

A NEW MATERIAL (POLYOLEFIN FIBER REINFORCED CONCRETE) FOR THE CONSTRUCTION OF PAVEMENTS AND WHITE-TOPPING OF ASPHALT ROADS

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ABSTRACT

This paper presents the performance characteristics of a newly developed polyolefin fiber reinforced concrete. These polyolefin fibers were used for the first time in South Dakota for the construction of a full-depth pavement and white-topping on scarified asphalt pavement.

The mixture proportions used, the procedure used for mixing, transporting, placing, consolidation, finishing, tining, and curing of the concretes are described. The feasibility of using this high performance polyolefin fiber reinforced concretes in the construction of highway structures has been established and presented in this paper.

These polyolefin fibers performed well in the mixing operation without causing any balling or segregation. This new polyolefin fiber reinforced concrete with enhanced fatigue, impact resistance, modulus of rupture, ductility and toughness properties is particularly suitable for the construction of pavements and white-topping.

INTRODUCTION

Concrete fiber composites technology has grown over the last three decades into a mature industry. Since the pioneering research on steel fiber-reinforced concrete conducted in the United States in the 1960's, there has been substantial research and development activities throughout the world. A major advantage of using fiber-reinforced concrete is the improved toughness or residual load carrying ability after the first crack and enhanced fatigue strength. Additionally, a number of studies have shown that the impact resistance of concrete can also improve significantly with the addition of fibers (1 to 9).

Combining the technical benefits and in place costs, fiber-reinforced concrete (FRC) was found to meet the prerequisites of Value Engineering particularly in airport and highway pavements. FRC had been used extensively in overlays and repair of airport pavements and bridge decks (1, 8). Synthetic (polyolefin) fibers have been developed recently with low aspect ratios. Like steel fibers, these fibers are available in various lengths and diameters and are added to improve the structural properties of concrete. These fibers can be mixed with concrete in large quantities, as much as 8 percent by volume without causing any balling, segregation or increase in air entrainment. The amount of fibers that could be added depends on the length and diameter of the fibers. Extensive research (10, 11) has been done to determine the performance characteristics, fresh and hardened concrete properties of polyolefin fiber-reinforced concretes and mortars.

Polyolefin fiber-reinforced concrete is one material that promises to provide many advantages over currently used steel and other polypropylene fibers while providing a practical approach to enhanced durability and cost effectiveness in concrete composites. Currently, polypropylene fibers are typically used at 0.1% to 0.3% by volume of concrete to reduce plastic shrinkage cracking. These fibers provide only minimal benefit to the mechanical properties of hardened concrete. Steel fiber, used more extensively in Europe, is typically incorporated in quantities up to 0.5% by volume of concrete, and while it does enhance the structural performance of hardened concrete, it poses other problems such as staining, inherent corrosion and potentially harmful protrusions.

The polyolefin fibers are longer and stronger than plastic fibers previously used to reinforce concrete, and a proprietary packaging technology enables rapid and uniform mixing into the concrete matrix at quantities up to 2% by volume. The addition of fibers significantly enhances the concrete's physical properties, especially toughness, ductility and resistance to shrinkage cracking. In this paper, an attempt is made to assess, evaluate and appreciate the behavior of the new polyolefin FRC. The performance of fresh concretes and the properties of hardened concretes with and without fibers are compared. A comparison is also made between the non-metallic polyolefin fiber-reinforced concrete and currently used steel fiber reinforced concrete.

TEST RESULTS AND DISCUSSION

The performance characteristics of the actual field concrete produced and used in construction (11) are presented and discussed in this paper.

The mixture proportions used in the Sheridan Lake Road pavement are given in Table 1. The fine/coarse aggregate ratio was 45/55 and the water to cementitious (cement + fly ash) ratio was 0.41 and the water to cement ratio was 0.5. Slight variations in the mixture proportions occurred from truck to truck in the field mixes.

The temperature of the fresh concrete was recorded and then it was tested for slump (ASTM C 143), air content (ASTM C 231), fresh concrete unit weight (ASTM C 138) and yield of the concrete. The actual fiber content in the field concrete was determined by washing the concrete from the unit weight container of a known weight and separating the fibers carefully. These fibers were dried and weighed to determine the fiber content in a cubic yard of concrete.

During the construction, concrete samples were taken on eight occasions. The concrete samples were taken from randomly selected different trucks. They were taken from the chute discharge of the truck and carried in wheelbarrows to the material testing site which was a few hundred feet from the placement location. There was a total of 8 different mixtures: three plain concrete mixtures, three Steel Fiber-Reinforced Concrete (SFRC) mixtures and two Non-Metallic Polyolefin Fiber-Reinforced Concrete (NMFRC) mixtures. Mixtures M1, M5, and M7 were control concretes without fibers. Mixtures M2, M3, and M8 were SFRC, and M4 was NMFRC. Mixture M6 was NMFRC-2 with a lower compressive strength. The actual mixture proportions calculated from the computer printouts given by the concrete supplier are given in Table 1.

The unit weights of both fiber and control concretes varied according to the measured air contents. The lower unit weight was for mixture M6, 2264 kg/m³ (141.32 lbs./cu.ft.) which had the highest air content of 10.4%. In general, steel-fiber concretes had slightly higher unit weights than NMFRC and control concretes. Mixture M8 with an air content of 5.6% had a unit weight of 2405 kg/m³ (150.12 lbs./cu.ft.), whereas mixture M4 with 5.0% had a unit weight of 2330 kg/m³ (145.43 lbs./cu.ft.).

