REFLECTIVE CRACKING IN INVERTED PAVEMENTS:

FINDINGS FROM SIMULATIVE LABORATORY TESTS

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ABSTRACT

doi 10.1515ijpeat-2016-0029

An inverted pavement (IP) is a type of the pavement in which an unbound granular material (UGM) layer is constructed between a stiffer cement-treated base (CTB) and a hot mix asphalt (HMA) surface. The presence of the CTB layer in the inverted pavement gives high overall pavement stiffness but also leads to the possibility of reflective cracking initiating from cracks in CTB and propagating through the HMA surfacing. This paper involves the detailed description of a new test mould designed for studying reflective cracking within an inverted pavement in a simulative laboratory test. The results show the dependency of reflective cracking in IPs on the various layer thickness combinations. The thickness of UGM with a given thickness of HMA surfacing was found to affect the reflective cracking resistance of IPs significantly, with a factor of up to 5 between the best and worst cases. As expected, the resistance to reflective cracking also improved with an increase in HMA surfacing thickness although the improvement depended on the respective UGM thickness.
Keywords: Inverted Pavement; Reflective cracking; laboratory mould; layer thicknesses.

Introduction

An inverted Pavement (IP) is an inventive highway pavement design where the lower supporting cemented layer is more rigid than the upper structural unbound granular material (UGM) layer. The design was developed in South Africa in the early 1970s and has been given different names including G1-Base, Inverted Base, Sandwich Pavement, and Upside-Down Pavement. The layer arrangement gives a good overall stiffness to the pavement structure but decreases the chances of reflective cracking initiating from CTB and propagating through the HMA surfacing which is a major distress in semi-rigid pavement structures (Wang et al., 2018).

Reflective cracking is one of the critical failure modes in the pavement structures. It is observed in HMA overlays in a pattern that reflects the underlying cracks and joints of the old pavement and cracks generally occur above an inconsistency, for example, a joint in a Jointed Concrete Pavement (JCP) as mentioned by (Baek, 2010). Existing cracks and joints in the underlying pavement structure reduce the bending stiffness of the resurfaced pavement and act as stress concentrators that increase the overlay stresses. Crack development occurs when the stresses at the top or bottom of the HMA overlay exceed the HMA strength (Ghauch and Abou-Jaoude, 2013). It may also be observed in pavement structures where the stiffness of the base layer has been improved by adding admixtures like cement. The brittleness of the cement results in cracks in CTBs which under load applications tend to propagate through the HMA surfacing causing a reflective crack. The cracking may be accelerated depending on the type of loading and temperature. The mechanism of crack development in a JCP either by temperature or traffic loading is shown in Figure 1.

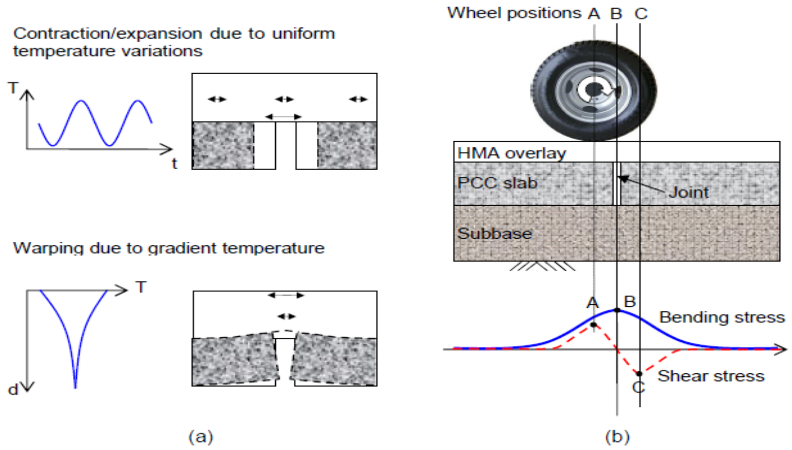

Figure 1: Schematic of reflective cracking mechanisms: (a) temperature variation and (b) traffic loading (after Baek, 2010 thesis)

Occurrence of reflective cracks in the overlays leads to the (1) loss of surface water-tightness which causes moisture to infiltrate through the pavement, reduces its structural capacity, and potentially deteriorates the subgrade; (2) increase in deformations at underlying pavement discontinuities, which induces higher stresses and strains throughout the pavement structure; and (3) loss of serviceability associated with the deterioration of the wearing course and stripping of asphalt overlay at joints (Ghauch and Abou-Jaoude, 2013).

