CAIT-UTC-NC14

Development of Concrete Mix Proportions for Minimizing/Eliminating Shrinkage Cracks in Slabs and High Performance Grouts

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16. Abstract
The two focus areas of this research address longstanding problems of (1) cracking of concrete slabs due to creep and shrinkage and (2) high performance compositions for grouting and joining precast concrete structural elements.

Cracking of bridge decks is a very common problem with no solutions other than pre-stressing. This is also a problem in other areas such as pavements in airports, seaports and highways. Reduction and possible elimination of cracking will improve the performance and increase the life span of these structures considerably.

The second part is to develop user friendly grouts that can be used for precast construction including filling of shear-connector pockets and joining precast slabs. Current non-shrinking grouts use expansive cements that are effective only if the expansion can be completely prevented. The aim is to develop a formulation that will be dimensionally stable with no need for induced expansion.

The best solution is to obtain concrete that has zero shrinkage but this is practically impossible. The next best solution is to restrict the shrinkage strains to the tensile strain capacity of concrete which range from 200 to 300 micro strains. If this can be achieved, the restrained shrinkage cracking problem can be solved resulting in durable structures that can last for centuries. An investigation was initiated to achieve this goal.

The results presented in this report provide information on potential formulations that could provide shrinkage strains less than 300 micro strains, higher tensile strain capacity and rapid set formulations for assembling precast slabs and shear connectors, which can be field-usable.

17. Key Words
Permeability, shrinkage, Portland cement, Phosphate cement, Sulfate cement, patching, repair, deck, bridge

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Introduction and Description of the Problem

Concrete shrinkage is an age old problem, identified as early as 1897 by J.B. Johnson in his *Treatise for Engineers on the Strength of Engineering Materials* in 1897. Other early publications on this subject include the papers published in American Concrete Institute Journals by Abrams, Davis and White. Shrinkage continues to be a problem that needs to be addressed by creating new materials, methods and type of fabrication to reduce the shrinkage strains. For example, low-shrinkage mixtures are needed to:

- Minimize cracking in bridge decks, with the ultimate goal of boosting service life
- Minimize curling and thereby help meet the increasing demand for very flat and level industrial floors
- Prevent delamination of repairs, and
- Cracking of slabs

Shrinkage of concrete contributes to loss of prestress, redistribution of stresses between steel and concrete in reinforced concrete, increase in deflections and relaxation of fixity over continuous supports. Shrinkage strains for typical concrete mixtures range from 800 to 1200 micro strains.

A second are of interest is the use of grout mixes for closure pours and in Accelerated Bridge Construction (ABC). Accelerated Bridge Construction (ABC) is a high priority area for US DOT and therefore the results of this research have high potential for early adoption in the real world. Concrete with high potential for crack free slabs and construction practices that eliminate potential deterioration locations are of primary importance.

Thus, the two focus areas of this research address longstanding problems of (1) cracking of concrete slabs due to creep and shrinkage and (2) high performance compositions for grouting and joining precast concrete structural elements.

Cracking of bridge decks is a very common problem with limited solutions. Cracking is also a problem in other areas such as pavements in airports, seaports and highways. Reduction and possible elimination of cracking will improve the performance and increase the life span of these structures considerably.

The second part is to develop user friendly grouts that can be used for precast construction including filling of shear-connector pockets and joining precast slabs. Current non-shrinking grouts use expansive cements that are effective only if the expansion can be completely prevented. The aim is to develop a formulation that will be dimensionally stable with no need for induced expansion.

The best solution is to obtain concrete that has zero shrinkage but this is practically impossible. The next best solution is to restrict the shrinkage strains to the tensile strain capacity of concrete which range from 200 to 300 micro strains. If this can be achieved, the restrained shrinkage cracking problem can be solved resulting in durable structures that can last for centuries. An investigation was initiated to achieve this goal.

The results presented in this report provide information on potential formulations that could provide shrinkage strains less than 300 micro strains, higher tensile strain capacity and rapid set formulations for assembling precast slabs and shear connectors, which can be field-usable.

How to read this report

State of the art on shrinkage of concrete is presented in “Literature Review.” Based on the information available in the literature it was decided to focus on non-Portland cement formulations and modified Portland cements. The focus was to develop formulations for repair and rehabilitation. Magnesium phosphate cements are known to provide shrinkage free concrete and therefore the mechanical properties of various formulations were evaluated. The results of this work are presented in “Details of the Experimental Investigation.”

Results of the evaluation of modified Portland cement and sulfate cement are presented in “Sulfate and Modified Portland Cements.” These formulations, with shrinkage strains in the range of 300 to 400 micro strains, have excellent potential for practical use. In addition to low shrinkage strains, the shrinkage stabilizes in about 3 months.

Conclusions and recommendations for field use are presented in the end.

Approach

The primary objectives are two develop two formulations, one suitable for casting slabs with least amount of creep and shrinkage and eliminate cracking due to restrained time-dependent strains and the second for specialized uses in grouting and gluing for precast construction. The first part of the research incorporated common constituent materials currently used in concrete including optimized mineral and chemical admixtures to formulate the mix. Standard protocols were used for mixing, placing and finishing of concrete.

The second part of the research focused on the development of high performance and fast-setting compositions, dimensionally stable and have high strength, stiffness and toughness. The mix also incorporates fiber reinforcement within the formulation with Portland cement and other cementing agents.

The research focused on the following:

- Reducing the shrinkage strains to the level of 300 micro strains or less
- Increasing the strain capacity of concrete to 300 micro strains or more
- Optimally combining the discrete and continuous reinforcement to keep the crack widths less than 50 micrometer if the cracks do occur.

Recent development in the area of mineral admixtures, chemical admixtures, and fiber reinforcement have provided avenues to achieve this goal. Use of fly ash and admixtures that accelerate hardening resulted in shrinkage strains in the order of 250 micro strains. Short polymeric fibers were effectively used to increase the tensile strain capacity of concrete up to 400 micro strains. Similarly, this research project incorporated these state of the art techniques to develop field usable, economical, and constructible reinforced concrete structural elements for use in flexure.

Methodology

The following tasks are undertaken in the first group:

(i) Review of literature and preparation of a synthesis that will identify potential formulations that will provide minimum shrinkage and maximum tensile strain capacity,
(ii) Development of trial mixes that provide good workability, needed air content, and compressive strength,
(iii) Preparation of samples test setup for evaluation of shrinkage and strain capacity,
(iv) Testing of samples,
(v) Analysis of test results and formulation of 2 mixes for field use, and
(vi) Preparation of guidelines for field use of the developed mix proportions.

The following tasks are undertaken in the second group:

(i) Review of literature for obtaining rapid set, non-shrinking and tough compositions for use in shear connectors and polymers for connecting the slabs,
(ii) Evaluation of the mixes using simulated shear connectors and assembling of slabs, and
(iii) Development of guidelines for use in the field. A comprehensive report will be prepared detailing the information obtained in all the aforementioned tasks and suggestions for field implementations.

Literature Review

In 1930, Davis presented a summary of investigations, dating from the nineteenth century, on moisture and thermal volume changes in concrete. The following 5 of the 11 factors identified by him are most pertinent to modern-day concrete practice.

- Composition and fineness of cement
- Proportions of cement and aggregate
- Type and gradation of aggregate
- Consistency of the mixture (well before today's admixtures, this was a measure of water content); and
- Amount and distribution of reinforcement.

Recent investigations have provided detailed evaluations of parameters such as water and paste contents, characteristics of the aggregates, and admixtures.

Phosphate Cement Introduction

Magnesium phosphate concrete, a type of rapid- hardening concrete, is composed of magnesium phosphate cement (MPC), instead of common Portland cement, as well as other cementitious materials such as fly ash, aggregate (generally a coarse aggregate such as gravel limestone or granite, plus a fine aggregate such as sand), water, and chemical admixtures. The density of magnesium phosphate concrete is generally less than the density of normal concrete, 2,400 kg/m^3 (150 lb/ft^3). Magnesium phosphate concrete has two specific characteristics that are suitable for rapid repairs encountered in transportation infrastructures. First, the concrete sets rapidly and can achieve the required strengths in less than 2 hours. In addition, Magnesium Phosphate concretes are known to provide very little shrinkage.

A number of investigators have evaluated the shrinkage characteristics of Magnesium phosphate concrete and the conclusion is that these concretes undergo limited shrinkage strains. For example, Yang, Zhu and Xu reported that Magnesium Phosphate mortar had a shrinkage strain of 34 micro strains whereas Portland cement mortar had shrinkage strain of 3000 to 5000 micro strain (Yang, Zhu and Xu 2000). Yue and Bing reported a similar shrinkage strain of 35 micro strain (Yue and Bing 2002). Key characteristics of these cements are rapid strength gain, excellent bonding to Portland cement substrates and low shrinkage. The mechanical properties of concrete made with these classes of cements are comparable to that of concrete made with Portland cements. Since the low shrinkage of these cements is well established, the results reported in this report focus on Strength aspects. Since in most rehabilitation applications the repair material is subjected tensile stresses, the focus of the current investigation was to evaluate tensile strength. Since flexural loading provides a consistent measure of tensile strength and easy to replicate this mode of loading was chosen for the investigation. Note that direct tension test of brittle materials provides results with large scatter. In addition, the repair material is subjected to some form of flexure.

Basic properties of magnesium phosphate cement

Magnesium phosphate cement is a blend of magnesium oxide and some form of phosphate. Ammonium phosphate is used in commercial products but this formulation releases gases. Therefore, for this investigation, mono-potassium, di- phosphate (KH_2PO_4) also called as MKP was used. These ingredients react with water, rapidly producing strength and heat. The reaction product is magnesium potassium phosphate ($MgKPO_4 \cdot 6H_2O$). Compared with Portland cement, this type of cement can obtain several thousand psi compressive strength and over thousand psi modulus of rupture in a very short time. Fly ash, sand, gravel, fiber and other admixtures and fillers can be incorporated to improve the economy and mechanical properties. Some of these cements are available as packaged patching material, such as Euro-Speed MP which requires only the addition of water. Thin formulations are also being used as a coating material.

Brief Synopsis of the History of Magnesium-Phosphate Based Cements

The fundamental work for these classes of cements, dates back to 1950, when Kingery published the results of his investigation. His work dealt with the fundamental aspects of phosphate bonding in refractory cement systems. Interestingly, none of the US patents reference this work. This reference could have been ignored (missed) since the classical cement compositions are based on calcium silicates. However, refractory cement systems encompass a number of composition systems that include magnesium phosphate. Note that the refractory cements must be able to tolerate exposure to corrosive environments at elevated temperatures.

The formulation and preparation of magnesium (or Ca or Al) phosphate based cements are based on the reaction of an acidic phosphate salt with an alkaline source product of magnesium oxide (or calcium oxide or aluminum oxide, respectively). The combination of these 2 components, in the right ratio, when exposed to water will result in an acid-base reaction that forms a very stable cementitious product. Early published and patented work was based on the use of phosphoric acid directly and/or in combination with acid phosphate salts including monosodium phosphate (MSP) and mono-ammonium phosphate (MAP).

- In 1950 Kingery publishes work on the fundamentals of phosphate bonding systems in refractory cement compositions; this sets the foundation for the use of magnesium phosphate and related phosphate systems for use as refractory cement compositions that are still used today.
- Mid ‘60’s / early ‘70’s, US patents were granted on the preparation and use of MgO in combination with phosphoric acid and/or acidic phosphate salts such as MAP, MSP, mono-

magnesium phosphate for producing rapid-set concretes. These products were used for a variety of applications including road repair and building construction.

- In the 1980's researchers started to improve the properties magnesium phosphate cement in the area of quality assurance. Consistent results were obtained by controlling the reaction mechanism. In most of the published work, the principal acid phosphate source used was mono-ammonium phosphate (MAP). MAP was usually preferred because it was readily available and economical. Note that MAP was also used as a fertilizer product.
- In the late 1990's / early 2000, Argonne National Labs completed work and patented the application of the magnesium phosphate based cement systems for encapsulation of nuclear and hazardous waste. They promoted a formulation based on the use of MgO with MKP.

In early 2000's, Argonne National Laboratories extended their work and obtained patents covering the use of magnesium phosphate for various construction applications.

Mechanical Properties

The mechanical properties of Magnesium-Phosphate Concrete (MPC) are very similar to Portland cement concrete. These include: compressive strength, modulus of elasticity, modulus of rupture and strain capacities in tension and compression. The primary differences are setting time and shrinkage strains. MPC bonds well to concretes made with Portland cement. Since these concretes (mortars) are used for repairs in thin sections, the current investigation focuses on behavior of thin sections. Of particular interest is flexural behavior and use of new formulations for improving economy and flexural toughness. Since the primary mode of failure in the field applications is flexure, strength and toughness properties were evaluated for a large number of variables. Note that shrinkage and shrinkage-related cracking are heavily influenced by both shrinkage strains and toughness.

Rapid Set Formulations Introduction

Rapid set formulations are an important class of materials because of their extensive use in repairs. Obtaining strength of 3,000 psi in 1 to 3 hours is an important requirement for use in repairs. This aspect is particularly important for repair of transportation structures because the structures cannot be taken out of service for extended durations. In the case of repairs, low-shrinkage is another important factor for lasting repairs. Shrinkage of repairs will lead to delamination, cracking at the junctions, cracking of repair patch and damage to parent concrete surface. In overhead applications delamination could lead to safety issues because the delaminated patch could fall on vehicles traveling underneath the structures. Fortunately, shrinkage strains of rapid set formulations are typically lower than the Portland cement mixes. The primary objective of this research program is to formulate mix that has shrinkage strains less than tensile strain capacity so that repair systems with zero crack potential can be developed. A strategy of reducing the water to cement ratio was used to reduce shrinkage and mitigate the effects of creep. Fibers were used to increase the strain capacity. The two basic classes of materials evaluated were sulfate cements and modified Portland cements, which are commonly used as patching materials in bridge repair. PennDOT approves the use of sulfate cements as a patching material. A list of approved PennDot patching materials is provided in Appendix A, Table 10.

Background information on Sulfate Cement

The sulfate cements are being used successfully for repair of transportation structures including bridges, pavements and miscellaneous structures. The following factors contribute to low shrinkage:

- Silicates are generally responsible for shrinkage and their volume fractions are low in sulfate cements as compared to Portland cements.
- Higher percentage of water used for obtaining workability is chemically bound to the structure of the concrete.
- The skeletal structure formed by early strength gain provides restraint for shrinkage.

The research results presented in this report focuses on formulating a flowable mix that will not crack under restrained shrinkage conditions. The information is for a formulation developed specifically for highway applications.

