International Journal of Science and Research (IJSR)
ISSN (Online): 2319-7064
Index Copernicus Value (2015): 78.96 | Impact Factor (2015): 6.391

To Investigate the Early Age Shrinkage Cracking in Bridge Deck Slab Using FRC and PFRC

Aakash Bhardwaj[1], Ashwani[2], Nitin[3], Indrajeet Singh[4]

[1]Assistant Professor at Northern India Engineering College, New Delhi, India

[2, 3]Student at Royal Institute of Management and Technology, DCRUST University, Sonepat, India

[4]Student at Ganga Institute of Technology and Management, MDU University, Rohtak, India

Abstract: ***Bridge deck cracking is a huge problem in India, and various agencies have sponsored research endeavoring to determine the underlying problems. The shrinkage and cracking performance of concrete bridge decks at very early age must be minimized in order to provide durable concrete. The main objective of this research project is to develop shrinkage-compensated concrete which might be used to engineer concrete possessing excellent shrinkage behavior as well as precautions that should be taken during construction to minimize ambient effects. A number of causes have been identified, including thermal movement, plastic shrinkage, and early age settlement, as well as a number of other issues. Polymer fibers are a possible solution to many of the causes of bridge deck cracking: they have been shown to help early age properties like shrinkage and movement, and as a bonus, fibers improve post-cracking behavior. More understanding of the benefits and uses of polymer fibers in concrete is needed. 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. Macrofibers and microfibers were found to have different impacts on concrete behavior, with different optimal dosage rates. Microfibers greatly dried out the concrete mixture, hindering workability. However, the microfibers substantially reduced plastic shrinkage and improved concrete strength at early age. Macrofibers, while not hindering workability, did not provide benefits as great as the microfibers to the concrete strength.***

Keywords: Shrinkage, microfibers, polymer, early-age-cracks, polymer

1. Introduction

Almost as soon as water is added to the mix, a chemical reaction between water and cement called hydration is initiated, although its effects may not be apparent for the first few hours. The impact of this time-dependent reaction on the setting, stiffening, hardening and strength development of concrete is well documented, but the fact that shrinkage occurs in the first few hours of its life has not been adequately recognized. The presence of early-age cracking in concrete bridge decks increases the effects of freeze-thaw damage, spalling due to sulfate and chloride penetration, and corrosion of steel reinforcement, thus resulting in premature deterioration and structural deficiency of the bridges. These cracks in the bridge decks provide an avenue for water, deicing chemicals, sulfates, and other corrosive agents to penetrate into the concrete and substantially diminish the decks' service life. Concrete deck repair is expensive and can result in significant traffic delays. Accordingly, there is an urgent need to reduce the extent of this cracking and thereby prevent the premature deterioration. Although the concrete materials, concrete mix designs, design specifications and construction technologies have changed a lot over the years, shrinkage cracking still remains a significant problem and is prevalent in construction.

2. Literature Review

The shrinkage of concrete is needed to be controlled and optimize to a value which may not affect the structure much. The problems associated with the first three to seven days of the life of concrete bridge decks are critical to the long-term properties of the hardened concrete. Poor construction, conditions, casting and curing, and harsh environmental conditions may all combine to produce undesirable effects such as plastic, drying, thermal shrinkage and eventually cracking of a concrete bridge deck. Other detrimental effects may be poor quality concrete as delivered by ready mix plants, and tightly imposed scheduling. In India and abroad, transportation agencies and research institutions have dedicated resources and logistics to tackle the issues of early age shrinkage and cracking of concrete bridge decks. In order to examine the extent of the problem of early age shrinkage and cracking of concrete bridge decks, parameters that contribute to the problem need to be identified and described. These parameters include drying and plastic shrinkage, thermal and hydration effects, mineral and chemical admixtures, ambient weather conditions, and aggregate size and type. The description of these parameters consists of their definition, and current knowledge and research.

2.1 Drying Shrinkage

Drying shrinkage is primarily an issue related to the cement paste and depends strongly on the amount of water present in the concrete mixture before hardening (plastic state) and remaining after hardening (hardened state).

Raina relates drying shrinkage to strains associated with the moisture loss within the unloaded concrete. Factors affecting drying shrinkage are ambient relative humidity, temperature, wind velocity, and time of exposure. The physical significance of drying shrinkage translates to a reduction in volume of the concrete. In a dry and hot ambient environment, both the rate and amount of shrinkage are expected to be greater than under moderate climatic conditions. The net effect of drying shrinkage is a reduction of concrete compressive strength. Drying shrinkage is a long-term process that evolves over weeks, months, and even years.

