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Micro Fiber Reinforced Cement Paste and Mortar Overlays – A Review

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Abstract: All cement composites have same deficiencies; weak tensile strength (brittleness) and limited deformation capacity in the presence of cracking. Due to these deficiencies they need repairing and rehabilitation from time to time in order to prolong the life of existing concrete structures. An overlay of cement composite (upto 100 mm) is considered one of the most practical approach and economical options available but it envisaged to have suffer durability of pavement structure due to debonding and spalling. To inculcate such shortcoming, employment of micro-fibers reinforced cement composites is believed to be a viable solution. For a thin sheet fiber reinforced cement concrete having initial flaw of approximately 60 μm, fibers with diameter <30 μm will be deemed microdiameter fibers. Generally micro-fibers are fine fibers with lengths less than 10 mm and diameters in range 25-40 μm. With their high specific surface areas (> 200 cm^2/g), they provide a large number of fibers in a given section of the composites and thus furnish more effective reinforcing mechanisms at the microcracking level (cracking due to thermal and mechanical shrinkage). This review paper has been framed in a manner to compile the available literatures related to overlays using micro-fibers and to serve as a literature reservoir for research scholars. In the present paper, role of fiber in the performance of concrete, mechanism of microcracks form and grow in the frontal process zones and application of various micro-fibers in high performance concrete were discussed. Advantages of thinner fibers over thicker fibers, role of polypropylene fiber (PP fiber), Poly Vinyl Alcohol (PVA), steel micro-fibers, carbon micro-fibers, wollastonite micro-fiber were discussed elaborately.

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Introduction

Cement Limitations and Role of Fiber

Cement-based materials have a relatively low tensile or flexural strength compared with their compressive strength. Plain concrete fails in a brittle manner with little warning. Reinforcement of cement pastes with randomly distributed short fibers may improve the tensile strength and the toughness of cementitious matrices by preventing or controlling the initiation, propagation, or coalescence of cracks. An investigation into the reinforcing behaviour of fibers in various cement composites laid five stages of composite damage. They are: Zone I, linear-elastic behavior; Zone II, nonlinear deformation; Zone III, stable growth of the failure crack; Zone IV, unstable growth of the failure crack; and Zone V, fiber bridging of the crack.

In all the composites, fibers influence the fracture processes ahead of the crack tip in the frontal process zone (FPZ) and behind the crack tip in the crack bridging wake (Fig. 1). It is what happens in the FPZ that determines the first crack strength of the composite. Preventing the formation of the first crack is highly desirable in the design of durable thin sheet, fiber-reinforced cement composites [1]. Initial flaws are always present in any cementitious material, whether it is a plain cement paste specimen or a fiber-reinforced cement composite (FRCC). When load is first applied to the FRCC, areas of stress concentration develop at the tips of the initial flaws. With additional loading, microcracks form and grow in the frontal process zones ahead of the crack tips.

It is assumed that the initial flaw will extend into the microcracked region when the microcracking has reached a saturated level. Its appearance signifies the onset of permanent damage. Cracking may initiate the processes that reduce durability. If the crack opens, the reinforcing fibers are exposed to environmental deterioration processes. However, if the crack does not, durability is not necessarily reduced. Crack width is strongly influenced by the stiffness, volume fraction, and bond properties of the fibers [1].

Studies have shown that the flexural strength and toughness of cement pastes can be significantly improved by the addition of a limited amount (<10% by volume) of different types of metallic, synthetic, mineral, or natural microfibers [2-5]. With proper incorporation of fibers, the failure mode of concrete can change from brittle to quasi-ductile [6-9]. The toughness of the material (measured, for example, from the area under a complete load-displacement curve) can also be significantly increased.

In concretes, it is normally the cement gel or hardened cement paste that shrinks, whereas the aggregate grains from most of the rock materials do not shrink or even restrain the shrinkage of the cement gel [10]. For this reason, the shrinkage of a concrete made of an aggregate made with a higher-strength rock is less than in the case of an aggregate made with a lower-strength rock. Consequently, tensile stresses arise in the cement paste, which quickly reach the tensile strength of a young concrete. The additional internal stresses that occur during the period of hydration of the cement are further increased by the temperature gradient that results from the heat of hydration released during the concrete hardening process. The occurrence of early cracks in concrete during its hardening is a consequence of these two physical phenomena mentioned.

Micro-fiber's Use in Repair Work

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Repair works suffer from debonding and spalling of concrete layer. The major reasons often cited for debonding and spalling of repairs are differential thermal movements, elastic incompatibilities, shrinkage stresses, occasional impact; rebar corrosion, substrate deficiencies, frost action, and poor workmanship [11-14]. These same reasons are responsible for cracks in an otherwise, a simple concrete pavement topping. Given these reasons for spalling and debonding of repairs, durable thin repairs (less than 25 mm thick) are particularly difficult to achieve. For a durable repair, the desired characteristics of the repair material include low permeability, a high tensile strength, adequate impact resistance, sufficient deformability (ductility), high fracture toughness, low shrinkage, good dimensional stability, good abrasion resistance, and most of all, a strong tensile and shear bond with the base concrete. Reinforcement of cement-based materials with metallic, synthetic, and natural fibers has produced composites with much of the preceding desired characteristics for a repair material [15]. For thin repairs, however, the maximum dimensions of both the aggregate particles and the fibers have to be limited. Consequently, for thin repairs, the use of cements and mortars reinforced with very fine fibers (often called "micro-fibers") is conceivable.

