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Early-Age Properties of Polymer Fiber-Reinforced Concrete

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Abstract: The cracking problem in concrete is widespread and complex. This paper reviews the problem and focuses on those parts of the problem that are more readily solved. Polymer fibers are shown to have promise in several important areas of the cracking problem. To investigate one of these areas of the cracking problem more completely, an experimental research program focusing on the early-age properties of fibers was carried out. This study researched the properties of four polymer fibers; two of the fibers were macrofibers, and two were microfibers. Each fiber was tested at several dosage rates to identify optimum dosage levels. Early-age shrinkage, long-term shrinkage, compressive strength, and tensile strength were investigated. Long-term shrinkage and strength impacts from the polymer fibers were minimal; however, the polymer fibers were shown to have a great impact on early-age shrinkage and a moderate impact on early-age strength.

Keywords: polymer fibers, early-age shrinkage, long-term shrinkage, compressive strength, tensile strength.

1. Introduction

Bridge deck cracking is a significant problem in the United States; nearly half of all bridges in the United States showed transverse cracking at early age.[1] Nearly all of the state Departments of Transportation have indicated that they had problems with early-age deck cracking.[2] Due to the magnitude of the problem, numerous studies have been performed identifying the primary causes of the early-age deck cracking. These include thermal movement, early-age shrinkage, and early-age settlement.[1-3] These sources of cracking are difficult to manage, since their causes are mostly outside the control of the engineer.

Bridge decks are not the only place where concrete has a cracking problem. Plain Portland cement concrete is a brittle material and is prone both to cracking and to shrinkage. All three of these characteristics are not good as a structural material. Particularly at early age, Portland cement concrete is susceptible to cracking. When sources of early-age stress such as thermal movement or shrinkage are coupled with the weak early-age strength and brittle behavior, early-age cracking is bound to be a major problem.[1,4] Use of polymer fibers can be an efficient solution to improve the early-age strength, ductility, and shrinkage behavior of Portland cement concrete.[3,5-7]

This experimental research investigated the early-age strength and shrinkage performance of polymer fiber-reinforced Portland cement concrete, specifically for bridge decks. Four Polymer fibers were used, at dosage rates ranging from low to very high. Two microfibers and two macrofibers were tested, and their behaviors contrasted.

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2. Background and previous research

The mechanics of cracking in concrete are quite complex. Primary factors in early-age cracking include shrinkage of the concrete; thermal movement; plastic settlement; and restraint on the concrete. As well, it can be affected by environmental effects such as weather, temperature changes, and curing conditions; and material properties such as the modulus of elasticity, tensile strength, and creep rate of the concrete. Though several other factors may influence cracking, the effects described herein are most significant at early-age.[1,3,8]

Some of the sources of cracking are within the control of the designer, and some are not. Environmental factors are difficult to control-the weather does what it will, and enforcing good curing practices has proven very difficult.[8] The mechanical material properties of concrete are fairly well understood, but tensile strength, modulus of elasticity, and creep are all interrelated. Increasing the tensile strength of concrete (by changes in the mix design) also increases the modulus. For crack reduction, high tensile strength and low modulus are desired. Thus, only a limited improvement can be made through the material properties. What remains that can be improved, then, is the shrinkage, plastic settlement, restraint, and to a small degree, thermal movement.

Shrinkage may be divided up into four primary categories: carbonation, autogenous, drying (long term), and plastic (early age). Carbonation is an environmental effect; environments with high carbon dioxide cause it, and thus it is outside the designer's control. Carbonation shrinkage is only important in a few specific situations.[9] Autogenous shrinkage is controlled almost exclusively by the water-to-cement ratio of the concrete, with the cement content playing some part, and is insignificant if that ratio is above about 0.4 or the strength of the concrete is below 41.5 MPa.[4,10-12] Drying shrinkage occurs long-term, and is a major player in long-term cracking issues; however, at early age it is insignificant. Plastic shrinkage and its result, early-age cracking, are the primary players in early deterioration of concrete. Once the concrete starts cracking at early age, the concrete is well on its way to failing before it reaches its design life.

Plastic shrinkage, curing conditions, and cracking at early ages are inextricably tied. The mechanism of plastic shrinkage is based on the relationship between the bleed rate of water from the concrete and the evaporation rate from the surface of the concrete. When the evaporation exceeds the bleed rate, desiccation occurs on the surface. This drying provides the force behind the shrinkage.[4,9,12,13] Good curing practices would do the most to solve the problem of plastic shrinkage cracking. Increasing the early-age strength and ductility of the concrete also would help, and this can be accomplished by the addition of polymer fibers as demonstrated later in this paper.

