Fracture Behavior and Properties of Functionally Graded Fiber-Reinforced Concrete

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Abstract. In concrete pavements, a single concrete mixture design is selected to resist mechanical loading without attempting to adversely affect the concrete pavement shrinkage, ride quality, or noise attenuation. An alternative approach is to design distinct layers within the concrete pavement surface which have specific functions thus achieving higher performance at a lower cost. The objective of this research was to address the structural benefits of functionally graded concrete materials (FGCM) for rigid pavements by testing and modeling the fracture behavior of different combinations of layered plain and synthetic fiber-reinforced concrete materials. Fracture parameters and the post-peak softening behavior were obtained for each FGCM beam configuration by the three point bending beam test. The peak loads and initial fracture energy between the plain, fiber-reinforced, and FGCM signified similar crack initiation. The total fracture energy indicated improvements in fracture behavior of FGCM relative to full-depth plain concrete. The fracture behavior of FGCM depended on the position of the fiber-reinforced layer relative to the starter notch. The fracture parameters of both fiber-reinforced and plain concrete were embedded into a finite element-based cohesive zone model. The model successfully captured the experimental behavior of the FGCMs and predicted the fracture behavior of proposed FGCM configurations and structures. This integrated approach (testing and modeling) demonstrates the viability of FGCM for designing layered concrete pavements system.

Keywords: concrete, fracture, fibers, cohesive zone model

INTRODUCTION

There is an increasing performance demand placed on the materials used for pavement infrastructure, while the availability of high quality construction materials is diminishing. The concrete material for a pavement structure is designed to be multi-functional by resistance to mechanical loadings, stresses from thermal or moisture gradients, early-age and long-term volumetric changes, skid/wear and noise from the surface texture, and to provide a drainable surface layer. Currently, a single, monolithic concrete mixture design is selected that attempts to optimize the aforementioned functional objectives, which typically results in greater slab depths and may not meet all the performance criteria desired.

The research, design, and manufacturing of functionally graded materials (FGM) have been extensively applied to high performance materials such as graded metals and composite metals/ceramics for high-tech applications [1-5]. An approach to maximize the performance while minimizing the cost of the concrete pavement is to

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design layers with different properties at specified depths. A functionally layered (or graded) concrete pavement structure could be constructed to address the multi-objective performance requirements. This process of building layered pavements has been used in Europe [6], and some areas of the United States [7, 8]. Several laboratory studies have also been performed on layered fiber-reinforced concrete systems to determine their affect on concrete strength and fatigue [9, 10].

The objective of this project is to demonstrate the structural benefits of functionally graded concrete materials (FGCM) for rigid pavements through testing and simulating the fracture behavior of plain and fiber-reinforced concrete material combinations in layers. A numerical model based on the Finite Element Method (FEM) utilizing cohesive elements with specific constitutive relations for plain and fiber-reinforced concrete will be generated and compared with the experimental results.

EXPERIMENTAL PROGRAM

The testing program included a total of 4 specimen configurations to analyze the effect of using different combinations of concrete mixtures on the top or bottom layer of the specimen. Three-point bending beam (TPB) specimens with dimensions 700 x 150 x 80 mm were utilized, as shown in Figure 1, to characterize the fracture behavior of the individual and functionally layered concrete materials. The depths of the layers were h_1=50 mm and h_2=100 mm. Three beam replicates were made for each configuration. A notch one third of the specimen depth (a_0 of 50 mm) was cut into each beam. The concrete fracture parameters derived from the TPB test were based on the Two-Parameter Fracture Model (TPFM) [11-12] and the Hillerborg work of fracture method [13].

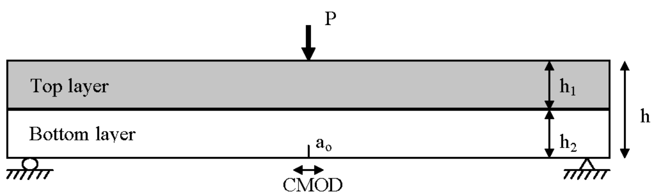

FIGURE 1. Three-point bending beam test setup for functionally layered concrete specimens.

Two concrete mixtures were cast for this comparative study of FGCM: ordinary plain concrete (PCC) and fiber-reinforced concrete (FRC). The material proportions of PCC and FRC mixtures were all the same except the addition of fibers in the FRC mixture. The plain and FRC batches were mixed and cast at approximately the same time to create a good bond between the layers. The FRC mixture incorporated a structural synthetic fiber of 0.78% by volume. The synthetic fiber is a polypropylene/polyethylene, straight, rectangular cross-sectional fiber. The fiber length is 40mm with an aspect ratio of 90. The compressive and split-tensile strengths of each mixture were measured. Compressive strength was unaffected by the addition of fibers, but the split-tensile strength increased slightly, not typically seen for lower fiber volume contents [14].