The compressive strengths of plain concrete, SFRC and NMFRC were almost similar. At age 28 days, the compressive strengths of plain concrete, SFRC and NMFRC were 37.2, 38.0, and 38.6 MPa (5388, 5505, and 5595 psi), respectively. The compressive strength of NMFRC-2 was lower 32.7 MPa (4740 psi). It can be said that the fibers did not significantly influence the compressive strength of the concrete. One important observation made during the compression test was the ductile mode of failure of the fiber concrete cylinders. The plain concrete cylinders failed instantly shattering into pieces with a loud noise at the first crack while the fiber concrete cylinders continued to sustain the load and underwent large deformations without disintegrating into pieces. A visual observation of the ultimate failure of the cylinders in compression had indicated that NMFRC specimens were more ductile than SFRC specimens. This change in the mode of failure from a brittle failure to a ductile failure, was also observed in case of NMFRC-2. An improvement in the flexural strength was seen due to the addition of fibers. The first crack strength and the flexural strength of the NMFRC were more than that of plain concrete and SFRC. The first crack strength and flexural strength of NMFRC-2 mixture were less than all the other mixtures.

Typical load deflection curves for plain SFRC and NMFRC are compared in Fig. 1. The plain concrete beam failed immediately after the first crack whereas, SFRC and NMFRC beams did not fail after first crack; but sustained the load at a reduced level. The load deformation characteristics and hence toughness and ductility of these beams were almost the same. The load-deformation behavior for NMFRC-2 was similar to that of NMFRC beams. However the flexural strength was lower for NMFRC-2.

An overall evaluation of the flexural test results and load-deflection curves had indicated that SFRC had higher variations in the test results compared to NMFRC. This was due to the number of fibers in the concrete. In the case of NMFRC, there were four times more fibers in the concrete compared to SFRC. The flexural test results were directly related to the actual number of fibers in the tensile zone and the actual number of fibers in the path of the tensile crack. When higher numbers of fibers were found in the path of the crack, the flexural strengths and toughness values were higher. Since there were 4 times more polyolefin fibers in the same volume of concrete, the probability of more fibers in the tensile zone and in the path of the tensile crack was greater. There was also more uniform distribution of fibers in NMFRC.

The first crack toughness values are shown in Fig. 2, and the calculated ASTM toughness indices are plotted in Fig. 3. At age 28 days, the first crack toughness, toughness indices and the toughness ratios for NMFRC were slightly higher than those of SFRC. At 28 days, the average ASTM toughness indices were 4.30, 8.28, and 15.68 times greater than plain concrete which had the toughness indices equal 1. The corresponding toughness indices for NMFRC were 4.75, 9.30, and 17.85. The ratios of toughness indices $I_{10/15}$ and $I_{20/110}$ were 1.92 and 1.89 for SFRC and 1.95 and 1.92 for NMFRC. These ratios and toughness indices were slightly higher for NMFRC indicating that NMFRC was more ductile and had higher toughness. The calculated ASTM residual strength factors, $R_{5, 10}$ and $R_{10, 20}$ are plotted in Fig. 3A. The comparison of R-values also confirms the above stated observations. At age 28 days, the first crack toughness, toughness indices and toughness ratios for NMFRC-2 were almost the same as for SFRC and NMFRC. The beams of NMFRC-2 were more ductile and had much higher toughness than plain concrete beams. It was observed that the addition of non-metallic fiber in concrete could even enhance the performance of low strength concrete.

The flexural toughness factor according to Japanese Concrete Institute (JCI) is the area under the load-deflection curve up to a deflection of $1/150$ of the span. At age 28 days, the flexural toughness factor for the NMFRC was slightly higher (7%) than SFRC. The flexural toughness factor for NMFRC-2 was 19 percent lower than SFRC and 24 percent lower than NMFRC. The equivalent flexural strength as specified by the Japanese Society of Civil Engineers (JSCE) was calculated for all mixtures and the results are given in Fig. 4.

The impact test results are shown in Fig. 5. It can be seen from the results that the NMFRC had better ability to resist the impact loads than the plain concrete and SFRC mixtures. The number of blows required for ultimate failure were 20, 125 and 273, for plain, SFRC and NMFRC respectively. NMFRC had 13.54 times higher impact strength when compared to plain concrete and 1-2 times higher when compared to SFRC. NMFRC-2 mix also had higher impact values than the plain and SFRC mixtures. The higher impact resistance of NMFRC may be due to the larger number of fibers and probably with a better distribution. The impact strength of NMFRC-2 was 9 times higher than that of plain concrete and 20 percent higher than SFRC and 34 percent lower than NMFRC.

To predict the fatigue life for concrete, the S-N curves (the fatigue stress vs. the number of cycles or log number of cycles) were used. The flexural fatigue strength (f_f) vs. the log number of cycles for all four concretes (plain, SFRC, NMFRC and NMFRC-2) are plotted in Fig. 6. There was a linear relationship between the fatigue stress (f_f) and the log number of cycles, until the fatigue strength (f_{max}) of that particular concrete was reached then the line became parallel to the x-axis indicating that there was an endurance limit for concrete. The same type of behavior was observed for all concretes. There was an increase in fatigue strengths and fatigue life with the addition of steel and polyolefin fibers. SFRC had slightly higher increase in fatigue life (9%) compared to NMFRC.

All beams which had withstood 2 million cycles were further tested for static flexural strength (f_{tA}). There was an increase in the static flexural strength (f_t) for both plain and FRC after they were tested for fatigue. This observed increase (from 10 to 20%) was higher than the strength gain that could be attributed to the aging of the test specimens. The same phenomenon was observed in all our earlier extensive fatigue testing of plain and fiber reinforced concretes. The amount of increase in f_t seemed to depend on the flexural fatigue stress (f_f) to which the specimens were subjected to during the fatigue testing (4, 7, 9). With lower f_f values, the increase in f_t was higher. It was suggested that this post fatigue increase in f_t compared to the pre-fatigue f_t was due to densification of concrete caused by initial low stress level cycling, in a manner similar to the improvement in strength under moderate sustained loading.

