RESEARCH ARTICLE

Effect of air voids on permeability and durability of hot mix asphalt

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Abstract: The existence of water in the layers of hot mix asphalt (HMA) concrete pavement can lead to weakening of bonds between bitumen and aggregates, and cause moisture damage. In the last few decades, various research studies have been carried out on the specific subject of moisture damage and permeability; however, only limited work has been carried out to study the relationship of air voids with permeability and durability in HMA. The key objective of this research was to study whether such a relationship exists. This was determined by using locally available materials and the most common gradation used in Pakistan. Laboratory permeability tests were conducted on the prepared slabs while an indirect tensile strength ratio (TSR) test of the prepared samples was performed in the laboratory, which was used as the moisture damage potential parameter against various air void levels. AASHTO T-283 test procedure showed a drop in TSR value while EN 12697-40 (80-B0093) test method showed an increase in permeability value with increase of air voids indicating that moisture damage followed. This research concluded that moisture damage is linked to the permeability of HMA and defined 6 % air voids as the threshold for National Highway Authority (NHA), Pakistan Class 'A' gradation. The outcomes of this research can be applied as benchmark values of the hydraulic conductivity (permeability) and durability of asphalt mixtures used in highway pavement construction.

Keywords: Air voids, coefficient of permeability, durability, hydraulic conductivity.

the pavement through different sources causes damage to the pavement by weakening the cohesive bond within the binder and deterioration of the bond between the bitumen and aggregates. This moisture damage is also linked with undue high temperature cracking and deflection. The initial phase of detecting the problems affected by the existence of moisture within pavement is estimating the permeability of hot mix asphalt (HMA) (Abou-foul & Chiarelli, 2018).

HMA is an elastic or permeable material that is composed of three constituents: aggregates, asphalt and air voids. A major factor prevailing on pavement performance is the ability of HMA to retain water within the pavement system. Impairments related to moisture can be provoked by two main mechanisms. The first mechanism is related with the chemical interaction of aggregates and asphalt with water, leading to the weakening of cohesive bonding within the binder and damage of adhesive bonding between binder and aggregates (Kim *et al.*, 2004). The other damage mechanism is the accretion of pore water pressure due to the saturation of voids with water and the dynamic traffic loading. Increase in moisture leads to excessive cracking, permanent deformation, deflection and decrease in the load bearing capacity of pavement (Lindly & Elsayed, 1995).

INTRODUCTION

One of the major issues all across the world is the damage of pavements by moisture. The availability of moisture in

Cedergren (1974) explained the effect of water on the serviceability of pavement. According to the study if pavements are not properly designed to prevent

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the penetration of moisture, it leads toward the self-destruction of pavement. Due to penetration of water into structural layers of the pavement, a multi-layer pavement system behaves as diaphragm pumps beneath the pounding of wheel loads. Due to heavy load impact, water moves towards the interface of wearing course and base course. This water finally erodes the material due to initiation of cracks at joints. Finally, this erosion of material leads towards the production of small cavities and channels that deteriorate the pavement which can result in the complete failure of pavement. Federal Highway Administration (FHA) in many reports stated that free water existing in the pavement system is the main factor leading towards pavement failure in the United States. Damage of asphalt pavements through moisture penetration is major problem throughout the world. According to Mogawer *et al.* (2002), 15 out of 27 States the USA depicted moisture related problems. According to Kutay *et al.* (2006), hydraulic conductivity is also known as the permeability of an asphalt pavement. It is one of the most important parameters that have a direct influence on pavement life.

The three possible sources of water movement inside the pavement is evaporation, capillary movement and infiltration (Tarefder & Ahmad, 2015). Permeable air voids are the leading parameter in these three main sources. Moisture damage in an asphaltic pavement can be reduced either by blocking water from percolating into the pavement or by increasing the stripping strength of the asphaltic pavement. Moisture can travel within the pavement by using the permeability route. Hence, if the permeability of the asphaltic pavement can be regulated, the moisture destruction may be prevented or overcome. According to Bhattacharjee and Mallick (2002), asphaltic concrete durability relies on porosity and permeability, and out of these two factors permeability is more important for determination of durability. Permeability deals with the moisture present in the permeable pores only, whereas porosity deals with the moisture present within both the permeable and impermeable pores (Celik, 2005).

