

Behavior of Concrete Mixtures in Ultra-Thin Whitetopping Composite Pavements

Amanda Bordelon¹ and Jeffery Roesler²

Abstract

Ultra-thin whitetopping (UTW) is an alternative pavement rehabilitation option to asphalt concrete overlays. UTW is typically a concrete overlay less than 5 inches thick on an existing distressed asphalt pavement. A research project was recently finished to refine the current UTW design methods and develop new recommendations for improved UTW performance. As part of this project, a laboratory study investigated various concrete mixture effects on UTW performance. Seven mixture designs containing various w/cm ratios, cementitious content, discrete fiber-reinforcement content, and two coarse aggregate types were studied. A composite beam test (concrete placed on an existing asphalt beam) was developed to predict the composite section behavior in the laboratory. For this small-scale 2D testing, the results were not as dramatic as expected between the different concrete mixtures. However, the fiber-reinforcement, which increased the total fracture energy of concrete, demonstrated improvement in the load carrying capacity after initial cracking. The concrete mixture design alone was not the sole indicator of the UTW performance. Higher strength concrete mixtures can fracture just as rapidly as normal strength concrete if the UTW exhibits debonding. It is recommended that structural fibers be added to the concrete to extend the performance life of the rehabilitated pavement, especially in the presence of existing asphalt cracks and potential interface debonding.

Introduction

Whitetopping is a rigid pavement rehabilitation method consisting of a new concrete pavement overlaid on an existing flexible pavement structure. Whitetopping is an alternative rehabilitation technique to hot-mix asphalt concrete (HMAC) overlays given there is a minimum asphalt concrete thickness for support and sufficient vertical clearance for a concrete overlay. In general, whitetopping may provide a greater cracking resistance, durability, and surface reflectivity relative to HMAC. Furthermore, in situations where the HMAC pavement shows signs of surface distresses, especially rutting, whitetopping is an effective alternative solution.

Whitetopping is classified based on the concrete thickness and concrete/HMAC bonding condition in the pavement structure. Conventional whitetopping is designed and constructed as a new concrete pavement section except it is placed over existing flexible pavement and a negligible bond condition is

¹ Amanda C. Bordelon; ISCP member; Graduate Research Assistant at the University of Illinois at Urbana-Champaign; B233 NCEL, 205 N Mathews Ave, Urbana, IL 61801; 217-333-7311; fax 217-333-1924.

² Jeffery R. Roesler; ISCP member; Associate Professor at the University of Illinois at Urbana-Champaign; 205 N. Mathews Ave., Urbana, IL, 61801; 217-265-0218; fax 217-333-1924.

assumed. Ultra-thin whitetopping (UTW) is designated for whitetopping pavements between thickness of 3 and 5 inches, and a bonded interface between the concrete and asphalt concrete layer is essential. Due to high surface to volume ratios, ultra-thin whitetopping is made with smaller slab sizes. The smaller slab size reduces the moisture curling, temperature curling, and load stresses in the concrete pavement and minimizes the chance of interface debonding. The slab size, saw-cut timing, and bond issues are important design parameters which are currently being investigated as part of other research projects. Currently no quantitative condition assessment of the existing HMAC pavement exists and no universal concrete mixture designs required to assure adequate performance of these concrete rehabilitation strategies are accepted.

Background

Several concrete mixture designs, thicknesses, and construction techniques have been recommended or developed since the 1990s for UTW. The American Concrete Pavement Association (ACPA) has been collecting information about UTW projects in the United States since 1991 and has developed design guidelines based on field, laboratory, and analytical studies (Ioannides 2007). Since 1998, Illinois Department of Transportation (IDOT) began paving several whitetopping projects in locations throughout the state at intersections and mainline roads. IDOT implemented the whitetopping projects on low and moderate traffic volume roads. A study to develop guidelines for future UTW designs was initiated by IDOT. The study investigated ten UTW projects throughout the state of Illinois (Winkelman 2005; Riley 2005). Several of the pavements have showed significant distresses as early as 3 years of service life, while other pavements are currently still in service with little to no distresses. The early and severe distresses may have been caused from several interacting sources (concrete mixture design, bonding conditions, underlying condition of the existing HMAC pavement, heavy vehicular traffic, etc).

UTW has been experimented in pavement projects around the world. For example, a study in Brazil investigated two UTW projects using high strength concrete (Pereira et al. 2006). The University of São Paulo campus roadway has performed with little distresses, while a nearby UTW on SP-280 highway was severely distressed after a short service life. In Taiwan, high early strength concrete was cast onto an insufficiently thin asphalt base and during a hot temperature day, resulting in alligator-type surface cracking in the UTW section after 2 months of service (Lin and Wang 2005).

Part of the research objectives was to evaluate more fracture resistant concrete mixtures for UTW pavements due to the inherent distresses present on the HMAC support layer. One example is the concrete mixture for the newly rehabilitated Dan Ryan expressway (I-94) near Chicago, IL. It was designed for a highly trafficked highway (with express and local lanes for traffic control) and was re-created in the laboratory to evaluate its fracture properties. The Dan Ryan mixture also contained a low cement content and ground granulated blast furnace slag as a supplementary admixture which should assist in minimizing the effects of the concrete shrinkage.

Motivation and Research Significance

Ultra-thin whitetopping pavements are a rehabilitation technique requiring very thin concrete slabs to be cast on distressed hot-mixed asphalt pavement. An investigation of the concrete material requirements has been made specifically to gain insight into the composite section response and cracking behavior. To understand what mixture design parameters resulted in undesirable performance issues seen in certain field projects, a study of the strength and fracture properties of various mixture proportions and constituents was undertaken. The field mixture designs have been repeated or adjusted in order to be reproduced in the laboratory at the University of Illinois at Urbana-Champaign (Roesler et al. 2008). The primary study investigated a selective set of mixtures in a composite beam on an elastic foundation system. The composite beam test developed for this study is a new, innovative technique to study the performance of UTW. The composite beam consisted of concrete cast directly on a notched asphalt beam and recorded vertical deflections of the entire section (concrete, asphalt and the soil) along with estimated crack opening displacements in the concrete. In addition, various material parameters including shrinkage, fracture toughness, and fracture energy were measured to characterize the behavior of each mixture.

Laboratory Testing

Fracture Test

The fracture properties the concrete mixtures are important for understanding the mechanisms behind the UTW pavement performance, especially load carrying capacity, reflective cracking resistance, and load transfer efficiency at joints. An experimental program was designed to determine the fracture properties of UTW concrete mixtures used in the field.

A RILEM procedure (Jenq and Shah 1985; Shah et al. 1995) using a single-edge notched beam [SEN(B)] was selected to determine the fracture properties of several UTW concrete mixtures. The single-edge notched beam specimen is configured for three-point bending with the load (P) and crack mouth opening displacement ($CMOD$) being measured.