Details of the Experimental Investigation

Phosphate Cement Specimen Study

The initial tests focused on basic formulations containing mono-potassium phosphate and Magnesium oxide. The formulations were improved using fly ash or alumino-silicates. Both fine sand and a combination of fine sand and small pebbles were used as fillers to improve economy and mechanical properties. Fibers were used to improve flexural toughness. The key variables were:

- Various types of phosphates
- Fly ash content
- Addition of coarse aggregates
- Alumino-silicates with high silica to alumina ratio, designated as W210
- Alumino-silicates with high silica to alumina ratio, designated as CC and
- fiber content.

Three-point flexure tests were conducted to obtain modulus of rupture and toughness. The results show that: 50% fly ash content by total volume cementitious materials with 0.5% carbon fiber (by volume) provides the best results. The carbon fibers also provide the least amount of shrinkage.

Materials

The materials used were: mono-potassium phosphate, di-potassium phosphate, magnesium oxide, type F fly ash, alumino-silicate commercially known as W210, fine sand, small pebbles, short carbon fibers and tap water. All the materials were obtained from commercial sources.

Fly ash

Fly ash (FA) is a byproduct of coal burning plants and it is available in large quantities. Actually fly ash cement not only reduces the cost of materials but also beneficial to sustainable environmental. Fly ash concrete was first used in the U.S. in 1929 for the Hoover Dam, where engineers found that it allowed for less total cement and formed a compound similar color to that of Portland cement. More importantly, when mixed with the novel MPC system, it is believed that the particles of fly ash fill the voids of the MPC paste and strongly bond together with hydrates of MPC. Meanwhile, the spherical shape of the particles of fly ash reduces internal friction thereby increasing the concrete's consistency and mobility, permitting longer pumping distances. Improved workability means less water is needed, resulting in less segregation of the mixture.

Alumino-silicates

Two types of alumino-silicates were used as mineral admixtures. The first one had silica to alumina ratio of 2. This admixture was designated as W210. The second type of alumino-silicate, designated as CC had silica to alumina ratio of 1.

Fibers

The concept of using fibers as reinforcement is not new. Fibers have been used as reinforcement since ancient times. Historically, horsehair was used in mortar and straw in mud bricks. Fibers are usually used in concrete to improve the flexural strength, ductility, toughness of the mixture and control plastic shrinkage cracking and drying shrinkage cracking. They also lower the permeability of concrete and thus reduce bleeding of water. However, too much fiber in the concrete will reduce the workability of the mixture and has limited effect on the tensile strength. In this report the amount of fiber added to a concrete mix is measured as a percentage of the total weight of MgO, KH_2PO_4, sand, gravel, fly ash and water.

Mixture proportions

The ratio of the basic components namely: magnesia (MgO), phosphate (MKP) and water were kept constant. The basic mix consisted of: 120g MKP, 40g MgO, 68g Water.

The mineral admixture was either type F fly ash or fly ash and W210. Fly ash with low carbon content was chosen to minimize the influence of fly ash in workability.

The two fillers were fine sand or/and gravel (pebble). Particle size of fine sand ranged from 0.0049 to 0.010 in (.25 to .025 mm). Gravel size ranged from 0.31 to 0.63 in (8 to 16 mm).

Since fly ash improved the properties significantly, only mixes with fly ash are presented in this report. More than 120 formulations were evaluated and only better performing formulations are presented in this report. The various combinations are presented in Table 1 (See Appendix A – Tables). These formulations can be grouped as follows:

Group 1:MKP + MgO + Sand +FA+Water, such as sample # 3 and 4.

Group 2:MKP + MgO + Sand + Gravel +FA+Water, such as sample # 7 and 8.

Group 3:MKP + MgO + Sand + Gravel +FA+ Fiber +Water, such as sample # 34 and 35.

Group 4:MKP + MgO + Sand +FA+W210 +Water, such as sample # 11 and 12.

Group 5:MKP + MgO + Sand +FA+ CC+Water, such as sample # 19 and 20.

Group 6:MKP + MgO + Sand + Gravel +FA+ W210+Water, such as sample # 15 and 16.

Group 7:MKP + MgO + Sand + Gravel +FA+ CC+Water, such as sample # 23 and 24.

Specimen Preparation

The specimens were prepared using small batch of materials. MKP, MgO, sand and fly ash with or without W210 and fibers, were blended in a high speed dry mixer. Water was added to this blended mix and the ingredients were mixed by hand using a stirrer. The following steps were used to prepare a rectangular plate which was cut into thin prism for flexural testing.

Step 1: Weigh the raw materials according to the composition of the sample.

Step 2: Pour the powder mixture and fiber (if needed) into a high speed mixer and mix them for one minute.

Step 3: Take out the powder from the mixer and put them in a 6in X 6in container. After the powder cools down, add required amount of water and mix by hand. For mixes with gravel, the gravel and water were mixed by hand.

Step 4: leave the mixture set and record the setting time.

Step 5: Leave the sample to cure in air, at room temperature, 25±2^{0}C. After 48 hours, take out the sample from the container and the sample is dry and hard.

Step 6: Cut the sample into thin prisms. Each piece was 6in long, 1in wide and about 0.5 in thick. The thickness of the individual group could vary slightly.

The sample in the mold and the cut samples ready for testing are shown in Figure 1 and Figure 2.

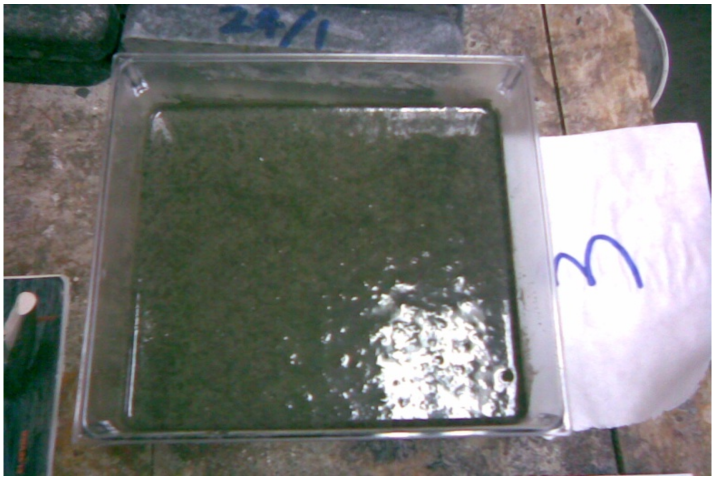

Figure 1. Sample in mold

Figure 2. Cut samples

Test Procedure

The specimens were tested under bending using three-point loading. MTS machine was used for the test and the prisms were tested over a simply supported span of 5 in and center-point loading. Loads and deflections were recorded till the failure. The information was used to obtain modulus of rupture and flexural toughness. The test setup and a typical tested sample are shown in Figure 3 and Figure 4.

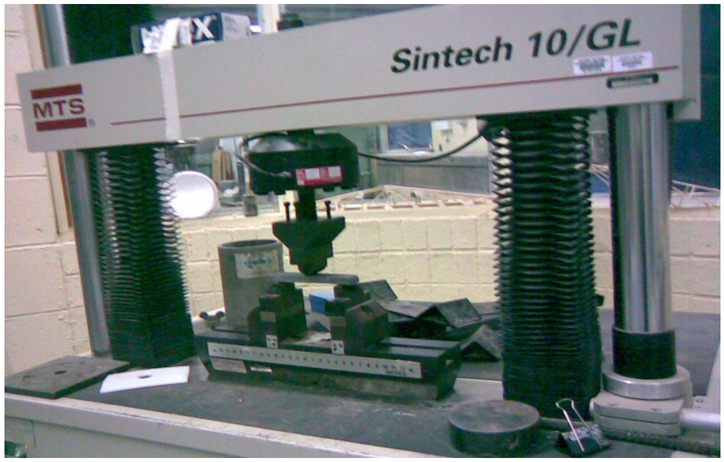

Figure 3. Test setup for the flexure test

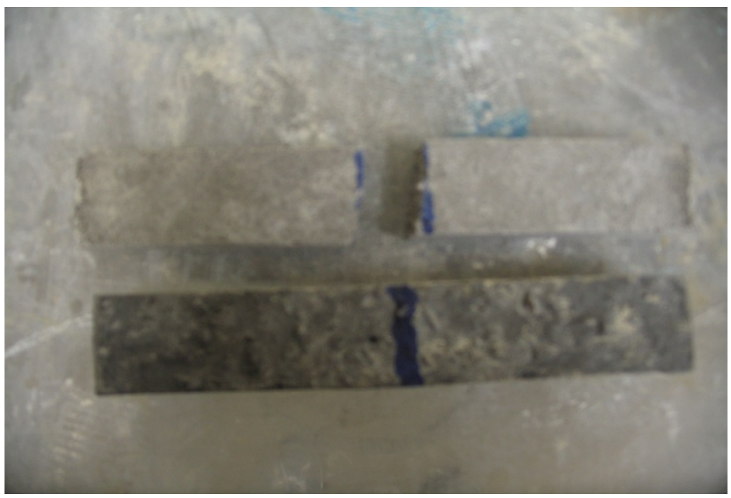

Figure 4. Sample after testing

Experimental Results and analysis

There was no problem for mixing the ingredients or mixing with water. For all the cases, the slurry with or without coarse aggregates were poured into the mold. For simplicity in construction, external vibration was not used for compaction. The vibration would enhance the strength. Working time varied from less than 1 minute to about 35 minutes. Test specimens were not cast for a few mixes that set in less than 1 minute. These samples were prepared using special MgO.

The test results for strength and stiffness are presented in both tabular and graphical form. The independent variables are:

- DKP/MKP ratio
- Fly ash content

- Two types of alumino-silicates
- Presence of coarse aggregate
- Use of fibers
- MKP/ Peek-acid ratio

The response variables are:

- Load-deflection response
- Modulus of rupture
- Modulus of elasticity
- Density

The coarse aggregates had a maximum size of 3mm or 0.125 in.

Load Deflection Response, Density, Modulus of Rupture and Toughness

The load-deflection behavior of the beams was obtained using the X – Y plotter of the machine. Typical curves for Sample 4 are shown below. The load-deflection behavior is shown in Figure 5, whereas the stress- deflection behavior is shown in Figure 7. Both curves show a seating error deformation at the origin and this error was removed for the toughness computations. The post-crack behavior is highlighted in Figure 6. These graphs and the digital data collected during the testing were used to compute modulus of rupture, f_r and toughness indices. Since the thickness of the samples could not be controlled to same exact thickness, the thickness values were measured for each sample. The thickness and width of the specimen were measured with digital caliper. The dimensions of the beams used for computations are presented in Table 2 (See Appendix A – Tables).

Modulus of rupture and density of the samples are presented in Table 3 and toughness indices of fiber reinforced samples are presented in Table 4 (See Appendix A – Tables).

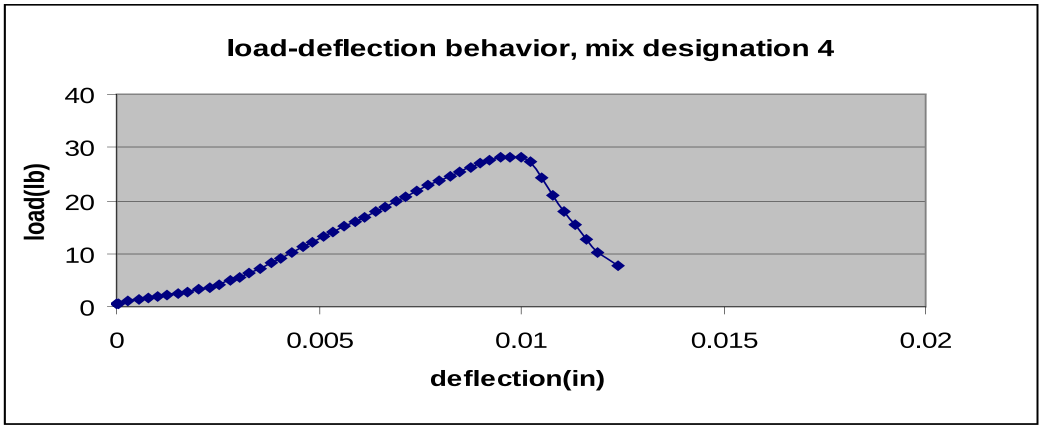

Figure 5. Load-deflection Behavior for Sample #4

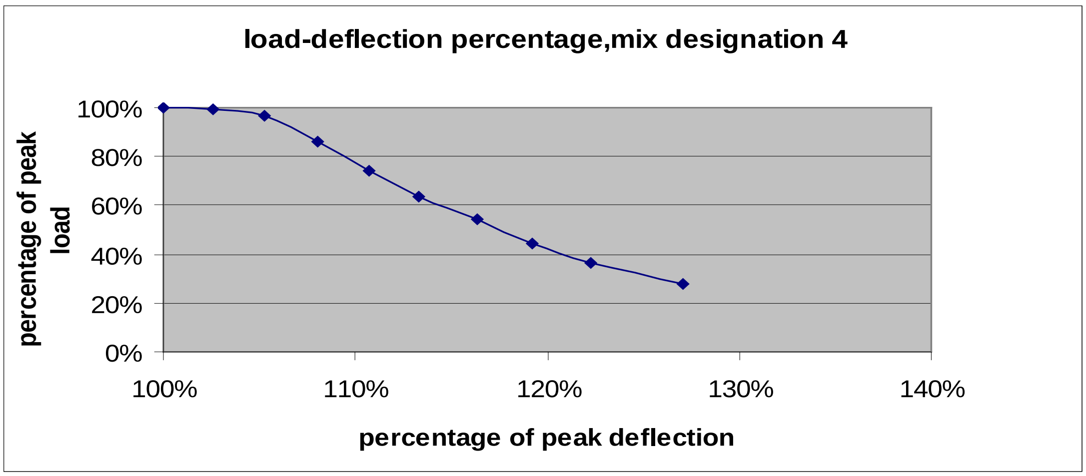

Figure 6. Load-Deflection percentage for Sample #4

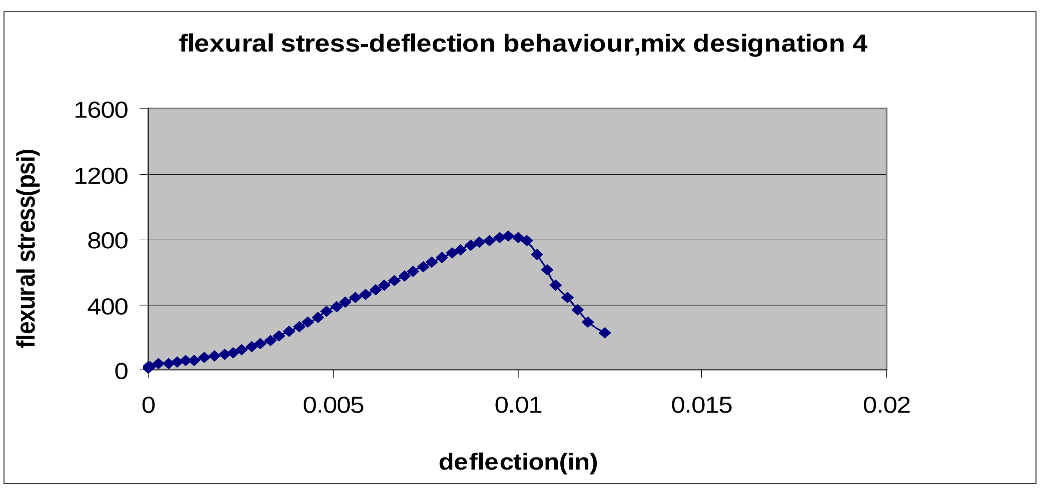

Figure 7. Flexural Stress-Deflection Behavior for Sample #4

General Observations

The average modulus of rupture ranged from 566 to 1300 psi among these 60 specimens tested. Sixteen out of twenty groups had strengths higher than 750 psi. Eleven out of twenty groups had strengths higher than 1000 psi. For design purposes strengths higher than 600 psi are considered adequate. A volume fraction of 25% fly ash provides very good results. Alumino-silicates did not provide better results as compared to fly ash. Addition of coarse aggregate in the form of gravel provides better strength. This is significant because the addition of gravel facilitates casting of thicker sections and the composite also becomes more economical. The influence of various dependent variables on the modulus of rupture and toughness are discussed in the following sections.