APPLICATIONS

The construction projects undertaken to evaluate the non-metallic polyolefin fiber reinforced concrete were the following two pavements:

1. Full depth fiber (both steel and polyolefin)-reinforced concrete pavement, on Sheridan Lake Road in Rapid City, SD.
2. White topping test section on the asphalt bridge approach road at Vivian, SD (the bridge on the U.S. 83 number 43-026-195, over I-90 south of Pierre, SD).

The research activities involved were the development of mixture proportions, quality control testing, and advice on the construction, monitoring and evaluation of the above structures. The research activities also involved periodic condition surveys to evaluate the performance of the constructed pavements and white topping. It was also proposed to compare the performance of this new non-metallic polyolefin fiber-reinforced concrete (NMFRC), with the plain concrete and steel fiber-reinforced concretes in the pavement.

CONSTRUCTION OF WHITE TOPPING

This work consisted of the construction of a nonmetallic fiber-reinforced Portland cement concrete pavement overlay (referred to as white-topping). The white-topping was constructed in September 1994. The approach on the north end of the structure had the white-topping placed with two different fiber contents 11.9 kg/m^3 and 14.8 kg/m^3 (20 and 25 lbs./cu.yd.) for east and west side respectively. The fiber concrete for the white-topping was produced using a concrete batch plant with delivery in truck mixers.

The actual mixture proportions used in the construction are given in Table 2. As soon as the asphalt was scarified, the pavement was inspected and the cracks were recorded. The scarified depths were not uniform. There was one major transverse crack. The width of the crack was 50 mm (2 inches). There were two more shorter cracks which were also more than 25 mm (1 inch) wide. These cracks extended very deep, possibly the entire depth of the base course. It was anticipated that there would be reflection cracks in the concrete overlay (white-topping). Just before concreting, after the forms were fixed, the actual depth of the white-topping was measured over the entire length of the overlay. The depth of the white-topping varied from 63 mm (2-1/2 inches) to 115 mm (4-1/2 inches). The dimensions of the white-topping were 8.5 m (28 ft.) wide and 32.6m and (107 ft.) long.

The west side lane of the white-topping was 4.3 m (14 ft.) wide and 32.6 m (107 ft.) long. The contractor wanted to open the lane for traffic in less than a week. Therefore, he wanted to add an additional 29.7 kg/m^3 (50 lbs./cu.yd.) of cement more than specified so that the concrete could achieve the required strength of 27.6 MPa (4000 psi) in less than a week. This proposal was accepted. This mixture contained 14.8 kg/m^3 (25 lbs./cu.yd.) of fibers. The concrete had adequate workability and the concreting operation went without any problem. A vibrating screed was used for consolidation. A hand vibrator was also used to vibrate the concrete in front of the vibrating screed. The finishing and tining operation followed the normal procedure. There was only one saw-cut joint in the white-topping. The east side lane was constructed with the same dimensions, 4.3 m wide and 32.6 m long (14 ft. wide and 107 ft. long). The same mixture proportions with a different fiber content 11.9 kg/m^3 (20 lbs./cu.yd.) were used. As in the previous occasion, the concreting was done without any problems. The same procedures for mixing, transporting, placing, consolidation, finishing and curing were used. During the inspection no shrinkage or other kinds of cracks were observed. A few fibers were visible on the surface. There was a good bond between the fiber and concrete. There was no damage or distress noticed on the surface. No reflection cracks were observed over the large cracks in the asphalt, and no reflection cracks had occurred so far (January 30, 1997).

CONSTRUCTION OF SHERIDAN LAKE ROAD PAVEMENT

As a part of this research work, the NMFRC pavement at Sheridan Lake Road was constructed in July 1994, next to the existing SFRC pavement, which was constructed in 1992. The NMFRC pavement had a total length of 47.6 m (156 ft.) which included one section of 29.3 m (96 ft.) and two transition sections of 9.2m (30 ft.) each. The width of the pavement was 14.6 m (48 ft.). The thickness of the section was 140 mm (5-1/2 inches). It was also proposed to keep the proportions of coarse and fine aggregate equal for the NMFRC mixture, resulting in more mortar and paste content of concrete, highly essential for the proper mixing and distribution of the polyolefin fibers. A steel fiber-reinforced concrete (SFRC) pavement was also constructed at the intersection of the Corral Drive and Sheridan Lake Road. Dramix Steel fibers (60 mm long and 0.8 mm dia.) were used.

The mixture proportions are given in Table 1. Laboratory trial mixes were made to determine if the same mixture proportions could be used for both SFRC and NMFRC. Based on the results, it was decided to use the same basic mixture proportions for both SFRC and NMFRC and observe the performance of the concrete in regard to workability, fiber mixing efficiency, placement, consolidation and finishing. This experiment showed that with a minor change in fine to coarse aggregate ratio in FRC compared to plain concrete, the fibers mixed well and uniformly distributed throughout the mixture without balling or segregation. The uniform mixing was also possible in trucks with a regular load of 6.1 to 6.9 m³ (8 to 9 cubic yards) of concrete in trucks with 8.4 m³ (11 cu. yd.) capacity.

STEEL FIBER-REINFORCED CONCRETE PAVEMENT (SFRC)

Dramix steel fibers (ZC 60/.80) at 39 kg/m³ (66 lbs./cu.yd.) were added to the concrete at the plant. A concrete paving machine (GOMACO 5800) was used. The vibrators had a capacity of 12,000 revolutions/minute. In the job, the vibrators were used at 8000 to 9000 revolutions/minute. It was specified that the slump of the concrete when it was discharged from the truck should be 25 to 50 mm (1 to 2 inches). However the concrete delivered had slightly higher slump 64 to 89 mm (2-1/2 to 3-1/2 inches). Therefore there was some delay in floating and finishing the pavement surface. There was no difficulty for placing, consolidating and finishing operations by the paver. The fibers were not sticking out and the 'roller-bug' was not used in the finishing operation. The surface was floated similar to the plain concrete. As the paver moved, the concrete surface was dragged with a wet burlap attached to the paver. There were two finishers, one with a rectangular float and another with a flat float. After the floating, a carpet drag (Astro-turf) was used in case of plain concrete and a plastic broom was used for fiber concrete for the final finish. In the case of SFRC, a carpet drag (Astro-turf) would have pulled the fibers out of the concrete; hence it was not used. The finish appeared to be satisfactory.