Jenq and Shah developed the Two-Parameter Fracture Model (TPFM) to determine the critical stress intensity factor (K_{IC}) and critical crack tip opening displacement ($CTOD_C$) of a monolithic beam based on an effective elastic crack approach. The nonlinear elastic fracture behavior was accounted for by using linear elastic fracture mechanics equations to calculate the effective elastic crack length from the measured loading and unloading compliance of the beam. Geometric factors were included in the calculations to account for the geometry and size of the beams. A span-to-depth ratio (S/d) was suggested in the TPFM to be 4; the initial notch depth a_0 is 1/3 of the total depth d , and the notch width should be less than 5 mm. The total beam dimensions (length x depth x width) chosen were 700 x 150 x 80 mm with a span of 600 mm and an initial notch depth of 50 mm. In addition to the initial fracture properties (K_{IC} and $CTOD_C$), the testing data from the SEN(B) concrete specimen was used to calculate the total fracture energy (G_F) as the normalized area under the load-crack mouth opening displacement ($CMOD$) curve

after Hillerborg (1985). Additional details and calculations of this testing can be found in Bordelon (2007).

Composite Beam Test

A composite beam test was developed (Bordelon 2007), consisting of a 75 mm thick concrete beam cast directly onto a 75 mm thick HMAC beam. The composite beams were tested on a clay soil foundation and several gages were attached, as seen in Figure 1. Prior to casting the concrete, the HMAC beams were saw-cut from a 1-year old asphalt pavement section in the field. The concrete was then cast directly onto the HMAC layer to avoid any initial slippage or lift off issues induced from the bending of the composite beam. It was determined that an uncracked HMAC beam would make it difficult to predict where cracking would occur and many UTW projects have distressed (cracked) HMAC support. Therefore, it was assumed that a simulation of a HMAC crack that reflects into the concrete layer may be appropriate to determining the load capacity of the UTW mixture. A 75 mm deep notch was saw-cut into the HMAC portion of the composite beam at midspan to resemble a crack in the underlying asphalt surface. The beam was cast together to ensure a good bonding condition.

Two LVDTs were used to measure the total vertical deflection of the composite beam (concrete, asphalt, and soil), and to measure the vertical deflection between the neutral axis and the top of the beam. A clip gauge was used to estimate the crack tip opening displacement initiated at the bottom of the concrete layer above the notched asphalt.

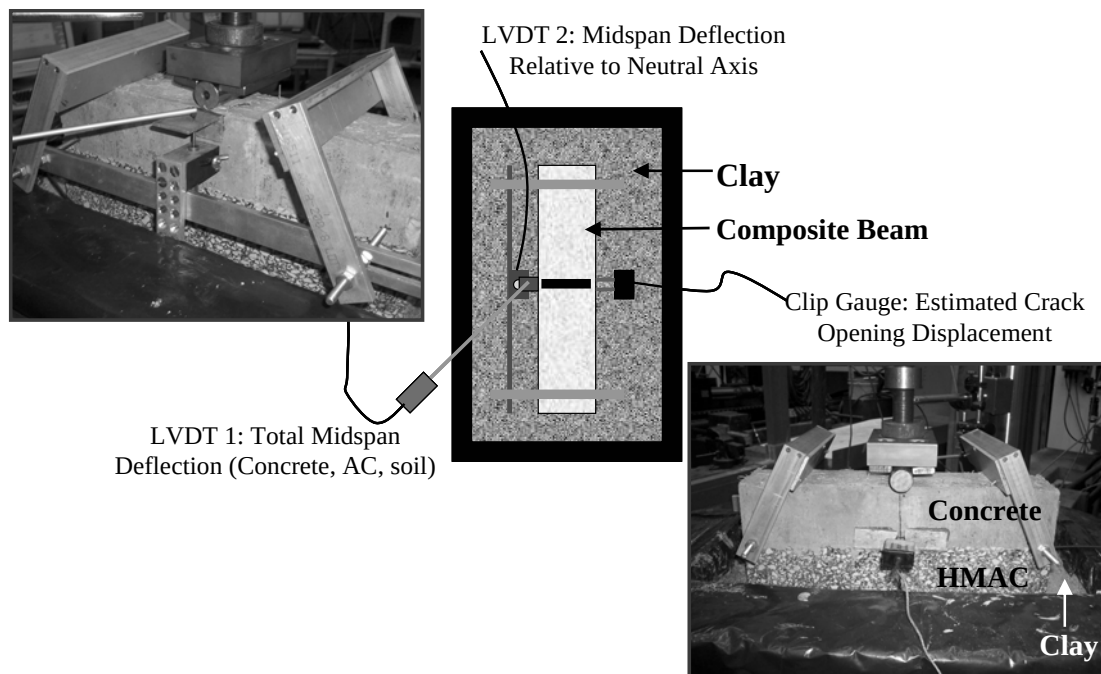


Figure 1 - Composite beam test setup (from Bordelon 2007).

Ultra-Thin Whitetopping Mixtures

The concrete mixture designs used were replicated from various UTW field projects, particularly Schanck Avenue and Anna County projects from Winkelman (2005), the Dan Ryan Expressway in Chicago, IL, and a highway project in Brazil (Pereira et al. 2006). A total of seven composite beam mixtures were created in the lab, these are shown in Table 1. Cast in 2005, the Schanck Avenue project contained 2 kg/m³ (4 lb/yd³ or 0.26 percent volume fraction) of structural fiber-reinforced concrete (FRC) and has no visible distresses to date. Three additional mixtures similar to Schanck Avenue – plain concrete without fibers, plain concrete with gravel instead of crushed limestone coarse aggregate, and a mixture with a higher volume fraction of fibers at 4 kg/m³ (6 lb/yd³ or 0.39 percent volume fraction) – were created in the laboratory. The Anna County project mixture used higher cement content and was placed at an intersection. The Anna County UTW sections showed a high frequency of cracking after 3 years of service (Winkelman 2005; Riley 2005). Similarly, the highway project in Brazil was to be studied due to its very early age distresses and high cementitious content. As a control design mixture, the continuously-reinforced concrete design from the Dan Ryan Expressway project was cast in the laboratory. It was expected that the High FRC Schanck Avenue mixture containing 4 kg/m³ would demonstrate the most favorable fracture behavior. In contrast, the fracture behavior of the Anna County mixture was hypothesized to not perform as well due to the early age distresses seen in the field sections.