Influence of Fly Ash

The amount of fly ash has significant effect on the modulus of rupture. Volume fraction of fly ash is computed by dividing the weight of fly ash by the weight of other cementing materials namely: MKP and MgO. The results of mixes with no fly ash are not presented in this report because they provided consistently lower strengths. The 3 volume fractions evaluated were: 12.5%, 25%, and 50%.

A typical comparison of two mixes with 25% and 50% are shown in Figure 8. It can be observed that higher volume fraction of fly ash provides better results. A large number of samples with 12.5% and 25% were tested. Higher fly ash content provides higher strength consistently. The authors recommend either 25% or 50% fly ash content for field use.

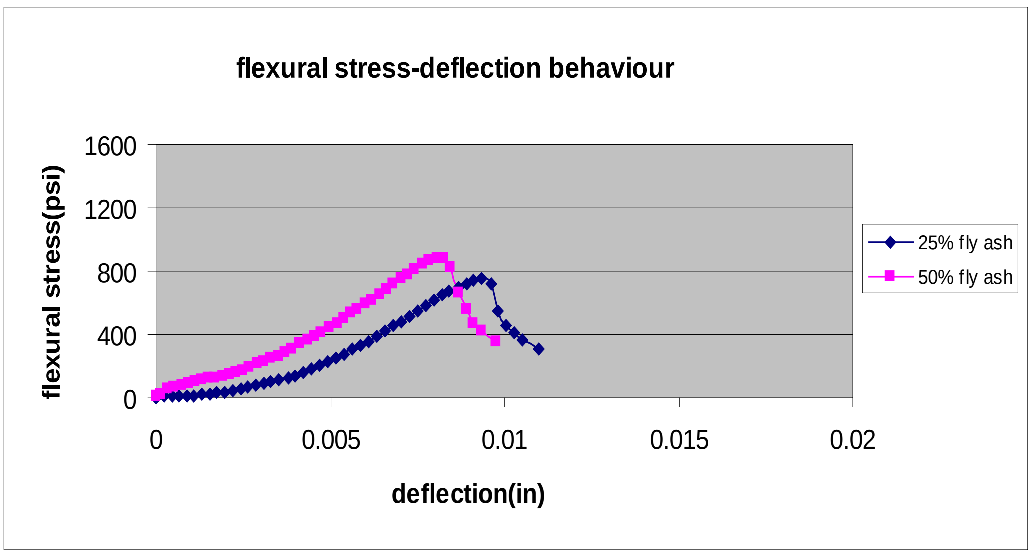

Figure 8. Influence of Fly Ash on Modulus of Rupture

Influence of Alumino-Silicates

Influence of alumino-silicate mineral admixtures (W210 and CC) is presented in Figure 9 and Figure 10. Results of mixes without coarse aggregates are presented in Figure 9. It can be observed from Figure 9 that neither admixture improved performance. The mix without admixtures provided better strength. However when coarse aggregates were added the admixtures provided a better performance as shown in Figure 10. The alumino-silicate with higher silica to alumina ratio, designated as CC performed better than the alumino-silicate with lower silica to alumina ratio, designated as W210.

Even though the alumino-silicate admixtures provided better performances in certain cases, these admixtures are not recommended for field applications because the higher cost of these materials and increase in number of components in the mixture. The magnitude of strength increase is not significant enough to justify higher costs.

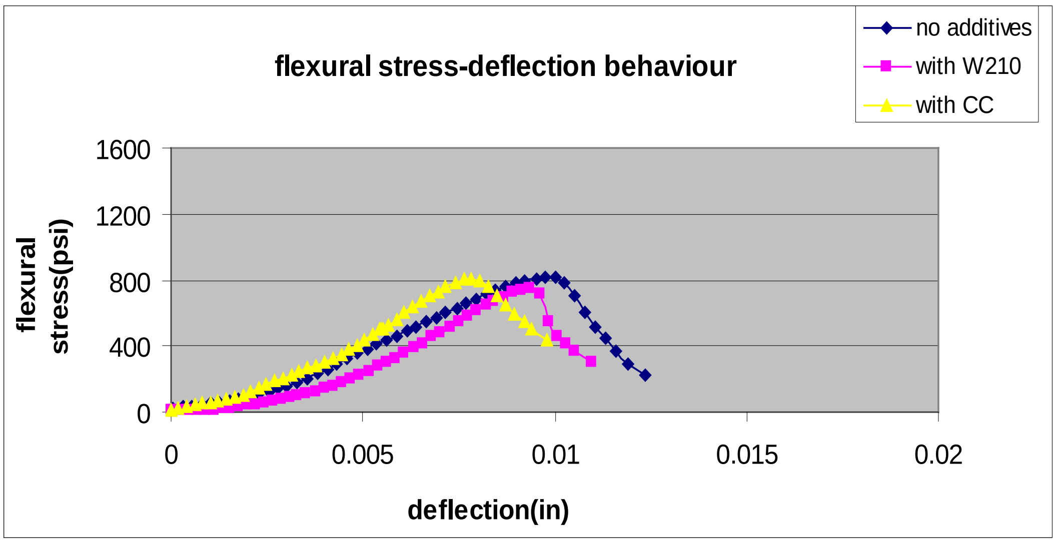

Figure 9. Influence of Alumino-silicates on modulus of rupture: samples without gravel

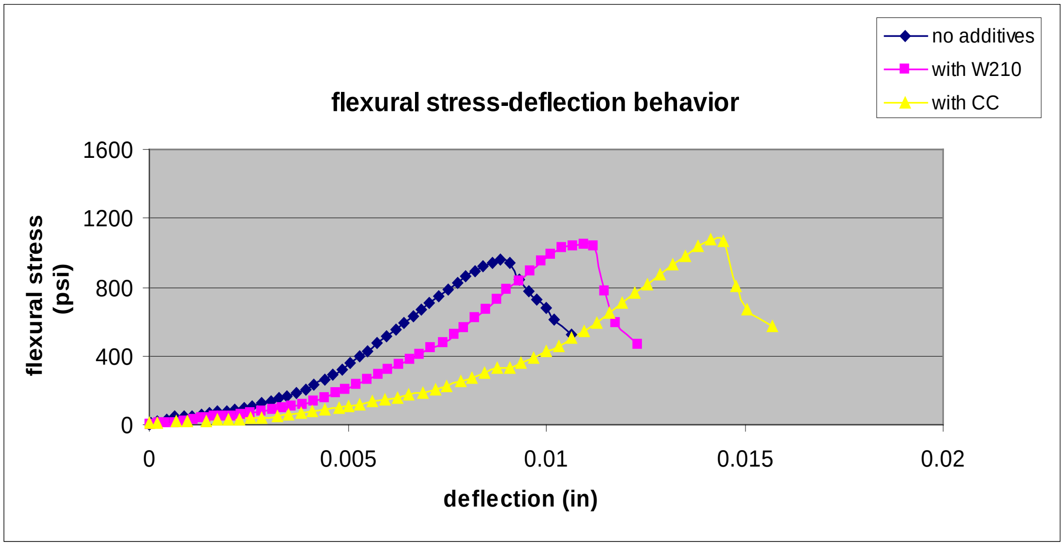

Figure 10. Influence of Alumino-Silicates on Modulus of Rupture: samples with gravel

Influence of Coarse Aggregates

Addition of coarse aggregates in the form of gravel improves the performance both in terms of strength increase and increase in stiffness. Typical load (flexural stress)-deflection behavior is shown in Figure 11. The strength increase of about 50%, is substantial. Note that addition of coarse aggregates have very high potential for decreasing the shrinkage strains and shrinkage strains of Magnesium-phosphate mortars are already much lower than the strains reported for Portland cement concrete.

For applications where the use of coarse aggregates is feasible, it is recommended to use gravel as coarse aggregates. Essentially, if the thickness needed in a given application is more than 0.5 inch, coarse aggregates can be used.

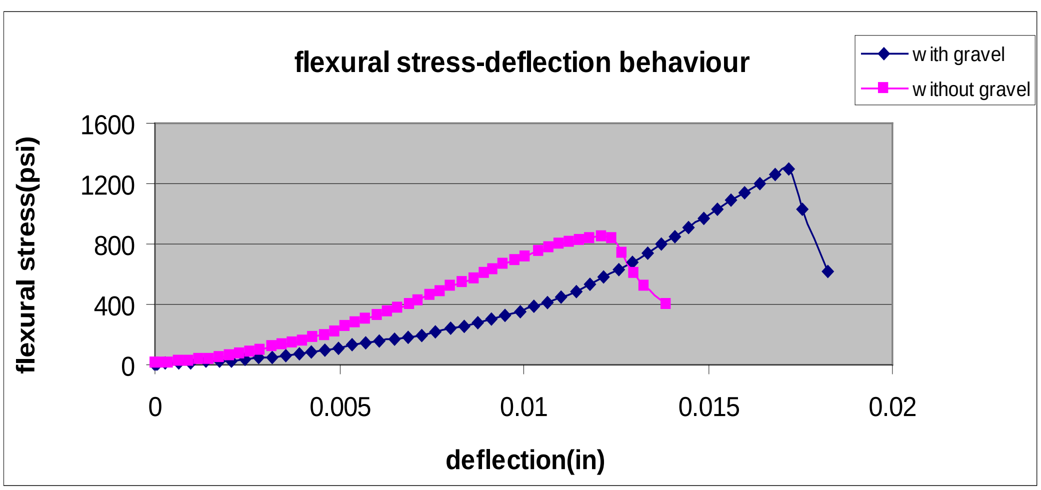

Figure 11. Influence of coarse aggregates on modulus of rupture

Influence of Fibers

Addition of fibers to brittle matrices such as Portland cement or Magnesium-phosphate mortars and concrete provide a number of advantages. The most useful and significant improvement is in the area of ductility which contributes to both short-term and long-term performance. The following are the major advantages provided by fiber addition.

- Increase in ductility measures using the parameter toughness index
- Post-crack resistance
- Increase in modulus of rupture
- Nominal increase in stiffness
- Increase in strain capacity resulting delay of restrained shrinkage cracking
- If cracks do occur, decrease in maximum crack width resulting in better long term durability
- Enhanced fatigue resistance and
- In the cases of repair application, improved bond to parent concrete

The results obtained in this investigation confirm the contribution of fibers for the first five factors of the aforementioned list. These contributions can be observed in Figure 12 in which the load (flexural stress)-deflection behavior of plain and fiber reinforced sample are compared.

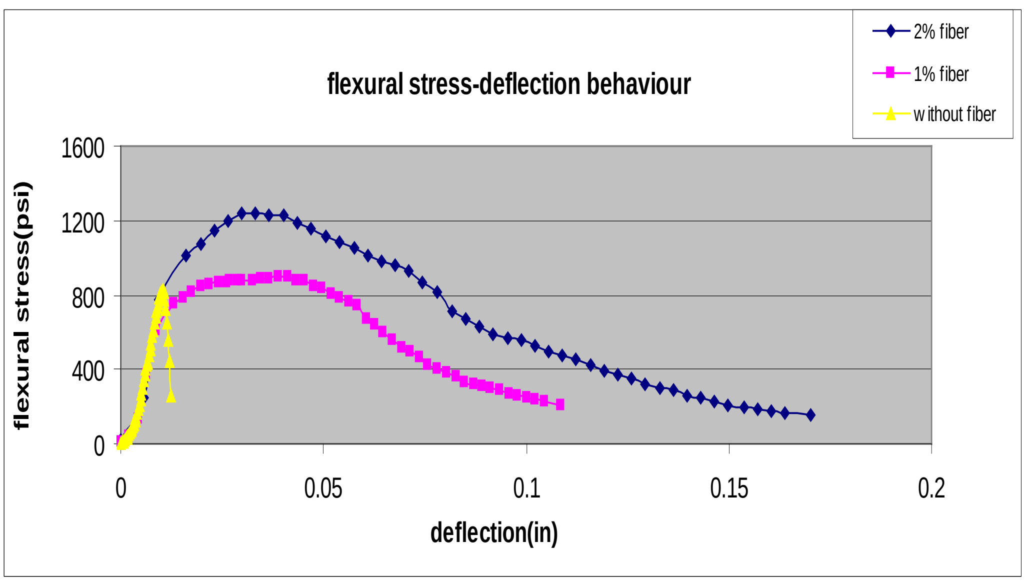

Figure 12. Influence of fibers on load-deflection behavior

The modulus of rupture values for samples with fibers is presented in Table 5 to emphasize the fiber contribution. From table 3.4 it can be seen that modulus values are higher than 1,100 psi for all samples. The fiber content was computed using the weight of fibers and the total weight of unreinforced mix. For example, the weight of fibers for sample 38 was 6.58 g and the total weight of unreinforced matrix was 658 g and therefore the fiber content was 1%. The fiber contents are expressed as volume fractions or on weight basis. In this report the percentage of fibers was computed on weight basis. Addition of fibers seems to provide better performance for mixes with coarse aggregates as shown in Figure 13.