Beyea ET al. reported laboratory experiments and results of concrete drying shrinkage intensity with varying W/C ratio (from 0.3 to 0.6) submitted to varying moist curing times (1, 7, 28, and 90 days). They concluded that high W/C ratio concrete exhibited large drying shrinkage regardless of the moist cure time applied, and that low W/C ratio concrete showed a dramatic increase in water tightness (or much lower drying shrinkage) as early as after 7 days of moist cure time.

2.2 Plastic Shrinkage

In contrast to drying shrinkage, which occurs within the cement paste, plastic shrinkage is associated with the evolution of shrinkage at the concrete surface. According to Nawy, plastic shrinkage occurs within the first few hours after placement of the fresh concrete while still in the forms. Concrete bridge decks are more prone to this type of shrinkage because of the relatively high concrete surface exposed to dry air. The moisture evaporation rate of the concrete becomes highly sensitive to the ambient conditions surrounding the concrete and affects the rate at which bleed water rises to compensate for the evaporated water present on the concrete surface.

2.3 Hydration Effects on Thermal Shrinkage

Springenschmid41 writes that temperature differences are frequent causes of cracking. The relative movement resulting from the cooling of structural members (after the peak heat generated by hydration of the cement) is a major factor affecting concrete bridge decks premature cracking. The main issue with thermal shrinkage cracking at an early age is that during the temperature rise phase, the concrete has very low modulus of elasticity because it is hardening. Restrained thermal contractions resulting from the cooling or other temperature changes constitute the main factors creating cracks at early age with structural members such as concrete bridge decks with thickness of 8 inches or more.

Thermal shrinkage is greatly affected by the ambient conditions existing at the time of placement of the concrete. A study performed by Hansen ET al. 51 reported that thermal stress development in concrete placed during high temperature (i.e. $T > 30^0$ C or 85^0 F) is significant during the first days after placement. A conclusion reached in the same study stated that thermal stress development is most severe when the peak reached in the heat of hydration coincides with the maximum ambient temperature.

2.4 Effect of Mineral Admixtures

Silica fume is a byproduct of the production of silicon metal and ferrosilicon alloys. Silica fume consists of amorphous silicon dioxide (SiO_2). It's extremely small size and the high content of SiO_2 cause the silica fume to be very reactive when used in concrete applications. Very high strength concrete and high resistance to chloride ion penetration can be obtained using silica fume. Though the addition of silica fume enhances some mechanical properties of concrete, recent applications of silica fume in concrete bridge decks and subsequent deck cracking have caused the engineering community to review the applications of silica fume in concrete for bridge decks.

Folliard and Berke and Folliard ET al showed that silica fume, when properly combined with either superplasticizers (HRWR), or shrinkage-reducing admixtures (SRA), or shrinkage compensating cement (SCC), reduced considerably the drying shrinkage and increased the chloride ion penetration resistance of concrete. They also showed that a proper combination of silica fume with SCC reduced the restrained expansion of concrete.

Fly ash reacts with water and the $Ca(OH)_2$ released from the hydration of Tricalcium Silicate (C_3S). The reaction produces Calcium Silicate hydrates, the primary binder of the cementitious agent in concrete. This chemical reaction ensures that $Ca(OH)_2$ crystals do not spread to form micro cracks, which in turns enhances the concrete resistance to chloride ion penetration.

2.5 Effect of Shrinkage Compensating Cement (SCC/SCA)

Krauss and Rogalla reported that shrinkage-compensating cement (SCC) and/or shrinkage compensating additive (SCA) was gaining popularity in the construction industry notwithstanding the workability issues surrounding the application of SCC/SCA concrete. SCC/SCA is different from regular Portland cement in that it stimulates a moist-sensitive volume expansion (caused by the formation of ettringite crystals) of the concrete during its critical hardening process immediately after setting of the cementitious paste. This expansive property alters the tensile and compressive stresses of the steel reinforcement and concrete respectively. While the alteration is taking place, drying shrinkage of the concrete is also causing stresses. The combined action of the expansive process and the drying shrinkage minimize shrinkage levels and the potential for cracking of concrete at very early age.