Very limited studies have been conducted so far on the correlation between moisture damage and permeability. Choubane *et al.* (2006) have related the degree of saturation with moisture loss. By increasing the degree of saturation, moisture damage is also increased. As given in previous studies (Torres, 2004; Masad *et al.*, 2006), separated air void content is classified into three groups: low (impermeable), pessimum (intermediate) and free drainage. The maximum loss arises at the pessimum stage, which relates to intermediate stage of

permeability. Nevertheless, laboratory test methods and various field environments have not been confirmed so far.

Permeability is currently evaluated both in the field and in the laboratory. Different states of the USA have developed their own Permeameter to determine the permeability of asphaltic pavements (California Test 341, 2000; Texas Department of Transportation, 2009). Permeability determination in the laboratory developed by Florida is mostly used because of its ease of handling (FM5-565, 2004). Air permeameter method (APM) is used in the field due to its improved results in comparison with the water permeameter because APM does not rely on the degree of saturation (Menard & Croveti, 2006). Nevertheless, field water permeability method developed by the National Centre for Asphalt Technology (NCAT) is used in the field due to its results correlating better with laboratory results (Cooley Jr, 1999).

Mechanical testing tools and visual assessment can be used to evaluate the damage in the pavement system by moisture. The failure between bitumen and aggregates usually happens at the interface layer and then thrives to upward layers. Hence, in this scenario it is not possible to evaluate the stripping by visual assessment only (Coree & Kim, 2005). Different mechanical methods are also widely tested and the AASHTO T283 method recommended for use has two limitations in this technique, i.e., it is very time consuming and variable degree of saturation may disrupt the outcomes. This method does not replicate the pore pressure cycle of the field as well (Liang, 2008). The process of conditioning and simulating the pore pressure cycle is performed by the recently developed machine moisture induced sensitivity testing (MIST) (InstroTek, 2012). Nevertheless, stripping occurs in the pavement along with the existence of other distresses like rutting. A device that can measure both stripping and rutting together is the Hamburg Wheel machine (Texas Department of Transportation, 2006). Therefore, it is advisable to evaluate permeability and moisture damage by using different techniques so that a better correlation can be developed.

Since HMA pavement performance and durability are affected by air void contents and thereby the water resistance capability of the HMA pavement, the main objective of this research was to evaluate the permeability of asphalt with different air void contents through the asphalt permeameter-silicon seal apparatus. The other objective was to evaluate the HMA durability with different air void contents through AASHTO T 283 test method.

METHODOLOGY

Materials

Bitumen was obtained from Attock Oil Refinery Limited (ARL) Rawalpindi, Pakistan. Aggregates were obtained from Margalla Resources of Pakistan. Mechanical and physical characteristics of all types of aggregates were determined as per ASTM, AASHTO and BS standards.

Permeability Test

Permeability evaluation test was conducted for hydraulic conductivity of HMA mixtures.

Procedure

Samples were prepared after sieving, batching and mixing, which were heated in an oven at 135 °C for 2 h and then compacted to different air voids, i.e. 4 to 9 % by using controlled roller compactor (RC) at specific pressure and number of passes as given in Table 1. A total of eighteen (18) slabs were cast using RC against

each air voids percentage to determine the average result. After compaction and achieving room temperature, silicon was applied under the base plate and put on the already casted slab and kept for 4~5 min. Meanwhile, a counterweight of 21 kg was placed on the top of the base plate and water was placed in a graduated cylinder. It was required to maintain the constant head for 10 min and noted the amount of water passed from the slab (Figures 1 and 2). Using the formula given in equation (1), hydraulic conductivity of each slab was determined against each air voids level. The average of hydraulic conductivity of 3 samples was taken into account.

$$\text{Hydraulic Conductivity} = \frac{\text{Discharge/s}}{\text{m}^2} \quad \dots(1)$$

Durability test

AASHTO T283 test method was used to evaluate the durability of HMA mixtures in terms of moisture resistance. The objective of the test is to evaluate the moisture sensitivity of the HMA mixtures. The methodology of this test was expressed in the form of a flowchart (Figure 3) and the test parameters of this test

Table 1: Material data for permeability sample preparation

Gradation	Aggregate	Bitumen	Dimensions of slab (mm × mm × mm)	Volume of moul d(cm ³)	Roller compactor pressure bars	Number of passes	Gmb	Percentage air voids (%)	Mass of aggregate + bitumen
NHA -A	Margalla	ARL 60/70	305 × 305 × 50	4651.25	2.5, 3.5, 4 and 2.5	10	2.398	4	11153.69
							2.373	5	11037.41
							2.348	6	10921.1
							2.323	7	10804.85
							2.298	8	10688.5
							2.273	9	10572.29

Figure 1: Permeability test on slab

Figure 2: Bottom view of base plate after performing permeability test

are summarised in Table 2. To determine the moisture sensitivity against 4 to 9 % air voids, 3 samples each for conditioned and unconditioned samples were casted for

each air void percentage to determine the average tensile strength ratio, hence a total of 36 samples were cast.