When used in mortars, the micro-fibers provide little, if any, improvement of the mechanical properties. Boisvert et al. concluded that the relatively poor mechanical properties observed for steel and carbon micro-fiber reinforced mortars are due, at least in part, to the fact that these mortars have an air content (up to 40% by volume in the paste) that is significantly higher than the air content in the corresponding cement pastes (1–7%) [16]. Hence certain additives and measures are needed to be taken, to make the use of micro-fibers in cement mortar beneficial.

Application in Ultra High Performance Concrete (UHPC)

Apart from cement pastes and mortars, a specific application of micro-fibers is their use in UHPC (Ultra high performance concrete), which would be discussed in detail later. UHPC's high strength, enhanced durability and lesser thickness motivates its use, in an increasing number of applications. The major problem associated with UHPC is shrinkage cracks. Once occurred, these cracks later facilitate the penetration of aggressive substances to concrete, leading to a reduction in its performance, serviceability, and durability [17].

Several methods have been advocated to minimize the cracking potential of concrete, including using coarser cement particles, expansive additives, shrinkage reducing admixtures and/or improving curing conditions [18-20]. These approaches primarily focus on reducing shrinkage strains in concrete, thereby reducing the level of residual stress that develops [21]. Different types of micro-fibers too, have been used as reinforcements for cementitious materials including organic, mineral, metallic, or synthetic micro-fibers [22, 23]. Metallic and wollastonite micro fibers have found beneficial use in UHPC.

Micro-fibers Reinforced Overlays

The benefit trend of fiber use has been given in the serial order of their appearance, as following:

Polypropylene Micro-fiber

Saje et al. investigated the time development of the shrinkage of polypropylene fiber-reinforced high-performance concrete [10]. The volumetric content of polypropylene fibers contained in the investigated concretes varied from 0 to 0.75%. Within this context, the influence of both dry and previously moistened polypropylene fibers added to the concrete on the shrinkage of the composites was examined. It was found that by increasing the content of the fibers up to 0.5% of the volume of the composite, the shrinkage of the fiber-reinforced concrete was considerably reduced, whereas with further increasing of the fiber content, the shrinkage reduction rate became relatively insignificant. The concrete that had been reinforced by previously moistened polypropylene fibers, which served as an internal water reserve, exhibited a lesser degree of early autogenous shrinkage than the concrete that had been reinforced by dry polypropylene fibers. The drying shrinkage of high-performance concrete, reinforced by previously moistened polypropylene fibers, was, however, approximately twice as large as that of dry polypropylene fiber-reinforced high-performance concrete.

Banthia and Gupta found that polypropylene fiber reinforcement was very effective in limiting cracking in concrete [24]. They suggested that polypropylene fibers generally result in a favourable decrease in the width and number of cracks. Thinner fibers are, according to them, more effective than thicker ones, and longer fibers are in turn more effective than shorter ones.

Kovler et al. stated that the presence of polypropylene fibers results in a considerable decrease in the plastic shrinkage of fiber-reinforced concrete [25]. With regard to the total shrinkage of fiber-reinforced concrete, they stated that the effect of polypropylene fiber reinforcement is virtually insignificant up to a volumetric content of 0.2%. According to their findings, crack width can be reduced by as much as 50% by increasing the volumetric content of polypropylene fibers. Swamy and Stavrides also found that the drying shrinkage of polypropylene fiber-reinforced concrete was about 20% less than that of concrete without added fibers [26]. Zollo and Zollo et al. have argued that, in the case of an appropriate quantity of added polypropylene fibers, the drying shrinkage of concrete can be reduced by as much as 75% [27, 28].

Bayasi and Zeng who investigated the influence of reinforcing fibers on the compressive strength of fiber-reinforced normal-strength concrete found that, concrete compressive strength increased by 15% when reinforced with 1.27-cm-long polypropylene fibers with a volumetric content of 0.1% and by 19% in the case of a volumetric content of 0.3%, whereas at a volumetric content of 0.50%, it decreased by 2.5%, compared with concrete having no reinforcing fibers [29].

Myers et al. however, are of the opinion that, when added to concrete, polypropylene fibers exert a very small influence on shrinkage [30]. Aly et al., who studied the effect of polypropylene fibers on the shrinkage and cracking of normal strength concrete [31], concluded that the shrinkage of test specimens made of fiber-reinforced concrete containing 0.50% by volume of polypropylene fibers increased by 15% after they were cured for 1 day and then exposed to a temperature of 23℃ and a relative humidity of 50%; and by 22% after they had been cured for 7 days, when compared with the shrinkage of concrete containing no polypropylene fibers. At the same time, however, they stated that their results were in disagreement with those of several other authors. They justified their results with the increased porosity of fiber-reinforced concrete as compared with the porosity of concrete having no fibers and with the accelerated decrease of moisture in fiber-reinforced concrete. From all the studies it is for sure that fibers' geometry bring certain change in the shrinkage of the cement composites.

Polyvinyl Alcohol Micro-fiber

Lawler et al. in a study, achieved a workable blend of micro-fibers {steel and polyvinyl alcohol (PVA)} and macrofibers in concrete and evaluated the flow of the wet mixture, mechanical performance, resistance to restrained ring shrinkage cracking and cracked permeability of concrete [32]. In terms of ultimate strength, the steel hybrid mixture performance was comparable to the macrofiber while the Poly Vinyl Alcohol (PVA) hybrid exceeded it by a significant margin. The toughness of the PVA hybrid was greater than that of the macrofiber mixture in flexural displacements less than 0.5 mm but not superior at larger deformations. Beneficial effects of the micro-fiber in the flexural testing were seen up to and shortly after the peak.