2.6 Fiber Admixture

When fiber is added to concrete, the property of concrete changes in relation with the amount of fiber added. Steel fiber can improve the strength of concrete. Shah and Weiss (2006) stated that the inclusion of randomly distributed steel fibers can slightly delay the age of visible cracking. Because fibers act as restraint inside the concrete, they can reduce the amount of cracking. The fibers only play a role when cracking is developed, and they are thus useful for post-cracking control.

2.7 Effect of Shrinkage Reducing Admixture (SRA)

Shrinkage-reducing admixtures (SRA) are not covered by any specifications in the available Standards. SRA was first developed in Japan. Berke ET al1 patented the product in the U.S. in 1996. Since its development, the construction industry has been anxiously engaged in applying this innovative admixture to concrete to reduce drying and thermal shrinkages. The SRA functions as a reducer of capillary tension that develops within the concrete pores as it dries. It can be applied in two ways. One is to simply spray it on top of the concrete surface, called the impregnation method or topical application. The second method is to integrate it in the mix during the mixing of concrete separately from any other admixtures. It has been found that the integration method provides much better results in reducing drying shrinkage.

3. Experimental Setup

The primary objective of this research was to evaluate the fibers' usefulness in controlling bridge-deck cracking. To study this, tests were selected that focused on the shrinkage behavior of the concrete. The primary tests included unrestrained shrinkage, compression strength, splitting tensile strength, and a new test (first used by Ramseyer, 1999, modified by Kao, 2005), unrestrained shrinkage from time zero. The fiber dosage rates were set at high levels, compared to those typically used for microfibers. It was hoped that the limits of the fibers' usefulness would be reached and the point at which the improvement of the mix diminished located for each fiber. The matrix used consisted of one, three and five pounds per cubic yard dosage rates, as those levels had given good results in previous research (Kao, 2005). The eight pound per cubic yard dosage was removed from the matrix, as the same research indicated that dosage was too high for microfiber mixes, as workability became a major issue, and shrinkage increased over the five pound dosage rate. For the macro fiber mixes, much higher dosage rates were possible without loss of workability, so ten and fifteen pounds per cubic yard dosages were tested as well, to evaluate the limits of the fiber usefulness.

3.1 Test

Each batch of the matrix had the same set of tests run on it. The fresh concrete tests performed were the slump test, air content test, temperature, and unit weight. The tests that were run included compressive strength, tensile strength, unrestrained shrinkage, and unrestrained shrinkage from time zero.

3.1.1 Fresh Concrete Tests

Several environmental conditions were measured at the time of batching, in addition to several fresh concrete tests being run. The air temperature and humidity were tested with a combined thermometer/hygrometer device. The concrete temperature was measured with a probe thermometer. The slump test was carried out according to ASTM C143, the slump cone apparatus in use.

3.1.2 Compressive Strength

The compressive strength of the concrete was obtained. Generally, twenty-five cylinders of concrete were cast in 4x8" plastic cylinder molds. These were greased with diesel prior to batching to facilitate the samples' removal. The molds were removed at about one day after batching, and the first samples broken. Three cylinders were broken at each testing time, unless there were not enough samples or one of the samples failed as a result of an obvious defect, in which case the result was thrown out. The cylinders were tested in a Forney compression testing machine; neoprene caps set in metal plates were used to provide an even loading surface. The load was applied at a rate between 16,000 and 38,000 pounds per minute. These tests were run at 1, 7, 14, and 28 days.

3.1.3 Split Tensile Strength

Tensile strength of the concrete was found using the splitting tensile test. Half of the cylinders batched were used for this test, three at each testing time. These tests were also run at 7, 14, and 28 days. The machine was again used, but the loading apparatus was changed. One inch wide strips of a thin fiberboard material were cut to provide a yielding bearing surface for the cylinders. One of these strips was placed on a steel plate on the bottom loading platen, and taped down to prevent movement. The cylinder was then laid down on the strip. Another plate with a strip of the wood was placed on top of the cylinder, with the strip resting along the cylinder and the steel plate spreading the load from the upper loading platen to the strip and cylinder. The load was applied at a rate between 5,000 and 10,000 pounds per minute until the cylinder split in half.

