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Characterization of porous friction course mixes for different Marshall compaction efforts

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ABSTRACT

Porous friction courses (PFCs) are mainly recommended as surface drainage layers on high-speed road-corridors and runway pavements. Permeability and sound attenuation characteristics are considered to be the indices for performance assessment of PFCs. One of the reasons for the loss of permeability in PFCs is densification under heavy traffic. But, resistance to ravelling too, is of main concern in the case of under-compacted PFCs. This paper summarises the details of laboratory investigation on the characterization of PFC mixes corresponding to four different gradations and two binder contents, for three levels of the Marshall compaction. The findings of the investigation suggest that the selection of the compaction level for PFC mix design should be based on the design traffic level, and the gradation selected.

1. Introduction

Porous friction courses (PFCs) are typical open-graded asphaltic mixes, composed of relatively uniformly-graded aggregate and asphalt cement or modified binders, and are mainly used to serve as drainage layers, either at the pavement surface or within the pavement structure [1]. Pavements surfaced with open-graded asphaltic mixes were found to improve wet weather skid-resistance, minimize hydroplaning, reduce splash and spray, improve night visibility during wet weather conditions, and reduce traffic tyre-noise [2,3]. In countries like the United States of America, Japan, the United Kingdom, Malaysia, Australia, New Zealand, and South Africa, open-graded mixes are in use as surface layers over high-speed and heavily trafficked highway pavements [2–8]. These are also recommended for surfacing runway pavements [9,10]. Many agencies around the world use different terminologies for open-graded mixes, and specifications that are slightly different. The various terminologies used include open-graded asphalt (OGA), porous asphalt (PA), open-graded friction course (OGFC), and porous friction course (PFC).

1.1. Background

The high air voids content in PFCs contribute towards pavement surface drainage and in attaining noise reduction. But, accelerated asphalt-film aging, may subsequently lead to loss of cohesion in the mastic, consequently poor adhesion between the mastic and aggregate results in ravelling. Experiences with the use of open-graded mixes in the USA indicated that ravelling was one of the major issues to be tackled [11]. Thus, structural durability of PFCs needs to be ensured based on the resistance to ravelling [12]. Some of the experiences with PFCs in Japan, the poor performance was related to the lack of compaction, or compaction at lower temperatures than the specified [6].

Permeability and sound attenuation characteristics are the main measures of performance life of PFCs [2]. Studies performed on test sections in Denmark, indicated that deteriorated mastic materials clogged the large-sized air voids in PFCs, which led to the formation of higher percentage of small-sized voids [12]. Clogging was found to be more pronounced on older pavement, especially along the wheel path, and also in the emergency lanes [13]. Although, PFCs are composed of relatively uniformly-graded aggregate [1], the use of thicker PFCs may undergo secondary densification during service, resulting in loss of permeability. Thus, the loss of permeability can be directly related to clogging of voids due to internal and external materials, and densification under traffic [2].

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An optimal design mix should ensure high air voids content and good resistance to ravelling. Procedure for mix design of PFCs recommended by various agencies include the evaluation of draindown losses in loose hot mixes, air voids content, stone-on-stone contact condition, permeability, and the abrasion resistance using the Cantabro abrasion test method [4,7,8,15]. One of the major differences observed in the specifications by various agencies is that of the consideration of traffic volume in the optimum mix selection criteria. The minimum air voids content and the maximum abrasion loss specified by some of the agencies were dependent on the traffic volume [4,7,8], whereas, this dependency was not considered by many agencies in the USA [2,10,15,16]. The level of Marshall compaction suggested by many agencies were found to be 50 blows per face, irrespective of the traffic volume. In addition, in the recent past many researchers adopted the same level of the Marshall compaction for the design of PFC mixes [17–20]. However, some of the researchers adopted or suggested the lower levels of the Marshall compaction, for characterizing the PFC mixes [21–24].

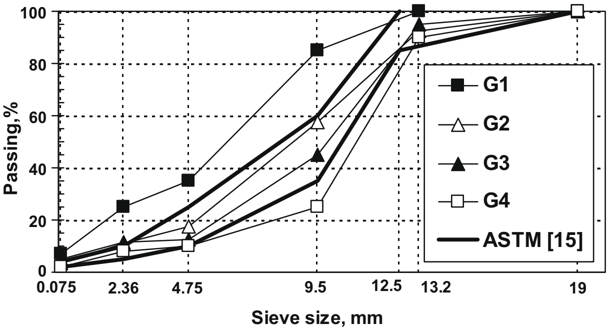

Fig. 1. Aggregate gradations used in the present study.