The mixture containing the PVA micro-fiber hybrid showed retarded development of restrained ring shrinkage cracking as the micro-fibers delayed the coalescence of cracks. However, at 44 days of age, the total crack width was approximately the same as that seen for the macrofiber specimen and much below that observed in the unreinforced concrete. The flow rate of water through cracked concrete is governed by the crack pattern. This is because for laminar flow conditions, flow rate is proportional to cube of crack width. For a given deformation, a specimen with multiple cracks will display much less permeability than a similar specimen with only one crack. While crack tortuosity was increased through the use of hybrid reinforcement, resulting in a small but significant drop in permeability, the hybrid reinforced composite material was not able to carry a high enough postpeak stress to cause additional cracks to develop [33]. Macrofiber reinforcement, on the other hand, resulted in multiple cracking and produced a lower permeability. Contrary to the trends observed in mortar, when used in the higher strength concrete, the PVA micro-fiber hybrid reinforcement was less effective at improving mechanical performance and reducing the crack permeability than macrofiber-only reinforcement. While initial, first cracking strength was improved by the hybrid, this improvement was not maintained much past the peak load as it was in the mortar matrix. This may be explained by the difference in the failure mechanism of the micro-fibers in the concrete compared to the mortar. The lower water/binder ratio in the concrete (less than 0.33 compared to 0.45 in mortar) produced a stronger matrix and stronger fiber-matrix bond and the micro-fibers broke instead of debonding and pulling out. This process consumed less energy so the micro-fibers were less effective at improving the composite toughness. In the dense concrete matrix, the micro-fibers increased the likelihood of macrofibers breaking. This type of macrofiber failure was much more likely to occur in the hybrid than in the concrete containing the macrofiber alone.

Steel Micro-fiber

Fwa & Paramasivam employed one mortar mix with a water/cement ratio of 0.55:1 and one type of steel fiber to evaluate the feasibility of using thin steel fiber cement mortar overlay for the rehabilitation of surface-deteriorated concrete pavements, with improved resistance to surface abrasion, and a load-carrying capacity equal to or higher than the original design [34]. The proportions of cement and sand used were 1:1.5 by weight. An accelerator was added at 1 litre per 22 kg of cement to give the desired high early strength. The steel fibers used were of the hook-end type, 30 mm long with an equivalent diameter of 0.4 mm.

Two surface abrasion tests were included in the preliminary phase. They are referred to as the polishing wheel test and the modified Dorry abrasion test. Flexural tests were conducted using prisms 500 mm long with cross-sections of 100 mm x 100 mm. Overlay thicknesses of 25 mm and 40 mm were studied. Flexural tests by means of third-point loadings were conducted for three cases as follows:

i. Tests producing tension in the bottom face of sound base concrete.
ii. Tests producing tension in the overlay which was cast on a sound base concrete.
iii. Tests producing tension in the overlay which was cast on a base concrete with a crack in its top surface. The base member was first loaded by third-point loading up to the peak resistance when a crack was formed close to the mid-span point. The crack usually measured between 0.04 mm and 0.20 mm in width, and extended to a depth between 50 and 75% of the thickness of the beam.

The test results suggested that 1% steel fiber cement mortar overlay would satisfactorily rehabilitate a surface-deteriorated concrete pavement, and that overlay 40 mm thick is preferable to overlay 25 mm thick.

Carbon Micro-fiber

Banthia and Dubeau investigated the effect of addition of carbon and steel micro-fibers separately to the cement composites [35]. It was concluded that more effective strengthening and toughening occurred due to carbon fibers as compared to steel fibers. At a low temperature of -50℃ fibrous composites are stronger but more brittle than at a temperature of 22℃. In general, the peak loads in the case of carbon fiber-reinforced composites occur at greater displacements than those for composites containing steel fibers. Tensile bond strength too showed an increase at low temperatures compared to normal, which was apparently negligible.

Chen and Chung used short pitch-based carbon fibers (0.5% by weight of cement, 0.189% by volume of concrete), together with a dispersant, chemical agents and silica fume, in concrete with fine and coarse aggregates [36]. An increase of 85% in flexural strength, 205% in flexural toughness, 22% in compressive strength was found, with an increase of 39% in material price. The slump was 102 mm at the optimum water/ cement ratio of 0.5. The air content was 6%, so the freeze thaw durability was increased, even in the absence of air entrainer. The aggregate size had little effect on the above properties. There was a decrement in drying shrinkage and electrical resistivity by up to 90% and 83% respectively.

Deng investigated [37] carbon fiber reinforced concrete by three point bending tests. The test results showed that the fracture parameters of carbon fiber reinforced concrete and plain concrete are reduced if the pre-cyclic loading stress levels are higher than a certain threshold, and this threshold value for carbon fiber reinforced concrete is higher than that of plain concrete. The critical effective crack length for carbon fiber reinforced concrete is significantly larger than that of plain concrete and independent of the pre-cyclic loading history and fatigue life. The flexural fatigue life of carbon fiber reinforced concrete beam with a central notch is much larger than that of the matrix, i.e., fatigue life of carbon fiber reinforced concrete with maximum volume fraction of 0.3% is about 2.8 times higher than that of plain concrete when the fatigue stress level is 0.9.

Hong and Choi [38] investigated nonlinear material behavior in tension of steel–carbon hybrid fiber reinforced cementitious composites (FRCC). The results showed that carbon in FRCC, contributes toughness in tensile behavior before reaching the maximum crack opening while steel in FRCC contributes tensile strength. As steel fiber content increased and carbon fiber content decreased, tensile strength showed an increase while the toughness index decreased. Since tensile behavior at large crack widths is predominantly governed by the steel fibers, fracture energy is mainly dependent on the steel fiber content rather than on the carbon fiber content.