3.2 Shrinkage Test

3.2.1 Unrestrained Shrinkage

This shrinkage test was performed. Molds 3"x3"x10" were prepared by coating them lightly with diesel, and set screws were placed in the ends. Concrete was cast in the molds, and allowed to cure for twenty-four hours. The molds were then removed, leaving concrete prisms with studs at each end, 10" apart. These were measured at 1, 3, 7, 14, and 28 days. The one day reading was considered the zero value, and the shrinkage of the prisms compared from there. The system is accurate down to $10x10^{-6}$ strain; it measures to 10^{-5} inches on a 10 inch prism.

3.2.2 Unrestrained Shrinkage from Time Zero

This test does not have an applicable ASTM standard, as it was developed at Fears Lab, with the initial design found in Chris Ramseyer's master's thesis (Ramseyer, 1999). Additional modifications were made by Jen Teck Kao (Kao, 2005). Further adjustments were made to the design for this project.

The apparatus tests a prism of concrete 3x3x10 inches, to permit direct comparison with results from the standard unrestrained shrinkage test. The concrete is restrained on one end by being cast around a bolt head, but is free to move on the other end. That end is cast around another bolt, but this bolt is anchored in an unrestrained sliding Teflon plate. The movement of this plate is then measured by a micrometer. See Appendix 1 for a full design of the device. Figure 20 shows the unrestrained shrinkage from time zero tests in progress, after the side molds have been removed at 1 day.

3.3 Fibers

The four types of fiber used in the primary matrix were Strux 90/40, Stealth, Grace Microfiber, and HPP. Each of these had distinct properties; the Strux and HPP were macrofibers, and tended to impede the finishing process. However, due to their fairly low surface area per pound, they did not significantly dry out the mix. The microfibers, Grace and Stealth, were much easier to finish, but did decrease the free moisture in the mix significantly. All of the fibers used are synthetic polymers either polypropylene, polyethylene or a blend. Therefore, the fibers all have a modulus of elasticity below that of cured concrete, limiting the fibers' effect to before final set and after cracking. However, these are the two most problematic areas in concrete: shrinkage cracking and associated problems, and lack of ductility after cracking.

3.3.1 Stealth

Fiber mesh Stealth is manufactured by SI Concrete Systems; it has since been replaced by Stealth which was renamed Fibermesh. Stealth is a microfiber; the fibers range from 0.25" to .75", but are very small diameter. They are made out of polypropylene, with a modulus of elasticity of $5x10^5$ psi. The recommended minimum dosage is 0.75 lb/yd; no upper limit is recommended by the manufacturer. The mixes tested have dosages significantly above this level.

3.3.2 Grace Microfiber

Grace Microfiber is a product of Grace Construction Products. As the name implies, the fiber is very small; there are over 50 million fibers per pound. The fibers are 20mm long and created of polypropylene, with a modulus of elasticity of 5x105 psi. Grace recommends a dose between 0.5 and 1 pound per cubic yard. Again, this fiber was tested at dosages well beyond this level. This fiber was specifically created to prevent cracking within the first 24 hours.

3.3.3 Strux

Stux is a coarse fiber produced by Grace Construction Products. It is primarily intended to provide crack control. The fibers are created of a synthetic polypropylene/ polyethylene blend. The fibers themselves are about 1.5 inches long, have an aspect ratio of 90, and a modulus of elasticity of $1.378x10^6$ psi, according to the manufacturer. Grace recommends a dosage between 3.0 and 11.8 lbs/yd3, so the dosage rates used in this research fully bracket that range.

4. Results

There were four fibers in the testing matrix, with several dosage levels for each. These were selected based on the results of the preliminary matrix and of Jen Teck Kao's research (Kao, 2005), of which this was an extension. Manufacturer recommendations were also taken into account. The microfiber dosages selected were one, three, and five pounds per cubic yard. These were chosen based upon Kao's research, which indicated that higher dosage levels were not useful for microfibers. However, higher macrofiber dosages were included in the matrix, ten and fifteen pounds per cubic yard. These higher dosage rates were selected based upon the manufacturer recommendations, and upon the impact that the macrofibers had upon the concrete macrofibers do not dry the mix out like microfibers, so higher dosage rates are possible. Several tests were conducted on each batch: compression, splitting tensile, unrestrained length change, and length change from time zero.

4.1 Compression Tests

The compression strength of concrete with and without fibers is very similar; however, the ductility of the failure is vastly increased with fibers. Instead of shattering at failure, at the higher fiber contents, the cylinders simply crack, and refuse to take more load. They do not fail entirely. See figures 29 and 30 for a comparison of plain concrete and fiber-reinforced concrete failures.

