Evaluation of Properties of Porous Friction Course Mixes for Different Gyration Levels

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Abstract: Porous frictions courses (PFCs) are characterized by high percent air voids content, and are widely used as pavement surface drainage layers. This paper presents details on the laboratory investigation performed on evaluation of properties of PFC mixes using the Superpave gyratory compactor. It also, provides a brief review of the latest specifications related to standard practices for mix design and the uses of these mixes adopted by various agencies. Major differences were observed in the design gyrations (N_{design}) and the design aggregate gradations. In this study, six gradations (G) were investigated with binder contents (BCs) ranging between 4.0 and 5.0% by mass of the total mix, for various gyration levels (N). The effect of N, G, and BC on the volumetric properties, unaged abrasion loss, permeability, and the permanent deformation characteristics of PFC mixes were investigated. The experimental results were statistically analyzed to identify the major influencing factors and their significance.

DOI: 10.1061/(ASCE)0899-1561(2009)21:12(789)

CE Database subject headings: Porous media; Asphalt pavements; Soil compaction; Voids; Permeability; Creep; Statistics.

Introduction

Porous friction courses (PFCs) are typical open-graded asphaltic mixtures. PFCs are characterized by higher percentages of interconnected air voids of more than 18% (ASTM 2008; Sabita 1995) than conventional dense graded asphaltic mixtures. This facilitates the function of PFCs as surface drainage layers. Pavements surfaced with open-graded asphaltic mixes were found to exhibit improved wet weather skid-resistance, minimized hydroplaning, reduced splash and spray, and better night-visibility during wet weather conditions (Huber 2000; Nicholls 1997). Moreover, the negative-texture of the surface, characterized by smooth riding-surfaces and high air voids content, facilitate the attenuation of tire-noise (Bullas 2004; Feighan 2006). Open-graded mixes are highly recommended for high-speed road-corridors (Huber 2000) and runway pavements (Federal Aviation Administration 1997). Many road agencies in the United States recommend the use of these layers for safety (Huber 2000), while many European countries widely use these as quiet pavements (Focus 2005). Road agencies in countries like, Japan (Nielsen et al. 2005), Australia (Australian Asphalt Pavement Association 2004), New Zealand (Transit New Zealand 2007), and South Africa (Sabita 1995) recommend open-graded mixes to achieve both safety and tire-noise-attenuation.

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Note. This manuscript was submitted on March 13, 2008; approved on June 3, 2009; published online on November 13, 2009. Discussion period open until May 1, 2010; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Materials in Civil Engineering***, Vol. 21, No. 12, December 1, 2009. ©ASCE, ISSN 0899-1561/2009/12-789–796/$25.00.

Many technical and road agencies around the world use different terminologies for open-graded mixes, and specifications that are slightly different. In this paper, open-graded mixes are referred to as PFC mixes. Table 1 provides brief information related to the terminology, aggregate gradation (G), binder content (BC) and type, and the design number of gyrations (N_{design}) for laboratory compaction using Superpave gyratory compactor (SGC), as specified by the Australian Asphalt Pavement Association (Australian Asphalt Pavement Association 2004), Transit New Zealand (Transit New Zealand 2007), American Society for Testing and Materials (ASTM 2008), Southern African Bitumen Association (Sabita 1995), Japan Highway Public Corporation (JHPC) (Asshi and Kawamura 2003), and Federal Aviation Administration (Federal Aviation Administration 2005).