POLYOLEFIN FIBER-REINFORCED CONCRETE PAVEMENT (NMFRC)

The fibers used were 50 mm (2 inch long) and 0.63 mm (0.025 inch) diameter, supplied by the 3M Company. The fibers were added at 14.8 kg/m³ (25 lbs./cu.yd.). The fibers mixed well without balling, segregation or lumping. The fibers were also uniformly distributed. In this project, it was proposed to study the efficiency of the mixing and uniform distribution when the fibers were added in a larger volume of concrete, in the truck. Therefore the fibers were added in the first truck with 3.8 m³ (5 cu.yd.) of concrete. The second truck contained 5 m³ (6.5 cu.yd.) of concrete. Subsequent trucks contained 6.1 m³ (8 cu.yd.) of concrete and the last truck contained 7.3 m³ (9.5 cu.yd.) of concrete. In all these trucks, the fibers were added at the plant and at the same dosage rate of 14.8 kg/m³ (25 lbs./cu.yd.). The fibers mixed very well and distributed uniformly without any balling, segregation or lumping together. The efficiency of the mixing was maintained even in the truck with 7.3 m³ (9.5 cu.yd.) of concrete (The capacity of the truck was 11 cu.yd.). It was observed that once the fibers were mixed well in the concrete, any amount of additional vibration or mixing did not induce any balling or segregation or lumping of the fibers. The plain concrete slump delivered at the site was specified as 37 to 50 mm (1-1/2 to 2 inches). At this slump level, the consolidation and finishing of the concrete by the paver was highly satisfactory. For the NMFRC pavement concrete, a lower water/cement ratio (0.41 water to cementitious materials ratio) was used in order to maintain the same strength for both plain and fiber concrete.

The slump of the NMFRC concrete delivered, by the first truck, at the site was 6 mm (1/4 inch). It was decided to retemper the concrete in the field to increase the slump to about 19 to 25 mm (3/4 to 1 inch). The retempering was done with 5 gallons of water in 6.1 m³ (8 cu.yd.) of concrete. After retempering, the concrete discharged as easily as the plain concrete. The paver operation, and the floating and finishing operation went smoothly, similar to that of the plain concrete. The paver operator and the concrete finishers were fully satisfied with the consistency and finishability of the concrete.

The same mixture proportions were used in the south bound lanes for the second phase. These mixture proportions had given a low workability [about 6 mm (1/4 inch) slump] after addition of fibers, and the concrete had to be retempered in the field with 19 L (5 gallons) of water for 6.1 m³ (8 cubic yards) of concrete to achieve a slump of 25 mm (1 inch) or more. This procedure worked well and there were no difficulties in discharging, placing and finishing with a paver.

However, it was decided to try out a new procedure to avoid retempering in the field. In this technique, it was decided to add one gallon of superplasticizer for each truck in the plant to get the required workability 25 to 50 mm (1 to 2 inches slump) when the concrete was discharged in the field. This technique was successfully applied for the rest of the concreting.

After comparing both procedures, our personal preference would be to follow the procedure in which superplasticizer was not used and the workability of the concrete in the field was controlled by retempering with an appropriate amount of water. Care should be taken to insure that the slump after retempering should always be less than the original slump obtained when it was initially mixed and that permissible W/C + FA is not exceeded.

The joints were saw cut 10 hours after the concrete was placed for plain concrete and SFRC pavements. In the case of NMFRC pavement, the joints were cut, with early-age sawing, about 4 hours after the placement was finished.

The pavements were inspected after one, two and three days for plastic shrinkage cracking. The inspection revealed that there were no plastic shrinkage cracks in all three pavement sections. These field inspections were made every week for the first three months, to observe the surface conditions for cracks, fiber protrusions, popouts, and any other pavement distress. Observations were made on all three sections of the pavements.

The North bound lanes were opened to traffic one week after placement. They were immediately subjected to heavy traffic loads, because all traffic including the concrete ready mix trucks with 10 cubic yards of concrete passed over them during the placement of the two west side lanes.

Some steel fibers were exposed on the surface. However, they were laying flat. Some fibers were bright at places where they were subjected to wheel traffic. Some polyolefin fibers were also seen at the surface. They were well bonded to the concrete and could not be pulled out. These fibers were not glaringly visible.

Three cracks were observed, one in the plain concrete pavement, one in the drain inlet at the SFRC pavement, and one in the NMFRC section of the pavement. The crack in the plain concrete pavement was 3.22 m (10 ft. 7 inches) long and 3.1 to 1.6 mm (0.124 to 0.0625 inches) wide. It seemed to be a shrinkage crack. The other two cracks in the SFRC and NMFRC had occurred due to the construction of the drainage inlet at these locations. The crack in NMFRC section was a diagonal crack 2.82 m (9 ft. 3 inches) long and 1.5 mm (0.06 inches) wide. It seemed to have occurred due to a settlement or disturbance in the sub-grade during the construction of the drainage inlet. In the SFRC, the crack occurred near the storm water drainage. Later inspections showed that the observed cracks remained stable and did not change in size.

CONCLUSIONS

The new polyolefin fibers with an innovative fiber delivery system had combined the structural benefits of steel fibers and the material benefits of polyolefin.