Early-age cracking prevention is of paramount importance for the health of the concrete. Once the early-age cracks are initiated, they remain through the life of the concrete as focal points for water and chloride ion penetration and as stress-concentration points. Although these cracks are typically small and shallow, their long-term impact on the concrete performance is large.[1,11]

Polymer fibers can greatly improve some of the very areas where concrete has the most problems–early-age issues and brittle behavior are the primary areas of concern. For polymer fibers to be effective, several properties are considered, such as; 1) tensile strength, 2) ductility, 3) elasticity, and 4) modulus of elasticity.[14] The tensile strength of polymer fibers, while below that of steel fibers, is significantly higher than that of plain concrete. The polymers used in fibers are quite ductile, and are elastic. However, it has lower modulus of elasticity than that of "hardened" concrete, indicating that polymer fibers in the concrete-fiber composite do not contribute much in resisting tensile loads during service.[14,15] At early age, the polymer fibers can contribute greatly to taking the tensile loads and thus preventing cracks, as the modulus of the concrete is very low (still below that of the fibers). In tests measuring crack width and time to cracking, the polymer fibers caused the concrete to develop cracks more slowly, and to develop several very small cracks rather than just one large crack.[5,6]

In the long term, however, it has been known that tensile strength is minimally impacted by the addition of polymer fibers,[3,5,7,15,16] but the failure type is greatly altered. Failures occur in a ductile mode rather than a brittle mode.[5,7] For instance, it was noted that in some cases the sample cracked, redistributed the load, and proceeded to take more loads.[8] Impact resistance is also greatly increased with the addition of polymer fibers.[16,17]

Cracking in concrete is a complex problem with many features. These may be categorized into two main areas; those internal and those external to the concrete. Internally, the mix design controls behavior. Externally, the environmental conditions (both natural and man-made) control behavior. These are dominated by curing procedures and the weather itself. Both of the internal and external effects have proven hard to control. Internally, modification of the basic mix design can provide some control over cracking; however, additional help in the form of polymer fibers can provide significant benefits in many areas of the cracking problem that is hard to control otherwise. In particular, the use of polymer fibers can be effective in improving early age and post-cracking behavior.

3. Objectives

The objectives of this research were to evaluate the early-age and long-term behavior of polymer fiber-reinforced concrete, focusing on early-age plastic shrinkage as the primary test. Several diverse types of polymer fibers were considered, at dosage rates ranging from normal to very high.

4. Test program

4.1 Base mix

The basic mix design used for this research project is shown in Table 1. This mix is the Oklahoma Department of Transportation (ODOT) type AA bridge deck mix with fly ash. When fibers were added, an equal volume of the fine aggregate was removed.

4.2 Matrix

The matrix of fiber dosage rates used for this research project was based to a large extent on the work done by Kao.[5] This work revealed that for polymer microfibers, a 3 kg/m^3 dosage is approximately the limit of usefulness, as the workability becomes unreasonable at higher levels. For macrofibers, however, dosages as high as 9 kg/m^3 were used to ensure that the full range of useful dosages was bracketed.

Four fibers were considered in this research; two microfibers and two macrofibers. These fibers are designated Micro-1, Micro-2, Macro-1, and Macro-2 in this paper. Table 2 presents the properties of the fibers as reported by the manufacturers. Both microfibers have similar characteristics (multifilament polypropylene). Micro-2 has over 110 million fibers per kilogram. The Macro-1 fibers are a ribbon-type macrofiber manufactured of a polypropylene/polyethylene blend with an aspect ratio of 90 and a length of 38 mm. The Macro-2 fiber is a stiff crimped fiber that is 51 mm long.

The two microfibers were tested at dosage rates of 0.6, 1.8, and 3 kg/m^3, and the two macrofibers were tested at dosages rates of 0.6, 1.8, 3, 6, and 9 kg/m^3. A plain concrete base mix was also tested to provide a baseline for the tests.

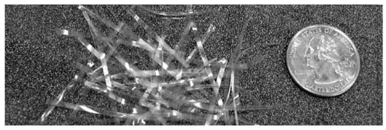
4.3 Tests

The test setup used in this research project was chosen to focus

Table 1 Base mix.

	Mix proportions
Total volume of mix	1 m^3
Cement (type I/II midlothian, TX)	312 kg
Fly ash (ash grove, KS)	78 kg
Coarse aggregate, #67 (limestone)	1,047 kg
Fine aggregate (dover sand)	823 kg
Water	159 kg
ADVA (HRWR)	153 cm^3

Table 2 Polymer fiber properties.