There have been many studies conducted to evaluate the development of reflective cracking in pavements. Forensic investigation (Sha, 1993), laboratory testing (Jayawickrama et al., 1987; Kuo and Hsu, 2003) and numerical simulations (Song, 2006) have found a variety of reflective cracking patterns, although generally it is considered as a predominantly bottom-up cracking phenomenon. Three different types of reflective cracking were observed by Jayawickrama et al. (1987) who applied horizontal loading in a laboratory test on a pavement consisting of two HMA layers jointed by a glass-grid interlayer, as shown in Figure 2(a). The three types of cracking pattern observed are shown in Figure 2(a) and are; Type I, crack was initiated at the bottom of the lower layer and propagated upward to the top of the upper layer, Type II, crack initiated at the bottom of the lower layer, propagated up to the interface of the layers and then followed the interface and type III, two cracks initiated at the top of the upper layer and bottom of the lower layer and headed towards the interface.

Kuo and Hsu (2003) studied the reflective crack patterns for an HMA overlay over a JCP reinforced with a geo-grid interlayer. They found three more crack propagation patterns as shown in Figure 2(b) on the basis of various finite element analysis cases by varying geo-grid position, overlay thickness and asphalt concrete stiffness etc. The results indicated the development of reflective cracking at the bottom of the lower asphalt concrete layer propagating towards the interface and in the upper asphalt layer when the interface between the lower HMA layer and geo-grid was debonded (Type IV). They observed cracking patterns similar to type III; the simultaneous development of bottom-up and top-down reflective cracking was observed when the interface bonding was broken. They termed it as type V reflective cracking pattern. In one of the analysis variations, they placed the geo-grid at the bottom of the lower HMA layer and debonded the interface between the HMA and underlying JCP layer; bottom-up cracking was observed and termed as type VI. They reported the more likely occurrence of top-down reflective cracking with the condition of a relatively stiff and thick overlay or at high temperatures.

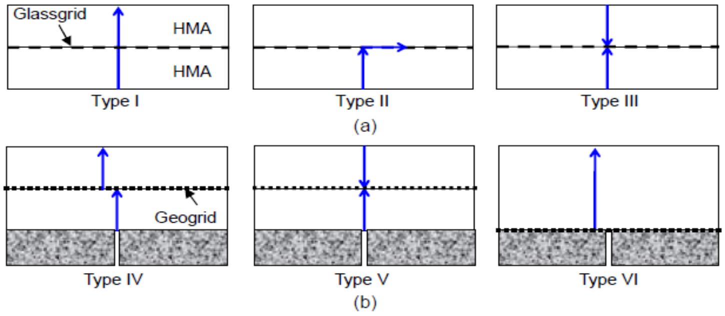

Figure 2: Reflective cracking paths observed in: (a) HMA/HMA structure with a glass-grid interlayer (Jayawickrama et al., 1987) and (b) HMA/PCC structure with a geo-grid interlayer (Kuo and Hsu, 2003)

Sha (1993) reported top-down reflective cracking observed in forensic investigations in the field. In the majority of cores, Sha found top-down reflective cracking in relatively thick (38–82 mm) HMA overlays, while the entire HMA overlay was cracked in relatively thin (28–38 mm) HMA overlays. He concluded that surface-initiated thermal cracking was the main distress in thick HMA overlays, and bottom-up reflective cracking occurred in thin HMA overlays. The phenomenon of top-down cracking for thick HMA overlays was also confirmed by Nesnas and Nunn (2004) who performed field observations as well as numerical analyses of the various cracking situations in the pavements. (Song, 2006) performed a series of fractured-base finite element (FE) analyses and reported the traffic and temperature-induced stresses to be the cause of development of bottom-up and top-down reflective cracking respectively. The chances of bottom-up reflective cracking could be decreased by ensuring that the underlying cracks have higher load transfer efficiency (LTE) as reported by Kuo and Hsu (2003). The reason for this reduction in the chances of reflective cracking was stated to be the lower stress concentration at the crack tip due to higher LTE. But this could also be associated with the increased chances of top-down cracking.