Table 1
Coding for each experiment.

Marshall compaction (MC) level	Binder content (BC), % by mass	Mix coding for selected gradations of PFC mixes			
		G1	G2	G3	G4
35 Blows per face	4.5	M1	M7	M13	M19
	5.0	M2	M8	M14	M20
50 Blows per face	4.5	M3	M9	M15	M21
	5.0	M4	M10	M16	M22
75 Blows per face	4.5	M5	M11	M17	M23
	5.0	M6	M12	M18	M24

1.2. Objective and scope

The main objective of this investigation was to characterize the PFC mixes for three levels of the Marshall compaction. The compaction levels investigated include 35, 50, and 75 blows applied on each end of the specimen. The effect of each compaction level was studied on eight different PFC mixes, which corresponded to four different aggregate gradations (G), and two binder contents (BC) of 4.5 and 5.0% by mass of total mix, using the neat bitumen of 85–100 penetration grade. The selection of gradation, binder type, and binder content were based on the previous studies performed on similar mixes [25,26]. Fig. 1 shows the details of the four aggregate gradations investigated. Table 1 provides details of the coding method adopted for designating the mixes for various compaction levels and mix compositions.

2. Specimen preparation and test plan

Straight-run bitumen and crushed stone aggregates are the major constituents of PFC mixes. The straight-run paving grade bitumen used in the present investigation was supplied by Mangalore Refinery and Petrochemicals Limited (MRPL), Mangalore. Crushed granite stone aggregates obtained from local stone-crushing plants were used in this study. Table 2 shows some of the physical properties of bitumen and aggregates tested in accordance with the requirements of the ASTM D 946 [27] and ASTM D 7064 [15], respectively. Ordinary Portland Cement (OPC) was used as a part of the mineral filler, constituting 2% by mass of total aggregates weighing 1000 g.

The procedure adopted for preparation of the PFC specimens was quite the same as that adopted for dense graded asphalt, as suggested in Asphalt Institute Manual Series-2 [28]. The properties of compacted mixes investigated include bulk specific gravity (G_{mb}), air voids content (V_a), stone-on-stone contact condition, permeability (K), moisture susceptibility, and unaged abrasion loss. These properties were evaluated in accordance with the guidelines of the ASTM D 7064 [15]. Table 3 provides details on the tests performed for various experimental mixes. Three observations were made on each experimental mix.

3. Characterization of PFC mixes

3.1. Bulk specific gravity of compacted mix

The tests for bulk specific gravity of compacted mixes (G_{mb}) were performed on 24 mixes as described in Table 3, with three replicates for each mix. The G_{mb} of each compacted mix was determined using the geometric measurements of diameter, height, and the mass of the specimen in air, in accordance with ASTM D 7064

Table 2
Physical properties of materials.

Materials Tested	Particulars of physical properties	Standard designation	Specification requirement	Test results
Paving grade bitumen	Specific gravity at 27 °C	ASTM D946 [2]	Not specified	1.01
	Penetration at 25 °C, 100 g, 5 s, 0.1 mm		85–100	89
	Flash point, °C		Min. 233	240
	Softening point, (R&B), °C		Not specified	46
	Loss on heating, % by mass		Not specified	0.2
	Ductility at 25 °C, cm after thin-film oven test		Min. 75	90
	Retained penetration after thin film oven test, % of original		Min. 42	62
Coarse aggregates	Flat and elongated particles, %	ASTM D7064/D 7064 M [15]	Max. 10	8.1
	Aggregate impact value, %		Not specified	20.1
	Los Angles abrasion value, %		Max. 30	26.6
	Water absorption, %		Not specified	0.15
	Soundness, magnesium sulphate solution, %		Not specified	0.21

Table 3
Test plan.

