Construction and Building Materials 23 (2009) 1211–1217

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

A comparative study on properties of porous friction course mixes with neat bitumen and modified binders

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ARTICLE INFO

Article history:
Received 18 April 2008
Received in revised form 6 August 2008
Accepted 10 August 2008
Available online 21 September 2008

Keywords:
Porous friction course
Bitumen
Polymer modified binders
Gradation
Durability
Performance

ABSTRACT

This paper summarises details of the laboratory investigation on the effect of various binders on the performance and durability of porous friction course (PFC) mixes. Three different modified binders and neat bitumen were investigated for three different aggregate gradations at two predetermined binder contents. The performance was evaluated in terms of stone-on-stone contact condition, air voids, and hydraulic-conductivity of compacted PFC mixes. The structural durability was investigated based on aged abrasion loss and moisture susceptibility. The findings provide a better understanding of the effect of each binder type on the performance and durability of PFC mixes.

1. Introduction

India has a road network length of 3.34 million km, which is considered to be second largest in the world [1]. The latest statistics indicate that, nearly 67,000 km of National Highways (NH) and 132,000 km of State Highways (SH) cater to the mobility requirements in addition to roads of other categories, of the country. The Road Development Plan Vision: 2021 [2] recommends the construction of 15,776 km of Expressways by the end of year 2020. It is expected that these high-speed road-corridors will enhance the effective movement of goods and passengers, and address the major concerns on road-safety especially during wet weather conditions, and noise-nuisance. International experiences suggest the use of open-graded asphalt mixes as surface courses in this connection.

Open-graded mixes are characterized by high percent interconnected air voids, which will ease the drainage of surface water. Various agencies around the world use different terminologies [3–8] for these types of surfaces (Table 1). In this paper, open-graded asphalt mixes are broadly referred to as porous friction course (PFC) mixes.

PFCs are found to offer multiple benefits like, improved skid-resistance, reduced splash and spray, and improved night-visibility during wet weather conditions, in addition to mitigation of hydroplaning [9–11]. Moreover, the negative-texture of these surfaces enables considerable reduction in tyre-noise [12].

1.1. Background

A high percent air voids content and better permeability will significantly enhance the performance of PFCs. Consequently, rapid oxidation of the asphalt binder films [13] and moisture susceptibility have an adverse effect on the structural durability of such pavement surfaces. The following provides a summary of relevant research findings.

Ruiz et al. [14] reported that out of the 30 million m^2 of porous asphalt roads in Spain, the surfaces with a voids content of less than 20% maintained their drainage capacities even after 9 years of construction under medium traffic conditions without any serious deterioration. But, sections under heavy traffic were closed up after 2 years of use. In the United Kingdom, porous asphalt trial sections made of neat bitumen of penetration grade-100 constructed during the 1980s, had an ultimate life of more than 7 years, while sections constructed with modifiers gave better results [15]. One of the major findings based on a review of TRL road trials on porous asphalt revealed that porous asphalt surfaces have a service life of more than 10 years on heavily trafficked roads, although binder hardening was considered to be a major limiting factor [10].

Experiences with use of open-graded mixes in the United States indicated that ravelling was the major cause of pavement failure in some regions, while a vast majority of states had a good experience

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doi:10.1016/j.conbuildmat.2008.08.008

Table 1
Terminologies and binder types used for open-graded mixes by different agencies

Country	Agency	Terminology	Binder type/grade	References
United States of America	American Society for Testing and Materials (ASTM)	Open-graded friction course (OGFC)	Performance grade (PG) asphalt cement	[3]
	Federal Aviation Administration (FAA)	Porous friction course (PFC)	Viscosity grade asphalt cement (AC-20)	[4]
Australia	Australian Asphalt Pavement Association (AAPA)	Open-graded asphalt (OGA)	Viscosity grade asphalt cement (C 320), and polymer modified bitumen (PMB)	[5]
New Zealand	Transit New Zealand (TNZ)	Porous asphalt (PA)	Penetration grades 80–100 and 60–70	[6]
South Africa	Southern African Bitumen Association (Sabita)	Porous asphalt (PA)	Penetration grade of 80–100, and polymer modified bitumen (PMB)	[7]
Japan	Japan Highway Public Corporation (JHPC)	Porous asphalt (PA)	High-viscosity improved asphalt (HVIA)	[8]

with the use of polymer modified asphalt binders [16]. Nielsen et al. [17] observe that in Japan, porous asphalt surfaces on highways and in urban areas cover more than 50 million m^2. The structural durability of these pavements was found to be same as that of dense graded asphalt mixes, while climatic conditions too were found to have a significant influence. High viscosity styrene–butadiene–styrene (SBS) modified binders were used in these cold regions to overcome distresses due rutting and raveling.