Reflective cracking in rigid or semi-rigid base pavements has been studied by many researchers incorporating different analysis methods including finite element, extended finite element (XFEM) and in some cases artificial neural networks. In some instances, in-situ pavements were monitored over the years for cracking but generally there has not been enough effort to study the phenomenon in the laboratory prior to road constriction. For example, the effect of subgrade and subbase stiffness, vehicle speed, overlay thickness and pavement temperature on the response at the bottom of an HMA overlay was observed by Ghauch and Abou-Jaoude (2013) by a finite element analysis. They generated an extrapolation of the strain history curve based on these parameters to estimate the number of load cycles to initiate a bottom-up reflective crack in an HMA overlay. Similarly, (Wang et al., 2018) used XFEM including a temperature model to study the influence of initial cracking lengths and inclined degrees of initial cracks on crack initiation and propagation. They reported the dependency of the cracking path on the inclination of initial cracks, and cracking width and stress distribution on initial cracking length and inclination of initial cracks. In another study, (Wang and Zhong, 2019) studied the reflective cracking mechanism under the combined effect of temperature and traffic loading by XFEM. The pavement temperature gradient was represented by an integrated climatic control model comprising solar radiation, surface heat flux and surface radiation. The traffic loads were simulated as standard biaxial loads including compressive stresses and horizontal shear. The results presented a new mechanism for studying reflective cracking by considering stress distribution, crack initiation temperature, cracking width and cracking paths. Researches have also been conducted to study the effect of different additives to improve the pavement resistance to reflective cracking. (Wang and Zhong, 2019) studied the influence of tack coat on the propagation of reflective cracking in semi-rigid asphalt pavements by XFEM under the combined effect of temperature and traffic loading. They stated that reflective crack resistance can be improved by decreasing the tack coat modulus between asphalt overlay and semi-rigid base.

But in the current project, reflective cracking has been studied in the laboratory by designing and constructing a new mould allowing the study and monitoring of crack initiation at the bottom of an HMA layer. The results showed the suitability of the mould for studying reflective cracking in the laboratory. The project, in the next phase, is to be extended to develop a model to predict reflective cracking initiation and propagation in an inverted pavement.

MATERIALS AND METHODOLOGY

The study was conducted on a simulative inverted pavement comprising HMA surfacing, UGM, CTB base and a 12mm thick rubber sheet as the subgrade. The materials used include 40-60 pen bitumen, crushed granite aggregate and cement with CEM II and 32.5kN strength. Figure 3 shows the aggregate gradations used during the project.

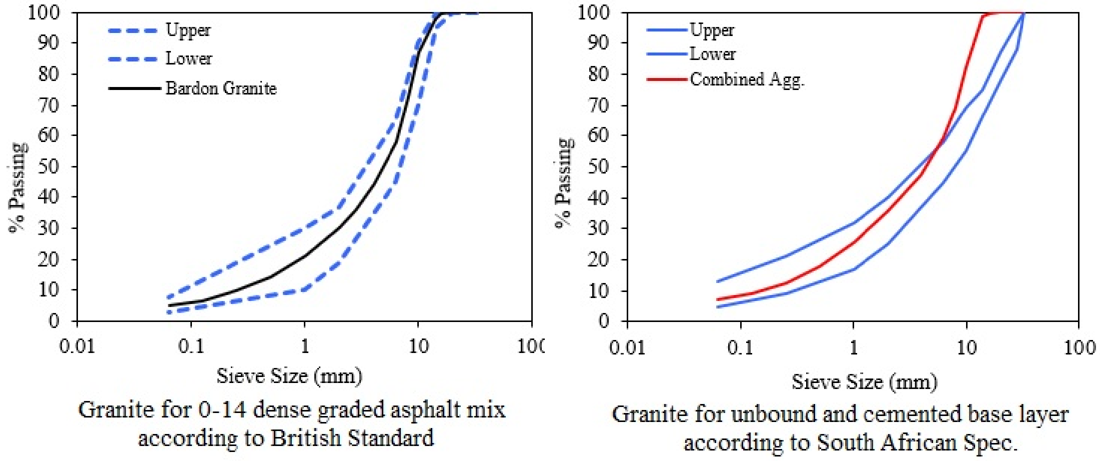

Figure 3: ***Aggregate gradations selected for the study***

To prepare the HMA, 5% of bitumen by weight was added as per BS 4987-1 (2005) while 4% of cement was added to the aggregate for the preparation of the CTB. The rest of the material properties are presented in Table 1.