Table 1 - UTW Mixture Designs for Composite Beam Testing

		Schanck Ave				Anna County	Dan Ryan	Brazil
		Plain	Low FRC	High FRC	Gravel			
Cement	kg/m ³	307	307	310	292	459	265	444
Fly Ash	kg/m ³	83	83	84	79	0	0	0
Slag	kg/m ³	0	0	0	0	0	67	0
Silica Fume	kg/m ³	0	0	0	0	0	0	44
Water	kg/m ³	159	159	161	151	166	140	171
Coarse Aggregate	kg/m ³	1174	1176	1186	1119	1098	1151	1142
Fine Aggregate	kg/m ³	596	597	602	568	613	750	558
Fibers	kg/m ³	0	2	4	0	0	0	0
Air Entrainment	ml/m ³	400	100	101	95	150	86	221
Water-Reducer	ml/m ³	600	601	0	0	898	519	0
Super Plasticizer	ml/m ³	0	0	606	0	0	0	1199
w/cm ratio		0.41	0.41	0.41	0.41	0.36	0.42	0.35

Results

Fresh and Hardened Properties

Table 2 shows the measured fresh and hardened concrete properties of the UTW mixtures. The Plain Schanck, Low FRC Schanck, and Anna specimens were tested at 14 days (this testing age was chosen because the fracture properties were predicted to be more stable after 7 days). The High FRC Schanck Gravel Schanck, Dan Ryan, and Brazil specimens were tested at 28 days.

The compressive strength of Plain Schanck mixture was lower than the others due to the higher entrained air content. The air entraining admixture was reduced for the remaining Schanck mixtures. The slumps of the High FRC Schanck and Brazil mixtures were extremely low even with the addition of superplasticizer. Due to the rounded, smooth gravel in the Gravel Schanck mixture, no water reducer or superplasticizer was used, which still resulted in a 23 cm slump. The Anna County and Brazil mixtures showed similar 28-day compressive strengths due to their similar cement contents and w/cm ratios. The High FRC Schanck mixture had a relatively high compressive strength. The Gravel Schanck mixture had a very high elastic modulus of 48.4 GPa after 28 days, which is attributed to the higher elastic modulus of the gravel coarse aggregates.

Table 2 - UTW Fresh Properties and Strengths

	Schanck				Anna County	Dan Ryan	Brazil
	Plain	Low FRC	High FRC	Gravel			
Fresh Propeties							
Slump (cm)	12.7	12.1	2.5	22.9	12.1	10.2	2.5
Unit Weight (kg/m ³)	2150	2287	2313	2378	2150	2286	2343
Air Content (%)	10.3	5.3	4.4	2.6	10.3	6.7	2.6
Hardened Properties							
Age (days)	14	14	28	28	14	28	28
Compressive Strength (MPa)	22.6	34.8	39.7	36.1	33.8	44.5	37.0
Split-Tensile Strength (MPa)	2.29	3.81	4.07	3.70	3.99	3.79	3.84
Elastic Modulus (GPa)	22.6	31.5	33.3	48.4	30.7	31.8	29.9

Fracture Results

The fracture properties of all the composite beam mixtures were measured to compare their behavior under different geometry and boundary conditions and to enable future 3-D modeling of the results. The load versus crack mouth opening displacement (CMOD) curves for each SEN(B) sample tested is shown in Figures 2 and 3 and their respective fracture properties are presented in Table 3.

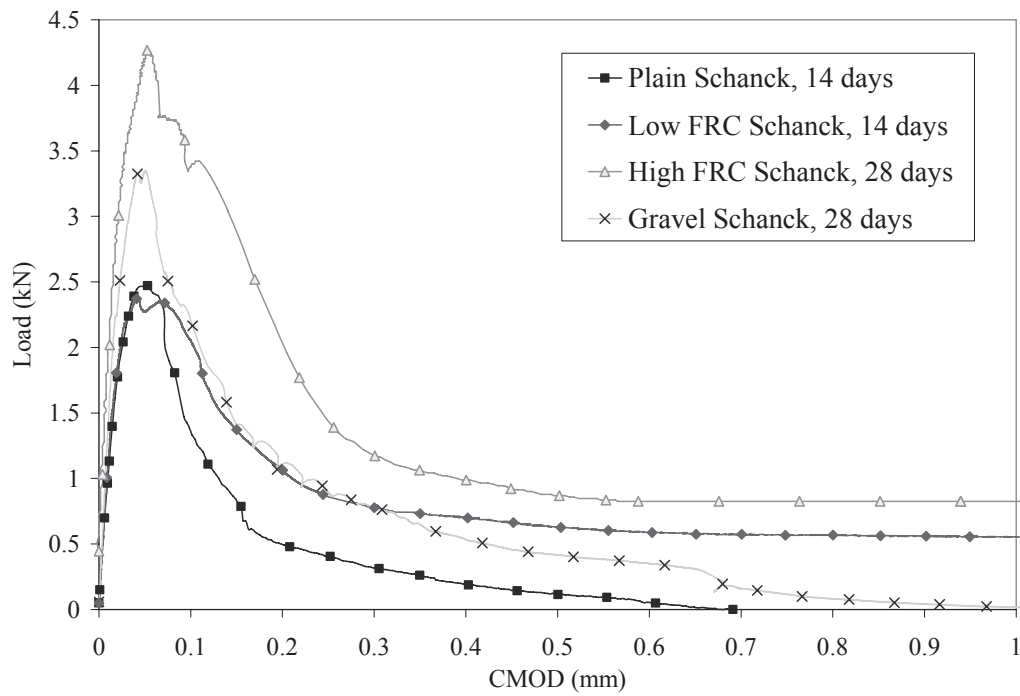


Figure 2 - TPB Specimen load versus CMOD curves for Schanck concrete mixtures.