TEST RESULTS AND FRACTURE PARAMETERS

Each TPB specimen was subjected to ten cycles of displacement-controlled loading and unloading followed by a final cycle of loading until the beam fractured or the displacement gauge went out of range. The load (P) and crack-mouth-opening-displacement (CMOD) were recorded. Fracture parameters such as the critical stress intensity factor (K_{IC}), critical crack tip opening displacement ($CTOD_C$), and initial fracture energy (G_f) were calculated from the loading and unloading compliance curves. Table 1 presents the average peak load (P_c) and the average fracture parameter results obtained from the TPB tests. The use of fibers did not significantly affect these critical fracture parameters since they are related to the crack initiation instead of crack propagation.

TABLE 1. Average Fracture Parameters for TPB Specimens.

Top / bottom layer	P_c (kN)	K_{IC} (MPa·m$^{1/2}$)	$CTOD_c$ (mm)	G_f (N/m)	G_{2mm} (N/m)	G_F (N/m)
PCC / PCC	3.710	1.05	0.016	38.1	119	119
FRC / FRC	3.482	1.03	0.016	36.9	378	3,409
PCC / FRC	3.714	1.08	0.017	40.3	249	-
FRC / PCC	3.569	0.96	0.016	35.2	216	-

The total fracture energy (G_F) was calculated based on a method proposed by Hillerborg [13], which is defined as the ratio between the total energy (the sum of the area under the raw load vs. CMOD envelope curve and the energy from the self-weight), and the concrete fracture area. The raw load versus CMOD for each layered system is shown in Figure 2. Due to the fibers' ability to effectively bridge cracks, the load can remain constant until large values of CMOD; a decrease in load was only seen between 4mm to 45 mm before the load reached zero. In many FRC studies, a cut-off criterion (e.g. 2mm CMOD) has been used to arbitrarily calculate fracture energy. In order to determine the total fracture energy of the FRC beams, additional TPB tests were performed to measure the CMOD until the load reached zero. The area under the envelope curve until total failure and until $CMOD_{max}$= 2 mm were then used to calculate two fracture energy quantities for the FRC: total fracture energy, G_F, and relative fracture energy, G_{2mm}, seen in Table 1.

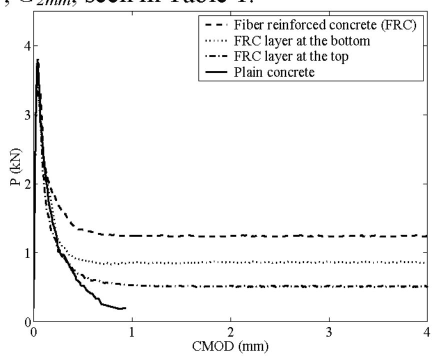

FIGURE 2. Average Load – CMOD envelope curves for TPB specimens with plain, synthetic fiber, and functionally layered concrete.

Although there is not a significant difference between peak loads in Figure 2, big differences can be seen when comparing the area under the load-CMOD curves. The FRC/FRC and PCC/FRC specimens had significantly greater fracture resistance compared to PCC/PCC. The FRC/PCC specimens still behaved better than PCC/PCC, but had a lower fracture resistance compared with the other FRC specimens. This is confirmed in Table 1, showing that the FRC/FRC beam increased the G_{2mm} by 218 percent over PCC/PCC. Specimens with FRC at the notch (PCC/FRC) had 109 percent greater G_{2mm} than PCC/PCC, and samples with FRC away from the notch (FRC/ PCC) had 82 percent greater than PCC/PCC. The synthetic fibers modulus and pull-out characteristics allowed for effective crack bridging behind the crack front. When fibers were located only at the top of the specimen, fibers were not able to dissipate as much energy due to the smaller bridging stresses behind the crack front.

NUMERICAL MODELING FOR NONLINEAR FRACTURE PROCESS ZONE

In order to numerically predict the fracture behavior of the FGCM, a FEM model to describe the nonlinear fracture process zone in concrete materials was required. Bulk elements representing the top and bottom layer materials were used. A refined mesh of cohesive elements close to the crack tip was inserted along the expected crack plane. The cohesive elements required a softening model to represent the fracture behavior of both materials (i.e. PCC and FRC) located in the respective layers.