Wollastonite Micro-fiber

Wollastonite is a naturally occurring, acicular, inert, white mineral (calcium meta silicate [ß - CaO-SiO2]) of high modulus of elasticity, which is less costly than steel and carbon micro-fibers [39]. Prices for wollastonite range from $0.2/kg to $0.37/kg depending of its size, which is substancially cheaper than that of steel ($6.6/kg) [40], carbon ($11/kg) or glass ($2/kg) fibers [41]. It is formed due to interaction of lime-stone with silica in hot magmas. It is formed in nature by the reaction of calcium carbonate CaCO3 with silica SiO2 in hot magmas. It contains nearly equal proportions of lime and silica; up to 45% each respectively. Therefore it is self cementitious too, in addition to being a pozzolan; also called as class C pozzolan. Wollastonite is mined commercially for use in refractory ceramics and as a filler in paints. The processed granular material is of high purity, inexpensive, and readily available.

Available in abundance along the Udaipur belt of Rajasthan state of the Indian union as a low cost material, it may be ground to fine powder, and is already finding applications in paint, dental care, ceramic tiles to name a few. Its composition of nearly equal proportions of lime and silica having fine particle size were favorable indicators for its admixing in concrete by partial replacement of cement. In itself, wollastonite does not possess binding properties like cement, but, in presence of microsilica, it improves the properties of admixed concrete by fine packing of inert material.

Microsilica is a by-product of silicon metal or ferro-silicon alloy industries. Its high siliceous composition and very fine particle size were utilized beneficially, under controlled volume in many works, to improve the properties of fresh and hardened concrete. One such study by Yener and Hinislioglu found that micro silica use in concrete slightly increased 28-days flexural strength and decreased the amount of liquid absorption by capillary suction thus increasing scaling resistance [42]. Ransinchung and Kumar found that micro silica when used with cement paste and mortar improved workability and compressive strength [43]. Both of these studies stated the reason for this phenomenon as: (1) strength enhancement by pore size refinement and matrix densification; (2) strength enhancement by reduction of Ca(OH)2 content; and (3) strength enhancement by cement paste-aggregate interfacial zone refinement. At larger contents, its excess doesn't improve mechanical properties further, but only cause the reduction in workability, because of the water demand increment caused by a subsequent increment in surface area. Reactivity of amorphous silica is directly proportional to the surface area.

Soliman and Nehdi investigated the effect of incorporating wollastonite micro-fibers in ultra-high performance concrete (UHPC) on its early-age properties [44]. UHPC can be achieved through enhancing homogeneity (for instance by eliminating coarse aggregates) [45], producing stronger and higher packing density microstructure through using very low water to cement ratio [46], and incorporating a high content of effective pozzolans. However, this unique mixture composition of UHPC increases its tendency to undergo early-age cracking [47]. Early-age cracking of cement based materials arises from the early rapid volume changes as a result of autogenous and drying shrinkage and thermal deformations [48]. Such volume changes induce tensile stresses within cement based materials. The tensile strength of such materials and its ability to resist tensile stresses increase with time [49]. Hence, a competition between the induced tensile stresses and the development of tensile strength of cement-based materials exists during early-ages. Once tensile stresses exceeded the tensile strength, micro-cracking develops and propagates leading to visible shrinkage macro-cracking.

Wollastonite micro-fibers were added at 0, 4, 8 and 12% as partial volume replacement for cement. Results showed that the early-age properties of UHPC mixtures incorporating wollastonite micro-fibers are highly affected by the micro-fibers content and aspect ratio. Increasing the wollastonite micro-fibers content resulted in compressive strength comparable to or higher than that of the control mixture without micro-fibers. Wollastonite micro-fibers reduced shrinkage strains and increased cracking resistance compared to that of the control mixture. However, no significant improvement in the flexural behavior was achieved with the addition of wollastonite micro-fibers apparently due to a sudden rupture of micro-fibers within the matrix [44].

Low and Beaudoin investigated the factors that influence the flexural strength characteristics of the cement-water and the cement-silicafume-water systems reinforced with inorganic wollastonite micro-fibers [39]. The effect of the wollastonite micro-fibers on matrix pore structure was investigated using mercury intrusion porosimetry and helium gas pycnometry. Fiber-matrix interaction was also examined using the conduction calorimetry method. Results from the study proved that incorporation of the wollastonite micro-fibers into cement and cement-silica fume matrices improves both the pre-peak and post-peak load-deflection response resulting in higher flexural strength and better ductility characteristics. It also modifies the microstructure of the cement based composite systems. Porosity, pore size distribution and solid density of the hydrated phases were significantly different in the cement-wollastonite and in the cement-silica fume-wollastonite composite systems. Wollastonite micro-fibers and silica fume addition appear to promote pore discontinuity in cement systems. It was suggested that, on the basis of conduction calorimetry measurements, there is no apparent chemical interaction between the wollastonite micro-fibers and the cement matrix during the hydration process. In a similar study Ransinchung et al. testified that up to 15% of wollastonite and 7.5% microsilica can be advantageously admixed with cement to significantly improve the water tightness of concrete, due to reduction in pore space and refinement of microstructure [50]. In case of wollastonite and microsilica reinforced mortar investigation, Ransinchung and Kumar concluded that mortar, which contains 82.5% cement, 10% wollastonite, and 7.5% microsilica, as cementitious material attains the highest compressive strength [43]. The mortar, which contains 77.5% cement, 15% wollastonite, and 7.5% microsilica, as cementitious material achieves compressive strength higher than the conventional OPC mortar along with rendering maximum cement replacement for better economy of concrete work. It was observed that the compressive strength of mortar varied logarithmically with the days of moist curing and linearly with the proportion of admixing.

