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ORIGINAL ARTICLE

Effect of aggregate gradations on properties of porous friction course mixes

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Abstract This paper presents the study on effect of aggregate gradation on the mix design and performance properties of porous friction course (PFC) mixes. Six aggregate gradations were tested with due consideration to gradations specified for PFC or similar mixes by different agencies around the world. The PFC mixes were characterized for volumetric properties, permeability, unaged and aged abrasion loss, moisture susceptibility, and rutting resistance. The results were statistically analysed to identify the factors that significantly influence the properties of PFC mixes. Findings of the study clearly indicate that the gradations specified by various agencies will have significant effect on the design properties of PFC mixes, thus they are different. It also, helps in framing the Master aggregate gradation band for PFC mixes. Generally, permeability property is considered to be an optional parameter in the design. However, the findings of the present study recommended considering the permeability as one of the prime parameters in the design of PFC mixes.

Keywords Porous friction course · Porous asphalt · Volumetric properties · Permeability · Abrasion loss · Moisture susceptibility

1 Introduction

Open-graded mixes are composed of relatively uniform graded aggregate and bitumen or modified binders, and are mainly used to serve as drainage layers, either at the pavement surface or within the pavement structure [1]. The different types of open-graded mixes used for surfacing or wearing courses are porous friction course (PFC), porous asphalt (PA), porous european mix (PEM), open-graded friction course (OGFC), open graded asphalt (OGA), two-layer porous asphalt (TLPA), etc. [2, 3]. These types of surfaces offer wide range of benefits including mainly increased permeability and noise reduction, in addition to advantages during wet weather conditions such as improved skid resistance, reduced splash and spray, and minimized glare effect.

OGFCs have been experimented widely in the United States over the past 50 years [2]. European experiences with porous mixes demonstrated its

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potential applications on high-speed road facilities that also produced exceptionally quiet pavements [4]. Porous pavements of Japan are known for their structural and acoustic durability [5]. The Federal Aviation Administration (FAA) recommends the use of porous friction courses (PFCs) as one of the techniques for improvement of runway pavement skid-resistance, and mitigation of hydroplaning [6].

1.1 Background

PFC mixes are characterized by a high percent of inter-connected air voids and are recommended to lay over a sound dense asphaltic surface. These mixes are designed to resist mainly two modes of deterioration, (i) ravelling, and (ii) clogging of pores. Ravelling is caused mainly due to aging of binder and moisture damage. The high percentage of air voids in PFC mixes subjected to rapid oxidization of bitumen binder in addition to more exposure to moisture. Generally, open-graded mixes with low percentage of air voids are more susceptible to clogging [7]. Clogging of PFCs will render the surface impervious, and cause water logging unless cleaned. High binder contents with result in thicker binder films over the aggregate surface providing more resistance to loss of aggregate. Use of larger-sized aggregate grading provides superior performance than finer graded mixes in terms of hydraulic-conductivity [8]. The aggregate gradation and binder content plays a major role in ensuring the hydraulic-efficiency and durability of the mixes.

Verhaeghe et al. [9] carried out studies on porous asphalt mixes and suggested that the selected aggregate gradation should result in at least 20% voids in the compacted mix. This was found satisfied, when the aggregate fraction retained on the 4.75 mm sieve was more than 75%. Cabrera and Hamzah [10] adopted the aggregate packing theory and proposed a gradation for porous asphalt based on the concept of “designing to target porosity,” while, Takahashi and Partl [11] reported the use of wet-packing-method for the design PFC mixes. Further studies reported by Poulikakos et al. [12] indicate that the properties of porous asphalt vary significantly with aging. Kandhal and Mallick [13] adopted voids in coarse aggregate of the compacted mix (VCA_{mix}) as one of the parameters in the design of OGFC mix. This approach was similar to the design of stone mastic asphalt (SMA) [14]. Authors concluded that the gradation with no more than 20% passing the 4.75 mm sieve is required to achieve stone-on-stone contact condition in the coarse aggregate skeleton and to provide adequate permeability in OGFC mixes. In the year 2004, American Society for Testing and Materials (ASTM) adopted the gradation of new-generation OGFC [13] as master range of gradation for OGFC in one of its standards, ASTM D 7064 [15]. Hamzah et al. [16] considered permeability and mix stability properties, to arrive at modified aggregate gradation for porous asphalt. Hassan et al. [17] investigated the coarser, medium and fine gradations of new-generation OGFC as reported by Kandhal and Mallick [13]. The results indicated that a binder content of 6.0% ensured stone-on-stone contact condition only in coarse graded mixes. While, Voskuilen et al. [18] were of opinion that the PA mixes acts better with higher binder content, generally at 5.5% of neat (pure) bitumen of 70/100 with some drainage inhibitors. In addition, it was concluded that the use of polymer modified bitumen can only reduce the initial damage and do not provide an additional service life. More information on durability aspects of porous asphalt can be found elsewhere [19].

