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Interface bond strength of ultra-thin whitetopping (UTW) and hot mix asphalt (HMA) composites by direct shear

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Highlights

- Bond strength of ultra-thin whitetopping (UTW) and hot mix asphalt (HMA).
- Evaluation of interface bond strength by direct shear approach.
- Effects of different interface treatments on bond strength.
- Effects of temperature and moisture conditioning on the interface bond strength.
- Variation in the interface bond strength due to change in design binder content of HMA.

Abstract

Whitetopping is a Portland Cement Concrete (PCC) overlay that is constructed on the top of existing bituminous or hot mix asphalt (HMA) pavement. The design and construction of UTW over HMA enables the composite to act as a monolithic layer. This article presents the findings of laboratory study performed on interface bond strength of UTW and HMA composites by direct shear approach. The objectives of the study were to evaluate the main effects of (i) different interface treatments, (ii) variation in the design binder content of HMA, and (iii) temperature conditioning and moisture conditioning on the interface shear strength. Based on the results of interface shear strength tests, conclusions were drawn on the range of interface shear strength of UTW-HMA. Age of UTW, temperature conditioning and moisture conditioning were found to have significant effects on the interface shear strengths of UTW-HMA composites.

Keywords

Ultra-thin whitetopping; hot mix asphalt; interface bond strength; interface treatment; temperature and moisture conditioning;

1. Introduction

Whitetopping is a Portland Cement Concrete (PCC) overlay that is constructed on the top of existing bituminous or hot mix asphalt (HMA) pavement. It is generally recommended for locations where rutting of HMA pavements is a recurring problem. Based on the degree of bonding between the underlying HMA with PCC overlay and the thickness of the overlay, whitetopping can be classified into three types: (i) conventional whitetopping with a thickness more than 200 mm (WT), (ii) thin whitetopping with a thickness in the range of 100 mm and 200 mm (TWT), and (iii) ultra-thin whitetopping (UTW) with a thickness in the range of 50 mm and 100 mm. Design and construction of WT and TWT are same as a new rigid pavement without assuming any composite action. The design and construction of UTW takes into consideration the bonding between underlying HMA layer and the overlay, thereby enabling the composite to act as a monolithic layer. The composite action, under the vehicular loading, shifts the neutral axis from the middle of UTW to the bottom of UTW. Thus, the UTW layer comes in compression zone and the HMA layer comes in tension zone [1-2].

Research initiated in the early 1990s used various techniques like power brooming, power brooming with air blast, milling, cement and water grout, and emulsion tack coat for enhancing the bond between PCC and HMA. Grove et al. [3] noticed that the whitetopping pavement section that had bond strength as low as 0.690 MPa also did not show any distress. Mack et al. [1] were of the opinion that before placing UTW the existing asphalt surface must be milled and cleaned to promote bonding between the concrete and asphalt layers. The study emphasized the need for investigations on the role of interface shear strength towards any possible failures. Armaghani and Tu [4] asserted that, it is necessary to consider shear strength at the UTW-HMA interface as one of the acceptance criteria to ensure excellent ride quality on traffic lane. The shear strength tests performed in the study on the core-samples indicated that the interface shear strength values were in the range of 0.46 MPa and 3.76 MPa. The study noticed that de-bonding at the UTW-HMA interface was the most likely cause for the corner cracks. According to Wu et al. [5] such distressed sections can be effectively repaired by panel removal and replacement method. Wu and Sheehan [6] performed tests to assess interface bond strength by two methods: (i) shear test method, and (ii) pull off test method. The bond strength was found to be in the range from 0.307 MPa to 0.922 MPa, and the maximum relative slab movement due to temperature differential was only 0.6 mm.

Stiffness of the asphalt and the quality of bonding between the UTW and HMA layers affect the performance of UTW [7]. Study on performance of UTW pavements conducted at Federal Highway Authority (FHWA)-Accelerated Loading Facility (ALF) suggested that the permanent deformation characteristic of support layer was the common element for each type of distress noticed on the surface of UTW [8]. However, the results of the parametric study performed by Kumar et al. [9] using three dimensional-finite element modeling (3D-FEM) on UTW behavior showed that asphalt stiffness, concrete stiffness, temperature differential, and subgrade modulus have little effect on maximum interface shear stresses. Nishizawa et al. [10] also used 3D-FEM for stress calculations in UTW. It was found that the viscosity of asphalt sub-base and the interface condition significantly affected the stresses in the concrete slab. Vandenbossche [11] suggested that UTW should be laid on a sound HMA layer, which is highly resistant to moisture-induced damage and is well compacted.

Nebraska Department of Roads considers whitetopping as a cost effective alternative to conventional pavement removal and replacement operations [12]. However, to avoid premature failure of UTW, it is necessary to avoid high pouring temperature and to ensure sufficient asphalt under UTW [13]. Hence, the use of high-strength concrete with a low water to cement ratio should be discouraged when the pour temperature is high. Otherwise, it can result in high shrinkage and premature cracking. A strong interface bond between UTW and HMA will reduce the curling stresses in UTW, thereby minimizing the chances of thermal cracking [14].

Cho and Koo [15] performed mechanistic analysis using finite element method (FEM). The study showed that the thickness and the stiffness of the asphalt layer significantly affect the behavior of the UTW pavement. The bonding condition between the two layers and the size of the slab were found to be important variables that affect the behavior of UTW. A recent field study revealed that deterioration in the bond interface led to reduction of effective thickness of the composite pavement [16].

Many studies have adopted direct shear test to characterize the interface bond strength between HMA layers [17-20]. However, studies on interface bond strength between UTW and HMA using direct shear test approach are uncommon [3, 6, 21]. National Cooperative Highway Research Program's synthesis on thin and ultra-thin whitetopping [2] serves as a comprehensive source for the state of the art practices in thin white topping and ultra-thin whitetopping overlays. One of the issues highlighted in the synthesis is related to the bond strength. The synthesis strongly recommends further research to be conducted to establish relationship between the quality of HMA and the bond strength. It also suggests that research should be undertaken to quantify the effects on the bond from various surface preparation techniques.

2. Objective and Scope

The aim of this research was to evaluate the bond strength between UTW and HMA layers under different interface treatments and test conditions. The specific objectives of the study were to evaluate the main effects of (i) different interface treatments, (ii) variation in the design binder content of HMA, and (iii) temperature conditioning and moisture conditioning on the interface shear strength. Mix designs for UTW and HMA were performed as per the guidelines of the Indian Road Congress and the Asphalt Institute Manual Series respectively. Interface treatments adopted included chiseling, grooving, shear-key, and application of paste of polymer modified cement based additives (PMCA) on the surface of HMA layer. Interface bond strengths of UTW-HMA composite specimens were evaluated by the direct shear approach. Tests were performed at ambient temperature on composite specimens after a curing period of 7-days and 28-days. The effects of temperature conditioning and moisture conditioning on interface bond strength were also studied.