Based on the results of current investigation, it is recommended to use 0.5% (by weight) of 6 mm (0.25 in.) long carbon fibers. Further increase fiber content interferes with workability and the economic advantage also decreases for fiber contents higher than 0.5%.

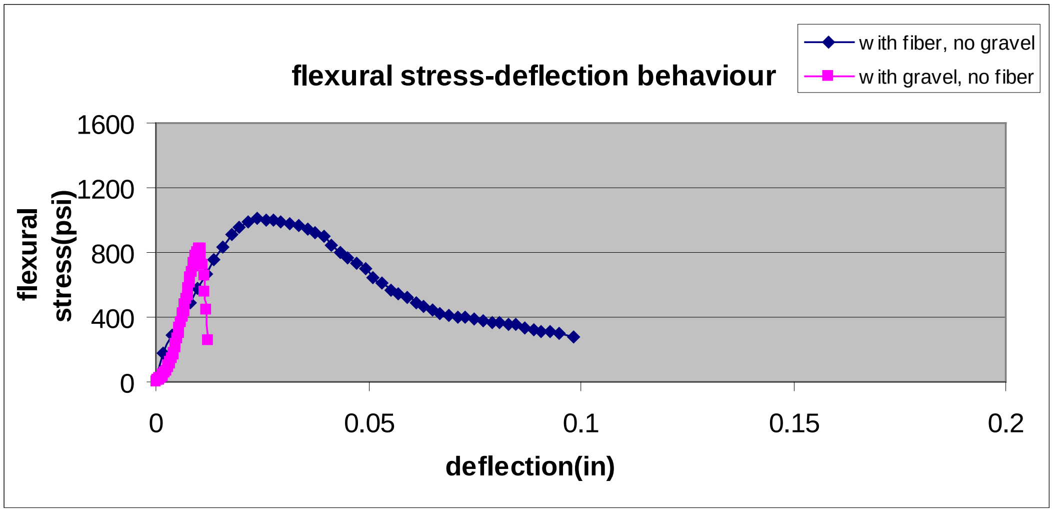

Figure 13. The effect of fiber on flexural stress against that of gravel

Summary of Observations

A careful review of the test results and observations made during the preparation and testing, lead to the following observations.

- Mixing the cementing components in a high shear mixer is critical to strength development and long term stability.
- The unit weight is about 120 lb/ft^3 (1,900 kg/m$^{3)}$ as compared to Portland cement concrete with a unit weight of about 150 lb/ft^3 (2,400 kg/m^3).
- For most cases, modulus of rupture (flexural tensile strength) is more than 1,000 psi and the highest value was 1,300 psi (Results of samples not presented in this report were as high as 1,767 psi). The values are about 50% higher than that of Portland cement concrete.
- Addition of fly ash improves the workability and the strength up to about 30% by weight of cementing materials. Addition of fly ash above 35% by weight of cementing materials results in reduction of strength.

- Fillers (fly ash, sand and coarse aggregate) were added up to 80% by total weight (1 part cement and 4 part fillers). Still the modulus of rupture was more than 1200 psi.
- Modulus of elasticity is lower than that of Portland cement concrete (about 80%). Addition of coarse aggregate further reduces the modulus of elasticity.
- DKP/MKP formulations provide better performance as compared to MKP samples. The optimum ratio of DKP: MKP is about 3:7.
- Strength results are comparable to results reported by other investigators and Magnesium Phosphate cement made using ammonium phosphate. The modulus of elasticity for this composition is slightly higher.

Addition of fibers provides more ductility and less variation among samples.

Sulfate and Modified Portland Cements

Materials

Materials used for this study are CTS Rapid Set Cement All, Quikrete – Commercial Grade FastSet™ Non-Shrink grout, Euclid 37 (High Range Water Reducer and Super-Plastizer), 3.6mm steel fibers, 13mm steel fibers, 6mm carbon fibers, 6mm brass fibers and 13mm brass fibers.

Based on the information provided by the company, the drying shrinkage of the basic mix of sulfate cement is 500 micro strains. A number of techniques were used to reduce this shrinkage value to around 300 micro strains. The shrinkage strains of modified Portland cement formulations were slightly higher. The strain values reported in the literature for rapid set concretes vary from 260 to 550 micro strains.

A study was conducted by the CTL Group on behalf of the Hawaii Department of Transportation to determine the resistance to penetration of water of the CTS Rapid Set Cement All. The CTL Group conducted rapid chloride penetrability method tests to determine the chloride penetrability level of Rapid Set. The results of the test found CTS Rapid Set Cement All to have negligible chloride penetrability. Based on the results of this study it can be concluded that corrosion is a negligible issue.

Mix Proportions

CTS Rapid Set Cement All and Quikrete Commerical Grade FastSet™ Non-Shrink Grout were used for this study combined with a high range water reducer to increase the workability of these two products. The addition of 3.6mm steel fibers, 13mm steel fibers, 6mm carbon fiber were used in varying amounts from 0.25% by volume to 5% by volume with the goal to reduce shrinkage and increase the tensile strain capacity. A total of 75 mix proportions were evaluated for high flow mixes, Table 8.

Research Program

Since the mechanical properties of the rapid set formulations are well established, the focus of the research presented in this report was reducing the shrinkage strains and increasing the tensile strain capacity to achieve crack free concrete. This is particularly important for repair materials because shrinkage is one of the primary reasons for failure. The repaired part essentially de-bonds from the parent surface due to shrinkage. Note that in almost all cases the parent surface has undergone all the shrinkage.

The reduction of shrinkage was attempted by reducing water content and the increase in tensile strain capacity was obtained using fiber reinforcement. Both steel and carbon fibers were used.

The primary response variable is shrinkage strain. Since rapid set materials attain the ultimate shrinkage in a shorter period of time, readings need not be taken for longer than 6 months. In some cases, there was no increase in shrinkage after 90 days.

The independent variables were:

- Type of cement
- Water content
- Admixtures
- Type of fibers, and
- Fiber content.

Three types of cements manufactured by Quickrete and CTS were used. The water content recommended by the manufacturer was reduced by adding high range water reducing admixtures. Short carbon and steel fibers were used for the fiber reinforced matrix formulations.

Specimen Preparation

A process of trial and error was used to determine a mixing procedure as well multiple placement procedures for field use based on the style of repair. The procedures are listed below.

Mixing:

1. Add required water to bucket
2. With Paddle mixer slowly turning add required amount of sulphate cement
3. Once the sulphate cement is uniformly mixed with the water (approximately 30 seconds), add in required amount of Super Plasticizer
4. Mix compound for a minimum of 3 minutes
5. Pause paddle mixer, add 3.6mm steel fibers

6. Use paddle mixer to evenly distribute fibers (approximately 15 seconds)
7. Let mix sit for 2 ½ minutes
8. Add 30 mm fibers
9. Use paddle mixer to evenly distribute fibers (approximately 15 to 30 seconds)
10. Pour mixture

Guidelines for Field Use:

Prepping and placement for a hole (Procedure 1):

1. Remove debris from placement area
2. Use air hose and/or vacuum to remove dust
3. Lightly dampen placement area
4. Pour mixture

Prepping and placement for a hole (Procedure 2):

1. Remove debris from placement area
2. Use air hose and/or vacuum to remove dust
3. Drill a ¼" hole every 2 square inches
4. Screw in a concrete screw into each hole
5. Lightly dampen placement area
6. Pour mixture

Prepping Placement Area (Flat Surface):

1. Remove debris from placement area
2. Grind placement surface with grinder (optional)
3. Use air hose and/or vacuum to remove dust
4. Lightly dampen placement area
5. Pour mixture

Test Methods

Fresh Concrete

For the free flow mixes, the mixed ingredients had to flow molds without any vibration or tamping. The water contents and high range water reducing admixture dosages were adjusted to obtain this consistency for all mixes including the mixes that contained fibers.

Hardened Concrete

Compressive strength was determined by making testing cylindrical samples and mortar cubes following the procedure in ASTM C39 and ASTM C109 respectively, recording the strength at 3-hours, 1 day, 3 days, 7 days, and 28 days. Shrinkage was determined by following the procedure outlined in ASTM C490, taking recordings at 1 day, 3 days, 7 days, 21 days, 28 days, 56 days, and 96 days. Elastic modulus was determined for 3 hours, 1 day, 3 days, 7 days, and 28 days by following the procedure outlined in ASTM C469.

Test Results and discussion

Since the primary focus of the research program was shrinkage characteristics the results presented in the following sections also focus on shrinkage strains. Only the most promising results are presented.

The shrinkage strains of the most promising mix proportions are presented in Figure 14 through Figure 20.

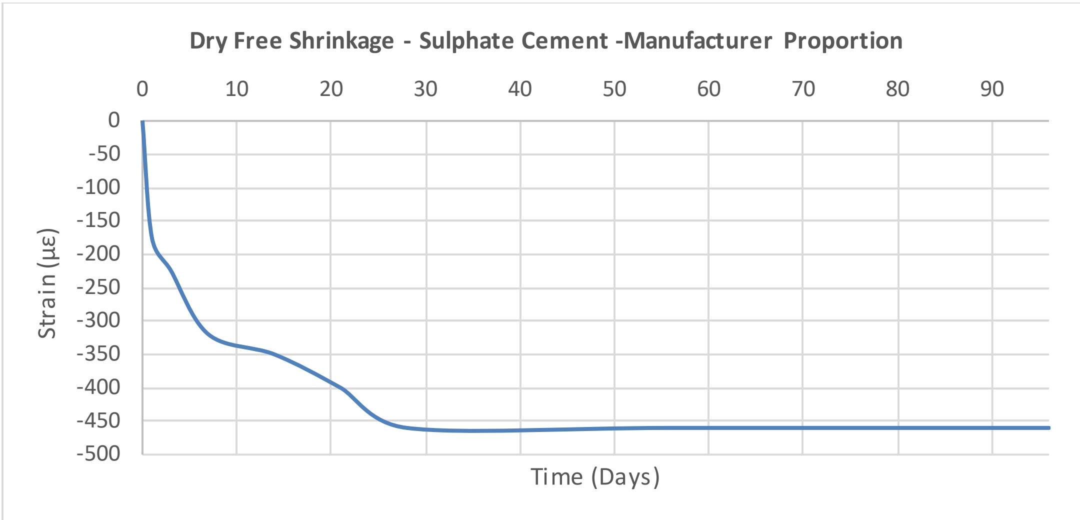

Figure 14. Shrinkage strain Vs Time: Sulfate cement with manufacturer mix proportion