Some of the latest specifications for PFC or similar mixes recommended by various agencies around the world are presented in Fig. 1. The agencies considered include the Australian Asphalt Pavement Association (AAPA) [20], Transit New Zealand (TNZ) [21], American Society for Testing and Materials (ASTM) [15], Southern African Bitumen Association (Sabita) [22], Japan Highway Public Corporation (JHPC) [23], and Federal Aviation Administration (FAA) [24]. There is a wide variation among these gradations corresponding to the quantity of coarser sized fractions (between 9.5 and 4.75 mm). The gradations of JHPC and AAPA seem to be more packed. The minimum binder content (BC) specified by these agencies vary from 3.5–6.0% by mass of total mix. It is difficult to compare the significance of the binders specified by different agencies, as there are differences in grading systems adopted and the type of binders specified (Polymer Modified Binder: PMB, Performance Grade: PG, High Viscosity Improved Asphalt: HIVA, viscosity grading of asphalt cement:AC-20, and penetration grade: 80–100 and 60–70) by these agencies.

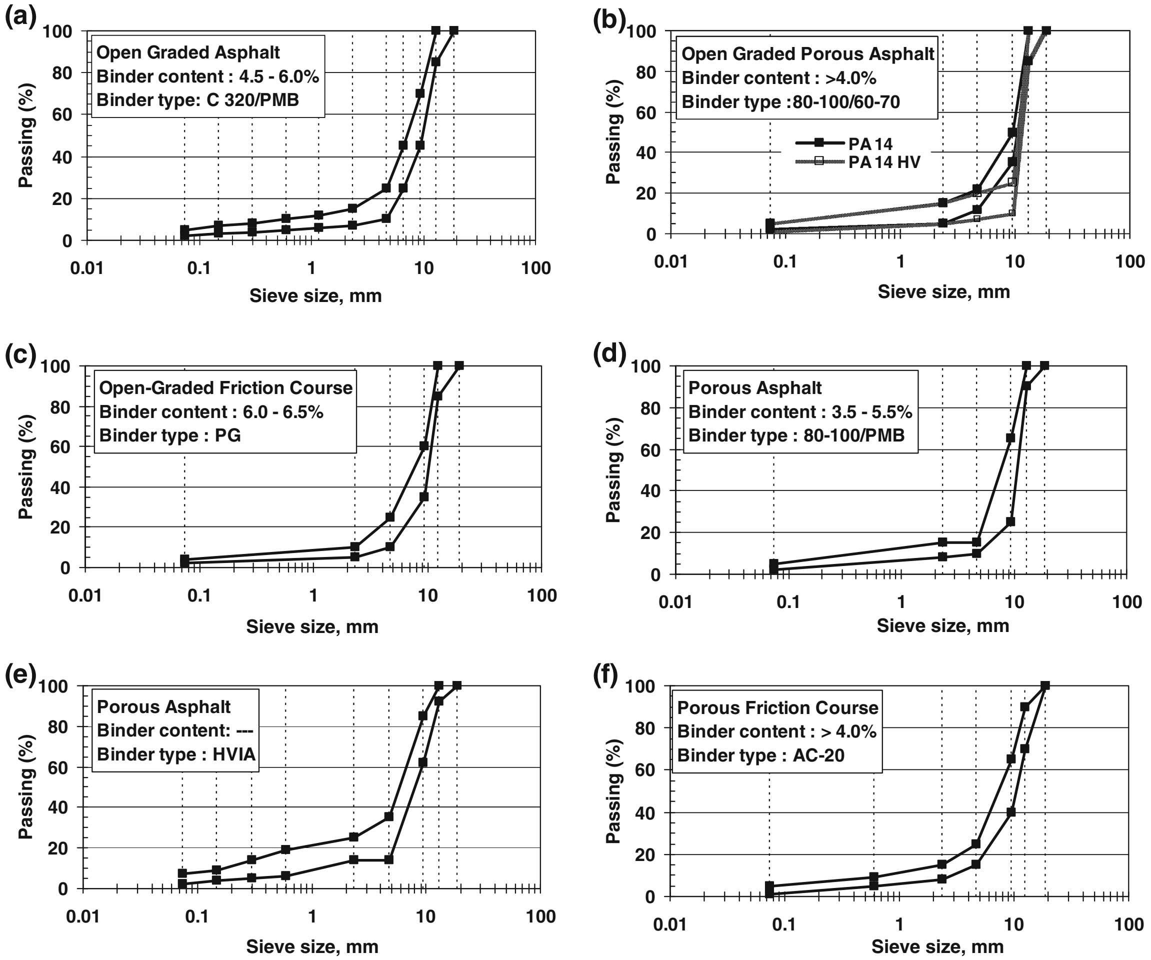

Fig. 1 Gradation band, terminology, binder content, and binder type specified for PFC mixes by the **a** AAPA [20], **b** TNZ [21], **c** ASTM [15], **d** Sabita [22], **e** JHPC [23], **f** FAA [24]

1.2 Objectives and scope

India has the second longest road network in the world. The recent highway development activities in India and its road development plan vision for the year 2021 clearly indicate the scope for potential application of PFCs on Indian highways [25]. It is necessary to formulate guidelines for the design and use of PFCs for various conditions of India. The present study is an effort in this direction.