3. Materials

The major ingredient materials such as asphalt, ordinary Portland cement, aggregates, and water that are required for the preparation of the mix designs of HMA mixes and UTW mixes were tested according to the Bureau of Indian Standards (BIS). Properties of asphalt, ordinary Portland cement, and coarse aggregate are presented in Table 1, Table 2, and Table 3 respectively. In order to improve the workability of UTW mix, superplasticizer was added at a rate of 1.25% by mass of total cement. To improve the ductility and fatigue resistance, synthetic fibers at a rate of

0.20% of total mass of cement were added in the design mix of UTW. A polymer modified cement based additive (PMCA) was used as one of the interface treatments between UTW and HMA layers.

Table 1
Properties of asphalt

Characteristics	Test Results
Absolute viscosity at 60 °C, Pas	265
Kinematic viscosity at 135 °C, mm^2/s	380
Penetration at 25 °C, 100 g, 5s, 0.1 mm	64
Softening point (Ring and Ball), °C	50
Flash point (Cleveland open cup), °C	240

Table 2
Properties of ordinary Portland cement

Characteristics	Test Results
Specific gravity	3.15
Normal consistency, %	32
Initial setting time, minute	82
Final setting time, minute	520
7-Day Compressive strength, N/mm^2	48

Table 3
Properties of coarse aggregate

Characteristics		Test Results
Specific gravity		2.70
Water absorption, %		0.60
Impact value, %		24
Los Angeles abrasion value, %		29
Flakiness index, %		14
Elongation index, %		12
Density, kg/m^3		
	Loose	1460
	Dry-rodded	1600

4. Experimental program

Experimental Design

The experiments were designed to study the variations in interface bond strength of UTW-HMA composites as response variable. The effects of different treatment factors like types of interface bond conditions and binder content in the HMA mix on UTW-HMA composite were studied for curing periods of 7-days and 28-days. Further, the effect of temperature-moisture conditioning on UTW-HMA composite was also studied for the curing period of 28-days. Particulars of response variable, treatment factors and their levels, and UTW concrete curing periods are listed in Table 4.

Mix Designs for HMA and UTW

HMA mix design corresponding to 19 mm nominal maximum size aggregate gradation was performed as per the Marshall method [22]. Table 5 shows the aggregate gradation adopted for the HMA mix design. Properties of the design mix such as design binder content (DBC), air voids content (V_a), voids in the mineral aggregate (VMA), void filled with the bitumen (VFB), Marshall stability (MS), and flow value (FV) are shown in Table 6. Mix Design for UTW was performed as per the guidelines of Indian Roads Congress [23] to achieve a minimum characteristic compressive strength of 40 N/mm^2 and a minimum flexural strength of 5.0 N/mm^2. Table 7 shows the mix proportion, workability, average compressive strength and average flexural strength of UTW design mix.

Table 4
Experimental Design

Response Variable	Treatment Factors	Levels	Curing Period	No. of Composite Specimens	Remarks
Interface shear strength	Type of interface treatment	Plain surface (PS) Chiseled surface (CS) Single groove (1G) Double groove (2G) Triple groove (3G) Shear-key 25 mm diameter (SK25) Shear-key 35 mm diameter (SK35) Shear-key 50 mm diameter (SK50) Application of paste of PMCA	7-days 28-days	3 x 9 x 2 = 54	DBC in HMA: 5.5%
	Variation in the binder content of HMA	5.0, 5.5, and 6.0 % by weight of total mix	7-days 28-days	3 x 3 x 2 = 18	Interface treatment: PS
	Temperature and moisture conditioning	Dry-conditioning temperatures: 40 °C, 50 °C, 60 °C in hot-air oven (Duration: 1 hour).	28-days	3 x 3 = 9	DBC in HMA: 5.5% Interface treatment: PS
		Wet-Conditioning (Freeze & Thaw) Cycles: 3 Freeze temperature: –2 °C in deep freezer (Duration: 16 hours). Thaw temperatures: 40 °C, 50 °C, and 60 °C in water bath (Duration: 24 hours).		3x3 = 9	

Table 5
Aggregate gradation adopted for HMA mix design

Sieve size, mm	37.5	26.5	19	13.2	4.75	2.36	0.300	0.075
Cumulative percentage passing	100	95	83	68	46	35	14	5

Table 6.
Properties of HMA design mix

DBC, %	V_a, %	VMA, %	VFB, %	MS, kN	FV, mm
5.5	4.0	13.5	70.3	11	3

Table 7
Properties of UTW design mix

Particulars of design mix	Values
Mix proportion	
Water-cement ratio	0.34
Cement content, kg/m^3	450
Cement: Fine aggregate: Coarse aggregate	1:1.19:2.87
Superplasticizer, % of total mass of cement	1.25
Synthetic fibers, % of total mass of cement	0.20
Workability	
Slump, mm	27
Vee-Bee consistency, s	05
Average compressive strength, MPa	
7-day	38
28-day	57
Average flexural strength, MPa	
7-day	4.6
28-day	6.1

Preparation of composite specimen

Steps followed for the preparation of UTW-HMA composite specimen are as below:

i) HMA specimen having dimensions of 101.15 mm diameter and 63.5 mm height was prepared as per the Standard Marshall Compaction method. Compacted HMA specimen was extruded from the mould after allowing a setting period of 24 hours. At most care was taken to achieve the leveled flat-circular surface on HMA specimen to ensure parallel interface bond between UTW and HMA.
ii) The flat-circular surface of HMA specimen was subjected to interface treatment. Only groove interface treatment was provided during the fabrication of HMA specimen.
iii) After interface treatment, the HMA specimen was inserted into the specially fabricated split type Standard Marshall mould-collar assembly. The illustration of the same is provided in Fig. 1.
iv) UTW design mix was prepared to the required quantity and placed on the HMA specimen. The mix was then compacted using table vibrator.
v) After allowing a setting period of 24 hours, the UTW-HMA composite specimen was removed from the split-mould assembly.
vi) About 2/3rd height of UTW portion of the composite specimen was immersed in the water bath and subjected to water curing for a period of 7-days and 28-days.