Method of Use

Concrete mix design method developed by Lawler is being preferred when steel macrofibers and steel or PVA micro-fibers are to be incorporated in the concrete mixes [33]. This concept is based on the optimum paste volume i.e. the minimum paste content that produced stable (resistant to bleeding) and maximum flow, is determined. This is done by evaluating the percentage flow (the percent increase in diameter of a concrete sample after removal of a forming cone and dropping the sample 13 mm, 25 times) of trial batches using a drop table according to ASTM C 230. Superplasticizer dosage is optimized in an incremental process to give the best workability possible while avoiding bleeding that result from an overdose. Stability is also considered; mixes in which bleeding and non uniformity or segregation of the constituents is observed are rejected. Fly ash replacement improves flow and is helpful for achieving a stable mix. A low water-binder ratio is used to reduce susceptibility to bleeding and to maximize the strength of the hardened concrete. During this evaluation, the macro-fiber concrete volume ratio is held constant as is the micro-fiber paste volume ratio. The optimum in this context is defined as a paste volume above which no additional flow is achieved and which is sufficiently high that small variations in batch quantities can be expected to have little effect on flow.

Dispersion of the fibers is important and is particularly challenging for micro-fibers at a small volume fraction. Chung assessed the degree of dispersion of short micro-fibers (such as carbon and steel fibers) in cement mortar or cement paste by measurement of the volume of electrical resistivity when the fibers were electrically conductive and were at a volume fraction below the percolation threshold [51]. Assessment of the degree of fiber dispersion by microscopy was reported to be ineffective in the study. It was found that the degree of dispersion is improved by the use of admixtures such as silica fume, acrylic particle dispersion, methylcellulose solution, and silane. Acrylic particle dispersion is more effective than latex particle dispersion.

Case Study

In Tennessee, a project involving polypropylene fiber reinforced ultra-thin white-topping (UTW), to experimentally repair road intersection was taken [52]. Procedure involved placing a layer 50 to 75 mm (2 to 3 in.) thick of high-strength polypropylene fiber reinforced concrete over milled asphalt. The use of polypropylene fibers allowed the concrete to be placed at a minimum thickness that did not encapsulate the wire mesh with sufficient concrete cover. Crucial to a long life for the thin concrete, a high synthetic fiber content, normally 1.4 kg/m3 (lbs/yd3) with joints spaced at a minimum of 0.92 to 1.22 m (3 to 4 ft) on centre, was provided. From 1992 to 1995, seven cities in Tennessee participated in UTW demonstrations. The primary use of UTW is to rehabilitate high average daily traffic intersections. Other potential uses include overlays of residential streets, parking lots, and airport aprons.

An unbonded Portland cement concrete pavement (PCCP) overlay was designed and built on 1-29 in Atchison County in north-western Missouri [53]. The location of the project is between Route A and US 136 in the southbound lanes. Eight test sections were established in the unbonded overlay. Three of the test sections were reinforced with steel fibers, three of the test sections were reinforced with polyolefin fibers and two of the test sections were non-reinforced PCC. There were fiber-reinforced test sections 9", 6" and 5" thick for each type of fiber reinforcement. Transverse joint spacing varied in the fiber reinforced sections from 15' to 200'. The two non-reinforced PCC test sections were 9"and 11" thick and all transverse joints were spaced at 15'.

The overlay was designed as an unbonded overlay, using a 1" bituminous interlayer, to decrease the reflective cracking of joints and cracks from the existing pavement into the new overlay. MoDOT (Missouri- Department of transportation) determined the compressive strength at 7 and 28 days and the flexural strength at 7 and 28 days for the steel fiber-reinforced concrete, the polyolefin fiber-reinforced concrete and the non-reinforced concrete mixes used in the overlay. Pavement distress surveys were performed at 1 day, 2 weeks, I month, 3 months, 6 months, 1 year. The University of Missouri-Columbia determined toughness and fatigue endurance. For this project, the cost of furnishing the steel fiber-reinforced concrete was $47.00/cu.yd. (cubic yard) more than the non reinforced concrete. Furnishing the polyolefin reinforced concrete was $60.00/cu. yd higher than the non-reinforced concrete. In this study, the use of polyolefin fibers mixed at 25 lbs./cu. yd. (pounds/ cubic yard) in concrete led to a significant decrease in compressive and flexural strength at 28 days, when compared to a non-reinforced concrete of similar mix proportions. The use of steel fibers in concrete had little effect on the compressive and flexural strength at 28 days. Both the steel fibers and the polyolefin fibers exhibited some non-uniform distribution of fibers in the concrete. The polyolefin fibers appeared more susceptible to mixing inconsistencies such as fiber balling and the presence of uncoated

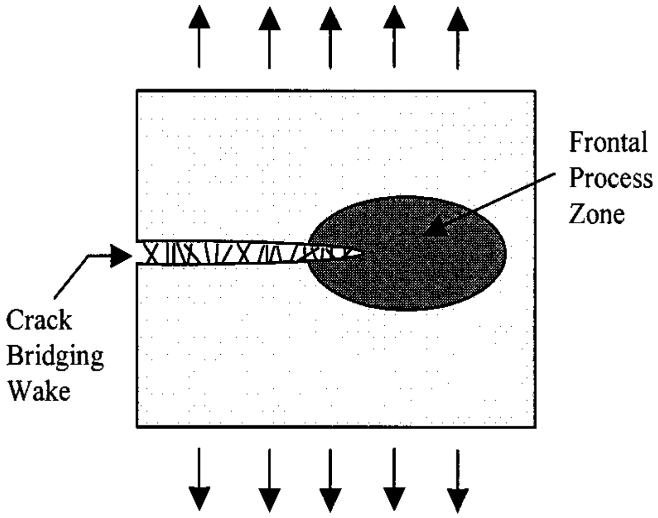

Fig. 1. Schematic of Composite Frontal Process Zone (FPZ) and Crack Bridging Wake [1].

fibers in the mix than the steel fibers. Diamond grinding of the PCCP overlay provided a smooth profile with no detrimental effect on the action characteristics of the pavement.