Response properties	Standard designation	Mix code
Bulk specific gravity	ASTM D 7064 [15]	M1–M24
Air voids	ASTM D 7064 [15]	M1–M24
Verification of stone-on-stone contact condition in the compacted mix	ASTM D 7064 [15]	M1–M24
Moisture susceptibility	ASTM D 7064 [15]	M1–M24
Unaged abrasion loss	ASTM D 7064 [15]	M19–M24
Permeability	IS: 2720 Part 17 [29]	M1–M24

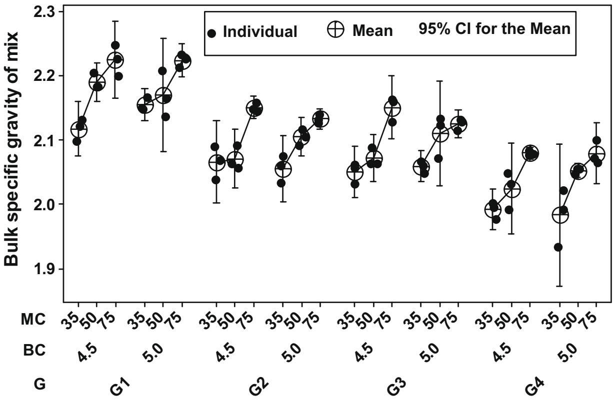

Fig. 2. Bulk specific gravities of compacted mixes (G_{mb}).

[15]. The individual and mean G_{mb} values were found to be in the range of 1.935–2.249, and 1.984–2.226, respectively, as shown in Fig. 2. It is evident that an increase in the compaction effort will lead to densification of the mix, resulting in higher densities. Further, it is evident from the 95% confidence intervals that there is no significant difference between the mean G_{mb} values among the mixes with binder contents of 4.5% and 5.0% when compared, for a particular gradation and compaction level. The mixes with gradations G1 and G4 exhibited higher and lower G_{mb} values, respectively, especially since G4 comprised of coarser aggregates. The mean G_{mb} values for the mixes with gradations G2 and G3 are approximately the same, as the minor differences in gradations have not affected the G_{mb} values significantly.

3.2. Air voids

The air voids (V_a) content in a compacted mix is related to the G_{mb} and the theoretical maximum density (G_{mm}) of the uncompacted mix, determined in accordance with the ASTM D 2041 [30]. The increase in the compaction effort results in higher G_{mb}, resulting in a decrease in V_a.

Fig. 3 shows the individual plot of V_a for each mix. It also indicates the mean V_a of the individual mixes tested, and the 95% confidence interval for the mean. The line connecting the mean V_a shows the trend in variations of the V_a with the compaction effort. The individual and mean V_a values were found to be in the range of 10–22%, and 10–20%, respectively. As per the standard requirements of ASTM D 7064 [15], PFC mixes should have a minimum V_a of 18%. The mean V_a corresponding to the mixes M19 (G4-35-4.5), M20 (G4-35-5.0), and M21(G4-50-4.5) satisfied this requirement, while, the mixes M7 (G2-35-4.5), M8 (G2-35-5.0), M9 (G2-50-4.5), M13 (G3-35-4.5), and M15 (G3-50-4.5) seem to satisfy this requirement at a confidence level of 95%. However, in the mixes tested for 75 blows, the individual, mean, and upper limits of 95% confidence interval of mean V_a failed to satisfy the minimum V_a requirement. All mixes corresponding to the gradation G4, i.e., M19–M24 were found to have mean V_a of more than 15%. The reduction in the mean V_a due to change in the compaction level from 50 blows to 75 blows was found to be in the range of 0.6–3.2%. Similarly, change in compaction level from 50 to 35 blows, resulted in an increase in mean V_a in the range of 0.2–2.9%.

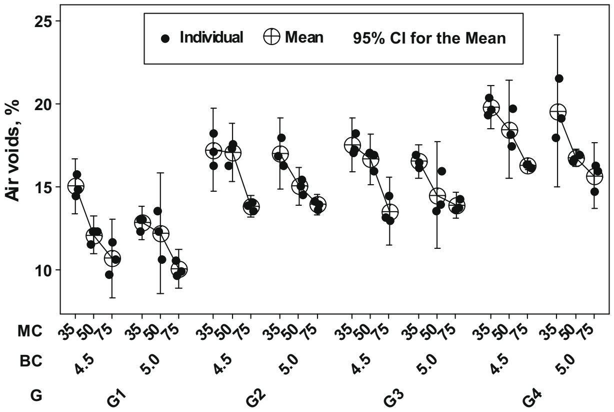

Fig. 3. Air voids in PFC mixes.