An optimal design mix of PFC should ensure high air voids (V_a) content and good resistance to ravelling. Based on the review of standard practices above, the following can be considered as the main components in the design of PFC mixes:

- Selection of materials: this includes aggregates, bituminous binders, and additives, if any, that need to satisfy the minimum requirements specified for dense asphalt surface courses.
- Selection of gradation: the aggregate gradation selected should ensure high air voids content ($V_a \geq 18\%$) in the compacted mix. Additionally, the coarse aggregate skeleton is required to satisfy the stone-on-stone contact condition, where the voids in the coarse aggregate of the compacted mix (VCA_{mix}) are required to be lesser than or equal to that obtained in the case of the dry-rodded technique (VCA_{DRC}).
- Determination of minimum BC: this can be accomplished by two approaches: (1) based on the aggregate surface area and asphalt film thickness (Halstead 1978), and (2) based on the Cantabro abrasion test method (Ruiz et al. 1990; Sabita 1995; ASTM 2008). The latter approach is considered to be the latest, and the most appropriate one that can be used to ensure resistance to particle loss (Ruiz et al. 1990).
- Determination of maximum BC: to avoid the draindown of asphalt mastic from the coarse-skeleton during mixing, transportation, and paving operations, it is required to limit the

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Table 1. Summary on Specifications for PFC Mixes by Different Agencies

Agency	Australian Asphalt Pavement Association	Sabita	ASTM	Transit New Zealand		JHPC	Federal Aviation Administration
Terminology	(OGA)	(PA)	(OGFC)	(PA 14)	(PA 14 HV)	(PA)	(PFC)
Sieve size (mm)				Percent passing			
19	100	100	100	100	100	100	100
13.2	85–100	90–100	—	85–100	85–100	92–100	—
12.5	—	—	85–100	—	—	—	70–90
9.5	45–70	25–65	35–60	35–50	10–25	62–85	40–65
6.7	25–45	—	—	—	—	—	—
4.75	10–25	10–15	10–25	12–22	7–20	14–35	15–25
2.36	7–15	8–15	5–10	5–15	5–15	14–25	8–15
1.18	6–12	—	—	—	—	—	—
0.6	5–10	—	—	—	—	6–19	5–9
0.3	4–8	—	—	—	—	5–14	—
0.15	3–7	—	—	—	—	4–9	—
0.075	2–5	2–5	2–4	2–5	1–5	2–7	1–5
BC, %	4.5–6.0	3.5–5.5	6.0–6.5	Minimum 4.0		—	—
Binder grade/type	C 320/PMA	80–100/PMA	PG	80–100	60–70	HVIA	AC-20
N_{design}	80	—	50	80	80	—	—
References	Australian Asphalt Pavement Association (2004)	Sabita (1995)	ASTM (2008)	Transit New Zealand (2007)		Asshi and Kawamura (2003)	Federal Aviation Administration (2005)

Note: OGA=open-graded asphalt; PA=porous asphalt; OGFC=open-graded friction course; HV=high air voids; PFC=porous friction course; PMA =polymer modified asphalt; PG=performance grade; HVIA=high viscosity improved asphalt; and C 320 and AC-20=viscosity grading of asphalt cement in Australia and in the United States, respectively.

maximum BC in the mix. This can be determined by the draindown test (ASTM 2005b).
- Ensuring that the mix can resist moisture-induced damages.

The design of PFC mixes can be carried out using the SGC or the Marshall compactor, or any other suitable form of compaction. However, in the design of PFC mixes using the SGC approach, it is found that the design gyrations (N_{design}) specified by different agencies, were not the same. The standard practice of ASTM (2008) recommends 50 gyrations, while Australian Asphalt Pavement Association (2004) and Transit New Zealand (2007) recommend 80 gyrations. But, in the design of friction courses mixes, Varadhan (2004) and Jaiswal (2005) adopted the compaction level corresponding to the gyration at the aggregate locking point (N_{LP}), at which the aggregate skeleton "locks" together and further compaction results in aggregate degradation without any significant achievement of compaction (Prowel and Brown 2007).