Lessons Learned

From the Tennessee test sections, it was learned that:

1. There are three potential causes for UTW failure: HMA thickness after milling, inadequately prepared asphalt base, and insufficient bond between concrete and asphalt.
2. To ensure an adequate base, it is necessary to core the site before construction, to make it certain that a minimum of 75 mm of asphalt will remain after the milling. To maximize bond, the milled surface must be properly cleaned.
3. The best joint spacing appears to be a ratio of 0.3 m/25 mm (1 ft/1 in.) of concrete depth. Exceeding this rule of thumb tends to exacerbate corner cracking, which is an aesthetic, not structural, problem.
4. The Tennessee DOT had chosen to use a minimum thickness of 75 mm on state-maintained roadways. 50 mm (2 in.) thickness needed joint spacing of 0.61 m (2 ft) which was more expensive.
5. The sawing of joints must be started as soon as the operator and equipment can be supported by the concrete. Some light foot tracks may occur when sawing this soon, but they seem to disappear with a few days' wear on the surface. Brooming and tining also can be done very early. A deep texturing of the surface is desirable for surface traction.
6. A concrete mix with a compressive strength of 20.67 MPa at 24 hr can be achieved by maintaining a low water-to-cement ratio. Traffic can be allowed on the surface within 18 to 24 hr. The use of a combination of admixtures, such as normal water reducers and high-range water reducers, will always cause retardation. This usually causes problems for the finishing crew by extending the time required for sawing by several hours and may also retard enough to lower the strengths at 18 and 24 hr. It is therefore best to use high range water reducers only in achieving slump requirement.
7. Using 1.362 kg of polypropylene fibers per 0.765 m^3 (1 yd) appears to provide superior ductility and strength while improving impact, crack, and freeze-thaw resistance. This figure is double the normal quantity of fibers used in industrial slabs.

Based on data from one year of service from Missouri test section it was learned that:

1. The steel fiber-reinforced sections of the unbonded overlay exhibited more transverse cracking than the polyolefin fiber-reinforced sections. Overall the steel fibers restricted the opening of cracks more than the polyolefin fibers.
2. The thickness of the overlay greatly impacted the development of transverse cracks in the overlay. In general, the thinner sections developed more transverse cracking than the thicker sections.
3. The small coverage of concrete over the dowel bars at transverse joints in the 5" steel fiber-reinforced sections contributed to spalling over those dowel bars. The thin overlay provides very little cover for the dowel bars, which can lead to spalling. The use or size of dowel bars for load transfer in thin overlays should be reconsidered.
4. A 1" thick asphalt interlayer treated with the white-pigmented curing compound sufficiently isolates the overlay from the existing pavement.
5. For long run (crack and fatigue resistance) steel fibers are better, inspite of the fact that, steel fibers don't cause much increase in compression and flexural strength in comparison to polyolefin fibers.

Conclusion

The following conclusions were drawn from the above literature review:

1. Micro-fibers resist the development of initial crack in cement pastes and mortars, and since ultimate strength depends upon the onset of initial crack development, thus micro fiber reinforcement is a necessity in concrete pavements, especially thin overlays where shrinkage and warping cracks originate to a large extent. As the thickness of section increases, the aggregate size increases and the mortars turns more and more into a concrete. For concrete, the ultimate strength remains unaltered for hybrid reinforcement, whereas it improves for macro-fiber reinforced concrete. Hence microfibers are effective only for cement pastes or high strength thin concrete overlays which are more alike mortar, where the water/cement ratio is high; and not for concrete in whom if a high water/cement ratio is there, will result in breakage of macro-fibers with lesser energy consumption.

2. As is clear from the case study that PP fibers improve the ductility and freeze thaw resistance of overlays but they are not a reliable solution for improving mechanical properties and porosity resistance. Steel and carbon micro-fibers, since provide reliable results for all cement composites, thus prove to be better option than PVA and PP fibers. The only disadvantage of their use is their high cost and more transverse cracking in thinner overlays.

3. Wollastonite micro-fiber proves to be a better fiber for all cement composites and moreover for all properties, especially for repair works due to its smaller size (approx 5μm). Though it needs

micro silica as an admixture for better performance, but the quantity of micro silica so needed is small enough to be neglected, seeing the benefit caused by replacement of cement with wollastonite. Hence it improves the mechanical properties of concrete overlays in addition to replacing the cement due to Class C pozzolanic action. Therefore its use is more economical with respect to other microfibers.