Figure 3: Flow chart of modified lott man test (AASHTO T 283)

Table 2: Test parameters for AASHTO T 283

Test parameters	Test requirement
Short term ageing	Keep loose mix at 60 °C for 16 hours in oven Keep compacted mix at 25 °C for 3 to 4 days
Air voids level	4 ~ 9 %
Saturation level	55–80 percent (%)
Freeze round	Freeze at -18 °C for 16 hours in freezer
Thaw round	Heat at 60 °C for 24 hours in water bath
Temperature balance	Heat all of the six specimens at 25 °C for 2 hours in water bath
Strength determination	Define indirect tensile strength

Figure 4: Samples in water bath to maintain temperature of 25 °C before testing **Figure 5:** Failure of specimen at maximum load**Table 3:** Material data for sample preparation of durability samples

Gradation	Aggregate source	Bitumen	Air voids	Mass of Aggregate (g)	Mass of bitumen (g)	Height (mm)
NHA-A	Margalla	ARL 60/70	4	7000	291.7	176.1
			5	7000	291.7	178.1
			6	7000	291.7	180.2
			7	7000	291.7	182.1
			8	7000	291.7	184
			9	7000	291.7	186.1

Procedure

The samples were prepared after sieving, weighing and mixing which were then placed in an oven for curing at 60 °C for 16 h and left to cool at room temperature. Samples were heated at 135 °C for 2 h, compacted

to different air voids, i.e. 4 to 9% by controlling the height in superpave gyratory compactor (SGC) using a formula and kept at room temperature for 72 to 96 h. The formula used to calculate the height of specimen in SGC is given in equation (2).

$$M = \left(\frac{1 - P_a}{100} \right) * G_{mm} * A * \left(\frac{H}{10} \right) / C \quad \dots(2)$$

Where $C = 1.025$, $A = 176$, P_a = percent air voids (%), M = total mass (g) and H = total height (mm). G_{mm} is the maximum specific gravity of compacted asphalt paving mixtures.

Based on Table 3, at 6 different air voids (4 to 9 %) a total of 36 samples were casted using this method and divided into two subsets; against each air void 3 conditioned and 3 unconditioned samples hence a total of eighteen (18) conditioned and eighteen (18) unconditioned were casted. A vacuum saturation with water (55–80 % saturation level) was applied. For conditioning, the samples were then placed in a freezer at -18°C for 16 h and then positioned in a water bath at 60°C for 24 h. After completing freeze and thaw cycles, all the samples were placed in a water bath at 25°C for at least 2 h to achieve temperature balance (Figure 4). Samples were set along diameter direction between the

jacks of UTM machine and a pulse load at the rate of 50 mm/min was then applied for indirect tensile strength test (ITS). Tensile strength of the conditioned samples was then linked to the unconditioned samples to define TSR (Figure 5 and 6). The average of tensile strengths of three (3) samples was taken into account. The estimate of materials is summarised in Table 3:

If the loss of strength is not more than 20 %, the samples are considered as moisture resistant as specified in AASHTO T 283 (1993). However, some agencies agree to take TSR value up to 70 %. The tensile strength of the sample is calculated using equation (3).

$$S_t = \frac{2000 * P}{\pi * t * D} \quad \dots(3)$$

where, S_t = tensile strength (KPa), P = maximum load (N), t = thickness of specimen (mm) and D = diameter of sample (mm). Tensile strength ratio (TSR) of a sample can be defined as the ratio between conditioned and unconditioned specimen (equation 4).

Table 4: Test results of binder

Sr. No	Description	Specifications	ARL 60/70
1	Specific gravity at 25°C	(ASTM D 70, 2014)	1.029
2	Flash point at ($^\circ\text{C}$)	(ASTM D 92, 2007)	302
3	Fire point at ($^\circ\text{C}$)	(ASTM D 92, 2007)	305
4	Softening point at ($^\circ\text{C}$)	(ASTM D 36, 2000)	50
5	Penetration (mm) at 25°C , 100g (0.1mm)	(ASTM D 5, 1997)	62
6	Ductility at 25°C	(ASTM D 113, 1999)	100 above