It was possible to incorporate the newly developed high-tech, non-metallic, synthetic (polyolefin) fibers in concrete at 14.8 kg/m³ (25 lbs./cu.yd.) without causing any balling, clogging and segregation. The advantages of adding polyolefin fibers compared to the best available steel fibers are:

1. Four times more number of fibers are added in concrete ensuring more uniform distribution and consistent results.
2. Less chance for balling, segregation, bleeding or causing any other construction problems during mixing, placing, consolidation, finishing and tining operations.
3. Fibers are non-corrosive, non-hazardous, non-metallic, and non-magnetic.

They do not protrude from the surface; if they do, they could be easily burned off.

Addition of polyolefin fibers at 11.9 kg/m³ or 14.8 kg/m³ (20 lbs./cu.yd. or 25 lbs./cu.yd.) enhanced the structural properties of concrete. There was a slight increase in flexural strength, and a considerable increase in toughness, impact, fatigue, endurance limit, and post-crack load-carrying capacity. This improvement was the same or in some cases (such as impact) better than the enhancement that could be achieved with the addition of 39.1 Kg/m³ (66 lbs./cu.yd.) of the best available steel fiber in the market.

A specially designed mixture worked very well for white-topping (an overlay of NMFRC over scarified asphalt road). There was no difficulty or problem encountered during the mixing, transporting, placing, consolidation and tining of the average 75 mm (3 inch) thick overlay with this mixture specially proportioned for the addition of polyolefin fibers. The required or specified workability and finishability was achieved using NMFRC.

The same construction techniques and construction equipment without any modification were used in the construction of pavements and white-topping using NMFRC.

Table 1 Mixture Proportions Used For Sheridan Lake Road Pavement

Mixture Type	Mix #	Mixture Proportions kg/m ³ (lbs/cubic yard)					AEA mL/m ³ (oz/cu.yd)
		Cement	Fly Ash	Coarse Agg.	Fine Agg.	Water	
Plain	M1	308 (519)	67.6 (114)	1050 (1770)	753 (1270)	144 (242)	580 (15.0)
SFRC	M2	311 (525)	67 (113)	969 (1634)	789 (1331)	156 (263)	445 (11.5)
SFRC	M3	311 (525)	67 (113)	969 (1634)	789 (1331)	156 (263)	445 (11.5)
NMFRC	M4	311 (525)	67 (113)	969 (1634)	789 (1331)	156 (263)	542 (14.0)
NMFRC	M4A	311 (525)	67 (113)	969 (1634)	789 (1331)	156 (263)	542 (14.0)
Plain	M5	308 (519)	67.6 (114)	1025 (1728)	737 (1242)	148 (250)	851 (22.0)
NMFRC-2	M6	311 (525)	67 (113)	969 (1634)	789 (1331)	156 (263)	774 (20.0)
NMFRC-2	M6A	311 (525)	67 (113)	969 (1634)	789 (1331)	156 (263)	774 (20.0)
Plain	M7	308 (519)	67.6 (114)	1025 (1728)	737 (1242)	148 (250)	967 (25.0)
SFRC	M8	311 (525)	67 (113)	969 (1634)	789 (1331)	146 (246)	851 (22.0)

Note: Quantity of Polyolefin fibers used in the NMFRC mixes was 14.8 kg/m³ (25 lbs/cu. yd.), and Steel Fibers in SFRC mixes was 39 kg/m³ (66 lbs/cu. yd.). The steel fibers used were Dramix ZC 60/80, 60 mm (2.36") long 0.80 mm (0.032 inch) diameter. Polyolefin fibers used were 3M type 50/63, 50 mm (2.0 inch) long and 0.63 mm (0.025 inch) diameter.

Table 2 Mixture Proportions Used For White Topping

Mixture Type	Mix #	Mixture Proportions kg/m ³ (lbs/cubic yard)					AEA ml/m ³ (oz/cu. yd)
		Cement	Fly Ash	Coarse Agg.	Fine Agg.	Water	
NMFRC	W1	341 (575)	68 (115)	830 (1400)	830 (1400)	173 (291)	464 (12)
NMFRC	W2	341 (575)	68 (115)	830 (1400)	830 (1400)	173 (291)	464 (12)

For both the mixes, 14.8 kg/m³ (25 lbs/cu. yd.) of Polyolefin Fibers (3M type 50/63) were added. These Fibers were 50.0mm (2.0 inch) long and 0.63mm (0.025inch) diameter.