This paper presents the results of the study carried out with the main objective of investigating the influence of aggregate gradations (G) and binder contents (BCs) on PFC mixes. Thus, the present study focused on evaluating the properties of single layer PFC mixes, with a nominal maximum size of aggregate 13.2 mm, which can be compacted to a thickness in the range of 30–45 mm. The studies were limited to the use of neat (pure) bitumen of penetration grade 85–100 [26]. This decision was taken based on the findings of the earlier studies [27–29]. Initially, thirty different PFC mixes were evaluated corresponding to six aggregate gradations and five binder contents, and the effects were evaluated in terms of mix design properties (volumetric properties, resistance to abrasion loss, and permeability). Further, for the selected gradations and binder contents, the performance properties like aged abrasion loss, moisture susceptibility, and permanent deformation characteristics were evaluated.

2 Materials and methodology

2.1 Materials

The coarse aggregate (particles retained on 2.36 mm sieve) and fine aggregate (particles passing 2.36 mm sieve and retained on 0.075 mm sieve) obtained from local stone crushing plant were used in this investigation. The physical properties of coarse aggregate were tested in accordance with ASTM [15] requirements and results are presented in Table 1. The stone dust and Ordinary Portland Cement (OPC) were used as filler (with 100% of particles passing 0.6 mm sieve and at least 85% passing 0.075 mm sieve). Bitumen complying with the specifications of ASTM [26] was used as a binder. Paving bitumen used in the present investigation was supplied by the Mangalore Refinery and Petrochemicals Limited (MRPL), Mangalore. Table 2 shows the properties of bitumen with regard to consistency, aging, and safety characteristics.

Table 1 Physical properties of aggregate

Particulars of physical properties	Specification requirement [15]	Test results
Flat and elongated particles, %	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 2 Properties of bitumen

Particulars of properties	Specification requirement [26]	Test results
Specific gravity at 27°C	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, % of original (after thin-film oven test)	Min. 42	62

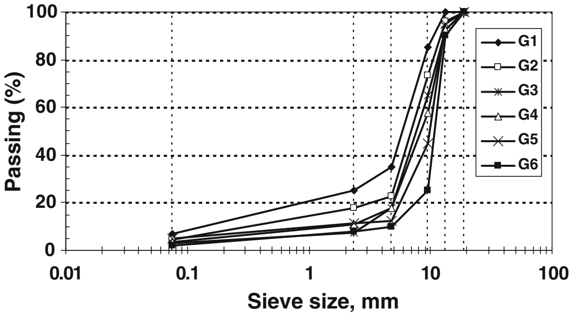

Fig. 2 Gradations used for PFC mixes

2.2 Selection of aggregate gradations

The first step in the selection of aggregate gradations was to fix the sieve sets for an open-graded mix. To meet this requirement, sieves set was framed by selecting the commonly used Indian Standard (IS) sieves, designated as 19.0, 13.2, 9.5, 4.75, 2.36 mm, and 75 μm (0.075 mm). The sieve sizes given vide British Standards (BS: 410) and American Society for Testing and Materials (ASTM E 11) are same as those specified in Indian Standard (IS: 460) [30]. Figure 2 shows details of particle size distribution for all six aggregate gradations selected in this study, designated as G1, G2, G3, G4, G5, and G6. The gradations selected for the study encompass the aggregate gradations specified for the PFC or similar mixes recommended by various agencies like AAPA, Sabita, ASTM, TNZ, JHPC, and FAA (see Fig. 1).

2.3 Methodology

The effect of aggregate gradations on PFC mixes for different binder contents were evaluated in terms of mix design properties (volumetric properties, permeability, abrasion loss, and draindown loss) and performance (aging loss, moisture susceptibility, and resistance to permanent deformation). Volumetric properties and permeability characteristic of the compacted PFC mix were considered to be of prime importance, the PFC to provide sufficient surface drainage. Cantabro abrasion tests were conducted on unaged Marshall specimens to evaluate the resistance of compacted mix to abrasion. The durability of the mix against long-term aging was evaluated in terms of aged abrasion loss. The moisture susceptibility of mixes was evaluated by indirect tensile strength tests and wet abrasion loss tests. In addition, draindown tests

Table 3 Treatment factors and response properties

Response properties	Treatment factors	
	G	BC (%)
Mix design properties		
G_{mb}; V_{a}; VCA$_{\mathrm{mix}}$; K; UAL	All six	3.5, 4.0, 4.5, 5.0 and 5.5
Draindown test	All six	5.0
Other properties		
AAL	All six	4.5 and 5.0
ITS$_{\mathrm{dry}}$ and ITS$_{\mathrm{wet}}$	G4, G5 and G6	4.5 and 5.0
WAL	G4, G5 and G6	5.0
Rutting test	All six	5.0

(for limiting maximum binder content in mixes) and slab rutting tests (for evaluation of plastic deformation characteristic of mixes) were conducted. Table 3 shows the treatment factors and response properties of experimental design. The response properties considered include bulk specific gravity (G_{mb}), percent air voids (V_{a}), voids in coarse aggregate of the compacted mixture (VCA$_{\mathrm{mix}}$), coefficient of permeability (K), unaged abrasion loss (UAL), draindown loss, aged abrasion loss (AAL), indirect tensile strength of dry-conditioned specimen (ITS$_{\mathrm{dry}}$), indirect tensile strength of wet-conditioned specimen (ITS$_{\mathrm{wet}}$), wet abrasion loss (WAL), and rut depth (RD). The data generated corresponding to response properties were statistically analysed using MINITAB® (Release 15, trial version) to study the influence of individual treatment factors and also their interaction effect.