References

1. Nelson, P.K., Li, V.C., Kamada, T. (2002). Fracture Toughness of Micro-fiber Reinforced Cement Composites, *Journal of Materials in Civil Engineering*, 14(5), pp. 384–391.
2. Bentur, A. and Mindess, S. (1990). Fiber reinforced cementitious composites. Elsevier Science, London, UK.
3. Beaudoin, J.J. (1990). Handbook of fiber-reinforced concrete: Principles, properties, developments, and applications, Noyes Publications, NJ, USA.
4. Banthia, N. and Sheng, J. (1991). Strength and toughness of cement mortars reinforced with micro-fibers of carbon, steel, and polypropylene, *Proceedings, 2nd Canadian Symposium on Cement and Concrete*, N. Banthia, ed., Vancouver, Canada.
5. Soroushian, P. and Marikunte, S. (1991). Cellulose fiber reinforced cement composites: State-of-the-art, *Proceedings, 1st Univ.-Industry Workshop on Fiber Reinforced Concrete*, N. Banthia, ed., pp. 44–58.
6. Li, V.C. and Leung, C.K.Y. (1992). Tensile failure modes of random discontinuous fiber reinforced brittle matrix composites, *Journal of Engineering Mechanics*, ASCE, 118(11), pp. 2246–2264.
7. Li, V.C. and Wu, H.C. (1992). Micromechanics based design for pseudo strain-hardening in cementitious composites, *Proceedings, 9th ASCE Conf. on Engineering Mechanics*, L.D. Lutes and J.M. Niedzwecki, eds., Reston, VA, USA, pp. 740–743.
8. Li, V.C. and Wu, H.C. (1992). Conditions for pseudo strain-hardening in fiber reinforced brittle matrix composites, *Applied Mechanics Review*, 45, pp. 390–398.
9. Leung, C.K.Y. (1996). Design criteria for pseudoductile fiber-reinforced composites, *Journal of Engineering Mechanics*, ASCE, 122(1), pp. 10–18.
10. Saje, D., Bandelj, B., Sustersic, J., Lopatic, J., and Saje, F. (2011). Shrinkage of Polypropylene Fiber-Reinforced High-Performance Concrete, *Journal of Materials in Civil Engineering*, 23(7), pp. 941–952.
11. Felt, E.J. (1956). Resurfacing and patching concrete pavements with bonded concrete, *Highway Research Board Proceedings*, 35, pp. 444-469.
12. Felt, E.J. (1960). Repair of concrete pavement, *Journal of American Concrete Institute*, pp. 139-153.
13. ACI Committee 546 (1980). Guide for repair of concrete bridge superstructures, *Concrete International*, 2(9), pp. 69-88.
14. Ramey, G.E., Moore, R.K., Parker, F. Jr. and Strickland, A.M. (1988). Laboratory evaluation of four rapid setting concrete patching materials. *Transportation Research Record*, No. 1041, pp. 47-52.
15. Razl, I. (1991). Novel materials for concrete restoration, *Proceedings, 1st Canadian University - Industry Workshop on Fiber Reinforced Concrete*, N. Banthia, ed., Laval University, Quebec City, Quebec, Canada, pp.118-128.
16. Boisvert, J., Pleau, R., and Pigeon, M. (1994). Proprie´te´s me´caniques de mortiers renforce´s de micro-fibres d'acier et de carbone. *Proc., Compte-rendus du Colloque francophone sur les be´tons renforce´s de fibres me´talliques*, F. Buyle-Bodin, ed., pp. 227–236 (in French).
17. Passuello, A., Moriconi, G., and Shah, S.P. (2009). Cracking behavior of concrete with shrinkage reducing admixtures and PVA fibers, *Cement and Concrete Composites*, 31(10), pp.699-704.
18. Bentz, D.P. and Peltz, M.A. (2008). Reducing thermal and autogenous shrinkage contributions to early-age cracking, *ACI Materials Journal*, 105(4), pp. 414-420.
19. Tazawa, E. (1998). Autogenous Shrinkage of Concrete, *Proceedings, International Workshop on Autogenous Shrinkage of Concrete*, Japan Concr. Inst., Hiroshima, Japan, E & FN Spon, New York, 358.
20. Nmai, C., Tomita, R., Hondo, F., and Buffenbarger, J. (1998). Shrinkage reducing admixtures, *Concrete International*, 20(4), pp. 31-37.
21. Shah, S.P., Weiss, W.J. and Yang, W. (1998). Shrinkage cracking-can it be prevented? *Concrete International*, 20(4), pp.51-55.
22. Andiç, O., Yardi Mci, M.Y. and Ramyar, V. (2008). Performance of carbon, polyvinylalcohol and steel based micro-fibers on alkali-silica reaction expansion, *Construction and Building Materials*, 22(7), pp.1527-1531.
23. Pierre, P., Pleau, R., Rhéaume, M. and Pigeon, M. (1997). The influence of micro-fiber on the drying behaviour of cement paste and mortars, *Proceedings of the Annual Conference of Canadian Society of Civil Engineers*, Sherbrooke, Québec, Canada, pp. 123-131.
24. Banthia, N. and Gupta, R. (2006). Influence of polypropylene fiber geometry on plastic shrinkage cracking in concrete, *Cement and Concrete Research*, 36, pp.1263–1267.
25. Kovler, K., Sikuler, J. and Bentur, A. (1992). Free and restrained shrinkage of fiber reinforced concrete with low polypropylene fiber content at early age, *Fourth RILEM Int. Symposium on Fiber Reinforced Cement and Concrete*, International Union of Laboratories and Experts in Construction Materials, Systems and Structures, Sheffield, UK, pp.91–101.
26. Swamy, R.N. and Stavrides, H. (1979). Influence of fiber reinforcement on restrained shrinkage and cracking, *Journal of American Concrete Institute*, 76(3), pp. 443–460.
27. Zollo, R.F. (1984). Collated fibrillated polypropylene fibers in FRC, Fiber reinforced concrete, *ACI SP-81*, American Concrete Institute, Detroit, USA, pp. 397–409.
28. Zollo, R.F., Ilter, J.A. and Bouchacourt, G.B. (1986). Plastic and drying shrinkage in concrete containing collated fibrillated polypropylene fibers, 3rd Int. Symp. on Developments in Fiber Reinforced Cement and Concrete RILEM Symposium FRC, 86(1), RILEM Technical Committee 49-TFR, Cachan, France.
29. Bayasi, Z. and Zeng, J. (1993). Properties of polypropylene fiber reinforced concrete, *ACI Materials Journal*, 90(6), pp. 605–610.