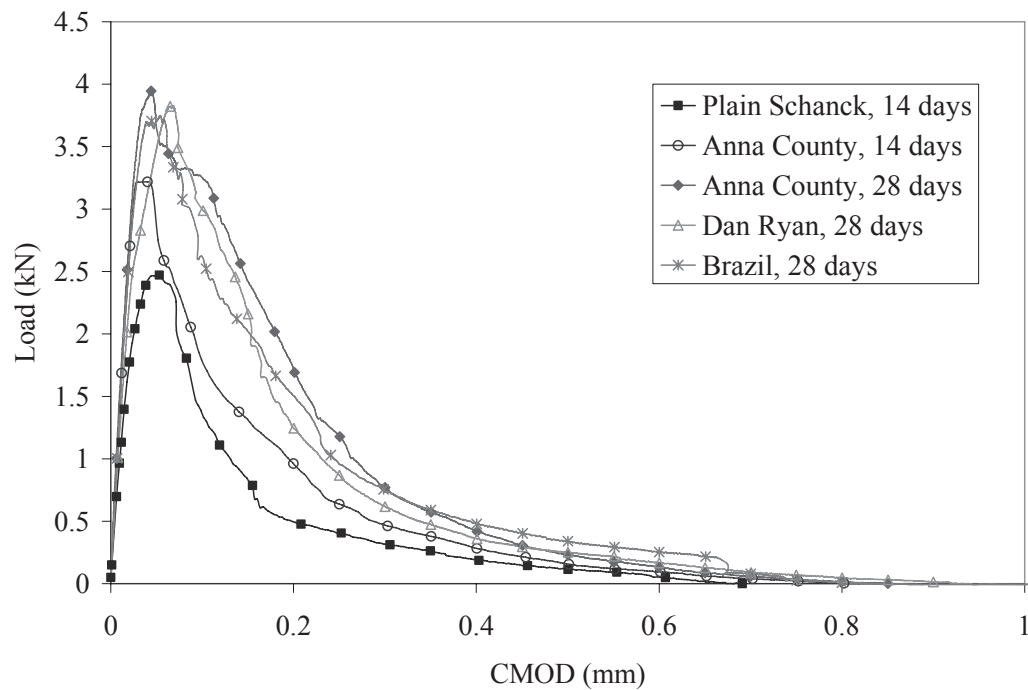


Figure 3 - TPB Specimen load versus CMOD curves for non-reinforced concrete mixtures.

Table 3 - Fracture Results of UTW Concrete Mixtures

Mixture		Age (days)	Peak Load (kN)	Calculated Elastic Modulus (GPa)	K_{IC} (Mpa-m ^{1/2})	$CTOD_C$ (mm)	G_f (N/m)	G_F (N/m)
Schanck Avenue	Plain	14	2.36	17.1	0.86	0.031	43.7	60
	Low FRC	14	2.35	20.5	0.82	0.025	33.8	1720
	High FRC	28	4.34	27.4	1.33	0.024	65.2	3550
	Gravel	28	3.23	30.7	1.10	0.018	39.2	112
Anna County		14	3.74	26.3	1.02	0.015	41.2	99
		28	3.69	27.6	1.05	0.016	40.0	115
Dan Ryan		28	3.67	27.8	1.24	0.019	55.7	133
Brazil		28	3.52	29.7	1.15	0.018	44.3	102

The fracture properties were determined for each mixture at their corresponding age used in the composite beam test. The higher cement content (Anna County and the Brazil) mixtures had higher compressive strengths and some of the highest peak loads at failure as seen in Table 3. For the SEN(B) tests performed at 28 days (with the exception of the Gravel Schanck mixture), the peak loads ranged from about 3.5 to 4.3 kN, much higher than the 14-day specimens at 2.4 to 3.7 kN range, and had similar initial fracture properties. The Gravel Schanck mixture has the highest elastic modulus, which reduced its initial fracture energy. The Anna County mixture demonstrated the lowest initial fracture energies at 14 and 28 days as expected. The Dan Ryan mixture had one of the highest initial and total fracture energies at 28 days for an un-reinforced concrete.

The High FRC Schanck mixture had the greatest peak and post-peak behavior when tested at 28 days as seen in Figures 2 and 4. As seen in Table 3, the initial fracture energy and the stress intensity factor for the High FRC Schanck mixture are slightly higher than the Plain Schanck due to the later age of testing and the increased compressive and tensile strengths. The Low FRC Schanck mixture had roughly the same peak load as the Schanck Plain mixture at 14 days; however the post-peak load is considerably higher even out to large CMOD values as shown in Figure 4. As expected, the total fracture energies for the Low and High FRC Schanck mixtures are considerably greater than the Plain Schanck, at 1,720 N/m and 3,550 N/m, respectively, versus 60 N/m. This additional energy capacity with fiber-reinforced concrete allows the UTW that has begun to crack to continue to provide adequate structural and functional service life.

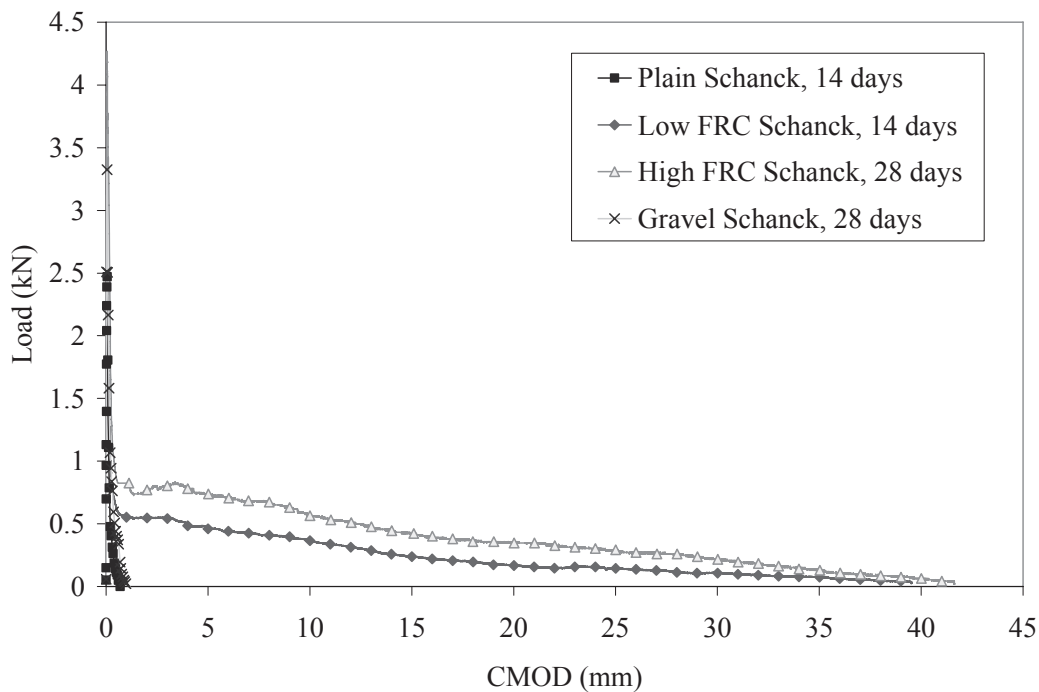


Figure 4 – TPB Specimen load versus CMOD curves for run-out tests for Schanck mixtures.

Shrinkage Results

In UTW designs, excessive concrete shrinkage could result in de-bonding between the concrete and existing HMAC layer. Higher strength mixtures were typically more susceptible to this behavior due to their higher total cementitious content. In order to assess the potential for excessive long-term shrinkage, specimens were cast with dimensions of 75 x 75 x 285 mm according to ASTM C157-99. Shrinkage specimens were de-molded 24 hours after casting, and then stored immediately in a controlled climate room at 50% RH and 23 °C. Shrinkage was measured at approximately 1, 2, 3, 7, 14, 28, 56 and 90 days after casting for several composite beam mixtures.