Table 5: Test results of engineering properties of aggregates

Sr. No.	Test description	Specification reference	Results	Recommended values (NHA General Specification)
1	Flakiness index (FI)	BS 812, part 1	5.70 %	15 (Max)
2	Elongation index (EI)	BS 812, part 1	9.40 %	15 (Max)
3	Aggregate absorption	AASHTO T 166	0.87 %	-
4	Sand equivalent	AASHTO T 176	75	45 (Min)
5	Los Angeles abrasion value (LAA)	AASHTO T 96, ASTM C 131	22 %	30 (Max)
6	Sodium sulphate soundness value	AASHTO T 104, ASTM C 88	4.65 %	12 (Max)
7	Deleterious material	Asphalt Institute, SP-2	0.8	0.2 – 10

$$TSR = \frac{S_2}{S_1} \quad \dots(4)$$

where, S_2 = tensile strength of conditioned sample (kPa) and S_1 = tensile strength of unconditioned sample (kPa). The AASHTO T-283 criterion for moisture resistance is $TSR \geq 80\%$.

RESULTS AND DISCUSSION

Bitumen test results

Basic properties of asphalt binder with '60/70' penetration grade bitumen were obtained using conventional tests as represented in Table 4.

Aggregate test results

Aggregate test results depicted that values of different aggregate characteristics are within the permissible specification limits, which indicates relatively good quality materials. The properties are summarised in Table 5 and aggregate gradation curve can be seen in Figure 7. Centre line gradation curve showed distribution of aggregate particles on each sieve size.

Gradation

Coarse aggregates are retained on sieve No. 4 (4.75 mm). Generally, asphalt mixtures contain 35–65 % coarse aggregates for nominal maximum aggregate size (NMAS) of 19 mm. This content generally gives a suitable texture for a heavily trafficked road (ASTM,

2003). For research purposes, centreline gradation of NHA class 'A' wearing course was selected. Table 6 shows that NHA-A gradation have NMAS of 19 mm, Super-pave Class-A and MS-II gradation have NMAS of 12.5 mm.

Figure 8 shows that NHA class A gradation was observed to have coarser gradation because it had percentage passing of about 42 % through 4.75 mm sieve size while Super-pave Class A and MS-II was considered finer gradation because they had percentage passing of 65 % and 59 % through 4.75 mm sieve size, respectively.

Table 6: Percentage (%) passing of different aggregate sizes

Sieve size (mm)	NHA class 'A' % passing	Super-pave A % passing	MS-II % passing
50	-	-	-
37.5	-	-	-
25	100	-	-
19	95	100	100
12.5	-	94	95
9.5	63	87	-
6.3	-	74	-
4.75	42.5	65	59
2.36	29	37	43
1.18	-	21	-
0.6	-	14	-
0.3	8.5	9	13
0.15	-	7	-
0.075	5	5	6

Figure 7: Gradation curve of Margalla crush

Figure 8: Aggregate centre line gradation curve for wearing course

Table 7: Permeability results for HMA samples having 4% to 9% air voids

Specimen	Bitumen type	Sealant applied	Surface texture	water quantity / time	Hydraulic conductivity (mL/sec/Sq.m)	Average hydraulic conductivity (mL/sec/Sq.m)
Air voids level 4 %						
1	60/70	Yes	Normal	1700 mL/10 min	113.333	93.333
2	60/70	Yes	Normal	1400 mL/10 min	106.667	
3	60/70	Yes	Normal	900 mL/10 min	60.000	
Air Voids Level 5 %						
1	60/70	Yes	Normal	2000 mL/10 min	133.333	128.889
2	60/70	Yes	Normal	1700 mL/10 min	113.333	
3	60/70	Yes	Normal	2100 mL/10 min	140.000	
Air Voids Level 6 %						
1	60/70	Yes	Normal	4000 mL/10 min	186.667	193.333
2	60/70	Yes	Normal	3000 mL/10 min	193.333	
3	60/70	Yes	Normal	3100 mL/10 min	200.000	
Air Voids Level 7 %						
1	60/70	Yes	Normal	4000 mL/10 min	266.667	380.000
2	60/70	Yes	Normal	7100 mL/10 min	473.333	
3	60/70	Yes	Normal	6000 mL/10 min	400.000	
Air Voids Level 8 %						
1	60/70	Yes	Normal	7700 mL/10 min	513.333	553.333
2	60/70	Yes	Normal	9300 mL/10 min	620.000	
3	60/70	Yes	Normal	7900 mL/10 min	526.667	
Air Voids Level 9 %						
1	60/70	Yes	Normal	11000 mL/10 min	733.333	775.556
2	60/70	Yes	Normal	9900 mL/10 min	660.000	
3	60/70	Yes	Normal	14000 mL/10 min	933.333	