30. Myers, D., Kang, T.H.K. and Ramseyer, C. (2008). Early-age properties of polymer fiber-reinforced concrete, *International Journal of Concrete Structures and Materials*, 2(1), pp. 9–14.
31. Aly, T., Sanjayan, J.G. and Collins, F. (2008). Effect of polypropylene fibers on shrinkage and cracking of concretes, *Journal of Materials and Structures*, 41(10), pp. 1741–1753.
32. Lawler, J.S. Zampini, D., and Shah, S.P. (2005). Micro-fiber and Macrofiber Hybrid Fiber-Reinforced Concrete, *Journal of Materials in Civil Engineering*, 17(5), pp. 595–604.
33. Lawler, J.S. (2001). Hybrid fiber reinforcement in mortar and concrete. PhD thesis, Northwestern Univ., Evanston, IL, USA.
34. Fwa, T.F. and Paramasivam, P. (1990). Thin Steel Fiber Cement Mortar Overlay for Concrete Pavement, *Cement and Concrete Composites*, 12, pp.175-184.
35. Banthia, J. and Dubeau, S. (1994). Carbon and steel micro-fiber-reinforced cement-based composites for thin repairs, *Journal of Materials in Civil Engineering*, 6(1), pp. 88-99.
36. Chen, P.W. and Chung, D.D.L. (1993). Concrete reinforced with upto 0.2 vol% of short carbon fibers, *Composites*, 24(1), pp. 33-52.
37. Deng, Z. (2005). The fracture and fatigue performance in flexure of carbon fiber reinforced concrete, *Cement and Concrete Composites*, 27, 131–140.
38. Hong, S.G. and Choi, K.K. (2012). Crack modeling of steel–carbon hybrid FRCCs, *Advanced Composite Materials*, 21(4), 283–298.
39. Low, N.M.P. and Beaudoin, J.J. (1992). Mechanical properties of high performance cement binders reinforced with wollastonite micro-fibers, *Cement and Concrete Research*, 22, pp. 981-989.
40. Zongjin, L. (2011). *Advanced Concrete Technology*, J. Wiley, New Jersey, USA.
41. Clark, P. (1998). Future of Automotive Body Materials: Steel, Aluminum & Polymer Co. Massachusetts Institute of Technology, < http://readpdf.net/file/future-steel-vehicle.html>.
42. Yener, E. and Hinisliolu, S. (2011). The Effects of Silica Fume and Fly Ash on the Scaling Resistance and Flexural Strength of Pavement Concrete, *Road Materials and Pavement Design*, 12(1), pp. 177-194.
43. Ransinchung, G.D. and Kumar, B. (2010). Investigations on pastes and mortars of ordinary portland cement admixed with wollastonite and microsilica, *Journal of Materials in Civil Engineering*, 22(4), pp. 305-313.
44. Soliman, A.M. and Nehdi, M.L. (2012). Effect of natural wollastonite micro-fibers on early age behavior of UHPC, *Journal of Materials in Civil Engineering*, 24(7), pp. 816-824.
45. Cheyrezy, M., Maret, V. and Frouin, L. (1995). Micro-structural analysis of RPC (Reactive Powder Concrete), *Cement and Concrete Research*, 25(7), pp.1491-1500.
46. Schmidt, M. and Fehling, E. (2005). Ultra-high-performance concrete: research, development and application in Europe, *Proceedings, 7th International Symposium on Utilization of High-Strength/High Performance Concrete*, Washington, DC, USA, 1, pp. 51-77.
47. Sorelli, L., Davila, R., Ulm, F., Perry, V. and Seibert, P. (2008). Risk Analysis of Early-Age Cracking in UHPC Structures, *Proceedings, 2nd International Symposium on UHPC*, Germany, pp.331-338.
48. Bentz, D.P., Sant, G. and Weiss, J. (2008). Early-age properties of cement-based materials: influence of cement fineness, *Journal of Materials in Civil Engineering*, 20(7), pp. 502-508.
49. ACI Committee 231 (2010). Report on Early-Age Cracking: Causes, Measurement, and Mitigation, Technical committee document ACI, 231R-10, Farmington Hills, Michigan, USA, pp. 46.
50. Ransinchung, G.D., Kumar, B. and Kumar, V. (2009). Assessment of water absorption and chloride ion penetration of pavement quality concrete admixed with wollastonite and microsilica, *Construction and Building Materials*, 23 (2), pp.1168 –1177.
51. Chung, D.D.L. (2005). Dispersion of Short Fibers in Cement, *Journal of Materials in Civil Engineering*, 17(4), pp. 379–383.
52. Speakman J. and. Scott III, H.N. (1996). Ultra-Thin, Fiber-Reinforced Concrete Overlays for Urban Intersections, *Transportation Research Record*, No. 1532, pp. 15-20.
53. Chojnacki, T. (2000). Evaluation of fiber-reinforced unbonded overlay. Missouri Department of Transportation Research, Development and Technology. Missouri Department of Transportation, RI 97-015, Jefferson City, Missouri, USA.