A number of laboratory investigations [18–21] report the evaluation of PFC mixes for various types of modifiers and modified binders. Verhaeghe et al. [18] were of the opinion that the use of modifiers to binders or the addition of fibres to the mixes resulted in lesser maintenance, and improvement in the structural performance of pavement wearing courses. Mallick et al. [19] report the performance of open-graded friction course mixes made of performance grade (PG) binders in combination with a few types of elastomeric polymers and various types of fibres. The findings indicated that the mean air voids in all the modified mixes did not exceeded 18%.

Punith et al. [20] studied on the behaviour of porous asphalt mixes with crumb rubber modified bitumen (CRMB), reclaimed polyethylene modified bitumen (RPEMB), and cellulose fibres (CF). The findings indicate that these mixes exhibited air voids of more than 18%. However, in this investigation the specimens tested were compacted on only one side. Hassan et al. [21] carried out studies on open-graded friction course mixes for neat bitumen of penetration grade 60–70, styrene–butadiene–rubber (SBR) modified binder, cellulose fibres (CF), and combinations of SBR and CF. The results indicated that the mean air voids of most of the mixes were more than 20%, and that failed to satisfy the abrasion loss requirements when unaged and aged specimens were tested. But, in the case of mixes with combinations of SBR and CF, the losses due to abrasion were within the limits. Also, the permeability values of these mixes were found to be within 50 m/day.

In brief, the research findings based on laboratory investigations mentioned above recommend the use of modified binders to improve the durability of PFC mixes. Also, trial sections constructed using modified binders in the above studies were found to have extended ultimate lifespan. Different agencies specify different binders for PFCs, based on the pattern of binder grading, the use of modified binders, and modifiers.

1.2. Objectives

In India, PFCs are yet to be experimented by highway agencies, and specifications for the same do not exist. In an effort to develop guidelines for the design and use of PFC mixes in India, the present investigation was focused on the use of various binders commonly used in the country, for the paving of highways, airfields, and rural roads.

2. Experimental program

2.1. Materials

The binder types (BT) studied includes, neat bitumen (NB), polymer modified bitumen of plastomeric thermoplastic base (PMB-P), polymer modified bitumen of elastomeric thermoplastic base (PMB-E), and crumb rubber modified bitumen (CRMB). These binders obtained from various sources in India were tested in accordance with the Indian Standards (IS). The grading requirements for these binder types were evaluated. The test results are presented in Table 2. The crushed granite stone aggregates obtained from local stone-crushing plants were used in this study. The results of physical properties of aggregates tested are given in Table 3. Ordinary Portland Cement (OPC) that constituted 2% by mass of total aggregates was used as a part of the mineral filler.

2.2. Experimental design

PFC mixes corresponding to each of the three gradations (G) shown in Fig. 1 were investigated for four binder types (BT) and for two predetermined binder contents (BC). Table 4 provides information on the combinations of 24 different PFC mixes and their coding. To evaluate the volumetric properties, hydraulic-conductivity, aged abrasion loss, and the tensile strength ratio (TSR), 15 replicates for each of the 24 mixes were prepared and tested. The tests for wet abrasion loss (WAL) were conducted for the mixes with higher binder contents. This decision was taken based on the observations made on the TSR values, the details of which can be

Table 2
Properties of neat bitumen and modified binders

Characteristics	IS test method	Properties of different binder type (BT)			
		NB	PMB-P	PMB-E	CRMB
Penetration at 25 °C, 1/10 mm	IS 1203	89	82	86	68
Softening point (R&B), °C	IS 1205	46	58	57	59
Flash point, °C	IS 1448 (P:69)	220	229	226	229
Elastic recovery of half thread in ductilometer at 15 °C	IS 15462	–	58	76	54
Separation, difference in softening point (R&B), °C	IS 15462	–	1	1	3
Thin film oven tests and tests on residue					
Loss in mass, %	IS 9382	0.2	0.1	0.15	0.2
Increase in softening point (R&B), °C	IS 1205	–	3.0	2.0	4.0
Reduction in penetration at 25 °C, %	IS 1203	39	20	15	31
Elastic recovery of half thread in ductilometer at 15 °C	IS 15462	–	52	59	43

Table 3
Physical properties of aggregates

Particulars of physical properties	Test method	Test results (%)
Combined flakiness and elongation index	IS 2386 P1	28.1
Aggregate impact value	IS 2386 P4	20.1
Los Angles abrasion value	IS 2386 P4	26.6
Water absorption	IS 2386 P3	0.15
Soundness, magnesium sulphate solution	IS 2386 P5	0.21