Cracking occurring in plain concrete is idealized as zones of micro-cracking, bridging and traction-free macro-cracking. Micro-cracks initiate ahead of the bridging zone before the applied stress reaches the material's tensile strength (f_t'). The nonlinear fracture process zone ahead of the crack tip depends on crack branching and aggregate interlocking [16, 16]. The final crack opening width (w_f) occurs when traction along the crack surface reaches zero. The nonlinear fracture process zone for plain concrete is best characterized by the cohesive zone model (CZM) [17], as depicted in Figure 3(a). The softening curve in the CZM is physically defined by four experimental fracture parameters [18]: tensile strength (f_t'), initial fracture energy (G_f), total fracture energy (G_F) and critical crack tip opening displacement ($CTOD_c$).

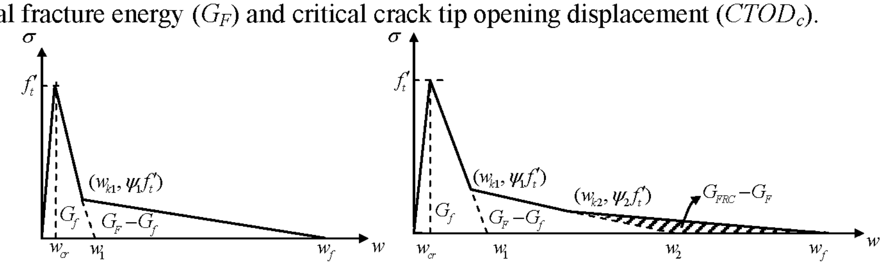

FIGURE 3. Experimental fracture parameter-based softening model for (a) plain concrete and (b) FRC.

Fracture mechanisms of FRC are different from those of plain concrete due to the effect fibers have on the nonlinear fracture process zone [16]. Although fibers do not generally influence the tensile strength at low volume fractions, fibers do increase the total fracture energy of plain concrete, which results in the observed high post-peak load behaviors [14]. The nonlinear fracture process zone for FRC (ahead of crack tip) can be divided into aggregate bridging and fiber bridging zones. The aggregate bridging zone is represented by the same softening model for plain concrete. The fiber bridging zone is characterized by a linear descending slope [20] depicted by the fiber de-bonding and pull-out mechanisms. The softening model for FRC, shown in Figure 3(b), is determined by the total fracture energy (G_{FRC}) of FRC, the w_f, and four experimental fracture parameters (f_t', G_f, G_F, $CTOD_c$) of plain concrete. G_{FRC} is the fracture energy from the total load-CMOD curve (G_F). In this study, the final crack opening width is defined as a quarter of the fiber length, which corresponds to the averaged pull-out length for randomly distributed fibers.

The bulk FEM model with the cohesive zone models proposed for plain and fiber-reinforced concrete were implemented for the different combinations of concrete layers. The CZM based on the measured fracture parameters of the PCC and FRC was successfully able to represent the fracture behavior as seen in Figure 4. These numerical results are similar to the actual experimental results shown in Figure 2.

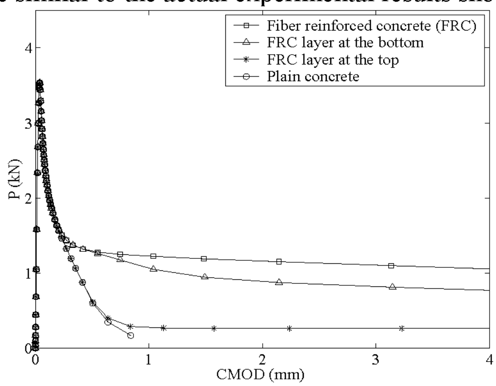

FIGURE 4. Load vs CMOD envelope curves for TPB numerical simulation.

CONCLUSION

The application of functionally graded (or layered) concrete materials (FGCM) for rigid pavement has shown promising results based on fracture testing and numerical modeling. As expected, all concrete specimens that used fibers showed an improved softening behavior over plain concrete. The G_f and $CTOD_c$ did not differentiate the fracture behavior of the plain, fiber-reinforced, and functionally layered concrete. The total fracture energy (G_F) or a cut-off fracture energy (G_{2mm}) were the key indicators quantifying how the fiber reinforced and functional graded concrete improved the cracking resistance of plain concrete specimens. The FGCM with synthetic fiber-reinforced concrete was more fracture resistant when the fibers were placed closest to the notch rather than near the top of the specimen due to fiber bridging behind the crack front. A finite element-based CZM was developed to predict the softening behavior of the FGCM systems based on the measured concrete material fracture properties. The numerical simulation of FGCM matched the experimental results of the various layered combinations of plain concrete and FRC. The numerical analysis is essential to quantify the fracture behavior of various concrete materials, thicknesses, and placements within concrete layers for future FGCM systems [21] since excessive testing would be required to quantify the fracture behavior of all fiber types, volume fractions, layer depths, and concrete mixture designs.

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