In order to evaluate various properties of PFC mixes, standard Marshall specimens (101.6 mm diameter) were prepared corresponding to each gradation and binder content. The binder contents were varied between 3.5 and 5.5% at an increment of 0.5% [22]. The earlier studies indicated wide variation in the results of permeability and abrasion loss tests [28, 29]. It was decided to prepare six replicate specimens for each binder content and gradation. In order to minimize the drainage loss, the mixing and compaction temperature for PFC mixes were selected in the ranges of 135–145 and 110–120°C, respectively.

2.4 Specimen preparation

The coarse aggregate, fine aggregate and mineral filler were blended to meet the required gradation. For each test specimen, 1000 g of blended aggregates were taken as against 1200 g specified in Asphalt Institute Manual Series-2 [31]. The required quantity of bitumen and an aggregate blend were separately pre-heated to the mixing temperature, and then manually mixed. Further, the loose hot mix was placed in an oven for 2 h at the compaction temperature. The standard Marshall compaction method was adopted for the design of PFC mixes, which is the common laboratory compaction method specified by many agencies [20–22]. Cylindrical specimens of 101.6 mm diameter were prepared by applying 50 compaction blows to each face.

3 Evaluation of mix design properties

3.1 Volumetric properties

The G_{mb} of compacted specimen was determined using geometric measurements and weight [32]. The theoretical maximum density (G_{mm}) of the uncompacted mix was determined according to ASTM [33]. Based on the G_{mm} and G_{mb}, other volumetric properties like V_{a} and VCA$_{\mathrm{mix}}$ were calculated. The voids in coarse aggregate of the aggregate blend (VCA$_{\mathrm{drc}}$) were determined by dry-rodded technique according to ASTM test method [34]. The V_{a} and VCA$_{\mathrm{mix}}$ are considered to be major responses to select an optimal mix, in addition to responses from the UAL test and loss in draindown test. According to ASTM D 7064 [15], the compacted mix having $V_{\mathrm{a}} > 18\%$ and VCA$_{\mathrm{mix}} \leq$ VCA$_{\mathrm{drc}}$ is considered as optimal.

The volumetric properties were evaluated for 30 different PFC mixes. The mean values for six replicate mixes are reported in Table 4. The mean G_{mb} of mixes were in the range of 1.985–2.219, and in each mixes, an increase in the BC resulted in an increase in G_{mb}. The values of VCA$_{\mathrm{mix}}$ and V_{a} seems to decrease with an increase in BC. Hence, it is expected that the mixes with lower BC will satisfy the optimal gradation criteria. The test results indicate that it is possible to consider all the gradations (except G1) at a BC of 3.5% as desired gradations. The mixes with gradation G3 and G6 found to satisfy these criteria even at the BC of 4.0 and 4.5%, respectively. The mean V_{a} values were in the range of 9.2–20.5%, and VCA$_{\mathrm{mix}}$ were in the range of 31.1–43.5%. The PFC mixes with gradation-G1 exhibited low V_{a} values (<18%) and VCA$_{\mathrm{mix}}$ were found to be higher than the VCA$_{\mathrm{drc}}$. It was

Table 4 Volumetric properties

BC	G	MF/BC[a]	G_{mb}[b]	VCA (%)[b]		AV (%)[b]
				Drc	Mix	
3.5	G1	2.00	2.109	40.3	42.9	16.3
4.0		1.75	2.113		43.1	15.5
4.5		1.56	2.108		43.5	15.1
5.0		1.40	2.153		42.6	12.6
5.5		1.27	2.219		41.1	9.2
3.5	G2	1.29	2.040	39.8	39.1	19.2
4.0		1.13	2.075		38.4	17.1
4.5		1.00	2.096		38.1	15.7
5.0		0.90	2.132		37.4	13.6
5.5		0.82	2.170		36.6	11.3
3.5	G3	0.86	2.023	39.1	32.3	20.0
4.0		0.75	2.052		31.7	18.2
4.5		0.67	2.048		32.2	17.7
5.0		0.60	2.096		31.0	15.2
5.5		0.55	2.142		29.8	12.7
3.5	G4	1.00	2.041	40.0	34.3	19.2
4.0		0.88	2.064		33.9	17.6
4.5		0.78	2.058		34.4	17.2
5.0		0.70	2.114		33.0	14.3
5.5		0.64	2.147		32.3	12.4
3.5	G5	1.43	2.064	40.7	33.8	18.0
4.0		1.25	2.066		34.1	17.3
4.5		1.11	2.057		34.7	17.0
5.0		1.00	2.092		34.0	15.0
5.5		0.91	2.146		32.6	12.1
3.5	G6	0.57	1.999	39.8	33.3	20.5
4.0		0.50	1.985		34.1	20.5
4.5		0.44	2.011		33.6	18.8
5.0		0.40	2.047		32.8	16.8
5.5		0.36	2.110		31.1	13.6

[a] Ratio of mineral filler (MF) and binder content (BC)

[b] Results are presented as mean value of six replicates

demonstrated that to achieve a stone-on-stone contact condition in the coarse aggregate skeleton, the particles passing 4.75 mm sieve should be less than 20% [13]. Higher quantities of fine aggregate result in an increase in the density and keep the coarse aggregate afloat between fine aggregates [35].