Shrinkage results for the Plain Schanck, Low FRC Schanck and Anna mixtures are shown in Figure 5. The addition of fibers in the Low FRC Schanck mixture compared to the Plain Schanck mixture led to a lower free shrinkage in the concrete. Other testing done to measure shrinkage of concrete has determined that the shrinkage was reduced by about 0.02% at 28 days with the addition of 0.5% volume fraction of polypropylene or steel fibers (Leung et al. 2005). The use of higher cement content in the Anna County mixture showed a greater drying shrinkage after approximately 14 days. Since the Anna County mixture has a lower water cement ratio of 0.36, some of the shrinkage seen here was likely due to autogenous shrinkage (Mindess et al. 2003) since a smaller amount of free water was lost to external evaporation.

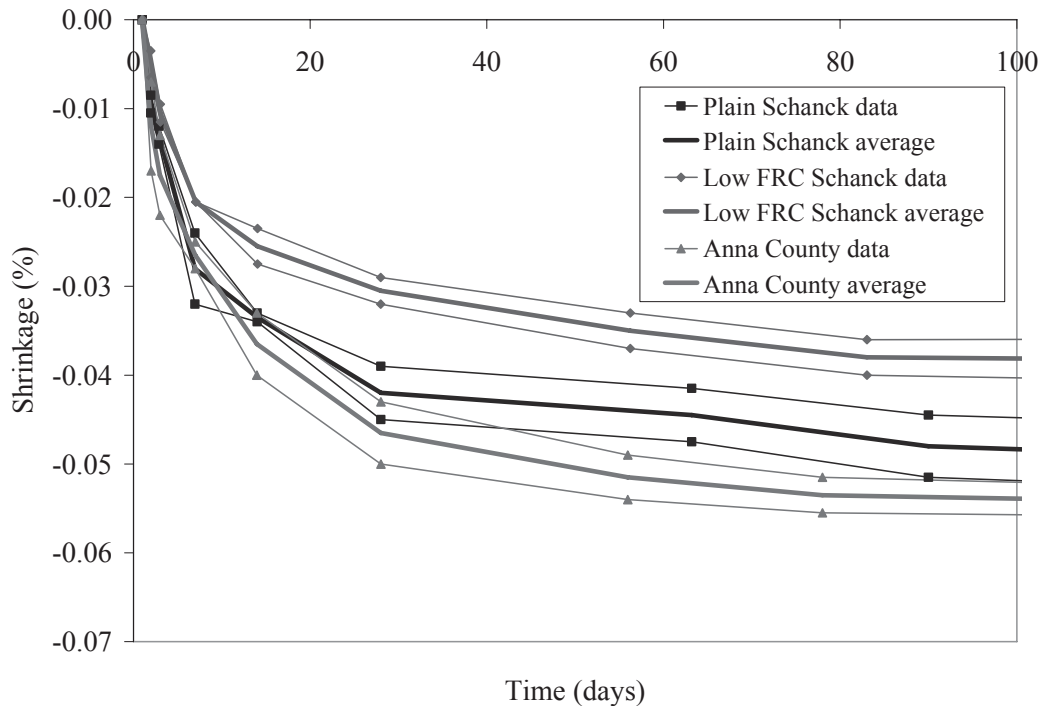


Figure 5 – Concrete free shrinkage results for the UTW mixtures.

Composite Beam Results

The vertical deflection (stroke) measured for each beam is shown in Figures 6 and 7. As seen in Figure 6, the 1st beam specimen of the same concrete generated larger vertical deflections as the soil compacted under the loading compared to the 2nd beam specimen (Figure 7). It appeared that when the soil moisture was lower (cracks occurred in the clay), the difference between the 1st and 2nd beam tested was lower and the magnitude of the vertical deflection was lower. The Anna County, Dan Ryan and Brazil mixtures were tested with the soil in a drier condition. The results from the LVDT measuring the total vertical deflection did not always work properly (particularly with the Low FRC Schanck beams) due to problems with the rigid connection. In general, the vertical deflection from the actuator stroke was expected to have some extraneous deformations and should not be considered the “true” total deflection.

The results of the estimated crack opening displacement (COD) were plotted versus load for the Schanck Avenue and all other concrete mixtures in Figures 8 and 9, respectively. The load versus COD curves was similar between the two composite beam specimens tested for each concrete mixture.

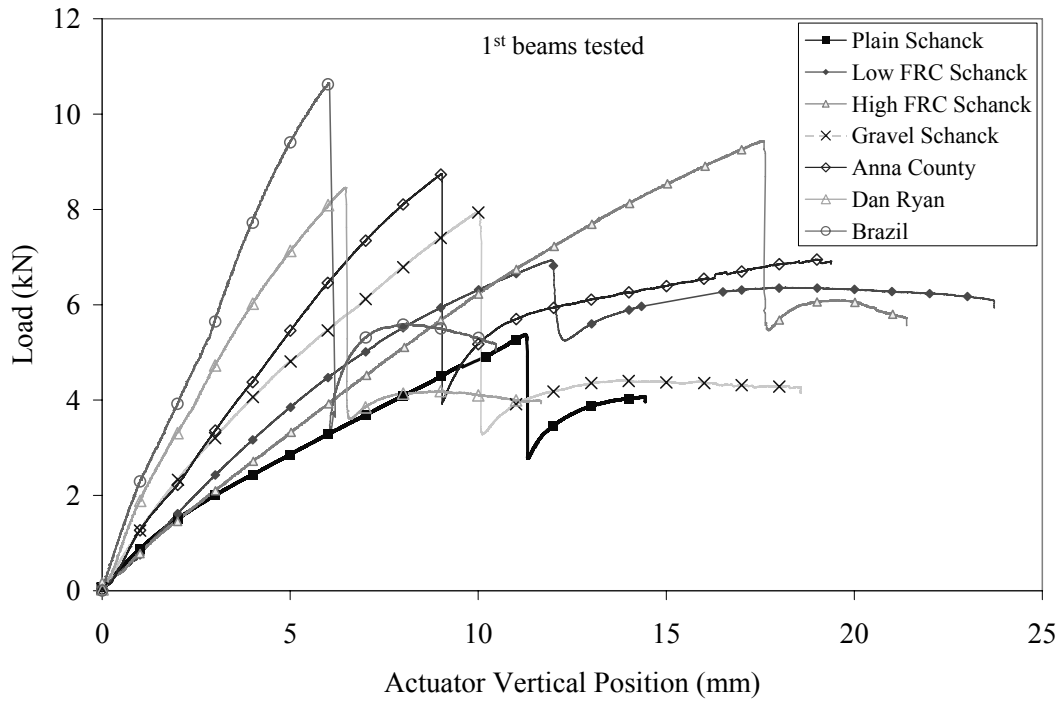


Figure 6 – Vertical deflections (stroke) for 1st composite beam specimen.