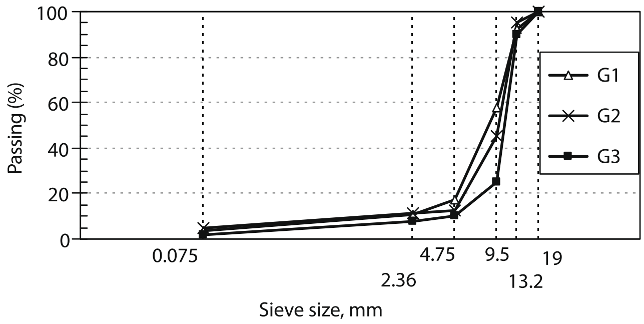

Fig. 1. Aggregate gradations used in the present study.

found in the later sections. The test plan comprising the details of different response properties studied are presented in Table 5.

2.3. Laboratory tests

The procedure adopted for the preparation of cylindrical PFC specimens was the same as that followed for dense graded asphalt, as suggested in the Asphalt Institute Manual Series-2 [22]. To prepare a cylindrical specimen of 101.4 mm diameter (*D*), loose hot PFC mix was compacted by applying 50 blows on each end of the specimen, using the standard Marshall hammer. Each specimen constituted 1000 g of the aggregate in addition to the binder used.

Table 4
Coding of different PFC mixes

Binder type with coded number		Binder content (BC, %)	Coding for mixes of different gradations		
			G1	G2	G3
NB	1	4.5	M1	M9	M17
		5.0	M2	M10	M18
PMB-P	2	4.5	M3	M11	M19
		5.0	M4	M12	M20
PMB-E	3	4.5	M5	M13	M21
		5.0	M6	M14	M22
CRMB	4	4.5	M7	M15	M23
		5.0	M8	M16	M24

Table 5
Test plan

Response properties	Details of mixes	Number of		
		Mixes	Replicates	Specimens
Volumetric properties and permeability	M1–M24	24	3	72
Aged abrasion loss (AAL)	M1–M24	24	3	72
Tensile strength ratio (TSR)	M1–M24	24	6	144
Wet abrasion loss (WAL)	M (even nos.)	12	3	36
Total number of compacted specimens				324

Compacted specimens were used to evaluate the volumetric properties, hydraulic-conductivity, aged abrasion loss, and the moisture susceptibility. The procedures adopted to evaluate these properties are summarized below.

The bulk specific gravity of compacted mix (G_{mb}) was determined using the geometric measurements of diameter (*D*), mean length (*L*), and the mass of the specimen in air. The theoretical maximum density (G_{mm}) of the uncompacted mix was determined in accordance with ASTM specifications [23]. The air voids content (V_a) in the compacted specimen was determined using the corresponding values of G_{mb} and G_{mm} [24] as in the following equation:

$$V_a = 100 \times \left(1 - \frac{G_{mb}}{G_{mm}}\right) \tag{1}$$

The presence of stone-on-stone contact condition in the compacted PFC mix was evaluated based on the percent voids in coarse aggregate of the compacted mixture ($\mathrm{VCA_m}$) and the percent voids in coarse aggregate of the coarse aggregate alone ($\mathrm{VCA_d}$) determined using the dry-rodded test procedure [25]. The $\mathrm{VCA_m}$ values were determined with due consideration to aggregate breakdown [26]. The $\mathrm{VCA_d}$ and $\mathrm{VCA_m}$ values were computed using Eqs. (2) and (3), respectively. The stone-on-stone contact condition was confirmed when the ratio of $\mathrm{VCA_m}$ to $\mathrm{VCA_d}$ was found to be less than unity:

$$\mathrm{VCA_d} = \frac{G_{CA}\gamma_w - \gamma_s}{G_{CA}\gamma_w} \tag{2}$$

$$\mathrm{VCA_m} = 100 - \left(\frac{G_{mb}}{G_{CA}} \times P_{CA}\right) \tag{3}$$