Fiber	Name	Brand	Shape	Length (mm)	Aspect ratio	Material	Modulus of elasticity (GPa)	View
Micro-1	Stealth	SI	Multi filament	6~20	-	PP	3.5	
Micro-2	Grace	Grace	Multi filament	20	-	PP	3.5	
Macro-1	Strux 90/40	Grace	Flat (ribbon)	40	90	PP/PE	9.5	
Macro-2	High performance polymer	SI	Crimped	50	-	PP	3.5	

on early-age properties of the concrete, particularly shrinkage and strength. Two shrinkage tests were conducted; the ASTM C-490 Unrestrained Shrinkage Test and a newer test, the Unrestrained Shrinkage From Time Zero Test (which is detailed in the following paragraph). As well, Standard ASTM compression strength and splitting tensile strength tests were carried out.

The unrestrained shrinkage from time zero test was first used by Ramseyer[7] and was refined by Kao.[5] A prism of concrete 76 × 76 × 254 mm was cast in a mold coated with heavy grease and a thin plastic sheet. One end of the prism was restrained, while the other end was attached to a Teflon plate. The plate slide within the mold. Its movement was measured with a micrometer. The results from this test closely matched those of the ASTM Unrestrained Shrinkage Test;[18] however, this test allowed measuring plastic shrinkage from the "batching" time. In this research project, readings were taken every hour for the first 6 hours (until final set) and then a normal pattern mirroring the reading times of the ASTM Unrestrained Shrinkage Test was adopted thereafter. For each batch, only one mold was used (due to budgetary constraints).

5. Test results and discussion

5.1 Fresh concrete properties

The addition of polymer fibers reduced the workability of the concrete. The type and magnitude of the reduction depended on the fiber and dosage level. Microfibers reduced the workability by drying out the mix due to their very high surface area to volume ratio. Finishing was not hindered by the microfibers. Macrofibers, on the other hand, made finishing difficult. They tended to stick out of the finished surface; however, they did not dry out the concrete mixture significantly.

The impact of the fibers on workability is clearly shown in Fig. 1. The two microfibers reduced the slump dramatically, approaching zero slump by the dosage rate of 3 kg/m^3. The macrofibers, on the other hand, did not reduce the slump as significantly as the microfibers did. It should be noted that a decreased slump in the concrete can be quite beneficial, as it greatly reduces plastic settlement issues. This improvement, however, must be balanced against placement issues, especially when pumping of concrete is considered necessary.

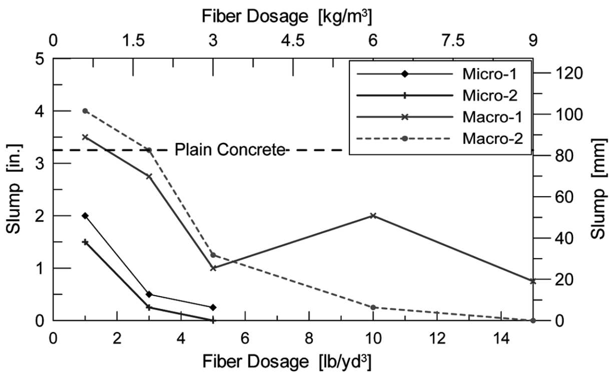


Fig. 1 Slump versus fiber dosage.

5.2 Unrestrained plastic shrinkage

Based on the unrestrained plastic shrinkage results, it was evident that fibers significantly reduced the plastic shrinkage. Increasing dosages typically reduced the plastic shrinkage. At very high dosages, some of the fibers yielded higher shrinkage results than lower dosages.

The Micro-1 (stealth microfiber) showed decreasing shrinkage with increasing dosages (Fig. 2). Interestingly, the 0.6 kg/m^3 dosage mix had higher plastic shrinkage than the plain concrete control mix. The reason for this behavior is unknown and warrants further investigation. The 3 kg/m^3 dosage mix showed a shrinkage reduction of over 50%, which would be a great benefit in preventing early-age cracking.

The Micro-2 (grace micro fber) showed less significant plastic shrinkage benefits than Micro-1 (Fig. 3). All three dosage rates tested showed moderate reduction in plastic shrinkage; however, there was minimal difference between the three batches.

The addition of Strux 90/40 macrofibers (Macro-1) greatly improved the plastic shrinkage behavior of the mix tested (Fig. 4).