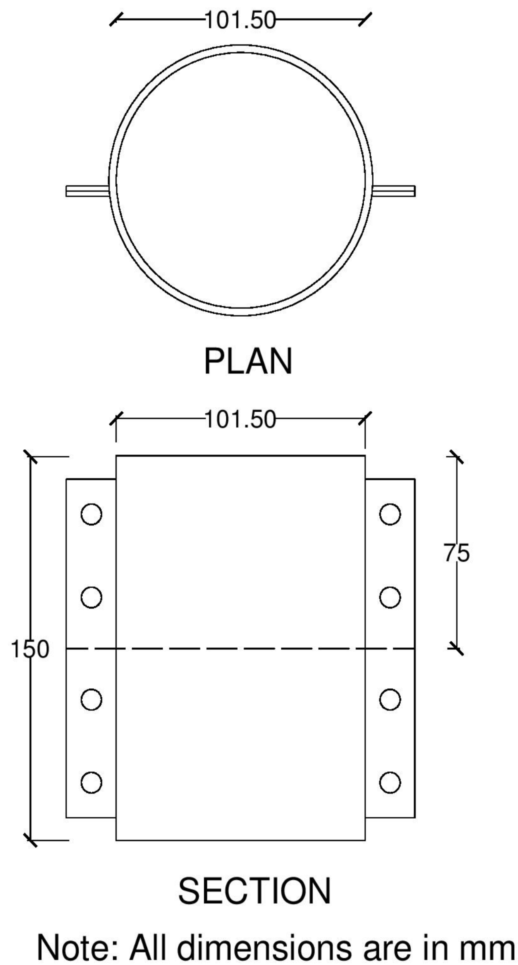


Fig. 1. Split-type standard Marshall mould-collar assembly

Interface treatments

Interface bond strengths of UTW and HMA composite specimens were evaluated for four types of interface treatments as mentioned in Table 4. Interface bond strengths of different interface treatments were compared with that of UTW-HMA composite specimens having plain surface (PS) treatment, where UTW was directly placed on HMA.

In the first type of interface treatment, HMA surface was chiseled randomly using bull-headed chisel. In the second type of interface treatment, the composite specimens were provided with grooves. Fig.2 gives illustrations of UTW-HMA composite specimens with groove(s) of dimension 5 mm x 5 mm. The illustrations also show the direction of application of shear force, which is parallel to the groove(s). In the case of composite specimen with 1G-type interface treatment, a groove was made on the surface of HMA along its diameter. In the case of 2G-type interface treatment, two parallel grooves each of 75 mm length were made on the HMA surface. In the case of 3G-type, three parallel grooves, a combination of 1G-type and 2G-type, were made.

Fig. 3 illustrates the steel shear-key frogs of three different dimensions used to create circular indentation of diameter 50 mm (SK50), 35 mm (SK35), and 25 mm (SK25) with a depth of indentation 5 mm. A circular indentation on HMA surface acts as a shear-key. This can be created by placing shear-key frog of required dimension at the center of the base plate of Marshall mould and subsequently compacting the loose HMA mix. Fig. 4 shows the drawings of UTW-HMA composite specimens with three different shear-key interface treatments and the direction of application of shear force.

In the fourth type of interface treatment, a 5 mm thick paste of PMCA was applied on the HMA specimen and allowed to set for 24 hours. Subsequently, UTM mix was placed on it and allowed to set and cure for a specific period of either 7-days or 28-days.

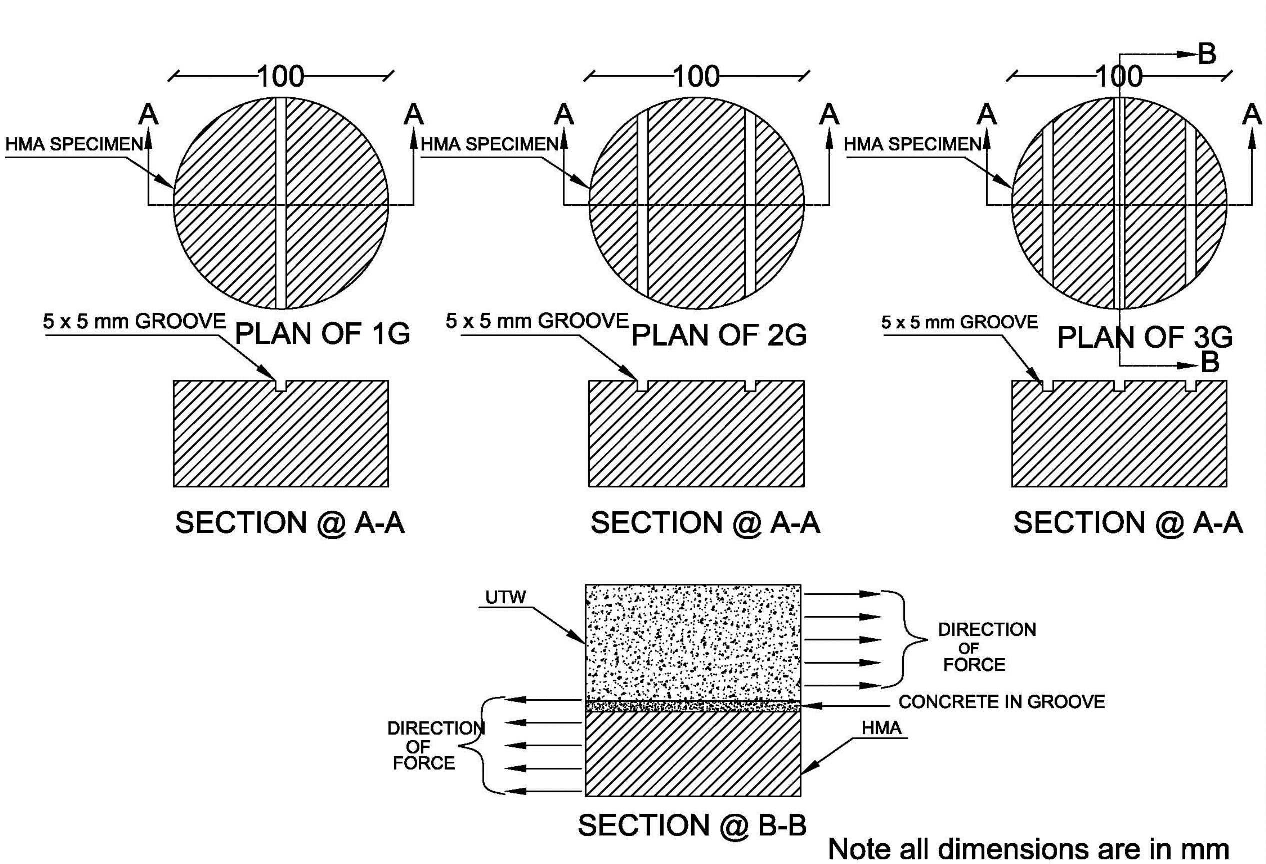


Fig. 2. Illustrations of UTW-HMA composite specimens with grooved interface treatment.