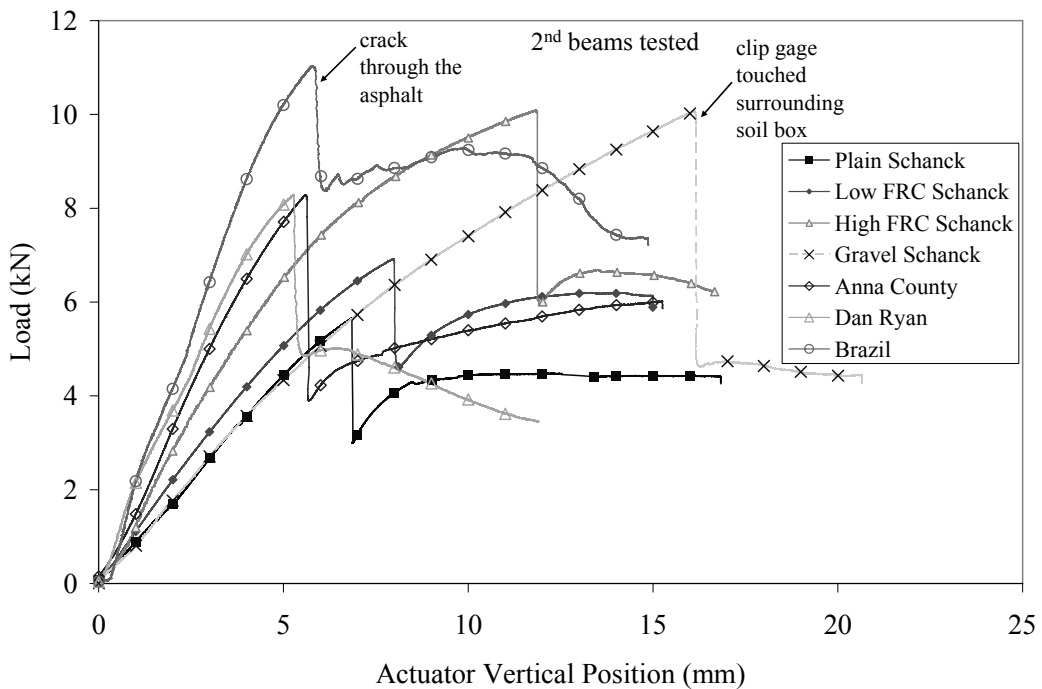


Figure 7 - Vertical deflections (stroke) for 2nd composite beam specimen.

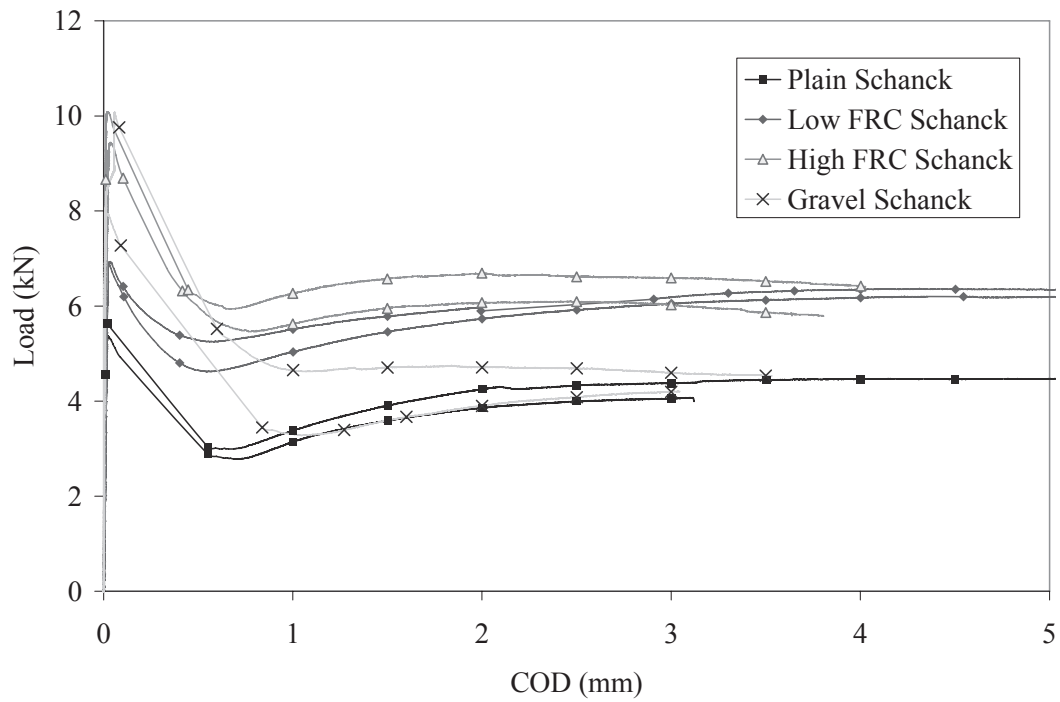


Figure 8 - Load versus crack opening displacement curves for Schanck Avenue composite beam specimens.

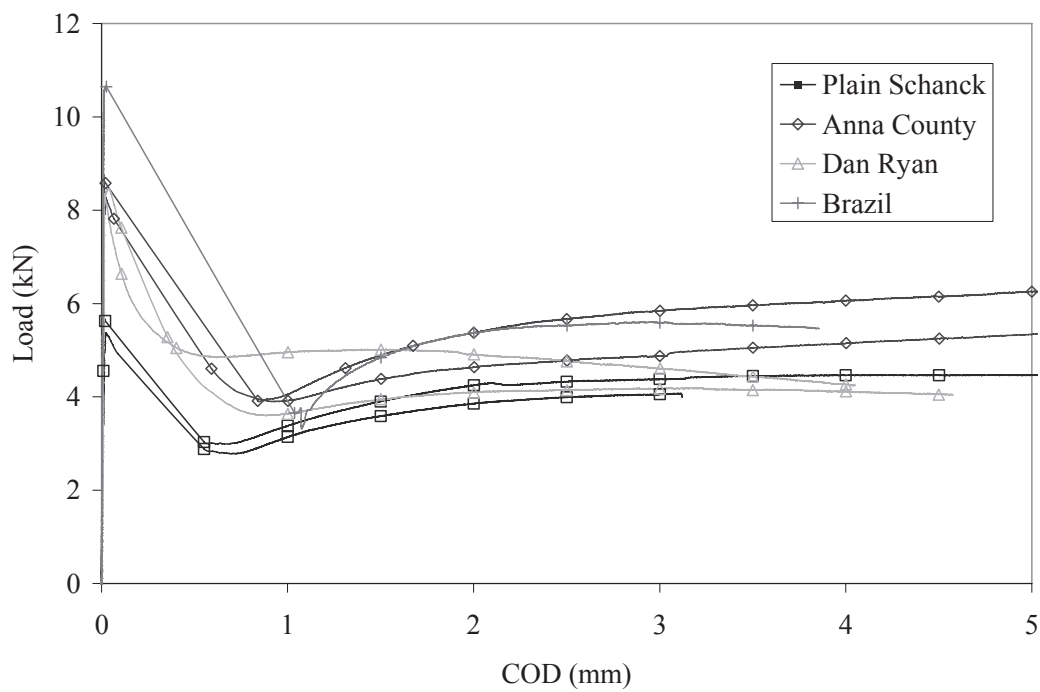


Figure 9 - Load versus crack opening displacement curves for non-reinforced composite beam specimens.