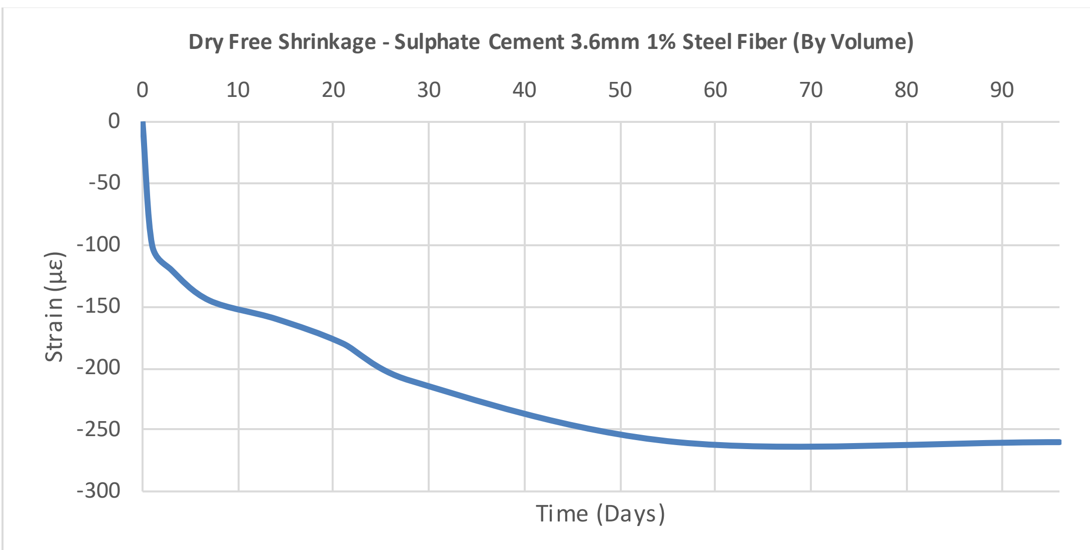

Figure 15. Shrinkage strain Vs Time: Sulfate cement with 1% steel fibers

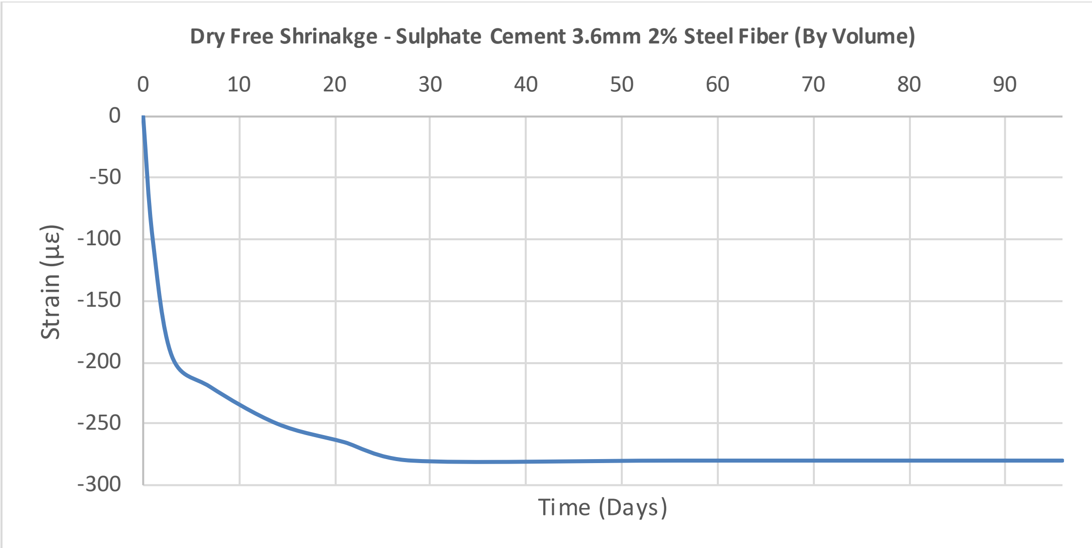

Figure 16. Shrinkage strain Vs Time: Sulfate cement with 2% steel fibers

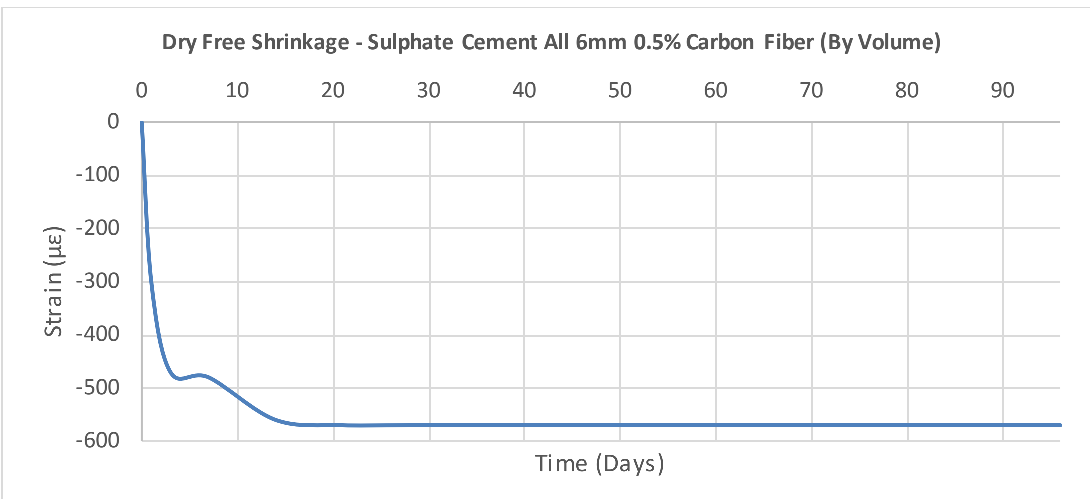

Figure 17. Shrinkage strain Vs Time: Sulfate cement with 0.5% carbon fibers

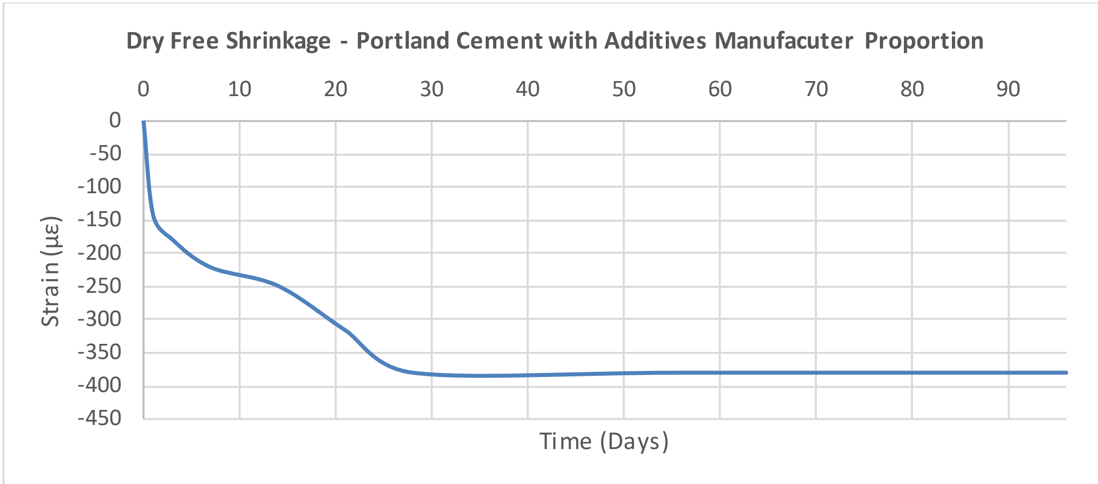

Figure 18. Shrinkage strain Vs Time: Portland cement with additives, Manufacturer recommended mix proportion

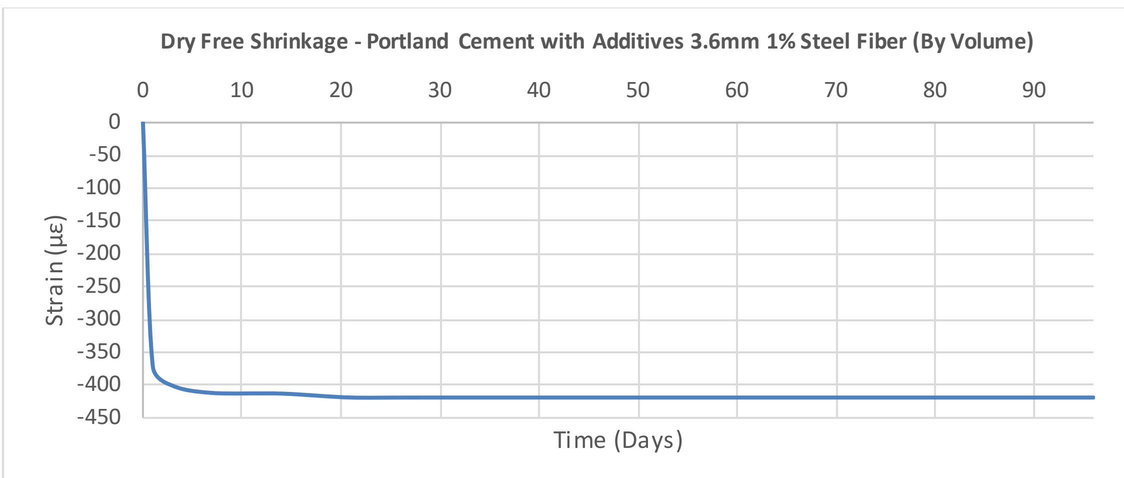

Figure 19. Shrinkage strain Vs Time: Portland cement with additives, 1% steel fibers

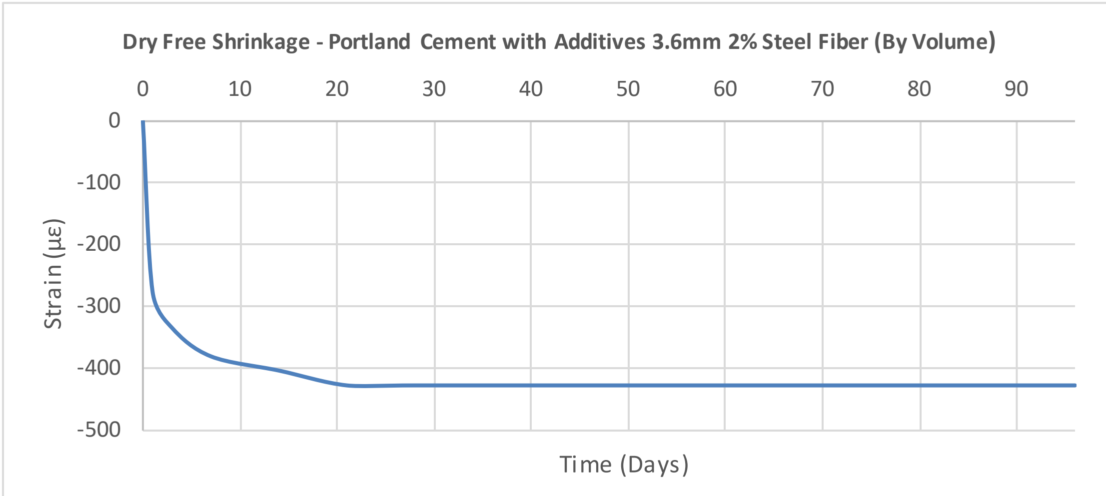

Figure 20. Shrinkage strain Vs Time: Portland cement with additives, 2% steel fibers

The shrinkage results show that it is possible to achieve a drying shrinkage strain less than 300 microstrains. The most promising mix was the sulfate cement with 2% steel fibers.

Strength Results

Limited strength tests were conducted to confirm the results reported by the manufactures. These results are presented in Figure 21 and Figure 22.

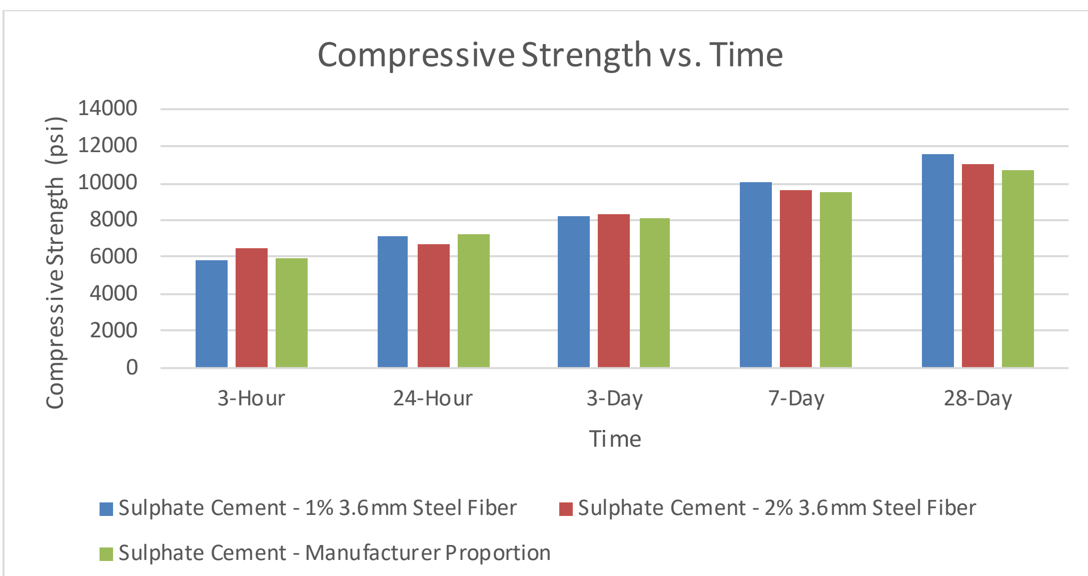

Figure 21. Compressive Strength tests

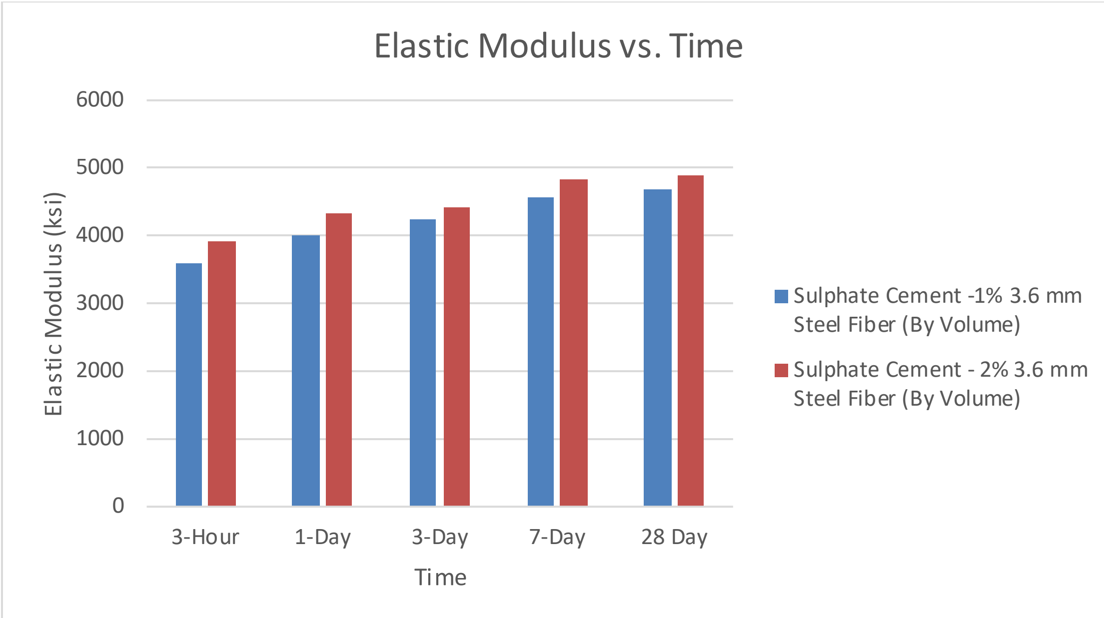

Figure 22. Elastic Modulus based on compressive tests

Conclusions and Recommendations

Phosphate Cement

The physical and mechanical properties of magnesium phosphate concrete with fly ash, similar to the conventional concrete, are determined by its ingredients. It has been proved that as a type of rapid hardening concrete, magnesium phosphate concrete incorporated with fly ash and fiber not only allows the greater deflection to satisfy the ductility demands but also obtains a higher tensile strength.

There is no doubt that additional fiber to magnesium phosphate concrete is a good choice in the flexure test. Fiber plays a major role to enhance both the tensile strength and ductility but too much fiber will affect the workability of mixture when mixed with gravel. Among all the samples tested, sample 39 with 0.5% fiber and 190g gravel has the highest modulus of rupture and sample 43 with 2% fiber, no gravel, has a little lower modulus of rupture but has the best ductility. To achieve desirable modulus of rupture and workability, 0.5% fiber content seems to be the best for magnesium phosphate concrete with composition: 120g MKP + 40g Mgo + 200g Sand + 190g Gravel + 40g FA + 68g Water. Also, it is recommended to reduce the weight of gravel while increasing the fiber content to improve both the tensile strength and durability.

Fly ash, a low cost material but with high efficiency, became an essential ingredient of magnesium phosphate concrete. The addition of fly ash didn't retard the reaction of MPC with water. On the contrary, the tensile stress increases significantly with the increase of fly ash content from 10% to 50%. For sample 7 and 8, the fly ash content is raised from 10% to 20%, the tensile strength increased by over 40%. Probably when the fly ash content is over certain amount, say 60%, it will have little effect on the tensile strength or even has side effect. This has to be confirmed in the further study. With respect to the additives W210 and CC, they are helpful to promote the bending strength of magnesium phosphate concrete with fly ash and CC is more functional than W210.

Sulphate and Modified Portland Cement

The physical and mechanical properties of sulphate and modified portland cement with the addition of fibers reduce the shrinkage strains and increase the tensile strain capacity making it possible to achieve crack free concrete. Based on the shrinkage results it is seen that the sulphate cement with the addition of fibers can achieve a shrinkage below 300 micro strains. By providing shrinkage strains less than 300 micro strains, and a higher tensile strain capacity, it is possible to produce more durable structures and repairs. Since the volume of material used for these applications is small, the cost is not as critical as for applications involving large volume use.

Future Research

Once the baseline mixes are established for low-shrinkage mixes, further extensive studies need to be carried out for incorporating the diverse aggregate types and developing different grades of concrete to suit the requirements of various structural components. Further possible research areas are: development of new fiber types, admixtures for internal curing and polymers for adhesion of concrete. Field demonstration projects are other potential candidates for large scale research projects.