3.3. Verification of stone-on-stone contact condition

The presence of stone-on-stone contact condition in the coarse aggregate skeleton is considered to be must, for the best performance of PFC [15]. In the compacted PFC mix, stone-on-stone contact condition was verified based on the percent voids in coarse aggregate of the compacted mixture (VCA_m) and the percent voids in coarse aggregate of the coarse aggregate alone (VCA_d) in dry-rodded test, conducted according to the ASTM C29/C29 M [31]. The stone-on-stone contact conditions were confirmed, when the ratios of VCA_m/VCA_d were below one. The VCA_d and VCA_m values were computed using the following equations:

$$VCA_d = (G_{CA}\gamma_w - \gamma_s)/(G_{CA}\gamma_w) \tag{1}$$

$$VCA_m = 100 - (G_{mb}P_{CA}/G_{CA}) \tag{2}$$

where G_{CA} = bulk specific gravity of the coarse aggregate; γ_s = bulk density of the coarse aggregate fraction in the dry-rodded condition; γ_w = density of water; and P_{CA} = percent coarse aggregate in the total mixture.

Generally, PFC mixes characterized with higher G_{mb}, higher P_{CA}, or a combination of these, result in lower VCA_m, ensuring better

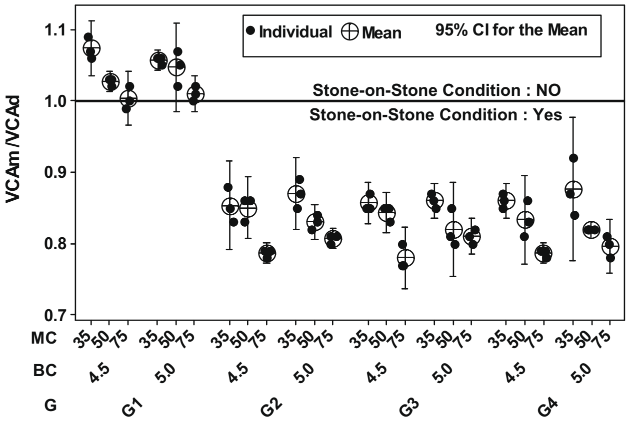

Fig. 4. Verification of stone-on-stone contact condition.

stone-on-stone contact conditions. The ratio of VCA_m/VCA_d for each replicate mix is shown in Fig. 4. It can be noticed that each replicate of the mixes M7–M24 (corresponding to gradations G2, G3, and G4), satisfied the stone-on-stone contact condition, even under lowest compaction level of 35 blows. Thus, the mixes corresponding to the gradation, between the bands of G2 and G4, are expected to offer best performance. The mixes corresponding to gradation G1 failed to satisfy the requirement. This might be due to the presence of more than 20% of aggregates passing 4.75 mm sieve [17]. The mixes investigated in the present study, based on the 95% confidence interval for the mean of the ratio of VCA_m/VCA_d, it can be observed that the mixes M4 (G1-50-5.0), M5 (G1-75-4.5), and M6 (G1-75-5.0) may probably satisfy the requirement for stone-on-stone contact condition.

3.4. Permeability

The coefficients of permeability of PFC specimens were determined using the falling-head method [29]. The details on the test procedure adopted can be found elsewhere [25,26].

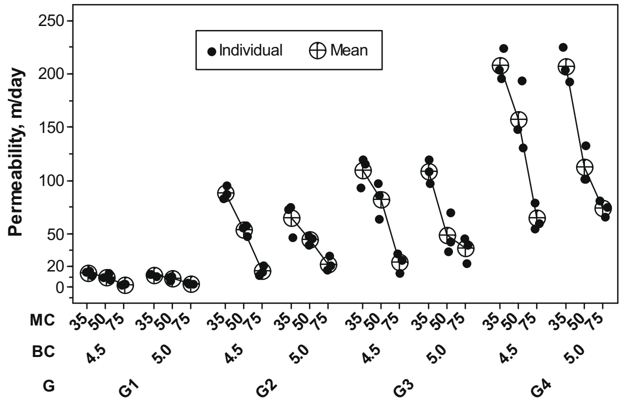

Fig. 5. Permeability of PFC mixes.