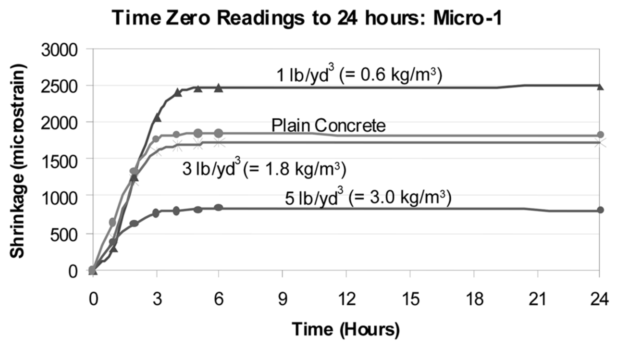


Fig. 2 Plastic shrinkage readings to 24 hours: stealth micro fiber.

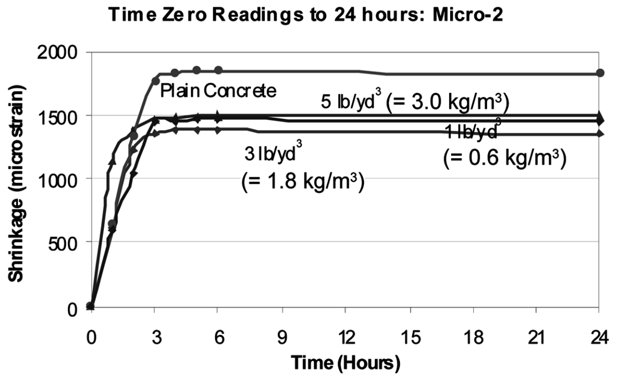


Fig. 3 Plastic shrinkage readings to 24 hours: grace micro fiber.

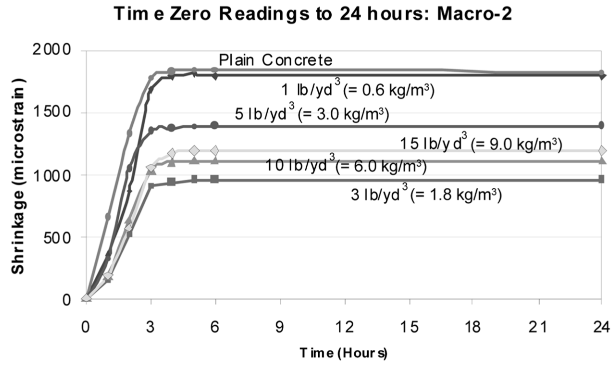


Fig. 5 Plastic shrinkage readings to 24 hours: HPP macro fiber.

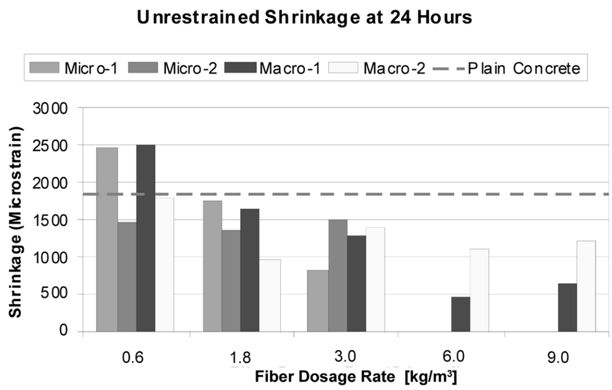


Fig. 6 Shrinkage at 24 hours: all fibers.

Increasing dosage rates of this fiber decreased the plastic shrinkage up to the 6 kg/m^3 dosage rate. At that rate the reduction in plastic shrinkage realized by the addition of fiber was about 75%. At the 9 kg/m^3 dosage rate, the plastic shrinkage increased somewhat, indicating that the 9 kg/m^3 mix is near the optimal dosage of this fiber for controlling plastic shrinkage.

The last fiber tested was the largest fiber, high performance polymer fiber (Macro-2). Fig. 5 shows the results of the unrestrained shrinkage from time zero tests. Again, significant benefits in the plastic shrinkage behavior were obtained by the addition of the high performance polymer (HPP) fibers. Most of the mixes showed a reduction in shrinkage of at least 25%.