Appendix A – Tables & Graphs

Table 1 - Mix proportions of components

Sample #	MKP	Mgo	FA	Fine Sand	Gravel	W210	CC	Water	Fiber
3-2	120	40	20	200	0	0	0	68	0
3-3	120	40	20	200	0	0	0	68	0
3-4	120	40	20	200	0	0	0	68	0
4-2	120	40	40	200	0	0	0	68	0
4-3	120	40	40	200	0	0	0	68	0
4-4	120	40	40	200	0	0	0	68	0
7-2	120	40	20	200	380	0	0	68	0
7-3	120	40	20	200	380	0	0	68	0
7-4	120	40	20	200	380	0	0	68	0
8-2	120	40	40	200	380	0	0	68	0
8-3	120	40	40	200	380	0	0	68	0
8-4	120	40	40	200	380	0	0	68	0
11-2	120	40	20	200	0	20	0	68	0
11-3	120	40	20	200	0	20	0	68	0
11-4	120	40	20	200	0	20	0	68	0
12-2	120	40	40	200	0	20	0	68	0
12-3	120	40	40	200	0	20	0	68	0
12-4	120	40	40	200	0	20	0	68	0
15-2	120	40	20	200	380	20	0	68	0
15-3	120	40	20	200	380	20	0	68	0
15-4	120	40	20	200	380	20	0	68	0
16-2	120	40	40	200	380	20	0	68	0
16-3	120	40	40	200	380	20	0	68	0
16-4	120	40	40	200	380	20	0	68	0
19-2	120	40	20	200	0	0	20	68	0
19-3	120	40	20	200	0	0	20	68	0
19-4	120	40	20	200	0	0	20	68	0
20-2	120	40	40	200	0	0	20	68	0
20-3	120	40	40	200	0	0	20	68	0
20-4	120	40	40	200	0	0	20	68	0
23-2	120	40	20	200	380	0	20	68	0
23-3	120	40	20	200	380	0	20	68	0
23-4	120	40	20	200	380	0	20	68	0
24-2	120	40	40	200	380	0	20	68	0
24-3	120	40	40	200	380	0	20	68	0

24-4	120	40	40	200	380	0	20	68	0
25-2	120	40	80	200	0	20	0	68	0
25-3	120	40	80	200	0	20	0	68	0
25-4	120	40	80	200	0	20	0	68	0
34-2	120	40	40	200	190	0	0	68	4.3
34-3	120	40	40	200	190	0	0	68	4.3
34-4	120	40	40	200	190	0	0	68	4.3
35-2	120	40	40	200	190	0	0	68	2.2
35-3	120	40	40	200	190	0	0	68	2.2
35-4	120	40	40	200	190	0	0	68	2.2
37-2	120	40	40	200	0	0	0	68	4.7
37-3	120	40	40	200	0	0	0	68	4.7
37-4	120	40	40	200	0	0	0	68	4.7
38-2	120	40	40	200	190	0	0	68	6.6
38-3	120	40	40	200	190	0	0	68	6.6
38-4	120	40	40	200	190	0	0	68	6.6
39-2	120	40	40	200	190	0	0	68	3.3
39-3	120	40	40	200	190	0	0	68	3.3
39-4	120	40	40	200	190	0	0	68	3.3
43-2	120	40	20	200	0	0	0	68	9
43-3	120	40	20	200	0	0	0	68	9
43-4	120	40	20	200	0	0	0	68	9
44-2	120	40	20	200	0	0	0	68	4.5
44-3	120	40	20	200	0	0	0	68	4.5
44-4	120	40	20	200	0	0	0	68	4.5

Note: Weight unit is gram. Three samples were tested for each variable.

Table 2 - Dimensions of samples tested

Sample #	L (in)	b(in)	h1(in)	h2(in)	h3(in)	$h_{average}$(in)
3-2	4.00	1.08	0.42	0.43	0.44	0.43
3-3	4.00	1.08	0.42	0.43	0.43	0.43
3-4	4.00	1.07	0.43	0.42	0.43	0.43
4-2	4.00	1.08	0.43	0.44	0.44	0.44
4-3	4.00	1.07	0.45	0.45	0.45	0.45
4-4	4.00	1.07	0.43	0.43	0.43	0.43
7-2	4.00	1.04	0.76	0.78	0.77	0.77
7-3	4.00	1.06	0.78	0.78	0.78	0.78
7-4	4.00	1.04	0.78	0.77	0.78	0.78
8-2	4.00	1.05	0.81	0.81	0.81	0.81
8-3	4.00	1.04	0.79	0.78	0.79	0.79
8-4	4.00	1.04	0.81	0.80	0.81	0.81
11-2	4.00	1.08	0.52	0.52	0.51	0.52
11-3	4.00	1.08	0.50	0.50	0.51	0.50
11-4	4.00	1.08	0.51	0.51	0.51	0.51
12-2	4.00	1.07	0.55	0.55	0.55	0.55
12-3	4.00	1.07	0.56	0.57	0.57	0.57
12-4	4.00	1.08	0.56	0.57	0.57	0.57
15-2	4.00	1.05	0.80	0.79	0.80	0.80
15-3	4.00	1.05	0.78	0.76	0.77	0.77
15-4	4.00	1.05	0.79	0.79	0.79	0.79
16-2	4.00	1.07	0.80	0.78	0.79	0.79
16-3	4.00	1.08	0.83	0.82	0.83	0.83
16-4	4.00	1.07	0.75	0.78	0.77	0.77
19-2	4.00	1.08	0.42	0.42	0.41	0.42
19-3	4.00	1.07	0.42	0.43	0.43	0.43
19-4	4.00	1.07	0.42	0.43	0.42	0.42
20-2	4.00	1.07	0.46	0.45	0.45	0.45
20-3	4.00	1.07	0.46	0.45	0.46	0.46
20-4	4.00	1.08	0.45	0.45	0.45	0.45
23-2	4.00	1.03	0.79	0.79	0.79	0.79
23-3	4.00	1.03	0.79	0.77	0.78	0.78
23-4	4.00	1.04	0.80	0.80	0.80	0.80
24-2	4.00	1.08	0.79	0.79	0.79	0.79
24-3	4.00	1.08	0.78	0.77	0.78	0.78
24-4	4.00	1.06	0.81	0.83	0.82	0.82

25-2	4.00	1.05	0.47	0.48	0.48	0.48
25-3	4.00	1.05	0.48	0.47	0.47	0.47
25-4	4.00	1.04	0.49	0.49	0.48	0.49
34-2	4.00	1.06	0.56	0.55	0.55	0.55
34-3	4.00	1.06	0.56	0.57	0.57	0.57
34-4	4.00	1.06	0.56	0.53	0.53	0.54
35-2	4.00	1.04	0.53	0.53	0.51	0.52
35-3	4.00	1.05	0.53	0.55	0.56	0.55
35-4	4.00	1.05	0.57	0.57	0.58	0.57
37-2	4.00	1.05	0.39	0.41	0.41	0.40
37-3	4.00	1.06	0.46	0.45	0.44	0.45
37-4	4.00	1.06	0.42	0.42	0.44	0.43
38-2	4.00	1.06	0.64	0.62	0.60	0.62
38-3	4.00	1.06	0.54	0.54	0.57	0.55
38-4	4.00	1.05	0.57	0.59	0.62	0.59
39-2	4.00	1.01	0.56	0.54	0.56	0.55
39-3	4.00	1.01	0.55	0.55	0.54	0.55
39-4	4.00	1.01	0.55	0.53	0.53	0.54
43-2	4.00	1.04	0.36	0.34	0.38	0.36
43-3	4.00	1.03	0.42	0.43	0.43	0.43
43-4	4.00	1.03	0.45	0.44	0.44	0.44
44-2	4.00	1.03	0.46	0.49	0.47	0.47
44-3	4.00	1.03	0.37	0.36	0.34	0.36
44-4	4.00	1.03	0.38	0.36	0.38	0.37

Table 3 - Density and modulus of rupture of samples

Sample #	Max. load(lb)	f_r (psi)	f_{r-avg}(psi)	density (kg/m^3)	average of density (kg/m^3)
3-2	30.89	932		1881	
3-3	20.60	633		1775	
3-4	22.50	697		1847	
4-2	28.38	830		2011	
4-3	33.40	928		1873	
4-4	30.50	925		1842	
7-2	61.70	598		2109	
7-3	66.00	614		2057	
7-4	87.47	837		2063	
8-2	110.80	964		2030	
8-3	123.20	1152		2100	
8-4	100.60	900		2032	
11-2	23.10	482		1776	
11-3	17.00	372		1771	
11-4	39.36	844		1778	
12-2	40.81	754		1757	
12-3	31.10	544		1683	
12-4	30.20	525		1680	
15-2	145.54	1317		2116	
15-3	100.00	963		2107	
15-4	100.40	915		2104	
16-2	142.50	1277		2146	
16-3	172.10	1407		2120	
16-4	110.13	1058		2115	
19-2	28.06	901		1766	
19-3	27.20	835		1786	
19-4	28.40	886		1830	
20-2	28.90	787		1952	
20-3	30.30	825		1796	
20-4	30.60	843		1914	
23-2	137.09	1277		2107	
23-3	106.20	1020		2047	
23-4	115.90	1044		2147	

24-2	121.99	1085	**1162**	2133	**2120**
24-3	124.40	1156		2107	
24-4	147.10	1244		2120	
25-2	35.36	893		1816	
25-3	31.00	789		1834	
25-4	28.60	694		1767	
34-2	71.14	1315		1911	
34-3	65.33	1152		1945	
34-4	69.95	1358		2152	
35-2	64.17	1352		2030	
35-3	56.81	1086		1995	
35-4	70.79	1231		1958	
37-2	38.96	1369		1861	
37-3	41.82	1169		1847	
37-4	37.30	1160		1901	
38-2	73.03	1075		1870	
38-3	72.59	1358		1956	
38-4	57.91	940		1862	
39-2	65.10	1268		1965	
39-3	63.20	1253		1917	
39-4	67.00	1378		1955	
43-2	22.90	1019		1870	
43-3	48.40	1549		1781	
43-4	41.40	1227		1865	
44-2	34.10	887		1964	
44-3	13.00	595		2017	
44-4	15.20	635		1512	

Table 4 - Toughness index summary for samples with fiber

sample	the wt.% of fiber	I_5	I_{10}	I_{20}
39-2	0.50%	4.5	6.5	7.9
44-3	1%	7.2	9.8	14.3
43-4	2%	7.5	15.3	21.1

Table 5 - Modulus of rupture for samples with fibers

sample #	Fiber content	fr-avg(psi)
35	0.30%	1223
39	0.50%	1300
34	0.70%	1275
38	1%	1125

Table 6 - Load-deflection Data for sample 39-2

Deflection(in)	Load(lb)	Ai(lb*in)
0	0.5976	0.0000
0.00345	27.3169	0.0481
0.00758	64.9515	0.1907
0.01158	32.9112	0.1955
0.01551	29.0460	0.1220
0.01937	27.1897	0.1085
0.02323	25.4733	0.1016
0.02709	23.9603	0.0954
0.03108	21.9451	0.0917
0.03494	20.1015	0.0811
0.03884	17.6857	0.0736
0.04274	15.9820	0.0656
0.04658	14.6661	0.0588
0.05047	12.9305	0.0538
0.05433	11.9642	0.0480
0.05825	10.8200	0.0446
0.06226	10.4830	0.0428
0.06616	9.8791	0.0397
0.07006	9.3260	0.0374
0.07392	8.5949	0.0346
0.07784	7.8321	0.0322
0.08171	7.6096	0.0299
0.08561	7.3998	0.0292
0.08953	6.8785	0.0280
0.09341	6.3826	0.0257

0.09732	5.7151	0.0237
0.10118	5.3337	0.0213
0.10504	4.8442	0.0196
0.10890	4.1131	0.0173
0.11282	4.0495	0.0160
0.11669	3.6808	0.0150
0.12059	3.2994	0.0136
0.12474	3.1087	0.0133
0.12862	2.8544	0.0116
0.13248	2.6001	0.0105
0.13642	2.5238	0.0101
0.14030	2.4094	0.0096
0.14419	2.1233	0.0088
0.14508	2.0914	0.0019
A_{20} = SUM(Ai)	1.8708(lb*in)	

Table 7 - Load Deflection Data for sample 43-4

Deflection(in)	Load(lb)	Ai(lb*in)
0	0.5213	0.0000
0.00582	8.1499	0.0253
0.00933	25.6195	0.0592
0.01610	33.6741	0.2007
0.01980	35.5812	0.1282
0.02315	38.0923	0.1233
0.02652	39.8406	0.1312
0.02984	41.0039	0.1345
0.03321	41.2900	0.1385
0.03656	40.9213	0.1375
0.04034	40.9404	0.1547
0.04370	39.5545	0.1355
0.04707	38.2831	0.1310
0.05047	36.9989	0.1282
0.05386	36.0135	0.1236
0.05748	35.1235	0.1288
0.06087	33.5469	0.1163
0.06421	32.7522	0.1110
0.06758	31.9894	0.1090
0.07093	30.9087	0.1052

0.07433	28.7981	0.1017
0.07817	27.1262	0.1073
0.08159	23.7124	0.0871
0.08500	22.3456	0.0784
0.08837	20.9279	0.0728
0.09173	19.4657	0.0680
0.09537	18.8618	0.0698
0.09874	18.3850	0.0627
0.10209	17.6222	0.0603
0.10547	16.4461	0.0577
0.10888	15.7023	0.0547
0.11221	15.0793	0.0512
0.11589	13.9350	0.0534
0.11927	13.0450	0.0457
0.12264	12.3139	0.0427
0.12600	11.5701	0.0402
0.12935	10.6165	0.0371
0.13301	9.9299	0.0376
0.13632	9.4532	0.0320
0.13969	8.6776	0.0305
0.14303	8.2008	0.0282
0.14636	7.5460	0.0262
0.14969	6.9293	0.0241
0.15370	6.5479	0.0271
0.15705	6.2110	0.0213
0.16039	5.9885	0.0204
0.16376	5.6388	0.0196
0.17024	5.2256	0.0352
A_{20} = SUM(Ai)	3.7145(lb*in)	