3.2 Unaged abrasion loss (UAL)

The Cantabro abrasion test method is used to ensure the adequate durability of the compacted PFC mix. Nowadays, most of the agencies recommend this test as a compulsory [20–23] or as an optional [15, 24] for the mix design of PFCs. The compacted PFC cylindrical specimens were directly tested according to the Cantabro abrasion test method. The specimens were 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. Loss in the specimen weight was expressed in percentage of ratio of weight of disintegrated particles to the initial weight of the specimen, and expressed as unaged abrasion loss (UAL). The temperatures recorded during complete testing process were in the range of 27 ± 1°C, within the specified range of 25 ± 5°C [15].

Figure 3 shows the individual plots of UAL for 30 different PFC mixes with six replicates for each and a mean UAL for each mix. The line connecting the mean UALs of the mixes of a particular gradation indicates the relationship between UAL and BC. It can be noticed that, with an increase in BC, the UAL will decreases, and slope of the line connecting the mean UAL indicates the rate of change of UAL against BC. The mixes with gradation-G1 exhibited good resistance to abrasion, compared to all other mixes even at a lower BC of 4.0%. While, mixes with gradation-G6 even at highest BC (5.5%) resulted in more abrasion losses (mean UAL > 20%). It is clear from Fig. 3 that the minimum BC of 4.5% is required for PFC mixes corresponding to all gradations (except G6) to keep the mean UAL below 20%. It can be noticed that, out of 180 responses from 30 different PFC mixes, no individual UAL was more than 50% and mean UAL was not more than 40%. The individual and mean values in the plot indicate wide variations in the Cantabro abrasion test results.

3.3 Permeability (*K*)

The coefficients of permeability (*K*) of the PFC mixes were evaluated using the falling-head permeability concept. The instrumentation for this test was very simple. The Marshall mould with the collar assembly constitute the main components, along with a graduated centimeter scale (least count = 1 mm), a digital stop watch (accuracy = 0.1 s), and a measuring jar (capacity = 1000 cc). The PFC specimen along with mould (i.e. before extrusion) and collar assembly was used for the test. To avoid water

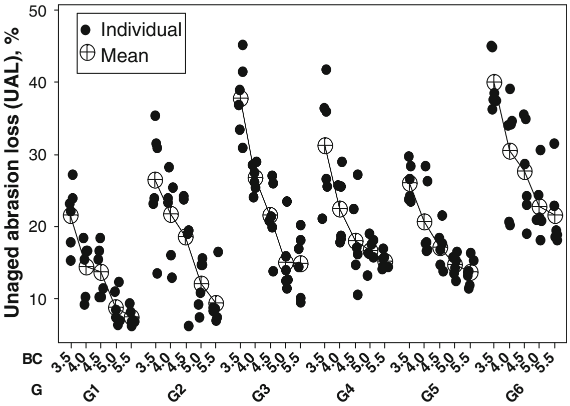

Fig. 3 Unaged abrasion loss (UAL) versus gradations (G) and binder content (BC)

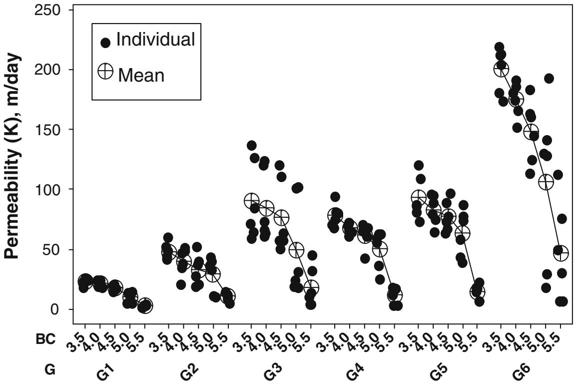

Fig. 4 Permeability (*K*) versus gradations (G) and binder content (BC)

leakage through the interface of the mould and the specimen, a thin paraffin wax coating was provided along the circumferential corner of both faces. The collar was mounted on the mould-specimen assembly by applying a thin layer of petroleum jelly along the grooves of collar-holder of the mould to minimise the water leakage. The entire mould-specimen-collar assembly was kept on a tripod. A graduated metallic centimeter scale was placed over the centre of the specimen and water was poured into the collar to maintain a water-head of 85 mm above the surface of the specimen. Initially, water poured into the collar was allowed to drain out to keep the specimen wet. Once again, the collar was refilled with water to the brim and was allowed to drain out. Meanwhile, the time taken for a drop in water level from 70–30 mm was recorded as t (measured in seconds). The trial was repeated three times and the mean value of time (t_m) was calculated. The permeability (K, m/day) of the specimen was then calculated using the thickness of specimen (L, mm) and the value of t_m on Eq. 1.

$$K = 208.49\frac{L}{t_m}\log_{10}\left(\frac{L+70}{L+30}\right)T_C \qquad (1)$$

where, T_C is the temperature correction factor for the viscosity of water.

The permeability tests were conducted on 30 different PFC mixes for gradations-G1 to G6. Six specimens were tested for each mix and the mean value for each mix was noted. Figure 4 shows the individual permeability value for each mix and their mean, and a line connecting the mean permeability values of mixes of particular gradation. Here too, similar to test results of UAL, the individual and mean plots clearly indicates wide variations in the permeability test results. The lines connecting the mean permeability values clearly indicate decreasing trends in the permeability with an increase in BC.