Table 4.1: Compression Test Results

Batch		Compressive Strength(psi)	
Fiber	Dosage lb/yd^3	7-days	28-days
Stealth	3	5890	6490
Grace microfiber	3	5790	6202
Strux	3	5402	6100
HPP	5	5880	6350
Plain Concrete	-	5210	6080

4.2 Splitting Tensile Tests

The primary matrix also was tested with the splitting tensile test to obtain the indirect tensile strength of the concrete. The cylinders were tested at 1, 7, 14, and 28 days, with three cylinders being broken at each testing time. On several occasions, less than three cylinders were broken; these are noted in the table below (Table 12). This test seems more likely to produce scatter than the compression tests; and in a few instances, the strengths showed behavior that is likely inaccurate, such as the strengths peaking at 7 days for the Grace Microfiber 5 lb mix. Such peculiarities are likely simply a product of the uncertainty inherent in testing a small sample. One behavior of the fiber mixes should be noted: quite often, the cylinders would continue to take load after they had split, as the fibers bridged the gap. This ductility was also shown in their post failure behavior—the fibers continued to hold the samples together even after splitting.

Table 4.2: Split Tensile Strength Test Results

Batch		Split Tensile Strength(psi)	
Fiber	Dosage lb/yd^3	7-days	28-days
Stealth	3	586	821
Grace microfiber	3	612	679
Strux	3	640	730
HPP	5	652	780
Plain Concrete	-	395	742

4.3 Unrestrained Shrinkage

Shrinkage evaluation is the primary objective of this research. Unrestrained shrinkage is the standard way of measuring this, though it starts at 24 hours, well after final set. The samples tested were removed from their molds and zeroed at 24 hours. There were three samples for each batch;

they were read at 1, 3, 7, 14, and 28 days. Some of the tests were read at 75 days as well.

There is plain concrete have the same mix proportions. It is noted, however, that the long term trends of both are similar, and that the fiber-reinforced mixes tend to have a trend toward less shrinkage at greater ages.

Table 4.3: Unrestrained Shrinkage Test Results (normalized at time 24 hrs.)

Batch		Shrinkage(microstrain)	
Fiber	Dosage lb/yd^3	7-days	28-days
Stealth	3	137	280
Grace microfiber	3	123	229
Strux	3	230	261
HPP	5	103	227
Plain Concrete	-	30	161

4.4 Unrestrained Shrinkage from Time Zero

The unrestrained shrinkage from time zero test is an innovative test used to obtain free shrinkage from the batching time. One test was run on each batch, so the potential for scatter was not accounted for. However, since the values for the free shrinkage vary so widely with different mixes, the scatter does not affect the usefulness of the data in comparing the mixes. The shrinkage gauge was read at the initial casting time, 1, 2, 3, 4, 5 and 6 hours after batching, and 1 day, 3 days, and 7 days after casting. On some of the batches the readings were continued out to 14 and 28 days. Table 14 gives the shrinkage values at 6 hours, 24 hours, and 7 days as found by this test.

Table 4.4: Unrestrained Shrinkage Test Results (normalized at time zero)

Batch		Shrinkage (microstrain)		
Fiber	Dosage lb/yd^3	6 hours	24 hours	7-days
Stealth	3	1710	1720	1910
Grace Microfiber	3	1390	1340	1560
Strux	3	1690	1640	1650
HPP	5	1380	1460	1510
Plain Concrete	-	30	161	

The shrinkage from time zero test gives insight into a period of concrete shrinkage that is rarely investigated. Since the ASTM unrestrained shrinkage test is usually normalized at 1 day, the early age shrinkage is missed. The data above shows that a very large portion of the free shrinkage of concrete is ignored with that test. In fact, most of the concrete's free shrinkage occurs before 6 hours. From 6 to 24 hours the concrete often actually expands, and then proceeds after 24 hours on the familiar shrinkage curves found by the unrestrained shrinkage test.

5. Discussion

This study is focused on the behavior of the four types of polymer fibers, particularly their impact on shrinkage. However, a full range of aspects of the fiber-reinforced concrete was investigated to see whether the fibers impacted them. Workability, a concern with fiber-reinforced concrete, was considered in detail. Shrinkage, both plastic and long term, was investigated in depth, and compression and tensile strength were also considered. The objectives were two-fold: to characterize the mixes and to determine which dosage rates of what fibers were best. To do this, appropriate plain concrete mixes were batched as controls. Each fiber was analyzed separately to determine its optimum dosage rates, and to see its strengths and weaknesses. Finally, a discussion of the differences between macro and micro fibers is presented.