Based on the results described in the preceding paragraphs, it is concluded that with high dosages of polymer fibers, a higher reduction in plastic shrinkage is obtained. This conclusion is also supported by Fig. 6 displaying a summary of the plastic shrinkage results of the unrestrained shrinkage from time zero tests. Although the trends for Micro-1 and Macro-2 are not as evident as those for Micro-2 and Macro-1, both microfibers and macrofibers appear to require higher dosages to realize the maximum benefits in terms of plastic shrinkage. It is also worth to note that the microfibers-3 kg/m^3 mix had essentially no slump and was difficult to work with (not good characteristics).

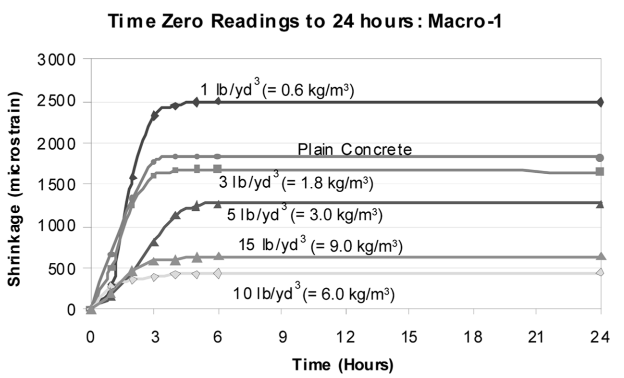


Fig. 4 Plastic shrinkage readings to 24 hours: strux 90/40 macro fiber

5.3 Unrestrained 28 day shrinkage

The tests have not shown any significant improvement in long term shrinkage behavior with the addition of polymer fibers. This was anticipated because the fibers have a lower modulus of elasticity than hardened concrete, and thus do not take loads once the concrete sets. This research project confirmed these results. Fig**.** 7 shows the ASTM Unrestrained Shrinkage Test results for all batches in the matrix. There were three prisms tested for each mix and all were zeroed at unmolding, 24 hours after batching. The bars in Fig. 7 show the data range found. Most batches showed a slight decrease in unrestrained shrinkage compared with plain concrete; however, these decreases were within the experimental scatter, and thus insignificant. One fiber, HPP (Macro-2), showed a moderate reduction with all of the different dosage rates. This reduction should be investigated further, but in general polymer fibers have little effect on 28-day shrinkage results (long-term).

5.4 Strength of polymer fiber-reinforced concrete

The final metric that should be considered in looking at the early-age behavior of the concrete is the strength of the concrete. Polymer fibers have not been shown to increase long term

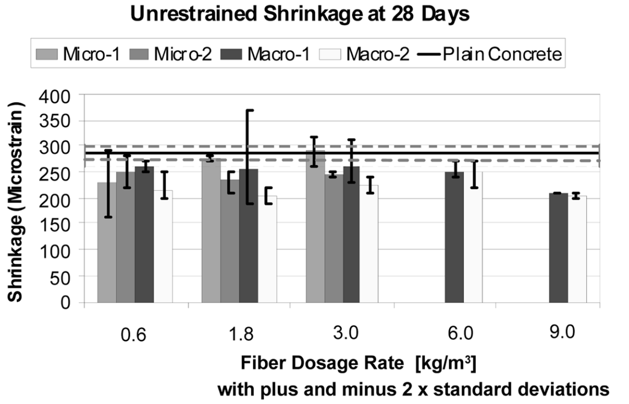


Fig. 7 ASTM unrestrained shrinkage at 28 days: all fibers.

strength, but there is some thought that they may increase early-age strength. This research corroborated this possibility.

First, the 24 hours strengths were evaluated. Fig. 8 shows the results for compressive strength, and Fig. 9 the results for splitting tensile strength. The bars on both figures show the data range at the testing time (3 cylinders were broken at a time). There was a significant increase in compression strength at 24 hours with the addition of polymer fiber. The best results appeared to come at medium doses of the fibers (1.8 to 3 kg/m^3). The splitting tensile test showed more erratic results, as is common with the test. No conclusive findings were seen with the addition of fibers, though it should be noted that for each fiber the best mix appeared to be near the middle of the tested dosage range.

The 28-day strengths of the fiber reinforced concrete mixes are shown in Figs. 10 and 11. The compression strength of polymer fiber-reinforced concrete did not appear to be decreased at 28 days. The microfibers performed better in the compression strength testing than did the macrofibers. Splitting tensile strength was once again subject to significant scatter, limiting the usefulness of the results. There did not appear to be any increase in splitting tensile strength at 28 days with the addition of polymer fibers.