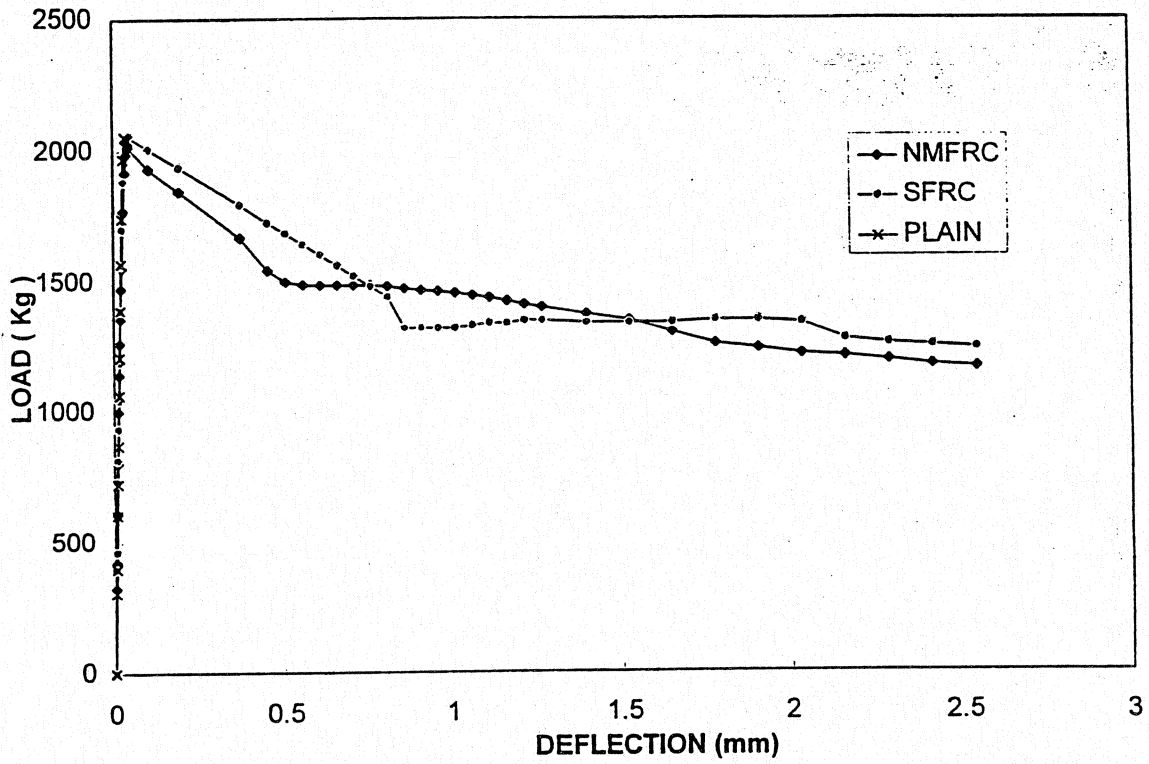


FIG. 1: COMPARISON OF TYPICAL LOAD DEFLECTION CURVES FOR PLAIN, SFRC AND NMFRC

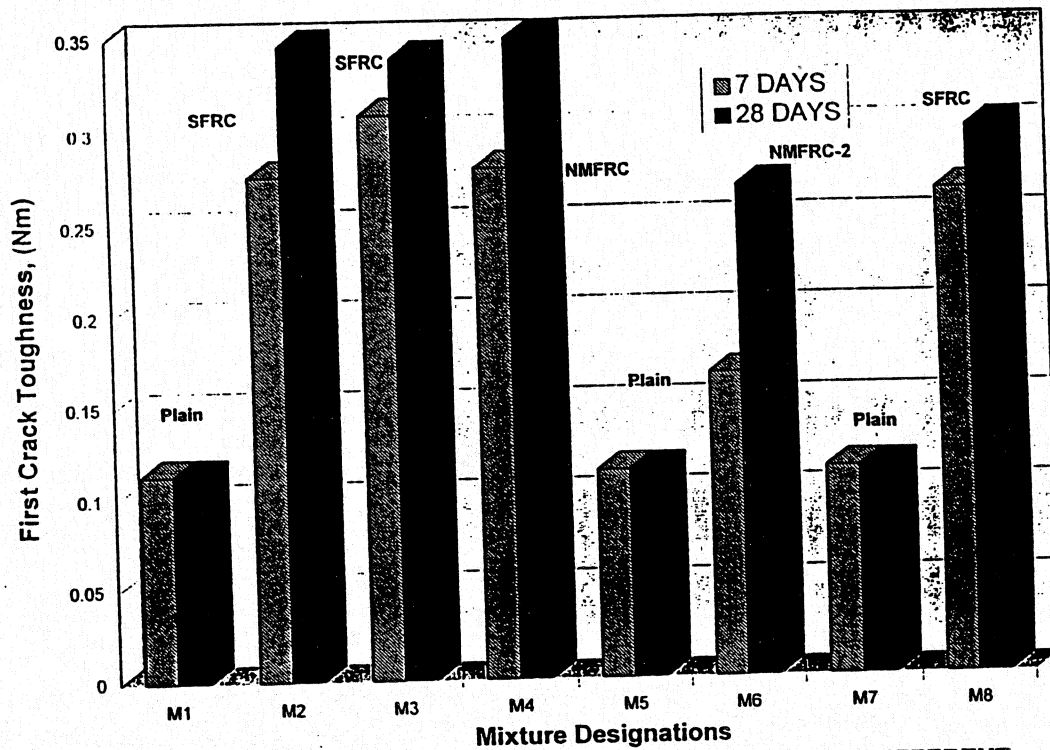


FIG. 2: COMPARISON OF FIRST CRACK TOUGHNESS FOR DIFFERENT MIXTURES