Permeability (K) value of each replicate, the mean K value of each mix tested, and the 95% confidence interval for the mean K, of the experiment are shown in Fig. 5. The ASTM D 7064 [15] suggests a minimum K of 100 m/day. The mean K values of mixes corresponding to gradation G4, compacted with 50 blows or lesser, and mixes corresponding to gradation G3, compacted with 35 blows, were found to satisfy this requirement. The mixes corresponding to gradation G1 exhibited poor permeability, with no individual value more than 20 m/day. The mixes compacted with a compaction efforts of 75 blows, had K values of lesser than 50 m/day, except in the case of mixes with gradation G4. For mixes compacted with 50 blows, the mean K values were found to be in the range of 8–158 m/day. For mixes compacted with 35 blows, the mean K values were higher by a factor in the range of 1.3–2.2. In the case of mixes compacted with an effort of 75 blows, the mean K values were reduced by a factor of 0.3–0.7.

3.5. Analysis of variance (ANOVA) for responses

The influences of main treatment factors such as the compaction effort (MC), gradation (G), binder content (BC), and the interactions between the main treatment factors (MC*BC, BC*G, MC*G, and MC*BC*G), were statistically analysed for the response properties V_a, VCA_m, and K. The tests for analysis of variance (ANOVA) were carried out using a three-factor model [32] as shown in Eq. (3). Statistical analyses were carried out with the aid of the statistical software, MINITAB® (Release 15, trial version).

$$y_{ijkl} = \mu + \tau_i + \beta_j + \gamma_k + (\tau\beta)_{ij} + (\tau\gamma)_{ik} + (\beta\gamma)_{jk} + (\tau\beta\gamma)_{ijk} + \varepsilon_{ijkl} \quad (3)$$

where y_{ijkl} is the response of an experiment of l^{th} replicate; μ is the mean of response; τ is the variation due to the Marshall compaction (MC) levels; β is the variation due to binder content (BC); γ is the variation due to gradation (G); ε is the error term; i, j, and k are number of levels in MC, BC, and G, respectively; and l indicates the replicate of the experiment.

The ANOVA tests for each of the responses were carried out in two groups, Group A comprises the responses for mixes M1–M24 (corresponding to all four gradations), and Group B comprising the responses for mixes M7–M24 (corresponding to the gradations

Table 4
Results of analysis of variance (ANOVA) tests.

Source of Variation	DF[a]	F_0	Results of ANOVA for different response properties								
			V_a			VCA_m			K		
			AMS	F	H_O	AMS	F	H_O	AMS	F	H_O
Group A (mixes: M1–M24, corresponding to all four gradations)											
MC	2	3.198	71.71	109.7	Reject	45.75	108.2	Reject	30541	197.7	Reject
BC	1	4.048	13.17	20.15	Reject	0.551	1.30	Accept	961	6.22	Reject
G	3	2.808	96.50	147.6	Reject	355.8	841.5	Reject	52553	340.3	Reject
MC*BC	2	3.198	2.388	3.65	Reject	1.707	4.04	Reject	1329	8.6	Reject
BC*G	3	2.808	0.045	0.07	Accept	0.035	0.08	Accept	101	0.66	Accept
MC*G	6	2.304	0.283	0.43	Accept	0.276	0.65	Accept	4304	27.87	Reject
MC*BC*G	6	2.304	1.667	2.55	Reject	0.964	2.28	Accept	380	2.46	Reject
Error	48		0.654			0.423			154		
S, R^2, AR^2			0.80, 93.7%, 90.6%			0.65, 98.3%, 97.5%			12.43, 97.1%, 95.8%		
Group B (mixes: M7–M24, corresponding to G2,G3, and G4)											
MC	2	4.102	52.80	81.8	Reject	36.82	81.21	Reject	38111	186.1	Reject
BC	1	5.480	9.459	14.6	Reject	0.463	1.02	Accept	1204	5.88	Reject
G	2	4.102	29.01	44.9	Reject	3.686	8.13	Reject	39250	191.7	Reject
MC*BC	2	4.102	4.592	7.11	Reject	3.176	7.00	Reject	1714	8.37	Reject
BC*G	2	4.102	0.059	0.09	Accept	0.049	0.11	Accept	28	0.14	Accept
MC*G	4	3.178	0.391	0.60	Accept	0.311	0.69	Accept	2605	12.72	Reject
MC*BC*G	4	3.178	0.362	0.56	Accept	0.213	0.47	Accept	376	1.84	Accept
Error	36		0.646			0.453			205		
S, R^2, AR^2			0.80, 88.9%, 83.6%			0.67, 84.7%, 77.4%			14.31, 95.9%, 93.9%		