Table 8 - CTS Rapid Set Mix Proportions

CTS Rapid Set Cement All					
			Mix Proportion		
			w/c	Superplasticizer (%)	Fiber Percentage (%)
1	M	Control Mix	0.11	0	0
2	M2	Control Mix	0.152	0	0
3	M3	Control Mix	0.266	0	0
4	M4	Control Mix	0.4	0	0
5	M2SP	Control Mix	0.152	0.5	0
6	M2SP2	Control Mix	0.152	1	0
7	M2SP3	Control Mix	0.152	1.5	0
8	M2SP4	Control Mix	0.152	2	0
9	0.25SF	Control Mix with 3.6mm Steel Fibers	0.152	2	0.25
10	0.5SF	Control Mix with 3.6mm Steel Fibers	0.152	2	0.5
11	1SF	Control Mix with 3.6mm Steel Fibers	0.152	2	1
12	2SF	Control Mix with 3.6mm Steel Fibers	0.152	2	2
13	3SF	Control Mix with 3.6mm Steel Fibers	0.152	2	3
14	5SF	Control Mix with 3.6mm Steel Fibers	0.152	2	5
15	0.25BF	Contol Mix with 6mm Brass Fibers	0.152	2	0.25
16	0.5BF	Contol Mix with 6mm Brass Fibers	0.152	2	0.5
17	1BF	Contol Mix with 6mm Brass Fibers	0.152	2	1
18	2BF	Contol Mix with 6mm Brass Fibers	0.152	2	2
19	3BF	Contol Mix with 6mm Brass Fibers	0.152	2	3
20	5BF	Contol Mix with 6mm Brass Fibers	0.152	2	5
21	0.25CF	Control Mix with 6mm Carbon Fiber	0.152	2	0.25
22	0.5CF	Control Mix with 6mm Carbon Fiber	0.152	2	0.5
23	1CF	Control Mix with 6mm Carbon Fiber	0.152	2	1
24	2CF	Control Mix with 6mm Carbon Fiber	0.152	2	2
25	3CF	Control Mix with 6mm Carbon Fiber	0.152	2	3
26	5CF	Control Mix with 6mm Carbon Fiber	0.152	2	5
27	0.25SF2	Control Mix with 6mm Steel Fiber	0.152	2	0.25
28	0.5SF2	Control Mix with 6mm Steel Fiber	0.152	2	0.5
29	1SF2	Control Mix with 6mm Steel Fiber	0.152	2	1
30	2SF2	Control Mix with 6mm Steel Fiber	0.152	2	2
31	3SF2	Control Mix with 6mm Steel Fiber	0.152	2	3
32	5SF2	Control Mix with 6mm Steel Fiber	0.152	2	5
33	0.25SF3	Control mix with 13mm Steel Fiber	0.152	2	0.25
34	0.5SF3	Control mix with 13mm Steel Fiber	0.152	2	0.5
35	1SF3	Control mix with 13mm Steel Fiber	0.152	2	1
36	2SF3	Control mix with 13mm Steel Fiber	0.152	2	2
37	3SF3	Control mix with 13mm Steel Fiber	0.152	2	3
38	5SF3	Control mix with 13mm Steel Fiber	0.152	2	5

Table 9 – Quikrete - Non-Shrink Grout Mix Proportions

Quikrete - Non-Shrink Grout					
			Mix Proportion		
			w/c	Superplasticizer (%)	Fiber Percentage (%)
1	QM	Control Mix	0.12	0	0
2	QM2	Control Mix	0.158	0	0
3	QM3	Control Mix	0.24	0	0
4	QM2SP	Control Mix	0.158	0.5	0
5	QM2SP2	Control Mix	0.158	1	0
6	QM2SP3	Control Mix	0.158	1.5	0
7	QM2SP4	Control Mix	0.158	2	0
8	Q 0.25SF	Control Mix with 3.6mm Steel Fibers	0.158	2	0.25
9	Q 0.5SF	Control Mix with 3.6mm Steel Fibers	0.158	2	0.5
10	Q 1SF	Control Mix with 3.6mm Steel Fibers	0.158	2	1
11	Q 2SF	Control Mix with 3.6mm Steel Fibers	0.158	2	2
12	Q 3SF	Control Mix with 3.6mm Steel Fibers	0.158	2	3
13	Q 5SF	Control Mix with 3.6mm Steel Fibers	0.158	2	5
14	Q 0.25BF	Contol Mix with 6mm Brass Fibers	0.158	2	0.25
15	Q 0.5BF	Contol Mix with 6mm Brass Fibers	0.158	2	0.5
16	Q 1BF	Contol Mix with 6mm Brass Fibers	0.158	2	1
17	Q 2BF	Contol Mix with 6mm Brass Fibers	0.158	2	2
18	Q 3BF	Contol Mix with 6mm Brass Fibers	0.158	2	3
19	Q 5BF	Contol Mix with 6mm Brass Fibers	0.158	2	5
20	Q 0.25CF	Control Mix with 6mm Carbon Fiber	0.158	2	0.25
21	Q 0.5CF	Control Mix with 6mm Carbon Fiber	0.158	2	0.5
22	Q 1CF	Control Mix with 6mm Carbon Fiber	0.158	2	1
23	Q 2CF	Control Mix with 6mm Carbon Fiber	0.158	2	2
24	Q 3CF	Control Mix with 6mm Carbon Fiber	0.158	2	3
25	Q 5CF	Control Mix with 6mm Carbon Fiber	0.158	2	5
26	Q 0.25SF2	Control Mix with 6mm Steel Fiber	0.158	2	0.25
27	Q 0.5SF2	Control Mix with 6mm Steel Fiber	0.158	2	0.5
28	Q 1SF2	Control Mix with 6mm Steel Fiber	0.158	2	1
29	Q 2SF2	Control Mix with 6mm Steel Fiber	0.158	2	2
30	Q 3SF2	Control Mix with 6mm Steel Fiber	0.158	2	3
31	Q 5SF2	Control Mix with 6mm Steel Fiber	0.158	2	5
32	Q 0.25SF3	Control mix with 13mm Steel Fiber	0.158	2	0.25
33	Q 0.5SF3	Control mix with 13mm Steel Fiber	0.158	2	0.5
34	Q 1SF3	Control mix with 13mm Steel Fiber	0.158	2	1
35	Q 2SF3	Control mix with 13mm Steel Fiber	0.158	2	2
36	Q 3SF3	Control mix with 13mm Steel Fiber	0.158	2	3
37	Q 5SF3	Control mix with 13mm Steel Fiber	0.158	2	5

Table 10 – PennDOT – Approved Patching and Patch-Related Materials

Packaged Dry Cement

- Rapid Set Concrete Mix

Rapid Set Concrete Patching Materials – Cementitious, Non-Metallic, Non-Staining

- BC Quick Patch #2
- Swift Set 120
- IFSCEM 110
- Bonsal F-77 Construction Grout
- Power Set 120
- Power Set 120A
- IFSCEM 115
- Tyberpatch HS
- Pavemend 15.0
- CGM Highway Patch
- Chemspeed 65
- Pave Patch 3000
- Perma Patch
- HD-50
- Thoroc 10-60 Rapid Mortar
- Road Patch II
- Thorite
- Set Instant Concrete
- Emaco T415 Repair Mortar
- Euco-Speed
- Speed Crete 2028
- Speed Crete Green Line
- Express repair
- 5 Star Highway patch
- 5 Star Structural Concrete
- 5 Star Structural Concrete V/O
- Gill 33B & P Superbond
- Durapatch Hiway
- Crystex
- Rapid Road Repair
- FastSet™ Non-Shrink Grout
- FastSet™ Dot Mix
- CG FastSet™ Concrete Mix
- Sikatop III
- Sika Set Road Patch
- SikaQuick 2500
- SikaQuick 1000

Rapid Set Concrete Patching Materials – Magnesium Phosphate Cement-based Materials

- Duracal
- Duracal-S
- Magna 100
- Set 45 regular
- Set 45 Hot weather
- Euco-Speed M.P.
- Darex 240

Rapid Set Concrete Patching Materials – Magnesium Phosphate Cement-based Materials

- Duracal
- Duracal-S
- Magna 100
- Set 45 regular
- Set 45 Hot weather
- Euco-Speed M.P.
- Darex 240

Rapid Set Concrete Patching Materials – Polymer Mortar and Concrete

- Emaco 2020
- RM 698 Epoxy Patch
- Duracryl
- Dural 317
- Flexolith
- T17 Polymer Concrete

Polymer Modified and Special Cements, Mortars and Concrete

- BC Non-shrink grouting & Aggregate
- Speed Patch
- ThoRoc HB2 Repair Mortar
- Thorogrip Anchoring Cement
- Emaco T415 Mortar
- Emaco R320 CI
- Emaco S88-CI
- Emaco R320
- Emaco R310
- Emaco S66-CI
- Rapid Set Cement
- Rapid Set Concrete Mix
- Chem Comp III
- CTS Type K
- Day Chem Ad Bond (J-40)
- HD-25
- Type S Cement
- Type M Cement
- Type N Cement
- Eurocrete Thin Top Supreme
- FastSet™ Commercial Grade Concrete Mix
- Concrete Top Supreme
- Dural Top Fast Set
- Dural Top Gel
- High Power Fast Setting Concrete
- HiCap Light Patching Compound
- HiCap Patching Compound
- Flexkrete Technologies 102
- PipeWipe
- Type IP Blended
- T-SF Blended
- Permacrete
- Blend Crete
- Shotcrete MS
- FastSet™ Cement
- FastSet™ Repair Mortar
- FastSet™ Non-Shrink Grout
- FastSet™ Dot Mix
- Speedcrete Red Line
- Sikatop Plus 111
- Sikatop Plus 121
- Sikatop Plus 122
- Sikatop Plus 123
- Sikadur 42 Grout Pak
- Sika Cem 133
- High Power DOT Grade Repair Mortar
- High Power Cement
- Thin Top Supreme
- Duracal

Appendix B – Computations

Computation of Modulus of rupture

In a flexure test, assuming a linear stress distribution across the cross-section, modulus of rupture, f_r in bending is termed the maximum tensile stress reached in the extreme fiber at failure. It is obtained by applying the flexure formula:

$$f_r = \frac{M}{Z} \qquad \text{.......................} \ (3.1)$$

Where M is the bending moment at failure, and Z is the section modulus.

For a simply supported beam and a concentrated load in the midpoint of the beam,

$$M = \frac{1}{4}PL \qquad \text{.................} \ (3.2)$$

Where P is the concentrated load, and L is the span of the beam.

For a rectangular section

$$Z = \frac{1}{6}bh^2 \qquad \text{.............................} \ (3.3)$$

Where b is the width, and h is the thickness of the beam.

An empirical formula is suggested by American Concrete Institute (ACI) code to estimate the modulus of rupture of normal weight concrete. This formula is:

$$f_r = 7.5\sqrt{f'_c} \qquad \text{...........................} \ (3.4)$$

Where f'_c is the compressive strength of concrete expressed in psi.

Computation of Toughness index

In order to quantify the effect of fibers on the post –peak ductility, the toughness index approach was adopted. The toughness index I is based on the energy dissipation during a flexure test. It is defined as the ratio between the energy dissipated until a certain multiple of the first-crack deflection and that dissipated until first-crack deflection.
To characterize the toughness, ACI committee on Fiber Reinforced Concrete recommends obtaining toughness index by computing the ratio of the area under the load-deflection curve up to a given deflection divided by the area under the curve up to the deflection of first - cracking. The numerator of the index can be considered as the total energy up to a given deflection and the denominator can be considered the elastic energy. Indices are defined at a number of specific points corresponding in particular to 5, 10 and 20. For an elastic perfectly

plastic response, the values of the index I_5, I_{10}, I_{20} etc. are equal to 5, 10, 20, etc. If achieving an index $I_5 > 5$, $I_{10} > 10$, $I_{20} > 20$, etc. is an indication of quasi-strain hardening behavior; moreover, the farther the sequence can be extended, the more ductile the material is.

I = Area under the curve/ elastic energy

Elastic energy = ($P_{max} \times \delta_e$) / 2 .... (3.5)

$$\delta_e = \frac{P_{max} \cdot L^3}{48 \cdot E \cdot I} \qquad \text{......................... (3.6)}$$

Where δ_e is the first-cracking deflection, P_{max} is the maximum concentrated load, E is the elastic modulus of the beam section, L is the length between the two supports and I is the moment of inertia of the beam cross-section.
The positions of δ_e and $5\delta_e$ are shown in Figure 23. A_5 means the area under the curve up to the given deflection 5δe; W means the elastic energy; toughness index $I_5 = A_5/W$. Similarly, A_{10} means the area under the curve up to the given deflection 10δe and $I_{10} = A_{10}/W$; A_{20} means the area under the curve up to the given deflection 20δe and I_{20}= A20/W. Technically, the area under the curve is treated as the sum of the area of many small trapezoids but the unit is lb*in.

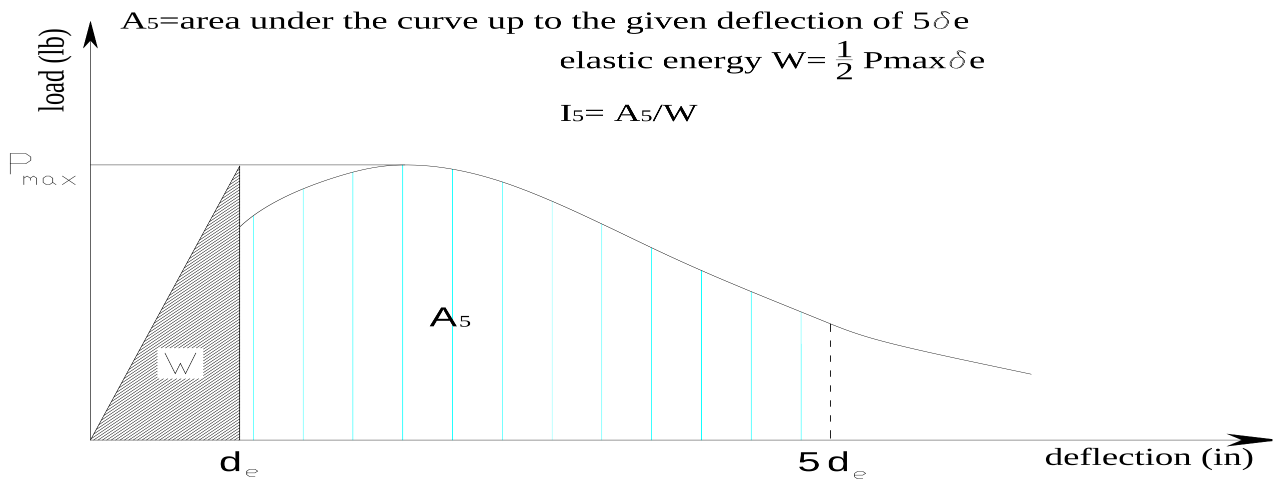

Figure 23. Graph for toughness index I_5

Computation of Toughness index (I)

Toughness index is an important parameter of fiber reinforced brittle matrices. This index not only provides a measure of the contribution of fibers but also can used for design and specifications. For example, strain hardening effect provided by fibers and load resistance even after cracking can be quantified using the toughness index. Therefore, this aspect is further elaborated in this section.