Table 8: Durability test results against 4 % to 9 % air voids

Specimen type	Thickness (mm)	Diameter (mm)	Maximum load (N)	Average tensile strength (kPa)	TSR (S2/S1) (%)	Remarks
4 % Air voids level						
Conditioned (S2)	76.2	152.4	15,620.00	815.315	86.074	Moisture resistant as per AASHTO T-283
			17,240.00			
			14,000.00			
Unconditioned (S1)			18,740.00	947.224		
			17,270.00			
			15,800.00			
5 % Air voids level						
Conditioned (S2)	76.2	152.4	15,680.00	861.844	83.22	Moisture resistant as per AASHTO T-283
			15,760.00			
			15,700.00			
Unconditioned (S1)			19,130.00	1035.529		
			18,630.00			
			18,880.00			
6 % Air voids level						
Conditioned (S2)	76.2	152.4	15,900.00	852.886	80.57	Moisture resistant as per AASHTO T-283
			15,200.00			
			15,550.00			
Unconditioned (S1)			19,000.00	1058.565		
			19,600.00			
			19,300.00			
7 % Air voids level						
Conditioned (S2)	76.2	152.4	13,200.00	770.248	79.12	Non-Moisture resistant as per AASHTO T-283
			15,240.00			
			13,690.00			
Unconditioned (S1)			17,750.00	973.551		
			17,700.00			
			17,800.00			
8 % Air voids level						
Conditioned (S2)	76.2	152.4	11,110.00	604.79	77.12	Non-Moisture resistant as per AASHTO T-283
			11,870.00			
			10,110.00			
Unconditioned (S1)			14,400.00	784.326		
			14,200.00			
			14,300.00			
9 % Air voids level						
Conditioned (S2)	76.2	152.4	10,080.00	289.231	76.15	Non-Moisture resistant as per AASHTO T-283
			11,460.00			
			10,100.00			
Unconditioned (S1)			13,850.00	379.822		
			14,300.00			
			13,400.00

Figure 9: Graphical representation of asphalt permeability vs air voids

Permeability test results

The values of permeability for HMA samples having 4, 5, 6, 7, 8 and 9 % air voids are 93.33, 128.89, 193.33, 380, 553.33 and 775.556 mL/sec/Sq.m, respectively as per EN 12697-40 (80-B0093) and other detailed calculations (Table 7).

In the permeability graph (Figure 9), permeability values have increasing unpredictability and higher mean values starting at about 6 % air voids level for asphalt permeameter test method. The HMA permeability sample values from 93.33 - 193.33 mL/sec/m² indicate that the values are within the specific criteria limits of permeameter apparatus.

Durability test results

The values of the durability test obtained for HMA samples having 4, 5, 6, 7, 8 and 9 % air voids are 86.074, 83.22, 80.57, 79.12, 77.12 and 76.15 %, respectively (Table 8). Thus, the maximum loss was more than 20 %. These specimens were considered as non-moisture resistant as per AASHTO T283.

In durability graph (Figure 10), asphalt TSR values start decreasing at about 6 % air voids level as per AASHTO T-283 test method.

CONCLUSIONS

Based on aggregate gradation curves, it was observed that the NHA class 'A' gradation is coarser because it

had percentage passing through 4.75 mm sieve size of about 42 %, while super-pave class-A and MS-II was considered finer gradation because it had percentage passing through 4.75 mm sieve size of 65 % and 59 %, respectively.

Coarser gradations are successful at limiting distress such as rutting but have resulted in other issues, namely, high permeability and less durability in terms of strength loss.

NHA class 'A' has nominal maximum aggregate (NMAS) size of 19 mm whereas super-pave class-A and MS-II have nominal maximum aggregate size of 12.5 mm.

Durability test results showed that the loss of strength from 4 ~6 % air voids level is less than 20 % while beyond 6 % air voids level the loss of strength is more than 20 %. Permeability test results showed that the hydraulic conductivity values have increasing variability and higher mean values starting at about 6 % air voids level for asphalt permeameter test method.

The threshold value of air voids based on permeability and durability test results is selected as 6 % for NHA class 'A' gradation.

Air voids level more than the threshold will lead to more infiltration of air and moisture due to interconnectivity and large size of voids, that will cause premature pavement distresses and thus cannot maintain adequate support for underlying unbound materials.

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