Note: DF = Degree of freedom; AMS = adjusted means squares; F_0 = critical F-statistic at a confidence level of 95%; F = F-static of responses; H_0 = null hypothesis; S = estimated standard deviation of the error in the model; R^2 = coefficient of determination; AR^2 = adjusted coefficient of determination.

Table 5
Ranking and weightage of the sources of variation for each mix design response.

Source of variation	Rank of each sources in each group						Weight (%) of each sources in each group					
	V_a		VCA_m		K		V_a		VCA_m		K	
	A	B	A	B	A	B	A	B	A	B	A	B
MC	2	1	2	1	2	1	39	55	11	82	34	46
BC	3	3	5	4	5	5	7	10	0	1	1	1
G	1	2	1	2	1	2	52	30	88	8	58	47
MC∗BC	4	4	3	3	4	4	1	5	0	7	1	2
BC∗G	7	7	7	7	7	7	0	0	0	0	0	0
MC∗G	6	5	6	5	3	3	0	0	0	1	5	3
MC∗BC∗G	5	6	4	6	6	6	1	0	0	0	0	0

G2, G3, and G4). Here, the null-hypothesis (H_0) is that the mean value of the responses due the effect of a particular source of variation is same. A confidence level of 95% was selected to test the H_0. If, the F-static (F) of the response was found to be lesser or equal to F-critical (F_0), then H_0 was accepted. Otherwise, it was rejected. The results of the ANOVA tests are presented in Table 4.

The common observations made based on the results of the ANOVA tests are given below:

(i) The responses corresponding to volumetric properties (V_a and VCA_m), and the permeability (K) were significantly influenced by the compaction levels and the gradations (MC and G), and the interactions between the compaction levels and the binder contents (MC*BC).
(ii) The bitumen content was found to have a significant effect only on the air voids content (V_a) and the permeability (K).
(iii) The R^2 values of the responses indicate that the model expressed as in Eq. (3) fits the response-data better.

The ranking of the sources of variation on the responses are provided in Table 5. The ranking was made based on the values of the *F*-statistic or the adjusted mean squares (AMS) determined as provided in Table 4. The source of variation carrying highest *F* or AMS value was treated as first rank, which indicates the major contributor to the variation. Similarly, the source of variation carrying the lowest *F* or AMS value was treated as last rank, which indicates minor contributor to the variation. The percentage of contribution by the sources of variation to the response properties was also determined by obtaining the ratio of the *F*-statistic for the source of variation to the sum of the *F*-statistic values for all the sources of variations. For example, if we consider the response V_a, from Group A, it may be observed that gradation (G) has major influence on the variations in air voids content. Its contribution to the variation is 52% as seen in Table 5.

3.6. Moisture susceptibility

The moisture susceptibility of the PFC mixes was evaluated based on the tensile strength ratio (TSR). The TSR refer to the ratio of average indirect tensile strength (ITS) of the wet-conditioned subset to the average indirect tensile strength of dry-conditioned subset, tested at a temperature of 25 ± 1 °C. Six identical specimens for each mix were prepared, out of which, each set comprising three specimens were used for ITS tests at dry- and wet-conditions according to the ASTM D 6931 [33]. The wet-conditioning was carried out as per the AASHTO T 283 [34], with the following main modifications:

- All the compacted mixes were subjected to wet-conditioning irrespective of air voids content.
- The number of freeze-thaw conditioning cycles was arrived at, based on the Indian Roads Congress recommendations for the design of stone matrix asphalt [35]. This was also incompliance with the suggestion of Watson et al. [36], i.e., only one freeze-thaw cycle is adequate for the moisture conditioning of PFC mixtures.