Essentially toughness index provides a measure of post peak resistance of fiber reinforced mortar (concrete). For unreinforced concrete the post-peak resistance is negligible and most case it is non-existent. This aspect is shown in Figure 24. It can be seen that fiber reinforced samples retained more than 80% of peak-load at 150% of deflection. This performance is consistent with the behavior of fiber reinforced Portland cement mortar (concrete).

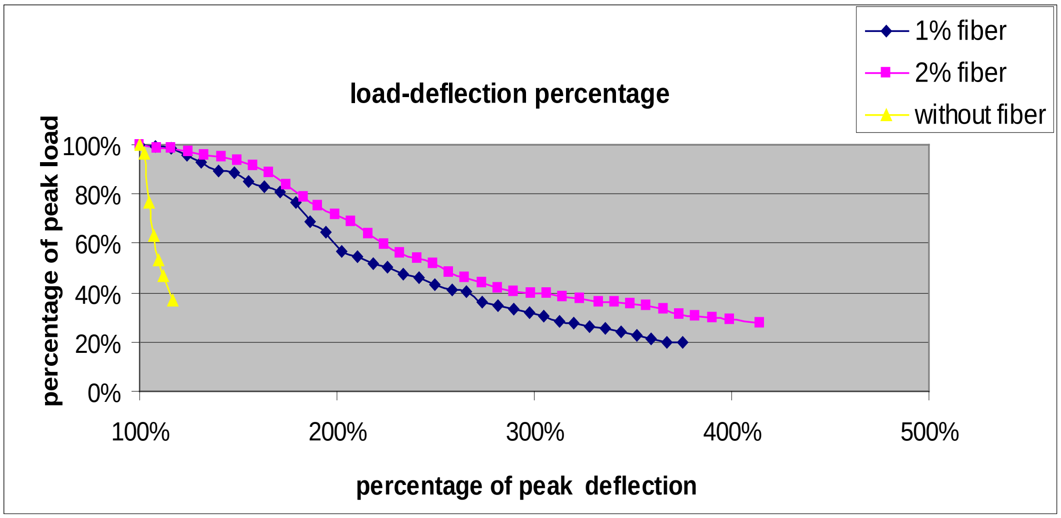

Figure 24. Influence of fiber on post-peak resistance

Computation of toughness indices are done using the load-deflection curves of samples tested under bending. A typical load-deflection curve for a fiber reinforced sample is shown in Figure 25. Toughness indices are calculated at various levels of post-peak deflection. The energy needed to reach the peak load is considered as elastic energy. Note that at the peak load the specimens crack and part of the tensile force resisted by matrix is transferred to the fibers. The fibers transfer the tensile stresses across the crack. Typically, the load capacity will drop after the first crack. The amount of drop in load depends on the fiber content and other fiber and matrix properties. The energy involved in the post-peak load is considered as inelastic energy which is quantified using toughness index. For example, toughness index I_5 is the ratio of: area under the load deflection curve at 5 times the peak-load deflection divided by the area under the load deflection curve at peak load.

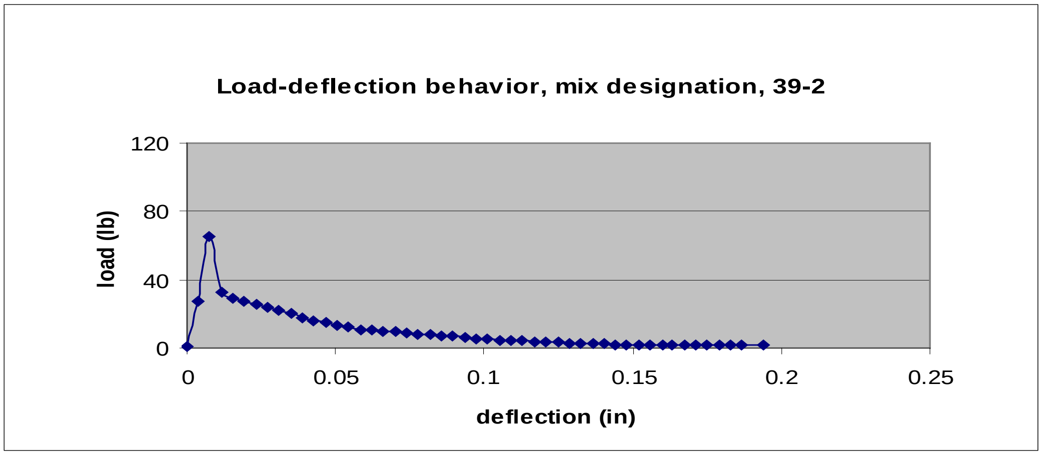

Figure 25. Load-deflection behavior of sample 39-2, fiber content of 0.5%

Computation of toughness indices for 3 samples are presented in the following sections. In order to obtain accurate values, it is recommended to use the actual deflections values obtained during the testing rather than using the graphs. Therefore, the values of loads and deflections are presented in tabular form for all the samples. If the behavior of elasto-plastic or there is no drop in load after peak load: I_5, I_{10} and I_{20} will be 5, 10 and 20 respectively.

Sample 39-2(fiber content is 0.5%)

The load deflection information is presented in Table 6 (See Appendix A – Tables).

The peak load is 65 lb and the deflection at peak load is 0.0076 in.
Therefore, elastic energy,

$$W = \frac{1}{2} P_{\max} \delta_e$$ = 0.236 in-lb.

I_5= Area under the curve up to 5δe / elastic energy

$$5\delta_e = 5 \times 0.0076 = 0.03627in$$

Area under the load deflection curve up to a deflection of 0.036 in is 1.0608.

Therefore,

$$I_5 = \frac{1.0608}{0.236}$$

$$I_5 = 4.5$$

A_{10} represents the area under the curve up to the deflection 10δe

I_{10}= Area under the curve up to 10δe / elastic energy

$$10\delta_e = 10 \times 0.007254 = 0.07254 in$$

$$I_{10} = \frac{1.5215}{0.236}$$

$$I_{10} = 6.5$$

A_{20} represents the area under the curve up to the deflection 20δe

I_{20}= Area under the curve up to 20δe/ elastic energy

$$20\delta_e = 20 \times 0.007254 = 0.14508 in$$

$$I_{20} = \frac{1.8708}{0.236}$$

$$I_{20} = 7.9$$

Since the fiber content was low, the flexural ductility for sample 39-2 is relatively low.

Sample 43-4 (fiber content is 2%)

The load deflection information is presented in Table 7 (See Appendix A – Tables).

$$I_5 = 7.2 > 5$$

$$I_{10} = 9.8 < 10$$

$$I_{20} = 14.3 < 20$$

Comparison of toughness indices of three samples with 0.5, 1.0 and 2.0% fiber content is presented in Figure 26. From this figure it can be seen that the increase in fiber content provide consistent improvement in toughness.

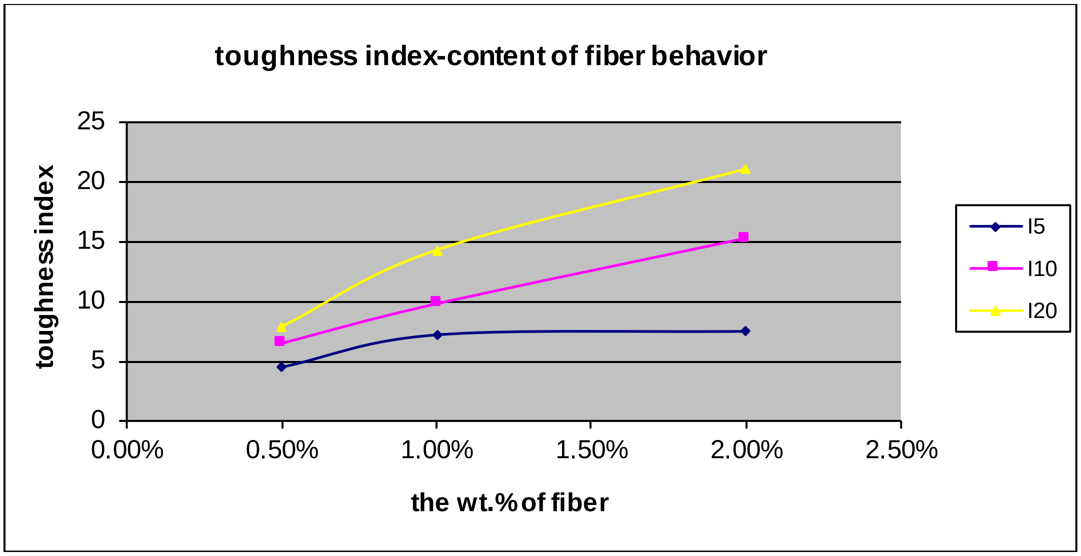

Figure 26 - Comparison of toughness indices

Appendix C – Manufacturer Product Specifications

CTS Cement Company: Sulfate Cement

CTS Cement Company is a major manufacturer of Sulfate Cements. The following are the basic information taken *verbatim* from the website of the company. The information is for a formulation developed specifically for highway applications.

Product Name

Rapid Set® DOT REPAIR MIX

Description

Rapid Set DOT REPAIR MIX is a high performance, fast setting, multi purpose repair material. Durable in wet environments, DOT REPAIR MIX is a blend of Rapid Set hydraulic cement, high performance additives and ASTM C33 concrete sand. DOT REPAIR MIX is non-metallic and no chlorides are added. Mix DOT REPAIR MIX with water to produce a flowable, quality repair material that is ideal where fast strength gain, high durability and low shrinkage are desired. DOT REPAIR MIX is ready for traffic and loading within 1 hour.

Uses

Use DOT REPAIR MIX for concrete repair, highway repair, dowel bar retrofit, construction of pavements and bridges, parking decks and ramps, sidewalks and steps, joint repair and formed work. DOT REPAIR MIX contains an air-entraining admixture, in some geographical areas, for freeze thaw durability.

Environmental Advantages:

Use DOT REPAIR MIX to reduce your carbon footprint and lower your environmental impact. Production of Rapid Set cement emits far less CO_2 than portland cement. Contact your Rapid Set representative for LEED values and further environmental information.

Applications

Apply DOT REPAIR MIX in thicknesses from 1/2" to 4" (1.2 cm to 10.2 cm). For thicker applications, DOT REPAIR MIX can be extended with up to 100% clean, dry coarse aggregate (up to 3/4") conforming to ASTM C33.

SURFACE PREPARATION

For repairs, application surface shall be clean, sound and free from any materials that may inhibit bond such as oil, asphalt, curing compound, acid, dirt and loose debris. Mechanically abrade surface and remove all unsound material. Apply DOT REPAIR MIX to a thoroughly saturated surface with no standing water.

Mixing

The use of a power driven mechanical mixer, such as a mortar mixer or a drill-mounted mixer, is recommended. Organize work so that all personnel and equipment are in place before mixing.

Use clean potable water. DOT REPAIR MIX may be mixed using 3 to 4.5 quarts (2.8 L to 4.3 L) of water per 55-lb (25 kg) bag. Use up to 5 quarts (4.7 L) when extended with dry coarse aggregate. Use less water to achieve higher strengths. Place the desired quantity of mix water into the mixing container. While the mixer is running add DOT

Repair Mix

Mix for the minimum amount of time required to achieve a lump-free, uniform consistency (usually 1 to 3 minutes). Do not retemper.

Placement

DOT REPAIR MIX may be placed using traditional construction methods. Organize work so that all personnel and equipment are ready before placement. Place, consolidate and screed quickly to allow for maximum finishing time. Use a method of consolidation that eliminates air voids. On flat work, do not install in layers; install full depth sections and progress horizontally. Do not wait for bleed water; apply final finish as soon as possible. DOT REPAIR MIX may be troweled, floated or broom finished. The working time for DOT REPAIR MIX is 10 to 25 minutes at 70°F (21°C). To extend working time use Rapid Set® SET Control® set retarding admixture LIMITED

Curing

Water cure all Rapid Set® DOT REPAIR MIX installations by keeping exposed surfaces wet for a minimum of 1 hour. Begin curing as soon as the surface starts to lose its moist sheen. When experiencing extended setting time due to cold temperature or the use of retarder, longer curing times may be required. The objective of water curing shall be to maintain a continuously wet surface until the product has achieved sufficient strength.

Yield & Packaging

DOT REPAIR MIX is available in 55 lb (25 kg) bags. One

55 lb (25 kg) bag of DOT REPAIR MIX will yield approximately 0.5 ft3. When extended 60% by weight with quality coarse aggregate, yield is approximately 0.7 ft3. When extended 100% by weight with quality coarse aggregate, yield is approximately 0.9 ft3.

Shelf Life

When stored in a dry location, out of direct sunlight, in an undamaged package, DOT REPAIR MIX has a shelf life of 12 months.

User Responsibility

Before using CTS products, read current technical data sheets, bulletins, product labels and safety data sheets at www.CTScement.com.

It is the user's responsibility to review instructions and warnings for any CTS products prior to use.

Quikrete Company: Modified Portland Cement

The basic information for the product used in this investigation was again taken from the website of the company.

Composition & Materials

FastSet™ Concrete Mix is made from a specially blended cement with carefully graded fine and coarse aggregates.
SIZE • 70 lb (31.8 kg) bag
YIELD One 70 lb (31.8 kg) bag of FastSet��Concrete Mix will yield approximately 0.52 cu ft (14.7 L).

Applicable Standards

ASTM International

- ASTM C39 Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens
- ASTM C191 Standard Test Method for Time of Setting of Hydraulic Cement by Vicat Needle
- ASTM C928 Standard Specification for Packaged, Dry, Rapid- Hardening Cementitious Materials for Concrete Repairs

Physical/Chemical Properties

FastSet™ Concrete Mix when tested in accordance with ASTM procedures provides typical results as listed in Table 1. FastSet™ Concrete Mix meets the requirements of ASTM C928 Type R3. It can be modified to meet specific requirements of the Department of Transportation of various states.

Table 11 - FASTSET™ CONCRETE MIX

TYPICAL PHYSICAL PROPERTIES	
Setting time final, ASTM C191	Final 25 - 45 min.
Slump, inches (mm), ASTM C928	> 3 in
Compressive strength, ASTM C39	3 hours 3000 psi (20.7 MPa) 24 hours 5000 psi (34.5 MPa) 7 days 6000 psi (41.3 MPa) 28 days 7000 psi (48.3 MPa)
Slant shear bond strength, ASTM C928	1 day 1000 psi (6.9 MPa) 7 days 1500 psi (10.3 MPa)
Shrinkage, ASTM C928	28 days in air > -0.03 28 days in water < +0.01
Scaling Resistance, ASTM C928	Visual

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