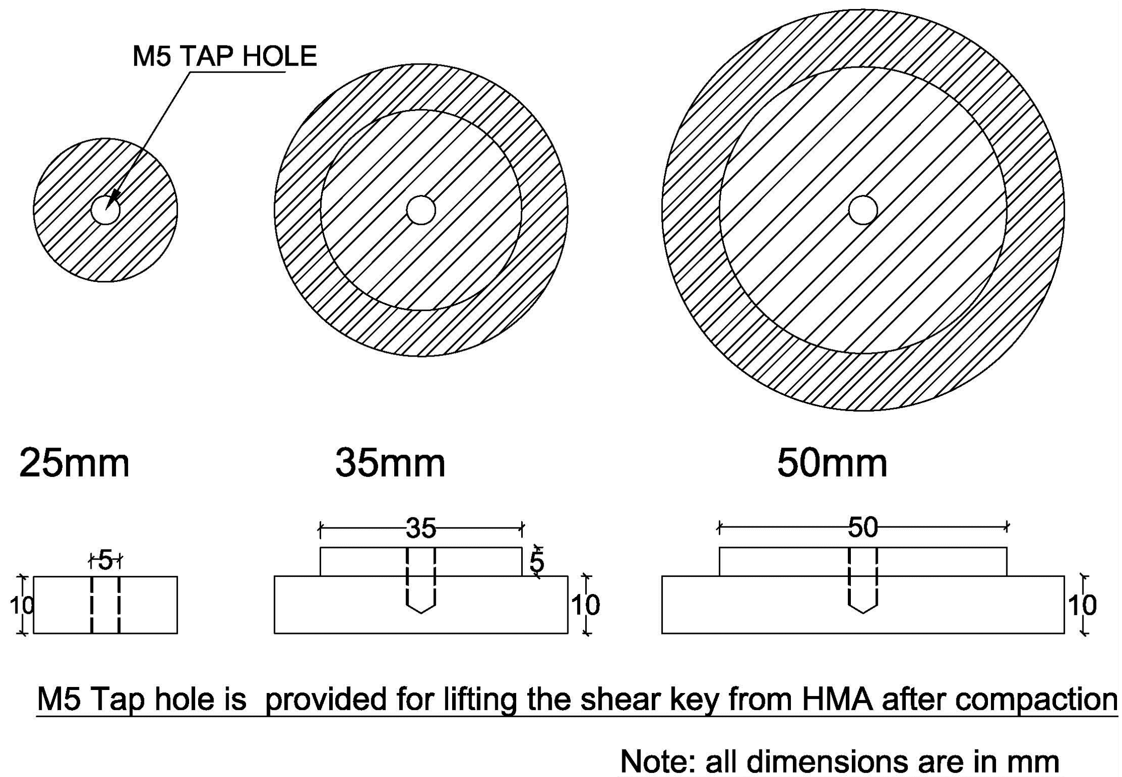


Fig. 3. Illustrations of steel shear-key frogs of three different dimensions

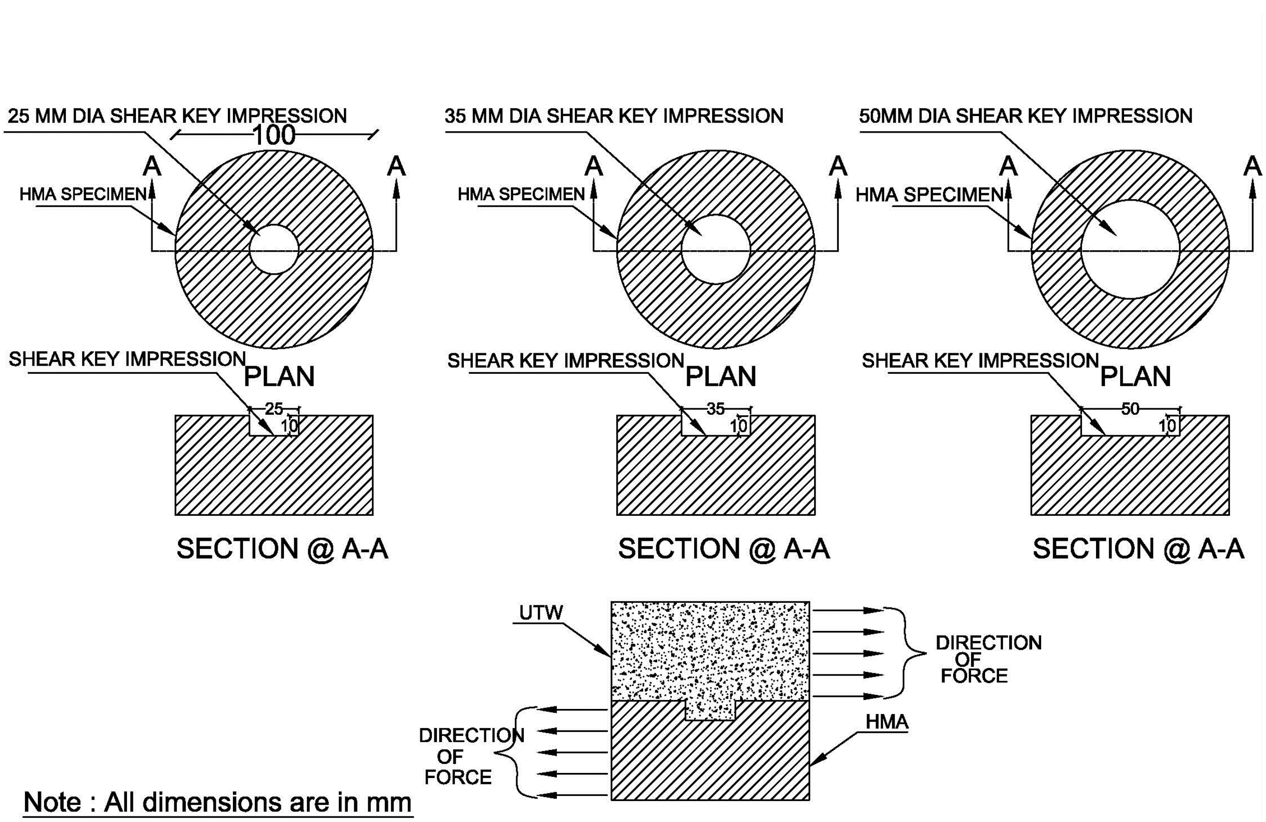


Fig. 4. Illustrations of UTW-HMA composite specimens with shear-key interface treatments