5.1 Workability

There is a strong correlation between fiber dosage and slump; workability is strongly affected by the fibers. Two of the fibers were macrofibers, the Strux and the HPP. Those fibers did not dry up the mix nearly as much as the microfibers. They did, however, affect the finishing more. Nevertheless, due to their lower surface area per weight, the macrofibers were easier to consolidate, and there was not as noticeable a difference between the low and high dosage rates.

5.2 Compressive Strength

It has long been debated whether fibers modify the compression strength. It seems that most researchers feel the impact is slight, though there may be some effect at early age, before the concrete attains much strength. The main reason polymer fibers would not do much to compression strength is their low modulus of elasticity they don't carry much load until the concrete cracks. What they add, then, is ductility upon failure. This was noted in the testing of the cylinders in compression after failure the cylinders did not disintegrate, but rather held together. Ductility and potentially early age strength are the beneficial impacts of fibers on the compression strength of concrete. Nearly all of the fiber dosage rates had an increase in strength that was statistically significant; some increased by as much as 750 psi. This test is very significant, and therefore will be used in determining the optimum dosage of each fiber.

5.3 Splitting Tensile Strength

The final test of importance in characterizing the mixes is the splitting tensile test. It has long been debated whether polymer fibers increase splitting tensile strength. The tensile strengths usually approximately mirror the compression test results, but in this research they often did not. In fact, most fibers decreased the strength with a 1 lb dosage rate. All of the fibers exhibit some sort of curve with increasing dosage rates. Again, the microfibers did not decrease strength nearly as much as the macrofibers at most dosage rates. The best dosage rates for each fiber are fairly easy to spot in this test, as the curves are all formed without any apparent outliers. A major issue with the splitting tensile test is the wide scatter commonly found. Because of this, very few batches ever showed statistically significant differences from the plain concrete control mix. It appears that using three samples is not enough to obtain solid results for the tensile strength. Nevertheless, trends are evident here, and will be considered in identifying the optimum dosage rate, though the statistical analysis indicates that the confidence in such findings is lower than might be hoped

5.4 Shrinkage

Shrinkage was the principle topic of interest in this study, as it relates most directly to the bridge deck cracking problem. The two tests used measure strictly unrestrained shrinkage, so the concrete's response to restraint is not evaluated. Nevertheless, the unrestrained shrinkage data obtained gives strong indications of how adding fibers to bridge deck concrete will impact the cracking problem. There are several topics within the shrinkage area that will be considered. First, the unrestrained shrinkage from time zero test itself will be discussed, including how consistent, how useful, and how accurate the test is. Next, an evaluation of the long and short term shrinkage, and how they relate, will be undertaken.

5.4.1 The Unrestrained Shrinkage from Time Zero Test

The unrestrained shrinkage from time zero test is a new test. It was first used, in a much different form, by Ramseyer (1999). Subsequently, the test was greatly modified by Kao (2005). The test was further refined for this project; the present design was discussed in the research scope section. Here, one sample was used for each batch, primarily due to the difficulty in setting up the test and to limited quantities available. The repeatability of the test has not been strongly tested. On one batch, there were two samples cast, one using the latest mold design, and one using Kao's design.

Primarily, the shrinkage is caused by evaporation, causing the free water surface to drop inside the concrete. The menisci of the surface exert a suction of sorts on the particles surrounding them, causing shrinkage. Because of this mechanism, the plastic shrinkage is very sensitive to the curing conditions, particularly wind, humidity, and temperature. This makes comparison of mixes not cured in identical conditions almost impossible. All of the batches in this research project were cured in an environmental chamber at 72° F and 50% humidity. The environmental chamber where the samples were cured is rather breezy from the air conditioner, dehumidifier, and other equipment. This probably contributed to the large magnitude of the plastic shrinkage readings. It does not, however, hinder comparison between mixes cured in identical conditions as these were.

5.4.2 Shrinkage from Time Zero

Shrinkage from time zero, as just discussed, provides a good insight into the plastic shrinkage behavior of the fiber-reinforced concrete batches tested here. First, the two microfibers will be discussed, with their behavior at early age, and then the two macrofibers.