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

The hydraulic-conductivity of the compacted specimens was expressed in terms of the coefficient of permeability determined using the falling-head method. The test-setup used was simple and economical. The compacted PFC specimens before being extruded from the Marshall mould were used in these tests. To prevent water leakage through the joints, the circumference of the specimen was covered with paraffin wax at the top and at the bottom. Care was taken to prevent clogging of voids in the specimen when paraffin wax was applied. The collar placed on the mould-specimen assembly, acted as a water reservoir. Water was allowed to flow through the specimen, and the average time (t_m) taken for a drop in the water level from 70 to 30 mm was recorded in seconds. The coefficient of permeability (*K*, m/day) of the cylindrical specimen of 101.4 mm in diameter and of mean length (*L*, mm) was calculated by using the following equation:

$$K = 208.49 \frac{L}{t_m} \log_{10}\left(\frac{L+70}{L+30}\right) \tag{4}$$

Aging of PFC specimens were simulated in the laboratory, and the Cantabro abrasion tests were conducted on these aged specimens to evaluate the aged abrasion loss (AAL). Compacted PFC specimens of a particular mix in triplicate were stored in a forced draft oven at a temperature of 60 °C for a period of 168 h. The specimens were then taken out and allowed to cool to the ambient temperature. These were then stored for a period of 4 h at a temperature 25 ± 5 °C as per the requirements for the Cantabro abrasion test [3]. The aged specimen was then placed in a Los Angeles abrasion drum without any abrasive charge, and the machine was operated at a speed of 30–33 revolutions/min for 300 revolutions. The loss in the specimen was expressed as a percentage of the ratio of the weight of disintegrated particles to the initial weight of the specimen.

The moisture susceptibility of PFC mixes was evaluated by two approaches: (i) retained tensile strength or tensile strength ratio (TSR) method [3], and (ii) the wet abrasion loss (WAL) method [7].

In order to evaluate the TSR, a total of six replicate specimens were prepared for each mix as per the experimental design. A subset of three specimens was tested in dry-condition, and another subset of three specimens was tested after wet-conditioning.

The wet-conditioning was carried out as per AASHTO procedure [27], with the following main modifications:

- All the compacted mixes were subjected to wet-conditioning irrespective of air voids content.
- The saturation of specimens was done by placing the specimens fully submerged in distilled water filled in a metallic trough, in place of adopting the vacuum saturation method.
- The specimens placed in the metallic trough were subjected to two freeze–thaw conditioning cycles.
- The indirect tensile strength (ITS) tests were conducted on the dry- and wet-conditioned specimens. Their mean ITS values were used to compute the tensile strength ratio (TSR) of the mix. The following relations were used to compute ITS and TSR.

$$\mathrm{ITS} = \frac{2 \times P_u}{\pi \times L \times D} \tag{5}$$

$$\mathrm{TSR} = \frac{\mathrm{ITS_w}}{\mathrm{ITS_d}} \times 100 \tag{6}$$

where P_u is the maximum load; $\mathrm{ITS_w}$ is the mean indirect tensile strength of the wet-conditioned subset; and $\mathrm{ITS_d}$ is the mean indirect tensile strength of the dry-conditioned subset.

The resistance to moisture-induced damage was also evaluated in terms of wet abrasion loss (WAL) values. In order to evaluate the wet abrasion losses in the selected mixes, the specimens were subjected to wet-conditioning as mentioned above. The abrasion resistances of the wet-conditioned specimens were evaluated by means of the Cantabro abrasion test.

3. Results and discussion

3.1. Volumetric properties

The bulk specific gravity of compacted mix (G_{mb}) of different PFC mixes were in the range of 1.993–2.172 g/cm^3. Mixes with modified binders exhibited relatively higher G_{mb} values, compared to mixes with neat bitumen (NB). The increase in the mean G_{mb} values was found to be in the range of 0.8–3.6%. The mixes with modified binders, PMB-P and CRMB were found to have higher values of G_{mb}. Also, most of the mixes with 5.0% BC exhibited marginally higher mean G_{mb} values. Among all the mixes, the lower and higher mean G_{mb} values corresponded to mixes of gradations G3 and G2, respectively. It may be observed that although all the gradations had coarse aggregate contents more than 80%, the mixes prepared with gradation G3 had comparatively higher amounts of coarser aggregate. The mixes with gradation G3 resulted in lower densities due to this reason. Fig. 2 shows the variations in the individual and mean values of the bulk specific gravity for various PFC mixes tested. The lines connecting the mean values of the G_{mb} of mixes of different binder types, for a particular binder content and gradation, are also provided to indicate the trends in variations.

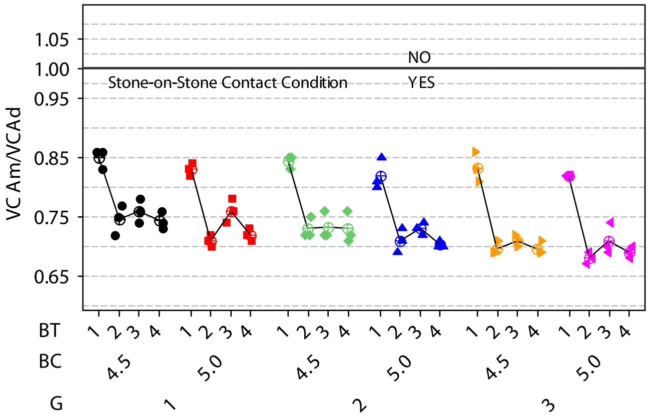

Fig. 3. Verification of stone-on-stone contact condition.