Table 1: Materials properties

Sr. No.	Material	Parameter	Value	Test Method
1	Bitumen	Penetration @ 25^0C	43	BS EN 1426 (2015)
2		Softening Point (^{0}C)	51	BS EN 1427 (2015)
3		Specific Gravity	1.03	BS EN 15326 (2007)
4	Aggregate	Maximum Dry Density (Mg/m^3)	2.63	BS EN 13286-4 (2003)
5		Optimum Water Content	5.75	
6		Fines Content (HMA)	5.5	
7		Fines content (UGM and CTB)	7.4	-
8	HMA	Stiffness Modulus (MPa)	5080	BS EN 12697-26 (2012)
9		Air void (%)	5-7	BS EN 12697-8 (2003)
10	CTB	Compressive Strength (MPa)	30.81	BS EN 13290-3 (2019)

Testing Program

A detailed testing programme was developed to study the initiation and propagation of reflective cracks in a scaled-down inverted pavement. Different thickness combinations were selected to assess the effect of individual layer thickness on the overall performance of the pavement under loading. The utmost effort was made throughout the research to keep all the parameters including particle size, moisture, density, testing load and testing temperature the same for all the specimens tested in order to obtain representative results from the tests. The testing matrix is shown in Table 2.

Table 2: Testing matrix

Layer Thickness (mm)					Total Thickness (mm)
Asphalt concrete	UGM	CTB/ Simulation	Subgrade	Wooden Filler	
15	20	30	12	53	130
15	35	30	12	38	
15	50	30	12	23	
15	60	30	12	13	
20	20	30	12	48	
20	35	30	12	33	
20	50	30	12	18	
20	60	30	12	8	
25	20	30	12	43	
25	35	30	12	28	
25	50	30	12	13	
25	60	30	12	03	

The thickness of the wooden blocks to fill up space was determined from the total thickness of the mould (130mm) minus the combined thickness of the four structural layers (AC+UGM+CTB+SG). The specimens were prepared in different steps starting from placing the wooden blocks and rubber sheet subgrade. An already prepared, cured and cut-into-beams cement-treated base was placed on top of the subgrade. The CTB was cracked in the middle to generate reflective cracks. The top two layers i.e. UGM and HMA were prepared in-situ by compacting with the help of a vibratory compactor. The UGM layer was compacted at optimum moisture content in two to three layers depending on total thickness. HMA surfacing was compacted at 160°C by using Kango vibratory compactor. The density of both in-situ layers was controlled by monitoring the thicknesses. The wheel tracking equipment at Nottingham Transportation Engineering Centre (NTEC) was used to assess the pavement performance in the laboratory. The testing was performed by applying a 1.5kN circular wheel load at a rate of 26.5 passes per minute having an approximate contact radius of 23.6mm and contact pressure of 850kPa. The temperature was kept at 10°C to enhance the cracking. It is also worth recording that all the specimens were conditioned at the test temperature for 10-24 hrs prior to testing. A GoPro camera was used to monitor the crack initiation in the specimen by taking a picture at intervals of 30 sec. The number of load applications was calculated from the wheel speed and the number of GoPro pictures at crack initiation and failure.

A new mould for studying reflective cracks

The wheel tracking test to study reflective cracking could not be performed in a conventional wheel tracking mould due to its steel walls hindering the ability to monitor the crack initiation and propagation in the HMA layer. Therefore, a mould was designed and manufactured with the ability to monitor crack propagation without compromising the ability to compact and test. It was designed considering that the highest tensile strains would be present at the bottom of the asphalt layer causing the crack initiation at that level.