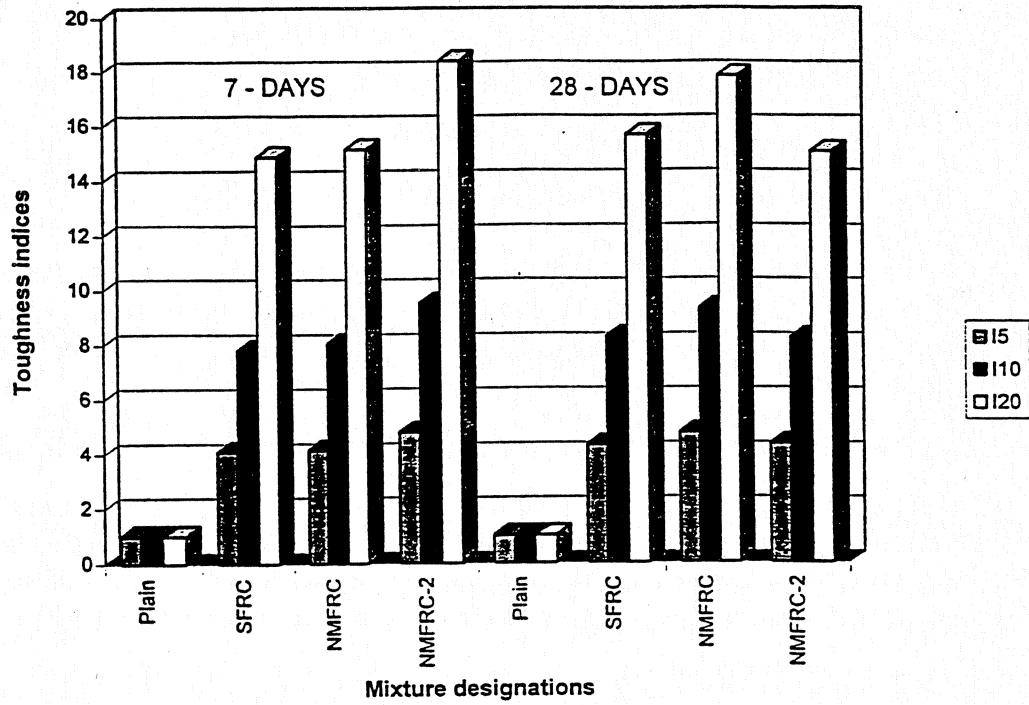


FIG 3: COMPARISON OF TOUGHNESS INDICES

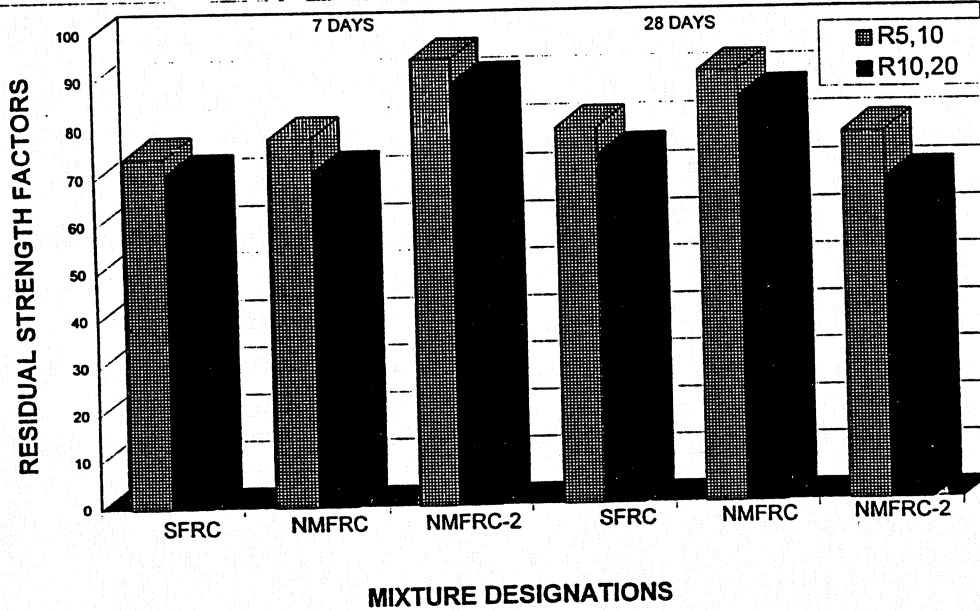


FIG. 3A COMPARISON OF RESIDUAL STRENGTH FACTORS

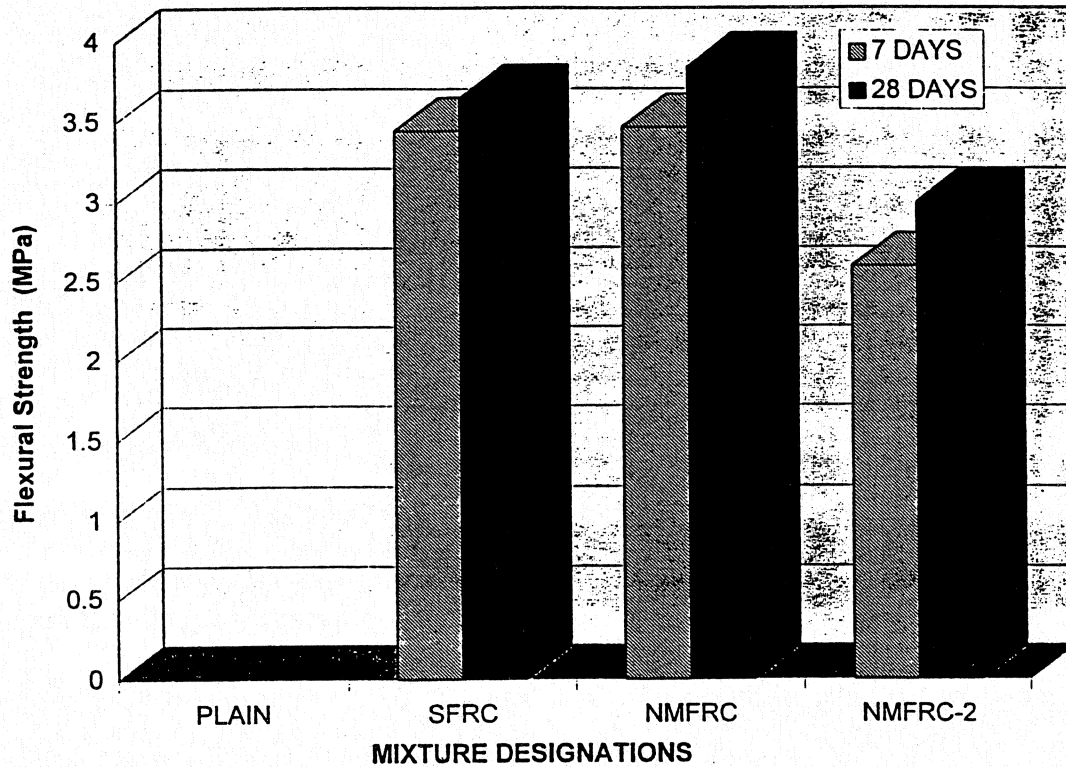


FIG. 4: COMPARISON OF EQUIVALENT FLEXURAL STRENGTH FOR DIFFERENT MIXTURES