Brown and Haddock [28] proposed a method to assess the stone-on-stone contact of coarse aggregate skeleton in the design of stone matrix asphalt (SMA) paving mixes for better rutting resistance. Mallick et al. [19] recommended the above method for the design of new-generation open-graded friction courses. In the present investigation, all the mixes were evaluated for stone-on-stone contact conditions. The ratios of VCA_m to VCA_d for various mixes are shown in Fig. 3. It is evident from the results that the requirements for stone-on-stone contact conditions in the coarse aggregate skeleton were satisfied in all the mixes tested. This is mainly due to the reason that in all the gradations selected for investigation, the coarse aggregate content was maintained at a minimum of 80% as recommended by Mallick et al. [19].

The air voids (V_a) contents in the compacted PFC mixes were found to be in the range of 12.4–19.8%. Fig. 4 shows the individual V_a, mean V_a, and an interval bar for 95% confidence level for mean air voids (V_a). As mentioned in the discussions on bulk specific

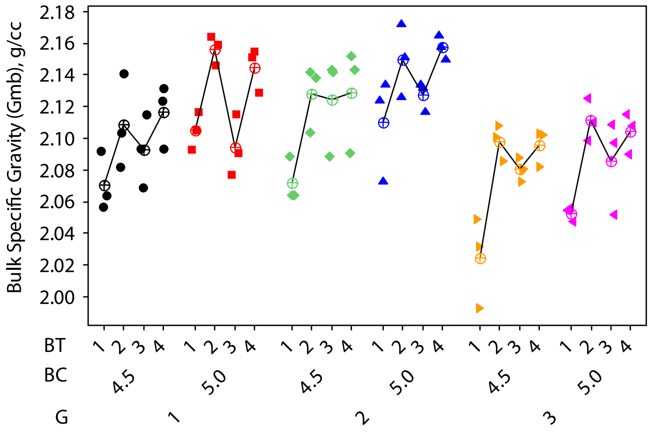

Fig. 2. Bulk specific gravities of compacted mixes (G_{mb}).

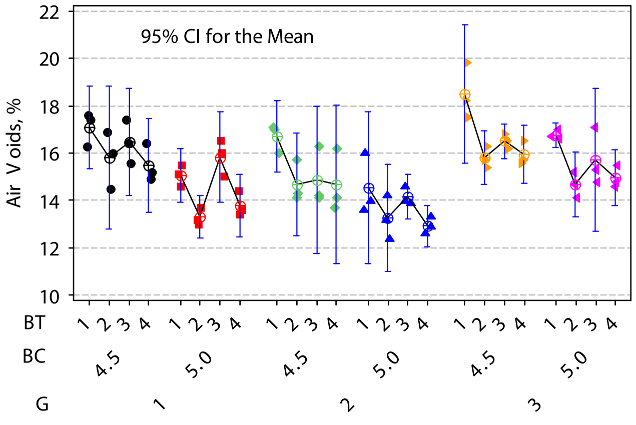

Fig. 4. Variation in air voids (V_a) content.

gravity above, it may be inferred that mixes prepared with gradation G3 exhibited much higher air voids content due to their lower densities as expected. It can be observed that mix M17 (NB-4.5-G3) satisfied the minimum requirement for maintaining air voids (V_a) at 18% [3]. The 95% confidence level for the mean V_a indicates that the mixes M1 (NB-4.5-G1), M3 (PMB-P-4.5-G1), M5 (PMB-E-4.5-G1), M9 (NB-4.5-G2), and M22 (PMB-E-5.0-G3) satisfy the minimum V_a requirement. Also, most of the mixes with modified binders exhibited lower air voids content, mainly due to higher G_{mb}. The reductions in mean V_a were found to be in the range of 3–15% of mean V_a of the respective mixes with neat bitumen (NB).

3.2. Permeability

Hydraulic-conductivity or permeability (K) is considered as one of the major indicators of the performance-life of PFC mixes [11]. Although, the standard ASTM practice [3] recommends the evaluation of permeability as an optional requirement, it is not recommended by agencies like FAA [4], AAPA [5], and the TNZ [6]. The permeability of all the 72 specimens of 24 different mixes was found to be between 11.3 and 193.6 m/day, as shown in Fig. 5. All the mixes satisfied the permeability requirements for maintaining good drainage conditions ($K > 8.64$ m/day) [29]. It may be seen that mixes M17 (NB-4.5-G3) and M18 (NB-5.0-G3) tested had permeability values more than 100 m/day, satisfying the requirements recommended by ASTM [3].