The newly designed mould, shown in Figure 4, part A, consists of a steel base plate, longitudinal steel walls, transverse steel walls, long and short steel angle sections, angles to support the specimen and a steel plate to support the top surface of a prepared specimen. All the angle sections were 40 × 40mm having a length equal to the wall they were welded or bolted to.

The base plate is the foundation of the mould which encompasses all the other components providing the required strength during compaction and testing. The base plate is welded to the long and short walls to assemble the basic mould frame. The short walls corresponding to the width of the mould were assembled to the full depth (130mm) of the mould. Along the length of the transverse sidewalls, angle sections were welded to provide lateral support to the mould during compaction and testing. The longitudinal side walls were manufactured in two different parts; removable and non-removable. The bottom 105mm was made by welding non-removable steel walls whereas the top 25mm was made up of removable pieces. These were designed to be removable during testing for better observation of crack initiation under loading. As UGB and HMA layers were prepared in-situ in the mould, the removable walls were made of 40 and 50mm height in order to accommodate the loose materials before compaction (Figure 4, part B). The welded transverse and longitudinal walls were also provided with 40×40mm steel angle sections along the length for lateral support to the mould during compaction and testing. A total of three different removable longitudinal wall pieces of 10, 40 and 50mm height were manufactured and used in the preparation of different specimens. Four steel angle sections of 40×40×40mm were manufactured for the lateral support of the prepared specimens during testing when side walls were removed. Two steel plates of 56×47mm were also prepared to overlap the HMA layer up to 7mm. These were provided on both ends of the prepared specimen in order to provide support to avoid the uplift of the specimen during wheel load application on the opposite end. The supporting angle sections and steel plates are shown in Figure 4, part C.

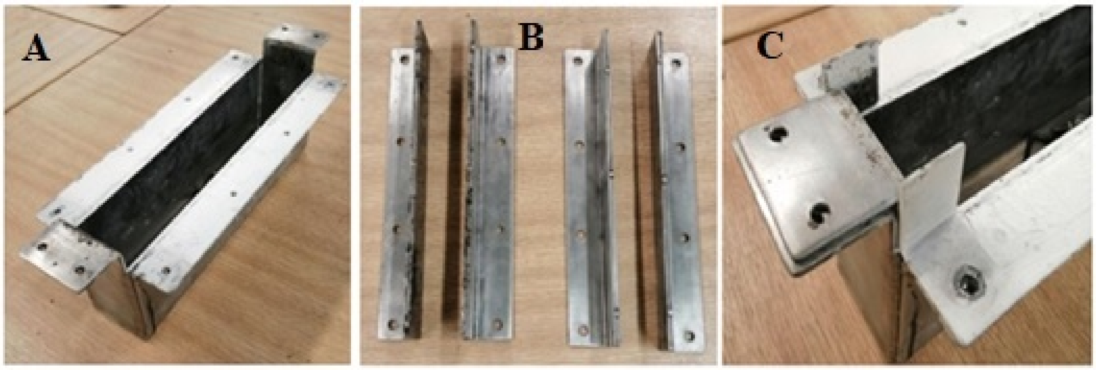

Figure 4: New assembled mould and parts

RESULTS AND DISCUSSION

The results obtained from the cracking tests are presented in Figures 5-7.