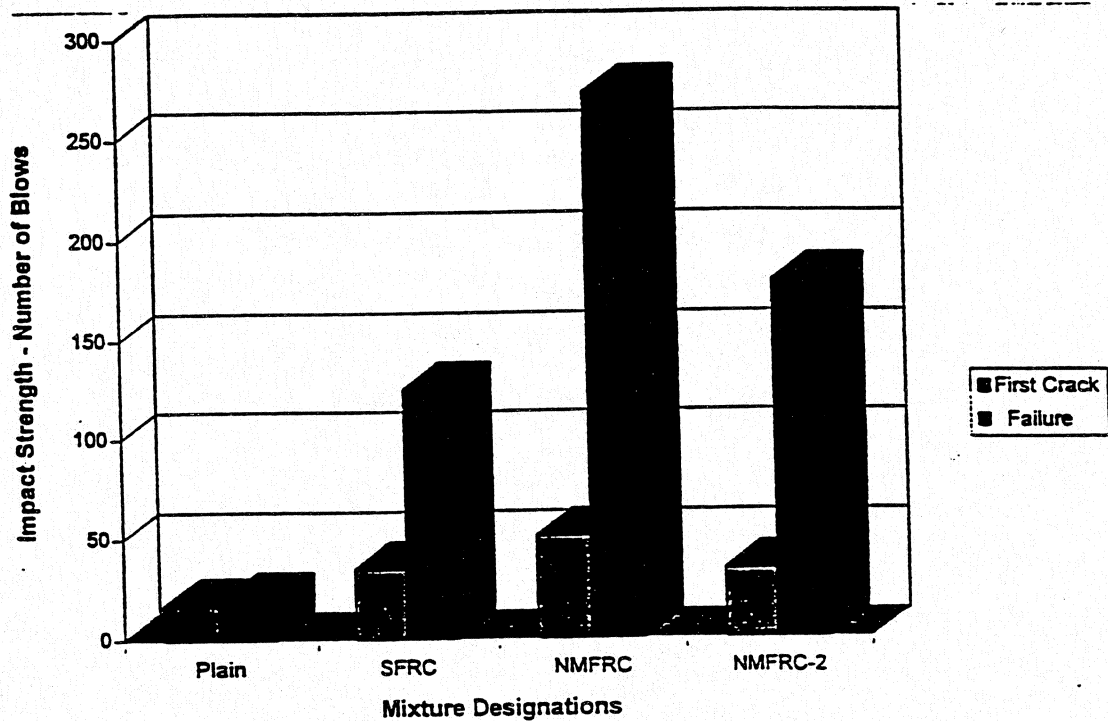


FIG. 5: COMPARISON OF IMPACT STRENGTH

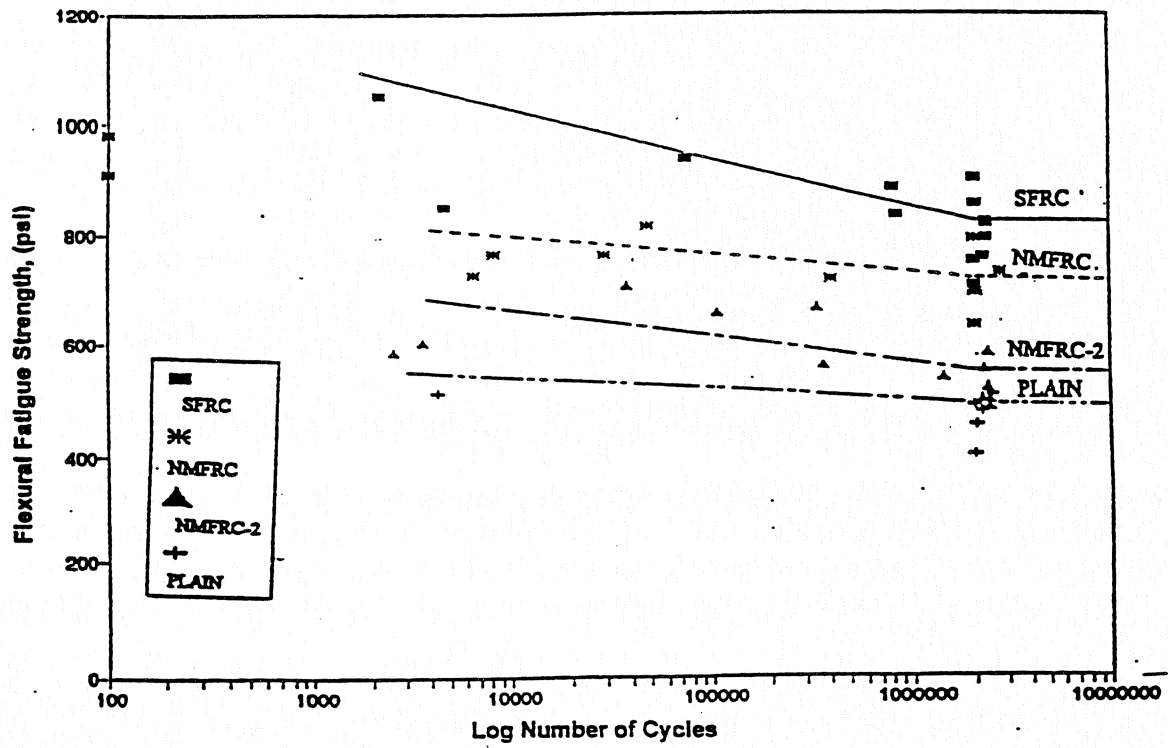


FIG. 6: FLEXURAL FATIGUE STRENGTH vs LOG NUMBER OF CYCLES

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