The individual permeability values of PFC mixes were found to be in the range of 1–225 m/day, while the mean permeability values were found to vary in the range of 2.5–200 m/day. The mixes corresponding to gradations-G1 exhibited lowest permeability, with a mean permeability less than 25 m/day, and mixes corresponding to gradation-G6 exhibited highest permeability with a mean permeability in the range of 50–200 m/day. The mean permeability values of the mixes corresponding to all the gradations (except for gradation-G6), at maximum BC of 5.5%, were found to be less than 25 m/day. The maximum mean permeability values of the mixes of all the gradations (except G6) were well below 100 m/day. On elimination of a few outliers, corresponding to gradation-G3 mixes; it is possible to correlate permeability to change in gradation.

3.4 Draindown test

The uncompacted PFC mixes corresponding to all the gradations at BC of 5.0% were subjected to evaluation of draindown characteristics by the basket drainage test as per ASTM D 6390 [36]. The reason for selecting this BC for draindown evaluation is quite clear, i.e. all the mixes with a BC more than 5% fail to satisfy the optimal mix criteria (with respect to volumetric properties) and exhibited low permeability

(<50 m/day). All the mixes, tested at 5% BC, had a draindown loss less than 0.3% by weight of total mix.

3.5 Influence of treatment factors on mix design properties

The aggregate gradations and binder contents were considered as treatment factors and the mix design properties as responses (see Table 3). The five response properties considered here were G_{mb}, V_a, VCA_{mix}, K, and UAL. The size of data generated for each response was 180 numbers, which corresponds to various mixes for 6 different gradations (G1–G6) and five different BCs (3.5–5.5%). Statistical analysis tools like analysis of variance (ANOVA) and multiple comparisons of mean values were adopted to investigate the effect of individual treatment factors (G and BC) and their interaction (G*BC) on the response properties. Table 5 shows the results of ANOVA, which include degree of freedom (DF), sequential sum of squares (SSS), adjusted mean square (AMS), Fisher–Snedecor distribution statistic (F), Fisher–Snedecor distribution critical (F_0), P value (P), and result of null hypothesis. The prime source for variation in the results of response properties were identified based on AMS. The gradation of the mix considered a prime source of variation in the test results of VCA_{mix} and K, and BC is considered to be prime source of variation in the test results of G_{mb}, V_a and UAL.

Table 5 Results of analysis of variance (ANOVA)

Source	DF	SSS	AMS	F	F_0	P
Bulk specific gravity (G_{mb})						
G	5	0.194	0.038	28.5	2.21	0.000
BC	4	0.290	0.072	53.2	2.37	0.000
G*BC	20	0.016	0.000	0.6	1.57	0.908
Error	150	0.205	0.001			
Total	179	0.706				
Air voids (V_a)						
G	5	305.6	61.1	27.3	2.21	0.000
BC	4	1120.2	280.0	125.1	2.37	0.000
G*BC	20	26.3	1.31	0.59	1.57	0.917
Error	150	335.7	2.23			
Total	179	1787.9				
Voids in coarse aggregate of compacted mix (VCA_{mix})						
G	5	2581.6	516.8	372.3	2.21	0.000
BC	4	117.7	29.40	21.2	2.37	0.000
G*BC	20	16.03	0.80	0.58	1.57	0.923
Error	150	208.0	1.38			
Total	179	2923.5				
Unaged abrasion loss (UAL)						
G	5	4094.4	818.9	37.5	2.21	0.000
BC	4	6609.3	1652.3	75.7	2.37	0.000
G*BC	20	439.1	21.9	1.01	1.57	0.459
Error	150	3273.5	21.8			
Total	179	14417				
Permeability (K)						
G	5	258563	51713	105.4	2.21	0.000
BC	4	113632	28408	57.9	2.37	0.000
G*BC	20	41810	2091	4.3	1.57	0.000
Error	150	73627	491			
Total	179	487632				

Here, the null hypothesis was assumed as, the difference in the means is not significant, i.e. the response will not vary with the variations in treatment factors. The null hypothesis was tested at a confidence level of 95%. The results indicate that the effect of G and BC on all the response properties are significant (as $F/F_0 > 1$). For example, the null hypothesis is that the mean G_{mb} will remain the same for mixes of all gradations or mixes of all BCs, but results of ANOVA in terms of F and F_0 statistic values ($F/F_0 > 1$) indicate that the assumption cannot be accepted. But, the interaction effect of these two treatment factors found to be significant only in case of Permeability test results. In this condition, the means of one factor (G or BC) may obscured by the interaction (G*BC) [37]. Hence, the multiple comparisons of means will help in discovering the specific differences. Tukey's simultaneous test method was used to conduct the multiple comparisons of means. This test was conducted at 95% confidence intervals. The test results indicated that the mean permeability value of the mixes corresponding gradation-G3 is same as G4 and G5, and mean permeability values of all other mixes are different. Similarly, the mean permeability values of the mixes corresponding to a BC of 3.5% and 4.0% are statistically equal, and 4.0 and 4.5% are statistically equal.