The Stealth microfiber is a very small and fine fiber, hardly visible in the concrete. It provides a drying impact on the mix, as well as a mechanical internal restraint. The fibers, particularly at the higher dosage rates, are ubiquitous through the mix every portion of the mixture is held to every other by many tiny fibers. This holding together of the mix accounts for the dramatic reduction of plastic shrinkage seen in these fibers at high dosage rates. It is unknown why the Stealth 1 lb dosage showed an increased plastic shrinkage. It appears that a dosage rate of at least 3 lb per cubic yard is needed to realize significant reductions in plastic shrinkage with this fiber. The 5 lb per cubic yard mix yielded one the lowest shrinkage from time zero results of any mix tested in this research. Unfortunately, the mix was also very dry and hard to work with due to the high water demand of the microfibers. The Stealth fibers, due to their huge number, form a web through the mix, and at the high dosage levels, nearly a mat, making consolidation very difficult. It is clear that plastic shrinkage can be reduced substantially with high dosage rates of the Stealth fiber, but other factors must be considered in determining an optimum dosage rate; that will be the subject of a later section.

Grace microfiber is similar to the Stealth fiber, though manufactured by a different company. Both are very fine and small. It would be expected that the early age shrinkage results would be very similar for the Grace fibers. One thing may have caused the odd results: the 1 and 5 lb dosage rate mixes were tested with old time zero molds. This may have somewhat decreased the apparent shrinkage for those mixes. With this accounted for, it appears that the Grace Microfiber 3 lb per cubic yard dosage rate was the best at reducing plastic shrinkage. A further analysis of what dosage rate is best for this fiber is undertaken later.

The Strux 90/40 fiber is the smaller of the two macrofibers tested. The 1, 3, and 5 lb mixes behaved similarly to the Stealth fibers: 1 lb per cubic yard dosage significantly increased the plastic shrinkage, while the 3 lb dosage rate was similar to the plain concrete control mix. The increase in plastic shrinkage at 1 lb dosage may be because the flat fibers act as slip planes in the matrix; whatever the reason, this phenomenon disappeared at higher dosage rates. At the higher dosage rates, the results got considerably better; the 10 lb dosage rate yielded the lowest time zero shrinkage result of any mix in this research. It is interesting to note that the 15 lb dosage rate had a higher plastic shrinkage than the 10 lb; it is likely that the 10 lb dosage is close to the optimum dosage for reducing plastic shrinkage with this fiber. Since these are macrofibers, they did not significantly dry the mix out, so very high dosages, like those undertaken here, were quite feasible.

The high performance polymer fiber was by far the largest and stiffest fiber tested. Low dosage rates of this fiber did not impact the behavior of the concrete very much, as there were simply too few fibers to do much. Like Strux, HPP reached a point where the addition of more fibers increased plastic shrinkage, rather than reducing it. It is uncertain, however, what dosage is the optimum, as there was no consistent trend. The HPP 3 lb mix readings may be an anomaly, but there was no other indication of odd behavior with that mix. Further analysis of the HPP fibers, and a determination of the optimum dosage for this mix, will be undertaken later on.

5.4.3 Unrestrained Shrinkage

The ASTM unrestrained shrinkage test is the industry standard test for determining shrinkage. It is normalized at 24 hours, so the plastic phase of the shrinkage has already been completed, and the shrinkage measured is drying and autogenous. The results of this test are important in evaluating long term shrinkage problems, but not early age cracking. However, the scatter in the results must be considered. At the highest dosages, there seems to be perhaps a 20% reduction in long term shrinkage, but at most dosage levels the difference is negligible. Apparently, the fibers, with their low modulus of elasticity, do not do much to the shrinkage once the concrete's modulus of elasticity is significantly higher than the fibers'. Since this test only considers shrinkage after the concrete has hardened, the fibers probably should not impact the results much.

5.5 General Survey of Fibers

When looking at the overall results, there are certain trends that are obvious: for example, the plastic shrinkage is greatly reduced by moderate to high dosages of fibers. Also, it is obvious that there is an optimum dosage point above which additional fiber is detrimental rather than beneficial. Long term shrinkage, compression strength, and splitting tensile strength, on the other hand, do not exhibit such obvious trends.