From Fig. 5, it can be further observed that for a particular gradation (G) and binder content (BC), the mixes with modified binders exhibited relatively lower K values compared to that of mixes with neat bitumen (NB). The mean K values of mixes with modified binders were found to be in the range of 0.33–0.94 times that of respective mixes with NB. Among the mixes with modified binders, the mixes with CRMB exhibited lowest K values, while most of the mixes with PMB-E exhibited relatively higher K values.

3.3. Aged abrasion loss

The aged abrasion loss (AAL) for the mixes tested ranged between 3.0% and 57.7%. Fig. 6 shows the individual and mean AAL values in addition to the interval bars for 95% confidence level for mean AAL values. The use of modified binders, PMB-P and CRMB resulted in reducing the mean AAL compared to that of mixes prepared with NB. The mean AAL of mixes with PMB-P were observed to be reduced by 0.83–0.53 times that of mixes with NB, while that of CRMB mixes were found to be reduced by 0.60–0.46 times. In the case of mixes with PMB-E, the mean AAL values were reduced by 0.95–0.42 times, except in the case of mixes with gradation G3. The individual and mean AAL values of all mixes were found to be within the maximum limits of 50% and 30%, respectively [3], except in the case of mix M22 (PMB-E-5.0-G3). From the above observations, it can be inferred that the reductions in the AAL values for mixes with modified binders were due to the lower air voids content and by virtue of the nature of modified binders themselves.

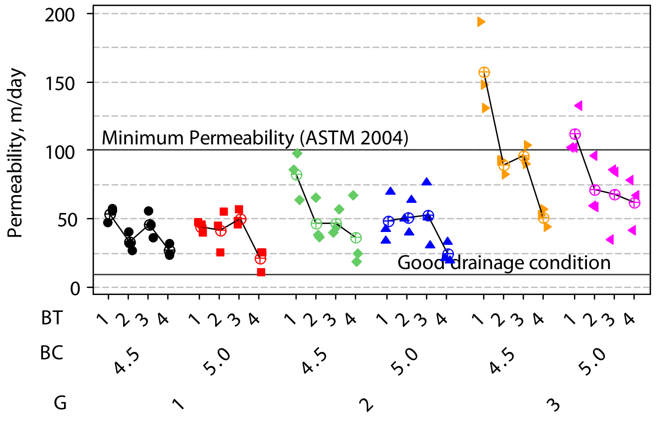

Fig. 5. Permeability (K) values.

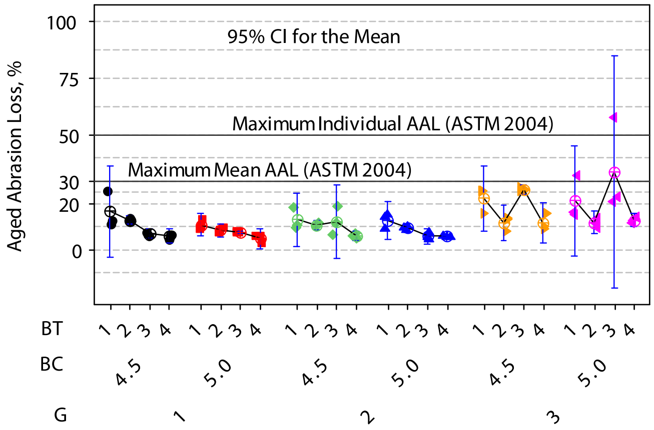

Fig. 6. Aged abrasion losses (AAL).

3.4. Moisture susceptibility

The moisture susceptibility of PFC mixes was evaluated in terms tensile strength ratios (TSRs) for all the 24 mixes, and the tests for wet abrasion loss (WAL) were then performed.

The individual plots for ITS_d and ITS_w for all the 24 mixes are presented in Figs. 7 and 8, respectively. The ITS values of dry-conditioned and wet-conditioned specimens of all PFC mixes prepared with NB, were found to be in the range of 291–631 kPa and 202–481 kPa, respectively. Mixes with modified binders exhibited higher ITS values, both in dry-condition and wet-condition. The increase in the mean ITS_d values for modified mixes was found to be in the range of 1.04–2.08 times that of mixes with of NB. Also, the increase in the mean ITS_w values for modified mixes ranged between 1.23 and 2.33 times that of the same. It may also be found that among the mixes prepared with modified binders, mixes with PMB-P exhibited higher strength when compared to mixes with PMB-E and CRMB.