Fig. 6 shows the mean indirect tensile strengths for all the 24 mixes, tested in dry-condition (ITS_d). Among the ITS_d values of all mixes, the response of mixes corresponding gradations G1 and G4 represent the upper and the lower extremes. Among the six mixes corresponding to gradation G4 (M19–M24), the mean ITS value did not exceed 300 kPa. In the case of mixes corresponding to gradation G1 (M1–M6), the minimum mean ITS values were found to be more than 300 kPa. The mixes compacted to higher compaction levels exhibited higher ITS values, while mixes with higher binder content exhibited relatively low ITS values. The increase in ITS is mainly due to the densification of mix that resulted in the reduction of air voids content. However, an increase in the binder content may result in the formation of thicker asphalt films that result in the loss of friction between the aggregate particles, leading to reduction in the strength.

Fig. 7 shows the tensile strength ratio (TSR) of each mix. The M19 (G4-35-4.5) and M20 (G4-35-5.0) mixes slumped during wet-conditioning at a temperature of 60 °C, hence, for these mixes the wet-conditioning temperature was reduced to 30 °C. Generally, a minimum TSR value of 80% is considered to be desirable to ensure resistance to moisture susceptibility [15]. But, the TNZ [7] recommend a minimum TSR value of 75%. In the present investigations, the mixes that failed to satisfy this requirement either corresponded to the lowest compaction level (35 blows), or lowest BC (4.5%). All the mixes compacted with 75 blows were found to satisfy the minimum TSR requirement. It is quite obvious that the mixes with higher V_a are more susceptible to moisture-induced damage, while mixes with lowest BC resulted in thinner asphalt film, with relatively lower resistance to moisture-induced damage.

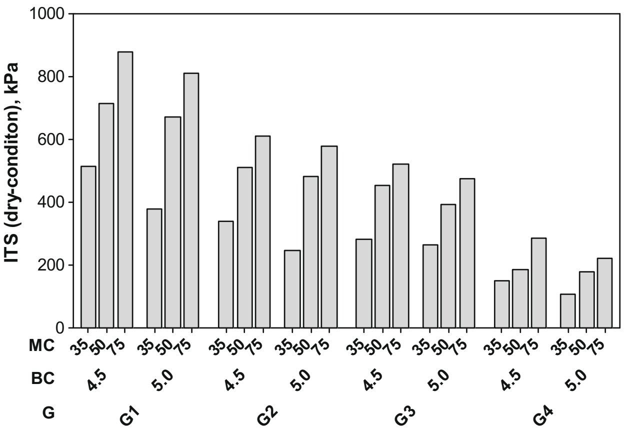

Fig. 6. Indirect tensile strength of PFC mixes in dry condition (ITS_d).

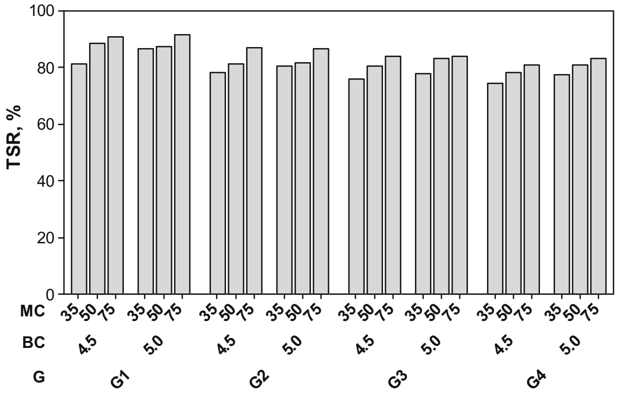

Fig. 7. Tensile strength ratio (TSR) of PFC mixes.

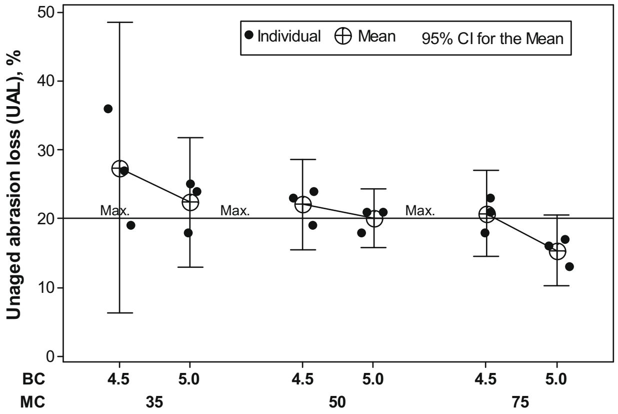

Fig. 8. Unaged abrasion loss (UAL) in PFC mixes (corresponding gradation G4).