The overall objective of the composite beam test was to determine the effect of the concrete mixture on the peak load capacity and residual load capacity after cracking. The first peak load occurred simultaneously with the sight of a macrocrack through the concrete layer above the HMAC notch. The load dropped off immediately as a plastic hinge was formed. The majority of the post peak load behavior was associated with the soil reaction with very limited beam bending and significant compression of the beam into the soil. Testing was halted once it was clear that the soil was contributing most of the energy from the test after the concrete had fractured.

The stroke vertical deflection and COD values at the peak and minimum load (after the drop), and the load drop percentage are shown in Table 4 for all the concrete mixtures. A schematic of the composite beam load-deflection response is shown in Figure 10. The Peak/Min Load ratio was found by dividing the peak load by the minimum load immediately after cracking, while the percent load drop was defined as

$$\% \text{ Load Drop} = \frac{(P_{Peak} - P_{Min})}{P_{Peak}}.$$

Table 4 – Average Composite Beam Specimen Results

Mixture	Age (days)	Peak Load (kN)	Min Load after cracking (kN)	COD (mm)		Machine Position (mm)		Peak/Min Load Ratio	% Load Drop
				@ Peak	@ Min	@ Peak	@ Min		
Plain Schanck	14	5.5	2.9	0.020	0.68	9.1	9.1	1.9	48%
Low FRC Schanck	14	6.9	4.9	0.027	0.57	10.0	10.2	1.4	29%
High FRC Schanck	28	9.8	5.7	0.027	0.72	14.7	14.8	1.7	42%
Gravel Schanck	28	9.0	3.9	0.039	1.06	13.1	13.2	2.3	56%
Anna County	14	8.5	3.9	0.017	0.88	7.3	7.4	2.2	54%
Dan Ryan	28	8.4	4.2	0.025	0.75	5.9	6.1	2.0	50%
Brazil	28	10.8	5.8	0.017	0.54	5.9	6.1	2.3	47%

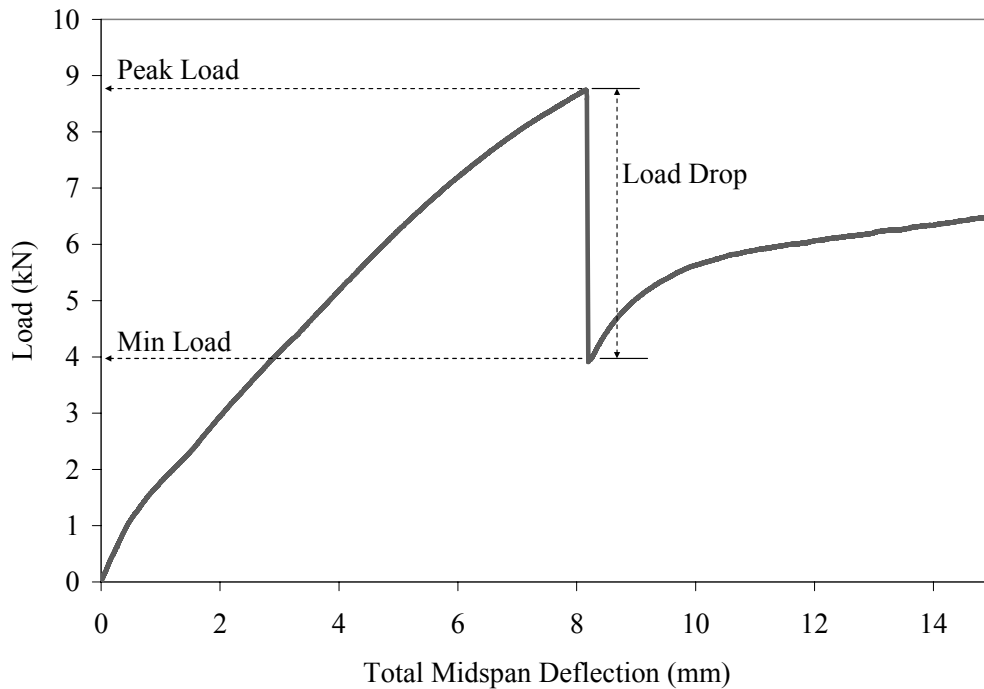


Figure 10 - Example of composite beam specimen load-deflection result.

The peak load for the Brazil mixture was the highest while the smallest peak load came from the Plain Schanck mixture; this is a similar trend as the compressive strength for the Brazil and Plain Schanck mixtures. The Anna County and High FRC Schanck mixtures showed higher peak loads also corresponding with their higher compressive strengths. Note the age of testing had an effect on the results. All of the specimens tested at 28 days showed higher peak loads, while among the 14 day specimens, only the Anna County mixture demonstrated a high peak load compared to the other mixtures. A high strength concrete mixture can be beneficial as long as full bond is maintained with the HMAC layer and cracking does not occur.

The drop in load was hypothesized as a significant factor to estimate the structural integrity of the UTW once a crack does form. For example, in the field the Anna County pavement section had the most cracking within each slab and with cracking appearing early on in the pavement life (Winkelman 2005). The magnitude of the load drop can be associated with the performance of UTW in the field after some initial cracking has occurred. Past research projects have demonstrated increased flexural capacity of plain concrete slabs when structural fibers are added (Roesler et al. 2004, 2006) and this additional capacity can be predicted based on the residual strength of concrete beams (Altoubat et al. 2008).