6. Summary and conclusions

It is evident that polymer fibers had a distinct impact on the properties of concrete. At early age (before and shortly after the concrete sets), polymer fibers greatly improved concrete behavior, as: 1) slump was decreased (reducing movement of all types), 2) plastic shrinkage was greatly reduced, and 3) compression strength was increased. In the long term, the impact of polymer fibers was minimal, because strength and drying shrinkage were not materially altered by the addition of fibers. However, other research[5,7,17-19] has shown that post-cracking the fibers come into play again, reducing crack widths and improving ductility.

Since early-age cracking has developed into a huge problem in bridge decks, polymer fibers should be considered for use in common bridge deck applications. These polymer fibers, in an appropriate dosage rate (1.8 to 6 kg/m^3), will reduce many of the factors

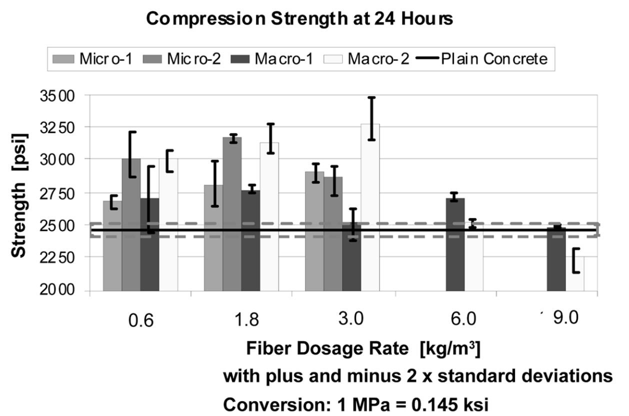


Fig. 8 Compression strength at 24 hours: all fibers.

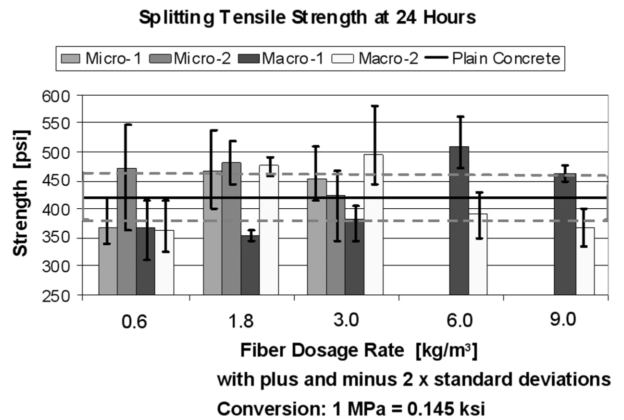


Fig. 9 Splitting tensile strength at 28 days: all fibers.

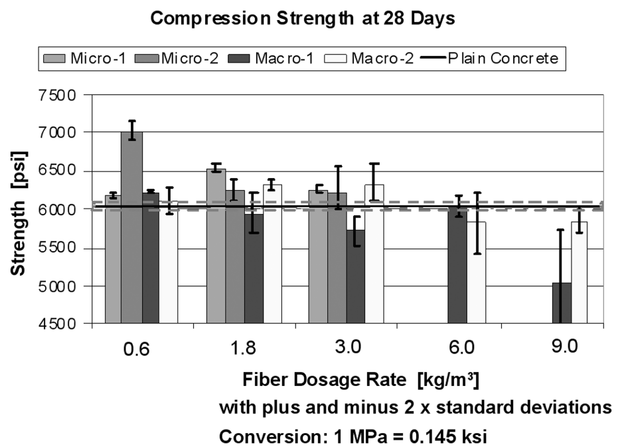


Fig. 10 Compression strength at 28 days: all fibers.

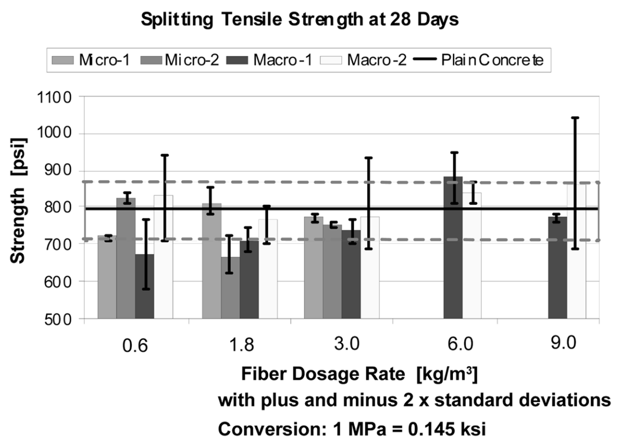


Fig. 11 Splitting tensile strength at 28 days: all fibers.

(such as plastic shrinkage and settlement) that drive the early cracking problem.

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