3.7. Unaged abrasion loss

The Cantabro abrasion test method was used to evaluate the abrasion loss of the unaged PFC specimens [14]. The test specimen was placed in a Los Angeles abrasion drum without any abrasive charges, and the machine was operated at a speed of 30–33 revolutions per minute for 300 revolutions. The percentage of weight loss in the specimen when compared to its initial weight was expressed as the unaged abrasion loss (UAL). The temperatures recorded during the test procedure were within the range of 25 ± 5 °C as specified in the ASTM D 7064 [15].

The mixes corresponding to gradation G4 (M19–M24) were subjected to the tests for UAL. These mixes were considered to be more prone to abrasion loss, as they exhibited relatively higher V_a, higher K, and lower ITS. Fig. 8 shows the results of UAL tests. As per the specifications, the maximum abrasion loss in unaged specimens should not exceed 20% [15]. In the present investigation, the individual and mean UAL values for mix M24 were found to satisfy this requirement. The mixes compacted at low compaction levels (35 blows) had mean UAL values below 30%, and no individual UAL value was observed to be more than 40%. The upper limits of 95% confidence interval for the mean UAL values were well below 50%. The increase in the compaction effort, and the binder content, thus resulted in an appreciable amount of reduction in the mean UAL values.

4. Conclusions and recommendations

Laboratory studies were conducted to characterize the PFC mixes for different compaction efforts using the Marshall compaction method. PFC mixes corresponding to four aggregate gradations and two binder contents (4.5% and 5.0% by mass of total mix) were studied for three levels of compaction 35 blows, 50 blows, and 75 blows. The effects of these treatments on various properties of PFC mixes were evaluated and the following conclusions were made:

- The properties of mixes corresponding to gradations G1 and G4 represent the upper and lower extremes, respectively. Mixes with G1 exhibited high bulk specific gravity (G_{mb}), with lower air voids (V_a) and permeability (K). The VCA_m and $\mathrm{ITS_d}$ values for these mixes were higher.
- The PFC mixes compacted at lowest compaction level adopted, and for the gradation between G2 and G4, exhibited the stone-on-stone contact in the coarse aggregate skeleton. Thus, these mixes are expected to offer best performance.
- It was observed that of all the mixes tested at highest compaction level of 75 blows, only mixes with gradation G4 provided a minimum mean V_a of 15%, and minimum K value of 50 m/day.
- The effect of compaction levels and gradations were found to be statistically significant on mix design properties of PFCs, while, changes in binder contents do not significantly affect the VCA_m. The compaction levels had a major influence on the variations in V_a and VCA_m of the mixes with similar aggregate gradations. Also, the variations in K values were mainly associated with the variations in the aggregate gradations, and the compaction levels.
- The indirect tensile strengths of dry-conditioned PFC mixes were in the range of 100–880 kPa. The mixes which failed to satisfy a minimum TSR value of 80% were prepared with lower binder contents and lower compaction levels. However, among all the mixes no individual had TSR values lesser than 74%.
- Based on the results of various properties of the mixes tested, it may be inferred that aggregates between the gradations G2 and G4 did not show much change in the various response properties.

Specifications by various agencies generally recommend the design of PFC mixes at a compaction level of 50 blows. However, an examination of the results presented above reveal that the compaction levels play a significant role in air voids contents, permeability and resistance to abrasion. In order to meet the minimum air voids requirement, it is suggested to design the PFC mixtures at a compaction level of 35 blows. The Marshall compaction level of 75 blows can be adopted to assess the over-compaction behavior of PFC mixtures. It is also suggested that the coarser gradations like G4 can be recommended for the PFC mixes, surfaced for heavy-traffic road-corridors, while finer gradations like G2 and G3 can be recommended for PFC mixes, surfaced for moderate- to light-traffic road-corridors. These aspects need to be verified in the field, in addition to comparisons with laboratory observations.

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