6. Conclusion

Bridge decks have problems with cracking. Concrete must be engineered to develop characteristics that provide sufficient protection against shrinkage and aggressive agents. Any micro and/or macro cracks network that will develop because of failure to produce high performance concrete will weaken the concrete and provide a path for steel corrosion, eventually leading to structural weakening. These problems are caused to a large extent by thermal movement, early-age shrinkage, and early age settlement. All three of these issues may be counteracted by the addition of polymer fibers. Polymer fibers also assist in reducing crack widths after cracking. Macrofibers and microfibers behave differently, and should be treated differently. Microfibers affect workability by drying the mix out; macrofibers by making finishing difficult. Low to moderate dosages of fibers improve early age compression strength significantly, but 28 day compression strengths are not influenced much. The addition of fibers slightly increases 24 hour splitting tensile strengths; 28 day effects are insignificant. Fibers slightly decrease ASTM unrestrained shrinkage results, measured from 24 hours to 28 days. Fibers drastically reduce early age shrinkage, depending on the dosage level; higher is better, up to a certain point that is different for each fiber.

Fibers dramatically change failure types; all failures were more ductile. The optimum dosage rate for Stealth fiber seemed was approximately 3 lb per cubic yard; the benefits were moderate. Grace Microfiber's optimum dosage rate was 3 lb per cubic yard, and the benefits seen were significant. The best dosage rate for Strux 90/40 was about 10 lb per cubic yard, and that dosage showed exceptionally good plastic shrinkage benefits, greater than any other mix in this research. Finally, the HPP fiber had its optimum dosage rate at either 5 lb per cubic yard, and had the best strength results in this study. The unrestrained shrinkage from time zero test performed excellently. This test allowed good quantitative measurements to be made of plastic shrinkage starting at the batch time. The results correlated well with the ASTM unrestrained shrinkage test.

References

[1] Raina, V.K. Concrete Bridges, McGraw-Hill. New York, 1996

[2] Beyea, S. D., Balcom, B. J., Bremner, T. W., Prado, P. J., Green, D. P., Armstrong, R. L. and Grattan-Bellew, P. E. (1998) "Magnetic Resonance Imaging and Moisture Content Profiles of Drying Concrete." Cem. Conc. Res. **28** (10) 453-463.

[3] Folliard, K. J., and Berke, N. S. (1997) "Properties of High-Performance Concrete Containing Shrinkage-Reducing Admixture." Cem. Conc. Res., **27** 1357-1364.

[4] Weiss, W.J., and Shah, S. P. (2002) "Restrained Shrinkage Cracking: The Role of Shrinkage Reducing Admixtures and Specimen Geometry" *Materials and Structures*, March, VOL. 35 - NO 246, pp. 85-91

[5] ASTM International. (2005). *Annual Book of ASTM Standards.* ASTM International, West Conshohocken, PA.

[6] Krauss, P. D., and Rogalla, E. A. (1996). "Transverse Cracking in Newly Constructed Bridge Decks." National Cooperative Highway Research Program (NCHRP) Report 380, Transportation Research Board, 1996. Washington, D.C.

[7] Ramseyer, C. (1999). *Investigation of Very Early Strength Concrete with Low Shrinkage Properties.* University of Oklahoma Press, Norman, Oklahoma

[8] Kao, J. T. (2005). *Investigation into the Use of Portland Cement Concrete with Fiber Additives for Bridge Decks in the State of Oklahoma*. University of Oklahoma Press, Norman, Oklahoma.

Author Profile

Mr. Aakash Bhardwaj received the B.Tech. and M.Tech. degrees in Civil Engineering from MDU Rohtak in 2011 and 2014, respectively. He is now with NIEC Delhi as Asst. Professor in the Dept. of Civil Engineering. His are of interest is structural analysis and design.

Mr. Ashwani received the B.Tech. degree in Civil Engineering from MDU Rohtak in 2014. He is now pursuing M.Tech. in Structural Engineering from Rayat Bahra Campus Panipat, affiliated to DCRUST Murthal. His area of interest is structural analysis and design with sustainable development.

Mr. Nitin received the B.Tech. degree in Civil Engineering from MDU Rohtak in 2014. He is now pursuing M.Tech. in Structural Engineering from Rayat Bahra Campus Panipat, affiliated to DCRUST Murthal. His area of interest is structural analysis and green concrete.

Mr. Indrajeet Singh received the B.Tech. degree in Civil Engineering from IPEC Ghaziabad affiliated to GBTU. He is now pursuing M.Tech. in Structural Design from GITAM, affiliated to MDU Rohtak. His area of interest is structural analysis and design.