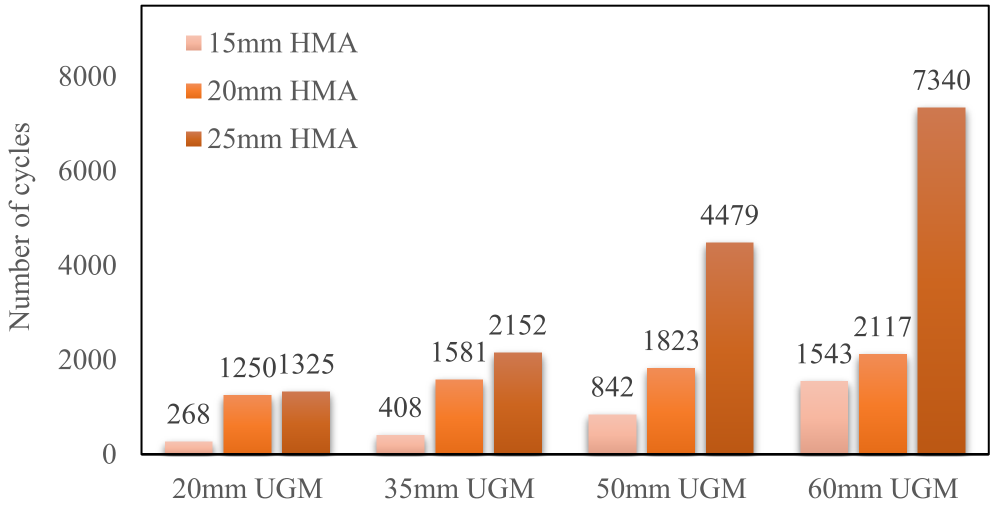

Figure 5: Cycle number to initiate cracking in wheel tracking specimens

Figure 5 shows the effect of increments in HMA thickness on pavement performance at any given UGM thickness. It clearly shows better pavement performance, as expected, under loading with increased thickness combinations. With an increase in UGM thickness for any HMA thickness, the pavement resistance to cracking increased. Taking the first thickness combination, 15mm HMA and 20mm UGM, as a baseline, the number of cycles required to initiate the cracks in the pavement increased by 52, 214 and 475% for specimens having UGM thicknesses of 35, 50 and 60mm respectively under the same test conditions. For 15mm HMA, an increase in UGM thickness from 20 to 60mm increased the pavement life by 475% with reference to the baseline. Similar results can be seen for an HMA layer of 25mm where an increase in pavement life up to 454% was observed with an increase of unbound thickness from 20 to 60mm. The percentage of increase in pavement life by increasing the UGM thickness at an HMA thickness of 20mm was not as high, only 70%, probably due to natural variation between individual test specimens. The minimum increase in pavement life observed for any layer increment was 15.3% by increasing the UGM thickness from 35 to50mm at 20mm HMA. Thus, it can be concluded that an increase in UGM thickness at any given HMA thickness improved the pavement performance significantly although the increase in performance was not directly related to increment in HMA thickness. It establishes the fact that these pavements resisted crack initiation based on the combined effect of the two-layer thicknesses. Clearly a thick HMA layer would be less susceptible to bending under load resulting in less tendency to crack and hence improved pavement life. Similarly, an increase in UGM thickness would reduce the bending above the crack in CTB and hence result in an improved pavement performance under loading avoiding the cracking.

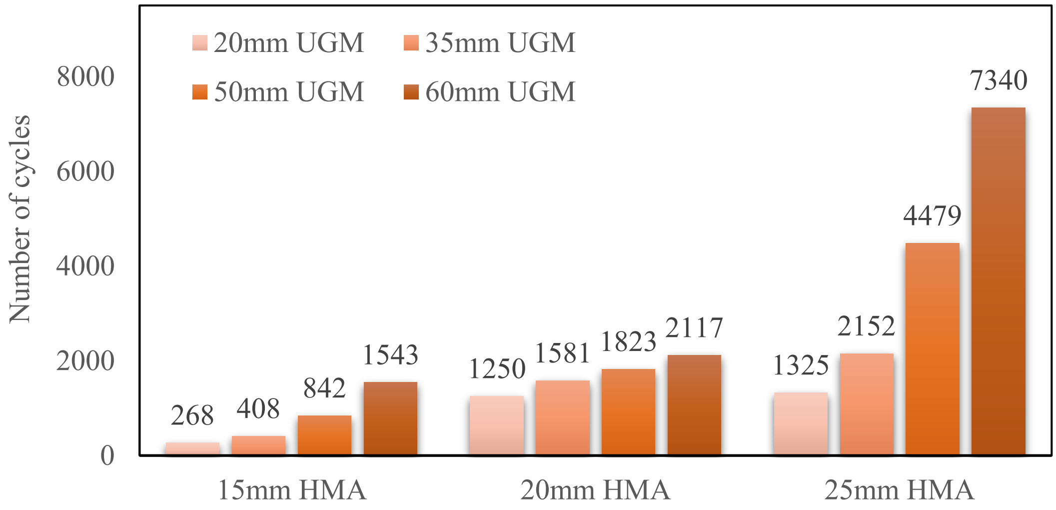

Figure 6: Effect of HMA thickness on cracking with varying UGM thicknesses

The effects of UGMs thicknesses at any given HMA thickness on pavement life are shown in Figure 6 and a summary of the findings is given in Table 3. An increase in HMA thickness from 15 to 20mm decreases the pavement life with every increment in UGM thickness whereas the reverse is resulted by increasing HMA from 20 to 25mm. This result augments the already mentioned, in previous paragraph, explanation that an inverted pavement resists the reflective crack based on the combined effect of the two-layer thicknesses.