Binder content variations in HMA

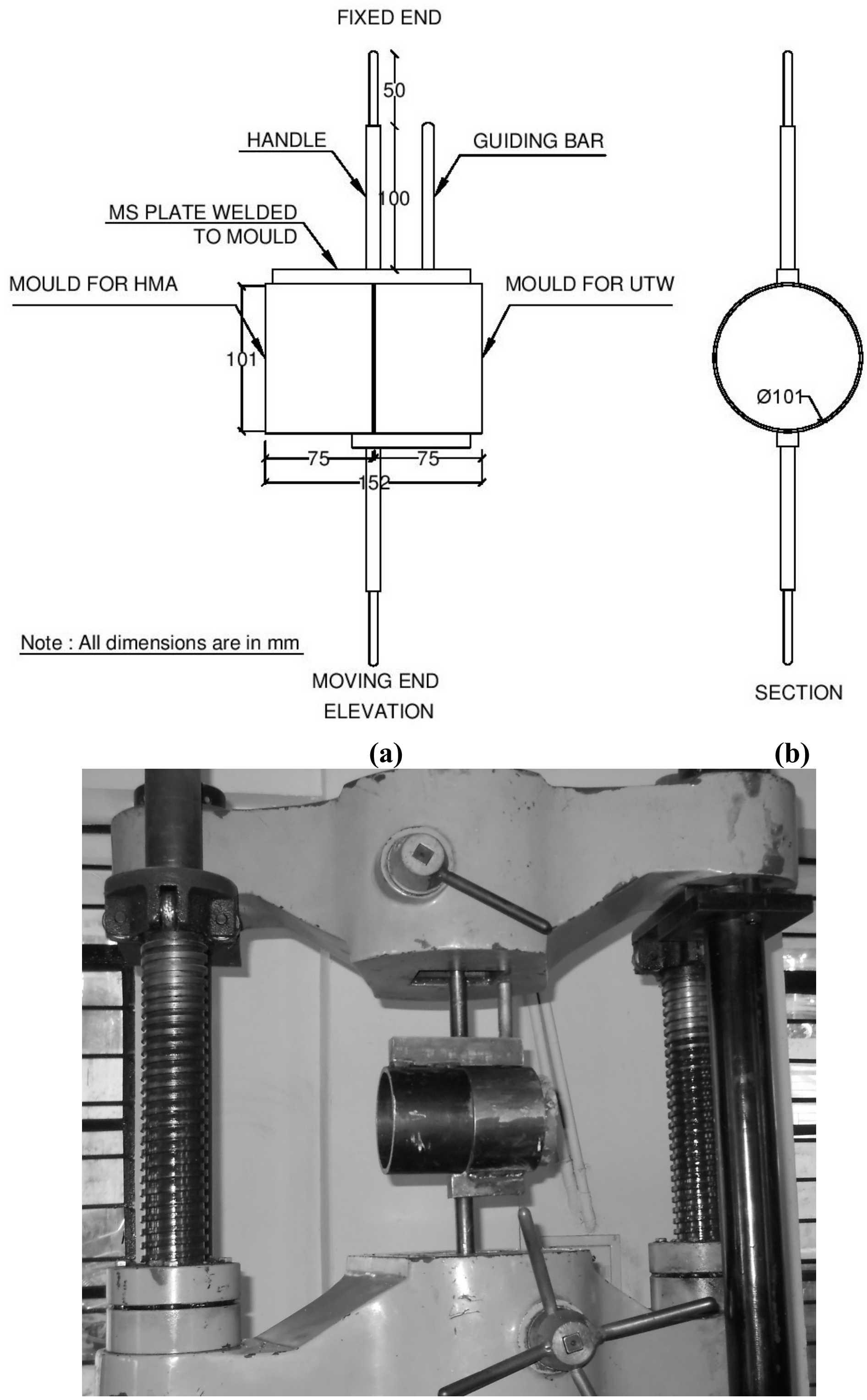
The effect of binder content in HMA on interface shear strength was studied by varying the binder content by DBC ± 0.5 percent. For this experiment, three sets of six PS-type UTW-HMA composite specimens were fabricated, where each set had different binder content in the HMA (DBC−0.5 percent, DBC, and DBC+0.5 percent). In each of the sets, three of the specimens were cured for 7-days and the other three were cured for 28-days.

Temperature conditioning and moisture conditioning

The effect of temperature on the interface shear strength was studied for dry conditioning as well as wet conditioning. In total, 18 PS-type UTW-HMA composite specimens, cured for a period of 28-days, were used for this experiment. Of these, one set of nine specimens was used for dry conditioning and another set of nine specimens was used for three cycles of wet conditioning. In the case of dry conditioning, the nine specimens were grouped into three subsets of equal sizes. Each of the subsets was dry conditioned at a different temperature (40 °C, 50 °C, and 60 °C) in a hot-air oven for a period of one hour. In the case of wet conditioning, all the nine specimens were first saturated with water and then stored in a deep freezer at a temperature of −2 °C for a period of 16 hours. Subsequently, these specimens were grouped into three subsets of equal sizes for thawing in a water bath at different temperatures (40 °C, 50 °C, and 60 °C) for a period of 24-hours. The procedure of freezing and thawing was repeated two more times for each of the subsets. Direct shear tests were then performed on all the dry conditioned and the wet conditioned specimens at a temperature of 25±1 °C. Shear strength values of wet conditioned specimens provided insight into the moisture sensitivity of UTW-HMA composites.

Testing of composite specimen

To perform direct shear tests on UTW-HMA composite specimens, a special shear breaking-head assembly was fabricated using Marshall moulds. Figs. 5 (a) and 5 (b) provide the illustrations of breaking-head assembly in elevation and section, respectively. Two moulds were positioned diametrically parallel with an interface gap of 5 mm. The top handle of the breaking-head was firmly gripped to fixed crosshead and the bottom handle was firmly gripped to the movable crosshead of the Universal Testing Machine (UTM) as shown in fig. 5 (c).



(c)

Fig. 5. (a) Elevation of shear-breaking head assembly, (b) Section of shear-breaking head assembly, (c) Photograph showing the shear-breaking head housed in the Universal Testing Machine.

Shear force was applied along the interface of the UTW-HMA composite by displacing the lower crosshead of UTM at the rate of 5 mm per minute. During shear force application, guiding bar helped to ensure parallel displacement of the composite specimen. After required duration of curing, the UTW-HMA composite specimen was subjected to air-drying. The specimen was then inserted into the breaking-head assembly and positioned in such a way that the interface of the composite specimen was exactly at the middle of 5 mm gap between the moulds of the breaking-head. Shear force was then applied by pulling the handles in opposite direction at a shear displacement rate of 5 mm per minute. The ultimate load (U_{max}) that led to the shear failure of the composite specimen was recorded. The interface shear strength of the composite specimen was computed as the ratio of ultimate load to the cross-sectional area (A) of the specimen. The test temperature was maintained at 25±1^{O}C. Fig. 6 depicts the relative positions of UTW and HMA due to shear failure.