3.6 Aged abrasion loss (AAL)

It is evident from the volumetric properties observed above, that the PFC mixes exhibit higher V_a in the order of 8–21%. The possibility for oxidation of

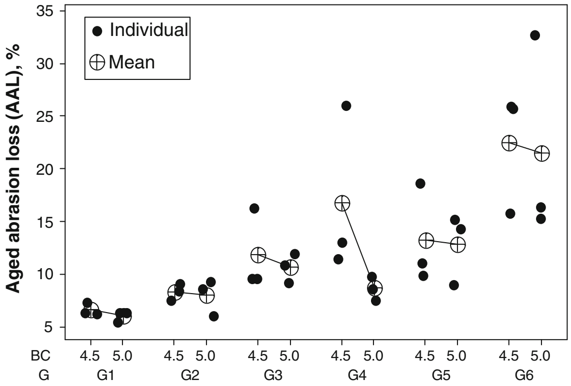

Fig. 5 Results of aged abrasion loss (AAL)

bitumen in the mix and the rate of oxidation or aging will be higher compared to dense graded mixes [22]. Aging of bitumen considered as one of the contributing factors for, reduction in the cohesion and adhesion property, ravelling of asphalt mixes [38–40]. To asses the abrasion resistance of the mix against aging, an accelerated laboratory aging test was conducted. To accomplish accelerated aging, compacted PFC specimens in triplicate were stored in a forced draft oven at a temperature of 60°C for a period of 168 h [15]. Then the specimens were taken out from the oven and allowed for cooling to ambient temperature, and stored for a period of 4 h at a temperature corresponding to the Cantabro abrasion test.

Figure 5 shows the aged abrasion losses (AAL) of the mixes corresponding to all six gradations for the BCs of 4.5 and 5.0%. In total, 36 specimens from 12 different mixes were evaluated for AAL. The maximum AAL of an individual was found to be less than 35%, and maximum mean AAL found to be less than 25%. Thus, all the mixes found to meet the acceptance criteria recommended in ASTM D 7064 [15]. The mixes corresponding to gradation-G6 exhibited higher AAL, while it was low for the mixes with gradation-G1. It is clear from the plots that the mixes with higher BC will results in lower AAL because of thicker bitumen layer over the aggregate surface.

3.7 Moisture susceptibility

The moisture susceptibility or resistance to moisture damage of the PFC mixes were evaluated by two approaches, (i) retained tensile strength or tensile strength ratio (TSR) as specified by ASTM D 7064 [15], and (ii) wet abrasion loss (WAL) according to Sabita Manual-17[22]. The procedure of moisture conditioning of the compacted PFC specimens was according to AASHTO T 283 [41]. The saturated specimens were submerged in water, and kept at freezing temperature for about 15 h. The frozen specimens were immediately transferred into the hot water bath for thawing at a temperature 60°C for 24 h. This cycle of freeze–thaw was continued for two times. After two cycles of moisture conditioning, the specimens were kept in cold water to bring down the temperature to 25°C before testing. The PFC mixes corresponding to gradations-G4, G5, and G6 were subjected for moisture susceptibility tests. The ITS tests were conducted for the mixes of BCs of 4.5 and 5.0%, and WAL tests were conducted for the mixes of BC 5.0%. Table 6 indicates the test results of retained tensile strength (TSR) and wet abrasion loss (WAL).

The individual ITS values of specimens of dry-and wet-conditioned were in the ranges of 291–698 kPa and 202–481 kPa, respectively. The TSR values indicate that all mixes exhibited poor resistance to moisture-induced damage, exception only for the mixes with gradation-G4 with a BC of 5.0%. Although, the TSR values were not of acceptable level, the ITS values in wet-condition seem to be in good agreement with earlier findings related to similar types of mixes [9, 17, 42]. The freeze–thaw (wet-) conditioned PFC specimens were evaluated for wet abrasion loss (WAL) in accordance with the Cantabro abrasion loss test. The average and individual WAL values of the three different mixes were well below the acceptance limits 30 and 50%, respectively [20].

It is evident from the results presented in Table 6 that the TSR shows strong sensitivity and that the WAL shows nothing at all. However, based on the mode of deterioration in the PFC mixes, it is appropriate to evaluate the moisture susceptibility of PFC mixes by WAL approach. The reason is, in general, the tensile strength tests are performed to assess the cracking potential of the dense asphalt mix, while the Cantabro abrasion tests are performed to assess the abrasion resistance (or resistance to particle loss) of compacted open graded asphalt mixes.

3.8 Immersion wheel tracking test

In this investigation, the influence of aggregate gradations on the permanent deformation characteristics of

Table 6 Results of retained tensile strength (TSR) and wet abrasion loss (WAL)

G	BC (%)	ITS_{dry} (kPa)		ITS_{wet} (kPa)		TSR (%)	WAL (%)	
		I	*M* (SD)	*I*	*M* (SD)		*I*	M (SD)
G4	4.5	396	524 (97.01)	360	347 (52.66)	66.3	–	
		631		277				
		544		404				
	5.0	356	437 (62.20)	357	431 (53.54)	98.6	25.6	25.7 (0.189)
		449		456			25.6	
		507		481			26.0	
G5	4.5	323	542 (159.58)	245	282 (36.23)	51.9	–	
		698		269				
		606		331				
	5.0	587	581 (34.18)	273	319 (42.32)	54.9	26.2	25.9 (0.205)
		536		308			25.9	
		619		375			25.7	
G6	4.5	291	367 (54.53)	242	274 (24.34)	74.6	–	
		396		279				
		415		301				
	5.0	356	429 (57.35)	237	228 (18.34)	53.0	26.9	26.9 (0.939)
		436		202			25.8	
		496		244			28.1	