ASTM standard practice [3] suggest a minimum TSR value of 80%, while TNZ [6] specifies a minimum retained tensile strength

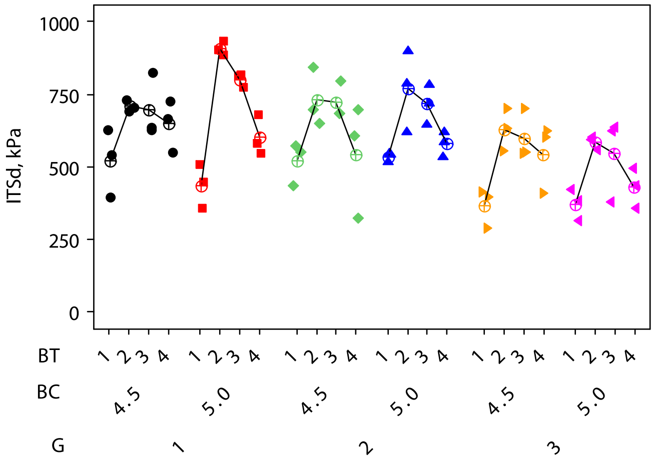

Fig. 7. Results of indirect tensile strength tests on dry-conditioned specimens.

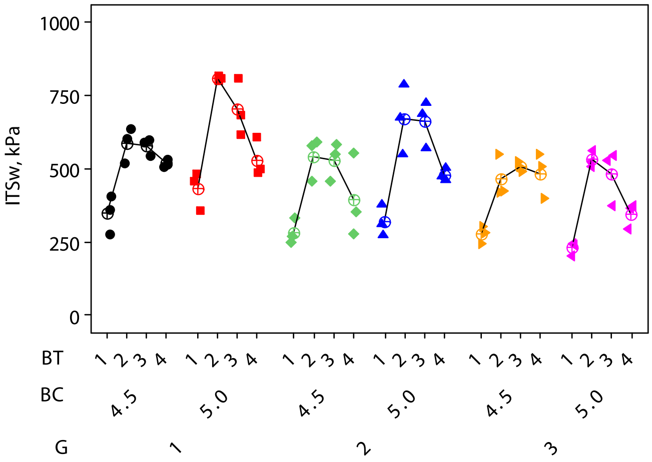

Fig. 8. Results of indirect tensile strength tests on wet-conditioned specimens.

of 75%, for mixes resistant to moisture susceptibility. Test results indicate that all mixes prepared with NB failed to satisfy the moisture susceptibility requirement, except in the case of mix M2 (NB-5.0-G1). Also, mixes M11 (PMB-P-4.5-G2), M13 (PMB-E-4.5-G2), M15 (CRMB-4.5-G2), and M19 (PMB-P-4.5-G3) failed to satisfy the requirements, although modified binders were used. Considering, these results, the TSR approach to assess the moisture susceptibility seems to be misleading. In Fig. 9, in the case of mixes of gradation G1 with a binder content of 5.0%, prepared using NB, it is observed that the TSR is higher than that for mixes with modified binders. But, on cross-verification with the corresponding ITS values of dry-conditioned and wet-conditioned mixes as in Figs. 7 and 8, respectively, it is found that the ITS is very much lower than that of mixes with modified binders. Thus, considering the TSR values as the only criteria to evaluate the moisture susceptibility of PFC mixes may not be correct.

Hence, in order to verify the moisture susceptibility, it was felt that further investigation based on the wet abrasion loss (WAL) tests need to be performed. The WAL test is another approach for the evaluation of moisture susceptibility of PFC mixes, as suggested in the Sabita manual [7]. Fig. 10 shows the individual and mean WAL values of mixes corresponding to all binder types (BT) and gradations (G) with binder content (BC) of 5.0%. The results also show that the individual and mean WAL values of the mixes tested were within the maximum limits of 50% and 30%, respectively, as suggested in the Sabita manual [7].

The results of the WAL tests shown in Fig. 10 revealed a decreasing trend when tested for gradations G1, G2, and G3 for various binder types. It can be further observed that mixes with modified binders generally resulted in lesser values of WAL as expected. Hence, the results of the WAL test are recommended to be given more importance in the evaluation of moisture susceptibility instead of relying solely on the TSR value.