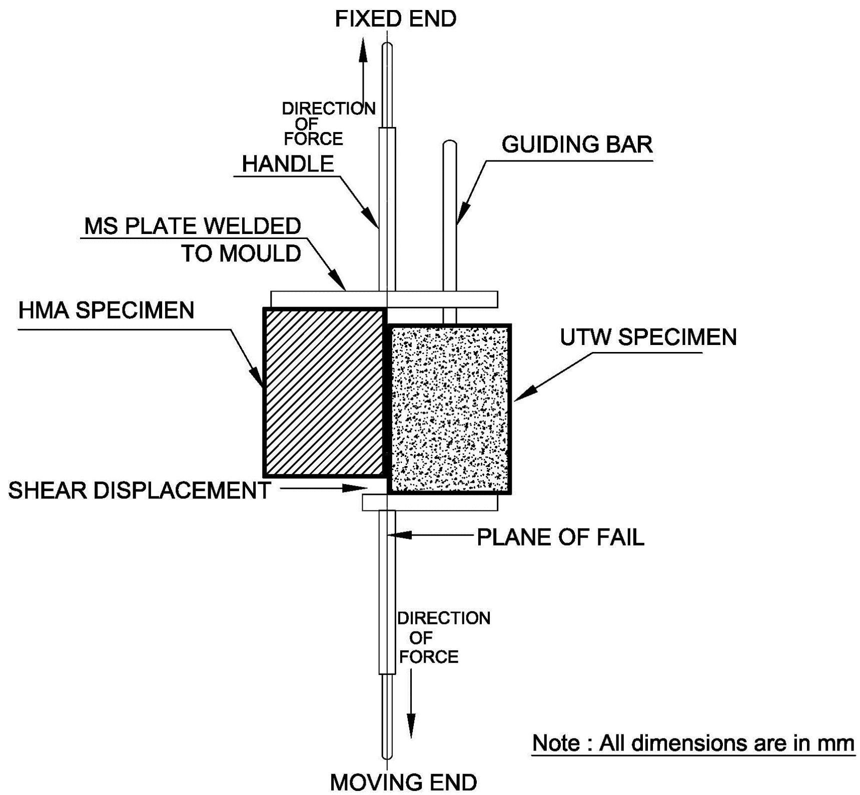
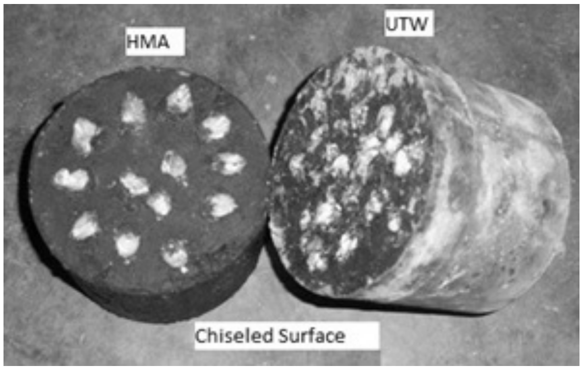


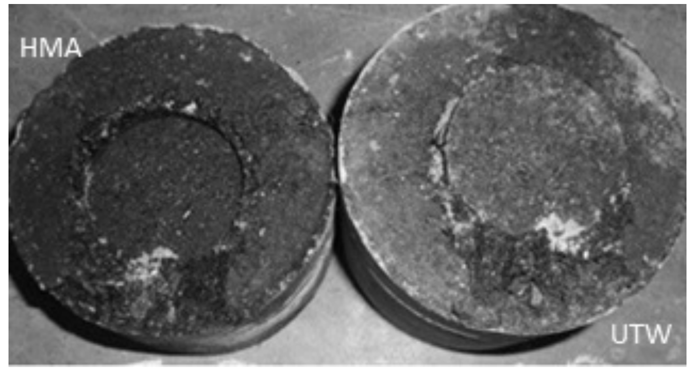
Fig. 6. Typical shear displacement of UTW-HMA composite specimen at failure load

5. Results and discussion

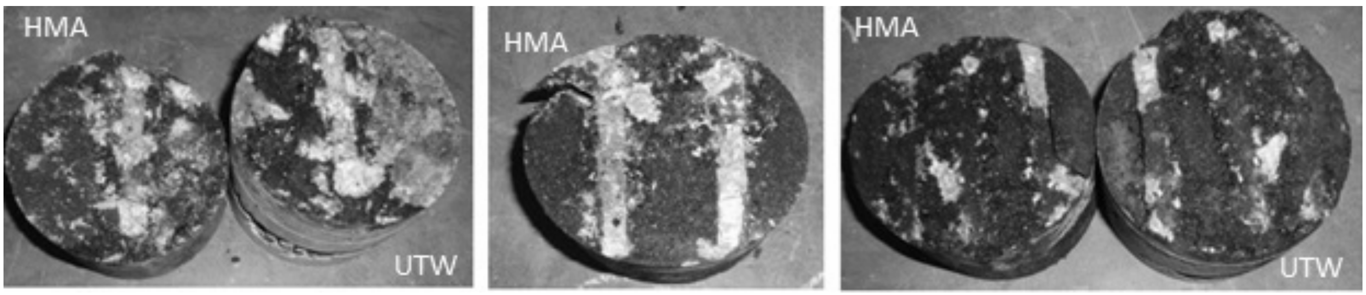
Interface shear strength tests were performed on UTW-HMA composites with different interface treatments. Fig. 7 shows the interface conditions of UTW-HMA composites for CS, G (1G, 2G, and 3G), and SK-type interface treatments after shear failure. These images provide confirmative evidence that the specimens did fail in shear along the interface.



(a) Chiseled interface (CS)



(b) Shear-key interface (SK50)



(c) Grooved interface (1G, 2G, and 3G)

Fig. 7. Interface conditions of UTW-HMA composites failed due to direct shear

Fig. 8 to fig. 10 shows the individual and the average shear strength values along with the 95 percent confidence interval (95-CI) plots for different treatment factors. It is evident from fig. 8 that the 95-CI plots of 7-days and 28-days strength values for a given interface treatment do not overlap. This implies that the age of concrete has a statistically significant effect on the interface shear strength. For the concrete curing periods of 7-days and 28-days, shear strength values were found to be in the ranges from 0.41 to 1.07 MPa and 0.58 to 1.28 MPa, respectively. Thus, the strength attained for the 7-days curing period was found to be in the range of 56 - 85 percent of the strength attained for the 28-days curing period.