I Individual, *M (SD)* mean (standard deviation)

the PFC mixes was evaluated, in terms of rutting behavior, using the Immersion Wheel Tracking Device (IWTD). The main components of IWTD are a rectangular hot water bath with slab-specimen platform, a static wheel encased with hard rubber tyre, cantilever loading arm, an electric motor, two Linear Variable Displacement Transducers (LVDTs), proximity switches (to reciprocate specimen platform), and a control unit.

Six rectangular slab specimens of 600 × 200 × 50 mm dimensions were prepared for each gradation, and for a BC of 5.0%. The tests were conducted at a contact pressure of 0.7 MPa, wheel width of 50 mm, an average contact length of 30 mm, a speed of 0.468 km/h, and a temperature of 50°C. The testing was conducted continuously for about 7–10 h or 6000–9000 passes. The vertical deformations under the wheel, at the centre of the slab specimen, were continuously measured by LVDTs and recorded in the Personal Computer. The mean rut depth value for each wheel pass was computed from the two LVDT readings, and the trend between rut depth and number of wheel passes are in Fig. 6. These plots indicate that all mixes will undergo post-compaction consolidation in the range of 0.5–1.5 mm at the end of 500 wheel passes. Furthermore, the trends observed as in Fig. 6, are comparable with that of the findings reported by others [13, 43–47]. In addition, for all the mixes tested, no sign of stripping was observed, during the entire test period, along the wheel path.

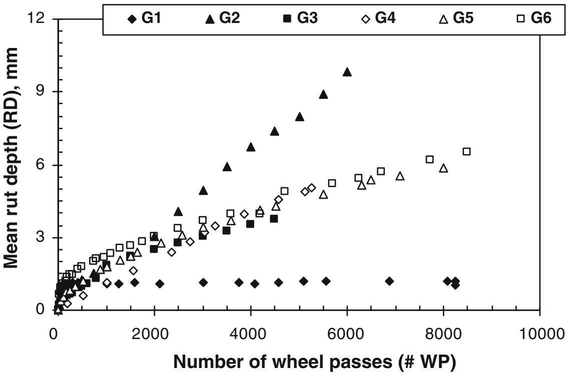

Fig. 6 Rut depth of PFC mixes

The mix corresponding to gradation-G1 exhibited higher rut-resistance (rut depth of 1.05 mm at 8000 passes) and the mix with gradation-G2 experienced more rut-depth (rut depth of 9.85 mm at 6000 passes) with higher rate of plastic deformation. It is difficult to differentiate the rutting behavior of all other mixes beyond the post-compaction consolidation point. One of the interesting observations is that the mixes which satisfied the stone-on-stone contact criteria had more rut depth than the mix that failed to satisfy the same criteria (G1). It may be related to the confinement induced within the mix, due to the presence of adequate mastic [45]. Here, it can be infer that the bitumen mastic will play a key role in addition to stone-on-stone contact condition for rut-resistant mix.

4 Conclusions

The effects of aggregate gradations and BCs on the mix design and performance properties of PFC mixes were investigated. The findings will help to frame new guidelines for the design and construction of PFC mixes, and also emphasize the scope for modifications in the current specifications for PFC by different agencies around the world. Based on the present investigation, the following conclusions can be made:

- The aggregate gradations and binder contents investigated were found to have significant effect on the mix design properties of PFC mixes. Aggregate gradations will significantly influences the voids in coarse aggregates (VCA) and permeability of the compacted mix, and binder content will have significant effect on the bulk specific gravity (G_{mb}), air voids (V_a), and unaged abrasion loss (UAL).
- The permeability of a compacted mix will be an actual index of drainage than the percent of air voids. Findings indicated that the variation in air voids were in the range of 7–24%, while wide range in the test results of permeability (1–220 m/day) and unaged abrasion loss (6–46%) were observed. Hence, the permeability property should be considered as one of the essential parameters in the mix design.
- The percent air voids, permeability, and loss in draindown tests limit the maximum binder content to 5.0% for all the gradations.
- The mixes, even without any modifiers or modified bitumen, exhibited good durability against aging i.e. the aged abrasion loss (AAL) of the mixes were within the acceptance limits [15, 21, 22].
- The retained tensile strength (TSR) test results indicate that these mixes are more susceptible to moisture damage, while the results of wet abrasion loss (WAL) test are contrary. Since PFCs are open graded mixes, it is more reasonable to consider the WAL than TSR for the evaluation of moisture susceptibility.
- Interestingly, the mixes with gradation-G1 that failed to fulfill the VCA criteria (stone-on-stone-contact) exhibited relatively high rut-resistance. While, mixes of gradation-G2, exhibited poor resistance to rutting, even though it satisfies the VCA criteria marginally. Although high penetration grade bitumen was used, the mixes exhibited reasonably adequate resistance to rutting [13, 43–47] and good aging resistance [15, 22].

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