seen as the most useful application of fiber reinforced concrete by the Department at this time. It is recommended that the Department consider the use of steel fibers in future thin bonded concrete overlays and in structural applications where crack control is desired. In the same vein, the use of fibers in concrete roadways to decrease crack propagation in jointless pavement may not be as cost effective for full depth new construction as more conventional methods like joint sawing.

2) It is recommended that on conventionally formed pavement, super plasticizers be used in conjunction with fibers in concrete as they enhance workability and long term strength. However, on slip form paving operations,the increased slump and/or workability associated with the use of super-plasticizers may be undesireable.

REFERENCES

1) ACI Committee 544, ACI 544.1R-82, "State of the Art Report on Fiber-Reinforced Concrete." (Reapproved 1986), Replaces report ACI 544.1R-73.

2) Jack C. McCormac, Clemson University and Thomas Y. Crowell of Harper and Row Publishers, "Design of Reinforced Concrete," Copyright 1978.

3) Sheldon Law and Masood Rasoulian, "Evaluation of Corrosion Inhibitor," Final Report, May 1980; Study No. 79-1C(B).

APPENDIX A

FLEXURAL DEFLECTION AND TOUGHNESS INDEX
FOR
DRAMIX ZP 50/50 STEEL FIBER
7, 28, 56 DAY TESTS

APPENDIX B

FLEXURAL DEFLECTION AND TOUGHNESS INDEX
FOR
RIBTEC (XOREX 1) 2" STEEL FIBER
7, 28, 56 DAY TESTS

APPENDIX C

FLEXURAL DEFLECTION AND TOUGHNESS INDEX
FOR
MITCHELL FIBERCON 1" DEFORMED END STEEL FIBER
7, 28, 56 DAY TESTS

APPENDIX D

PHYSICAL PROPERTIES
AND
MANUFACTURER'S SPECIFICATIONS OF FIBERS

APPENDIX D

PHYSICAL PROPERTIES
AND
MANUFACTURER'S SPECIFICATIONS OF FIBERS

MITCHELL FIBERCON
(DEFORMED STEEL FIBERS)

Ultimate Tensile Strength	50 to 100 ksi
Cross-sectional Area	0.01 in x 0.022 in.
Length	3/4 in. and 1 in.
Addition Rate (Pavements)	85 to 100 lbs/cu.yd.

Mitchell Fibercon Steel Fibers, Mitchell Fibercon, Inc., 100 South Third Street, Evans City, PA 16033.

RIBTEC CORRUGATED STEEL FIBERS

Tensile Strength	140 ksi
Length	2 in.
Aspect Ratio (Length/Diameter)	57
Addition Rate	60 to 140 lbs./cu.yd.

Ribtec Steel Fibers, Ribtec Ribbon Technology Corporation, P. O. Box 30758, Gahanna, Ohio 43230.

DRAMIX HOOKED-END STEEL FIBERS

Tensile Strength	150 ksi
Length	1.75 in.
Aspect Ratio	100
Specific Gravity	7.8
Addition Rate	80 to 100 lbs./cu.yd.

Dramix Steel Fibers, Bekaert International, 1395 Marietta Parkway, Marietta, Georgia 30067.

ARG FIBERGLASS FIBERS

Tensile Strength	>1.85 x 10^2 ksi
Young's Modulus	1.1 x 10^4 ksi
Strain	>1.5%
Specific Gravity	2.7
Fiber Diameter	0.00053 in.
Elongation at break	1.5 to 2.5
Application Rate	40 to 85 lbs./cu.yd.

ARG Fiberglass Fibers, manufactured by Nippon Electric and Glass Co., Ltd., Japan. Distributed by Henry J. Molloy and Associates; Inc., P. O. Box 515, 1828 Carpenter Road, Hutchins, TX 75141.

GRACE POLYPROPYLENE FIBERS

Length	1/2", 3/4"
Specific Gravity	0.9
Application Rate	0.75 to 1.5 lbs./cu.yd.

Grace Polypropylene Fibers, W. R. Grace and Co., Construction Products Division, 62 Whittemore Ave., Cambridge, MA 02140.