The specimens with an interface treatment of 'PS' type exhibited lowest average strength of 0.45 MPa and 0.61 MPa for 7-days and 28-days, respectively. The specimens with other types of interface treatments exhibited a 28-days bond strength that was higher than 0.690 MPa, which can ensure sound bond for whitetopping [3]. Interface treatments like grooving, chiseling, and shear-keys resulted in larger interfacial contact area compared to plain surface, thereby resulting in higher strength.

The average 28-days strength values of specimens with interface treatments 1G, 2G, SK35 and SK50 were found to be more than 1.0 MPa and the corresponding 95-CI plots indicate that there is no significant difference among these average strength values. Grooves with closer spacing, that is, specimen with 3G-type interface treatment, exhibited lower strength compared to the composite specimens with 1G-type and 2G-type interface treatments. This, most probably, has happened due to the presence of thin ridge of asphalt mix, which is prone to rupture during load application.

Composites with PMCA as an interface treatment resulted in considerable improvement in the interface shear strength as compared to that of specimens with PS-type interface treatment. The average 28-day strength of the PMCA composites was found to be lower than that of the specimens with other types of interface treatments like chiseling, grooving and shear-keys.

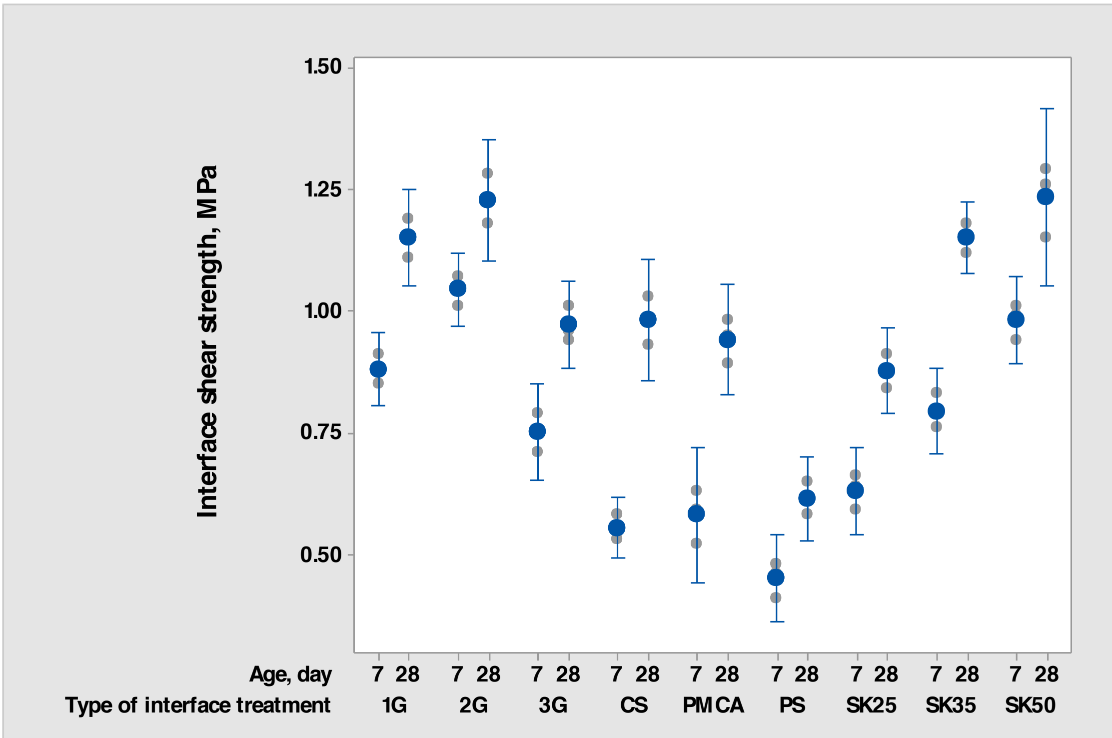


Fig.8. Variations in interface shear strength due to interface treatments and age of concrete.

Fig. 9 shows the results of interface shear strength tests performed on UTW-HMA composite specimens with PS-type interface treatment and three different binder contents in HMA. The test results indicated that the average 7-days and average 28-days strength values show similar variations. That is, when DBC was reduced by 0.5 percent the average strength values increased and when DBC was increased by 0.5 percent the average strength values decreased. However, the 95-CI plots indicate that these variations are not statistically significant. Generally, HMA with binder content lower than DBC exhibits more air voids content and higher macro-texture, which enhances interface bond strength. However, such HMA mixes may be more prone to moisture-induced damage and thereby result in reduced interface bond strength.

As mentioned earlier, experiments were also conducted to study variations in the interface shear strength due to temperature and moisture susceptibility of HMA. The results of interface shear strength tests are shown in Fig.10. The results clearly indicate that the average strength values decrease with increase in dry-conditioning temperature. The average strength values, with respect to the strength of unconditioned specimen, reduced by 15 percent, 24 percent, and 36 percent respectively for the conditioning temperatures of 40 °C, 50 °C and 60 °C. In the case of three-cycles of wet-conditioning, the average strength values reduced by 33 percent, 47 percent, and 64 percent respectively for the conditioning temperatures of 40 °C, 50 °C and 60 °C. The 95-CI plots indicate that the variations between the strength values for conditioning temperatures of 40 °C and 60 °C were statistically significant. However, the variations between the strength values for conditioning temperatures of 40 °C and 50 °C were not statistically significant. The variations between the strength values for conditioning temperatures of 50 °C and 60 °C were also not statistically significant. Overall, the strength values for specimens subjected to wet conditioning were significantly lower as compared to the strength values for specimens subjected to dry conditioning.