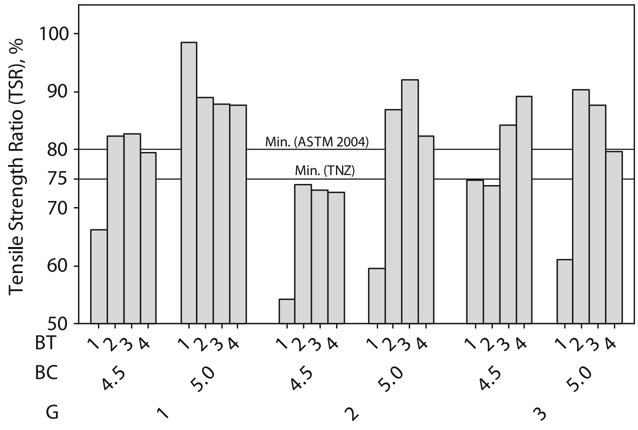

Fig. 9. Tensile strength ratios (TSRs).

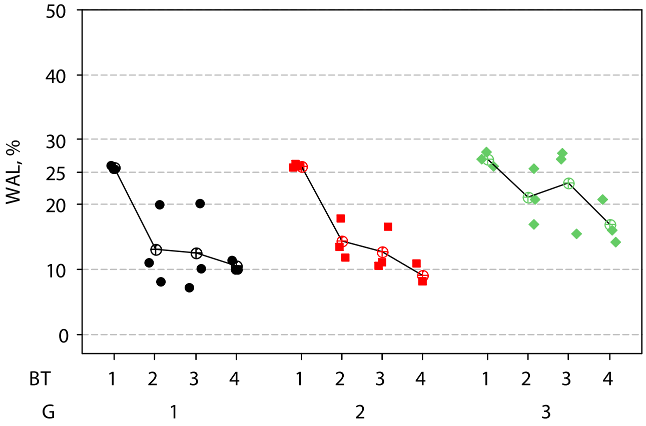

Fig. 10. Results of wet abrasion loss (WAL) tests.

4. Conclusions and recommendations

The above investigations were conducted to characterize PFC mixes with three different modified binders, PMB-P, PMB-E and CRMB, and neat bitumen (NB), for binder contents of 4.5% and 5.0%, and three gradations, G1, G2, and G3. The effect of binder type (BT), binder content (BC), and gradation (G) on PFC mixes were evaluated in terms of the volumetric properties, permeability, aged abrasion loss, and the moisture susceptibility. Based on these response properties tested, the following conclusions can be made:

- The aggregate gradations (G) and the binder type (BT) were observed to be the main sources for the variations in the response properties of PFC mixes.
- The mixes with modified binders exhibited higher bulk specific gravity (G_{mb}), which resulted in lower percent air voids (V_a), lower permeability (K), and higher possibilities of maintaining stone-on-stone contact conditions in compacted mixes, when compared to mixes prepared with neat bitumen (NB).
- The mixes with gradation G3 with higher quantities of coarse aggregate, exhibited lower bulk specific gravities (G_{mb}), higher percent air voids and higher permeabilities, when compared to mixes with other gradations.
- The results of AAL tests indicate that the mixes prepared with modified binders, especially CRMB, exhibited higher resistance to aged abrasion losses.
- The results of the tests for ITSd and the ITSw clearly indicate that the use of PMB-P and PMB-E in PFC mixes significantly contributed to their strengths, when compared to mixes with NB and CRMB.
- The TSR values indicate that the mixes with modified binders satisfied the minimum retained tensile strength requirements specified by TNZ [6] and ASTM [3] for mixes with a binder content of 5.0%. Also, the results of the WAL tests on these mixes confirmed their adequacy in resisting the moisture-induced damages.
- The results of the WAL tests indicate that the use of modified binders in particular, contributed to lower WAL values indicating higher resistance to moisture-induced damage. The mixes with the CRMB offered the highest resistance, when compared to that of mixes with PMB-P and PMB-E.

The results of the above investigation thus indicate that the use of modified binders is more appropriate for PFC mixes with coarser gradations. The above studies also indicate that the WAL approach to evaluate the moisture susceptibly of PFC mixes is more appropriate when compared to the TSR approach. Moreover, it is inferred that the design of PFC mixes with modified binders at lower compaction efforts, may ensure higher air voids content and better permeability. Further studies are required to be performed to address the effect of various levels of compaction on the properties of PFC mixes with modified binders.

Acknowledgements

The authors acknowledge the financial support extended by the Ministry of Science and Technology (Government of India) under FIST-2005, for this research, and the National Institute of Technology Karnataka for having provided the basic infrastructure, manpower, and other timely assistance. Acknowledgments are also due to the suppliers of bitumen binders, M/s MRPL, Mangalore, India, M/s OSNAR Chemicals Pvt. Ltd., Mumbai, India, M/s HINCOL, Mangalore, India, and M/s Southern Asphalt, Mangalore, India.

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