Based on the results here, the Anna County mixture does show slightly poorer results as far as the having a 54 percentage drop in load capacity after cracking. The Gravel Schanck mixture has the greatest load drop of 56 percent. This load drop is likely associated to the fact that these specimens fractured around the aggregates even at 28 days. On the other hand, the fiber-reinforced concrete mixtures (Low FRC Schanck and High FRC Schanck) have the two lowest load

drops at 29 and 42 percent, respectively. Some concrete construction issues with the High FRC Schanck mixture may have caused the higher load drop than the Low FRC Schanck mixture. Overall the drop in load was not as significant as expected. In addition, the geometry of the test, as previously mentioned, impacted the fracture behavior of the composite beams. This behavior was attributed to the 2-D nature of this test which does not allow the cracking propagation resistance between fiber-reinforced and plain concrete to be realized as has been seen slabs (Roesler et al. 2004).

Discussion of Laboratory Test Results

Several issues related to this composite beam testing apparatus have occurred, as was expected with a new testing technique. First of all the specimen geometry influences the fracture behavior of the beam. The soil moisture state also affected the deflection measurements. The results did show enough information to gain an idea of the fracture performance of the composite section and how the concrete constituents and proportions may be selected.

Concrete mixtures which achieve higher compressive strength or peak loads in composite beam testing are not inherently bad materials to select if bonding is maintained between the concrete and the HMAC layer. However, if significant cracking exists in the existing HMAC layer which may be reflected to the concrete surface, a fracture resistant concrete mixture is more desirable. Therefore concrete mixtures with moderate strength can be used along with minimized drying shrinkage; and structural fibers offer the improved fracture resistance against reflective cracking, greater load carrying capacity, greater residual load capacity, and more insurance in the case that de-bonding does occur at the HMAC/concrete interface. Ultimately the service life of an UTW section is an interaction of the existing condition of the HMAC layer, loading condition, UTW structural design, and finally the concrete materials selected. Further research on characterizing the existing HMAC and bonding conditions should be investigated to improve design and construction of future UTW pavements.

Conclusion

A new test method was developed of composite beams composed of concrete cast onto HMAC and tested on a clay subgrade to predict the fracture performances of UTW mixtures found in the field. The composite beam test results and SEN(B) fracture properties had similar peak load trends when comparing between mixtures. The magnitude of the percent load drop was not significantly different between the various plain concrete mixtures. Fiber-reinforced concrete specimens tested in a fully supported composite beam, demonstrated improved toughness compared to plain concrete mixtures. The percent load drop after each beam cracked was determined to be one means of differentiating the performance between fiber-reinforced concrete and plain concrete mixtures used for UTW projects. Fracture properties derived from SEN(B) specimens alone could be misleading as they did not always correlate to the performance seen in the field. Overall, the behavior and performance of UTW systems depends on the combined effect of loading, concrete material fracture properties, concrete/HMAC bond, geometry of the slab, and support condition. The

presence of debonding and cracking in a UTW section can rapidly fracture the UTW section even with high strength concrete mixtures. Fiber-reinforcement should be added to the concrete mixture to improve the cracking resistance, flexural capacity of the UTW, and increase the service life of UTW especially when bonding or support conditions are less than ideal.

Acknowledgement

This publication is based on the results of ICT-R27-3A, “Design and Material Requirements for Ultra-Thin Whitetopping”. ICT-R27-3A was conducted in cooperation with the Illinois Center for Transportation; the Illinois Department of Transportation, Division of Highways; and the U.S. Department of Transportation, Federal Highway Administration.

References

- Altoubat, S.A., Roesler, J.R., Lange, D.A., and Rieder, K.-A. (2008). “Simplified Method for Concrete Pavement Design with Discrete Structural Fibers.” *Construction and Building Materials*, 22(3), 384-393.
- Anderson, T.L. (2005). *Fracture Mechanics Fundamentals and Applications*. 3rd Edition. Taylor & Francis Group: Boca Raton, FL.
- Bordelon, A.C. (2007). *Fracture Behavior of Concrete Materials for Rigid Pavement Systems*. M.S. Thesis, University of Illinois at Urbana-Champaign, Urbana, IL.
- Hillerborg, A. (1985). “The Theoretical Basis of a Method to Determine the Fracture Energy GF of Concrete.” *Material and Structures, RILEM*, 16(4), 291-296.
- Ioannides, A. M. (2007). *Evaluation of UTW and Whitetopping Design Procedure*, Interim Report for the Illinois Center for Transportation, Cincinnati, Ohio.
- Jenq, Y. and Shah, S.P. (1985). “Two Parameter Model for Concrete.” *Journal of Engineering Mechanics*, 111(10), 1227-1241.
- Leung, C. K.Y., Lai, R., and Lee, A.Y.F. (2005). “Properties of wet-mixed fiber reinforced shotcrete and fiber reinforced concrete with similar composition”, *Cement and Concrete Research*, 35(4), 788-795.
- Lin, D.-F., and Wang, H.-Y. (2005). “Forensic Investigation of Ultra-Thin Whitetopping Failures in Taiwan.” *Journal of Performance of Constructed Facilities*, 19(2), 165-171.
- Mindess, S., Young J.F., and Darwin, D. (2003). *Concrete*, 2nd edition. Prentice Hall: Upper Saddle River, NJ.

Pereira, D.D.S., Balbo, J.T. and Khazanovich, L. (2006). "Theoretical and field evaluation of interaction between ultra-thin whitetopping and existing asphalt pavement". *International Journal of Pavement Engineering*, 7(4), 251-260.

Riley, R.C., Mallela, J., and Gotlif, A. (2005). "Whitetopping: Atypical Is Typical", *International Conference on Best Practices for Ultrathin and Thin Whitetoppings Conference Proceedings*, Denver, Colorado, 120-148.

Roesler, J. R., Bordelon, A., Ioannides, A. M., and Beyer, M. (2008). *Design and Concrete Material Requirements for Ultra-Thin Whitetopping*, Draft Report for Illinois Department of Transportation, ICT-R27-3A, Urbana, IL.

Roesler, Jeffery R., Altoubat, S.A., Lange, D.A., Rieder, K.-A., and Ulreich, G.R. (2006). "Effect of Synthetic Fibers on Structural Behavior of Concrete Slabs-on-Ground." *ACI Materials Journal*, 103(1), 3-10.

Roesler, J.R., Lange, D. A., Altoubat, S.A., K.-A. Rieder, and Ulreich, G.R. (2004). "Fracture of Plain and Fiber-Reinforced Concrete Slabs under Monotonic Loading." *ASCE Journal of Materials in Civil Engineering*, 16(5), 452-460.

Shah, S.P., Swartz, S.E. and Ouyang, C. (1995). *Fracture Mechanics of Concrete: Applications of Fracture Mechanics of Concrete, Rock and Other Quasi-Brittle Materials*. Wiley-Interscience: New York, NY.

Winkelman, T.J. (2005). "Illinois' Whitetopping Experience, A Practical Approach." *International Conference on Best Practices for Ultrathin and Thin Whitetoppings Conference Proceedings*, Denver, Colorado, 77-105.