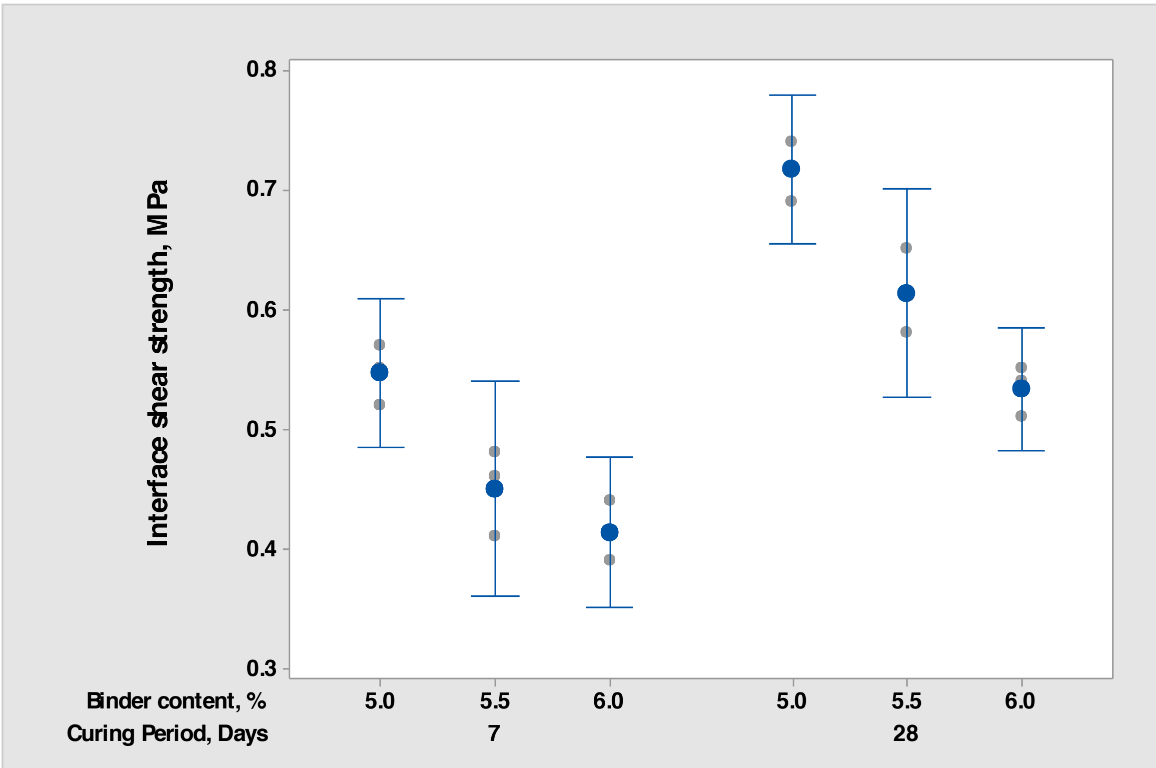


Fig. 9. Variations in interface shear strength due to HMA binder contents.

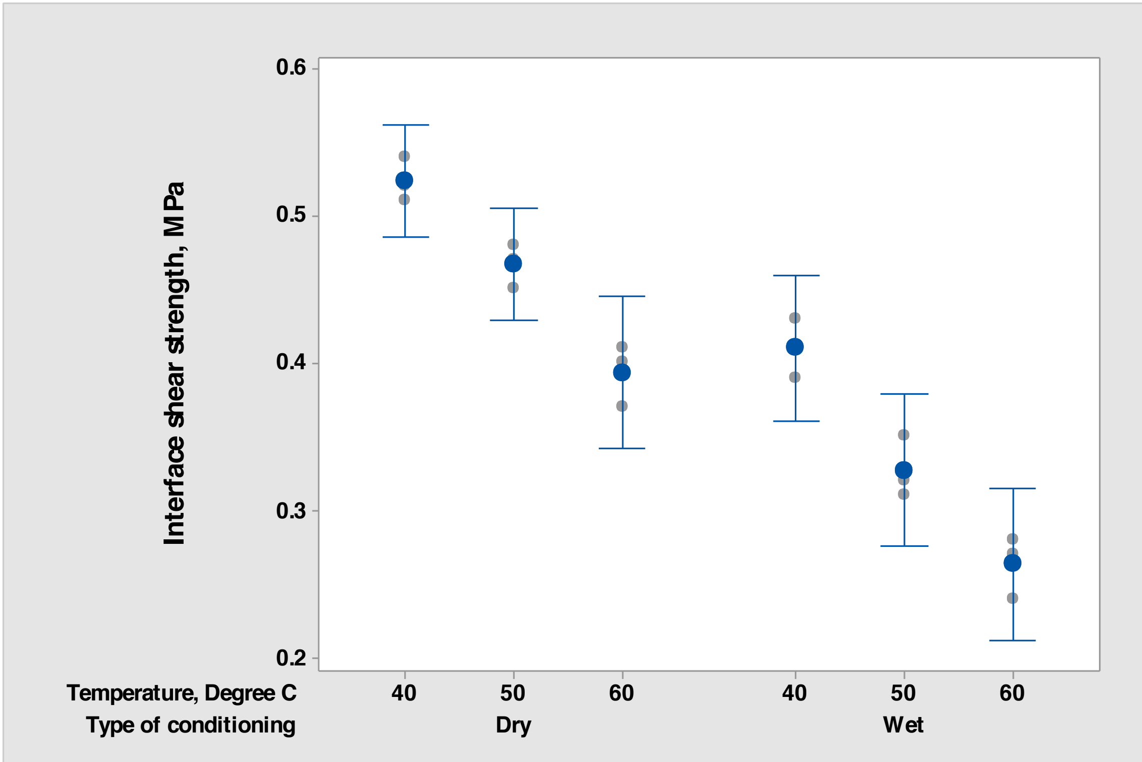


Fig. 10. Variations in interface shear strength due temperature and moisture conditioning.

6. Conclusions and recommendations

This paper presents the findings of experimental studies conducted on interface bond strength between the UTW and HMA. Several direct shear strength tests were performed on UTW-HMA composite specimens prepared in the laboratory. Experiments were performed to assess the effects of different interface treatments, binder content variations in HMA, and temperature conditioning and moisture conditioning on the strength. The following conclusions can be drawn on the basis of the results of the experimental studies:

- The interface shear strength of UTW-HMA varies between 0.22 MPa and 1.29 MPa for the tested conditions.
- Age of the UTW has a significant effect on the interface shear strength irrespective of the type of interface treatment.
- UTW-HMA composites without proper interface treatment may fail to ensure sound bonding of UTW and HMA. The best interface treatment for UTW-HMA pavements would be grooves with appropriate spacing.
- Variations in the DBC of HMA by ± 0.5 percent would not significantly influence interface shear strength.
- Temperature and moisture conditioning significantly affect the strength.

The findings of this study indicate that the interface bond strength of UTW-HMA does depend on various factors. Therefore, the effects of composition of HMA, pavement service temperatures, and drainage conditions on interface strength should be evaluated for UTW-HMA composites.

In this study, the effect of normal stress on the interface shear strength was not considered. In-situ interface shear strength values of UTW-HMA composites, under the influence of normal stress are likely to be different from the values reported in this study. Hence, there is a need to investigate the variations in the interface shear strength in the presence of normal stresses.

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