Table 3: Percentage increase in pavement life

Sr. No.	Percentage increase in pavement life (%)		
	UGM thickness (mm)	Increments in HMA thickness	
		15mm to 20mm	20mm to 25mm
1	20	368%	6%
2	35	287.5%	36%
3	50	116.5%	146%
4	60	37%	247%

The findings point towards the possibility of an optimum relationship between the layers to resist the crack initiation and propagation, where the pavement performance is related to the relative thickness of the HMA and UGM layers. This may be found by further analysis which may be carried out in the next phase of the study.

Figure 7 shows the number of cycles at the end of each test (i.e. failure). Tests were stopped on the visual appearance of a fully cracked specimen. The criteria to stop the test were similar for all the specimens.

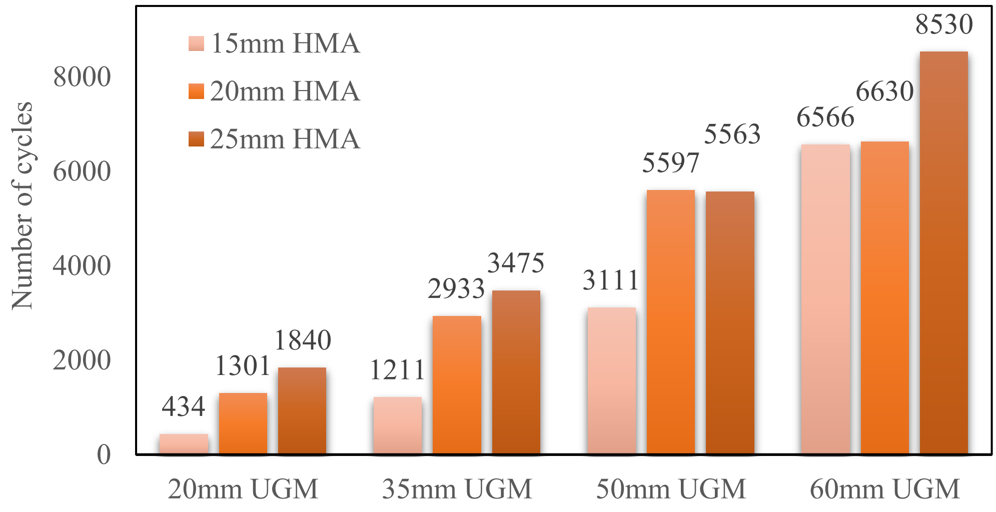

Figure 7: Cycles to failure on visual inspection

CONCLUSIONS

Following are the findings from this study;

- An increase in individual layer thickness increased the pavement response to resist reflective cracking under load. The improved pavement response was observed by increasing the thickness of either of the layers under consideration i.e. HMA surfacing and unbound granular layer.
- The number of cycles to initiate the cracks in the pavement depended upon the layer thicknesses and combinations. An increase in unbound thickness while keeping the asphalt thickness constant increased the pavement life significantly. For this study, increases in pavement cracking resistance up to 475% were observed.
- The response of the pavement to an increase in HMA layer thickness while keeping the unbound layer thickness constant was found to be dependent on the unbound layer thickness. For thin unbound layers, asphalt thickness increase from 15mm to 20mm generally resulted in significantly enhanced pavement life whereas further increase had less effect. This was due to the combined effect of unbound thickness and asphalt bottom tensile strains on crack propagation. For thick unbound layers, an increase in asphalt from 20 to 25mm increased the pavement resistance to cracking significantly.

ACKNOWLEDGEMENTS

The authors would like to thank Mirpur University of Science and Technology (MUST), Mirpur (AJK), Pakistan and University of Nottingham, UK for their financial and technical support to carry out the current research project.

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