The concept of "locking point" was developed by the Illinois Department of Transportation (W. J. Pine, Internal report to Illinois Department of Transportation, 1997). Vavrik and Carpenter (1998) provided a refined definition for N_{LP}, where it is said to correspond to the first gyration in the first occurrence of three gyrations of the same height proceded by two sets of two gyrations with the same height (measured to the accuracy of 0.1 mm). This approach is illustrated in Fig. 1 that shows the relationship between the height of the mix inside the gyratory mold and number of gyrations based on the present study. As per the above definition, the N_{LP} for the sample data presented in Fig. 1 can be identified as 62. A number of studies were performed in the recent past on the evaluation of aggregate locking point on similar lines (Prowel and Brown 2007; Mohammad and Al-Shamsi 2007; Verhaeghe et al. 2007).

Research Objectives and Scope

It is evident from Table 1 that the design gyration (N_{design}) and the aggregate gradations adopted by different agencies are not the same. In addition, among numerous research findings reported on PFC mixes (Mallick et al. 2000; Cooley et al. 2000; Tan et al. 2000; Tan et al. 2004; Watson et al. 2004; Sridhar et al. 2005; Hassan et al. 2005; Shen et al. 2008; Suresha et al. 2009a; Suresha et al. 2009b), a few reports address the compaction characteristics of PFC mixes (Cabrera and Hamzah 1996; Varadhan 2004; Jaiswal 2005). Hence, the present investigation was carried out with the prime objective of evaluating the effect of gyration levels (N) and aggregate gradations (G) on the properties of PFC mixes.

A SGC complying with the requirements of Strategic Highway Research Program was used in this study. This equipment was configured for a vertical consolidation pressure of 600 kPa, a

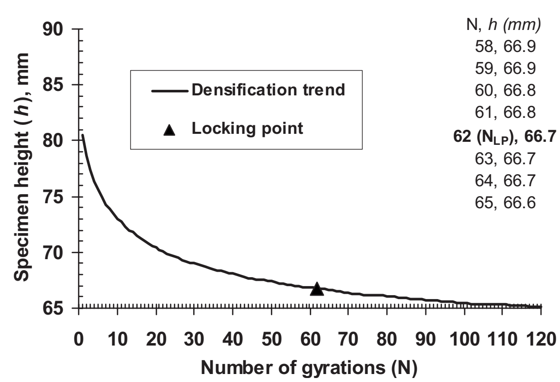

Fig. 1. Mix densification trend and locking point

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Table 2. Selected Aggregate Gradations

Sieve size (mm)	Gradations (percent passing)					
	G1	G2	G3	G4	G5	G6
19	100	100	100	100	100	100
13.2	100	96	93	93	95	90
9.5	85	74	65	58	45	25
4.75	35	23	18	18	13	10
2.36	25	18	8	11	11	8
0.075	7	5	3	4	5	2

gyratory angle of 1.25°, and a rate of gyration of 30 rpm. To accomplish the objective of the present investigation, six aggregate gradations were selected as shown in Table 2. These gradations were found to encompass the gradation-bands specified by the agencies listed in Table 1. The PFC mixes of each gradation were prepared using neat asphalt cement binder for three BCs (4.0, 4.5, and 5.0%). The selection of binder type and the BCs were based on the findings of earlier studies (Suresha et al. 2009a).

The ASTM (2008) standard practice for mix design of open-graded friction courses, mainly recommends the use of two parameters for the identification of the optimum mix, (i) percent air voids content in the compacted mix, and (ii) presence of stone-on-stone contact in the coarse aggregate skeleton. The other properties like permeability (K), and unaged abrasion loss (UAL) are considered as optional requirements by the ASTM (2008). In this context, the volumetric properties of PFC mixes were evaluated at the 50th (N_{50}), 80th (N_{80}), and the 120th (N_{120}) gyrations, in addition to the gyration corresponding to the aggregate locking point (N_{LP}) as defined by Vavrik and Carpenter (1998). Generally, specimens prepared at higher compaction levels exhibit lower permeability, while specimens prepared at lower compaction levels exhibit poorer abrasion resistance. Thus, it was considered appropriate to study the permeability of the mixes at the highest compaction level of N_{120}, and the UAL and creep properties at the aggregate locking point (N_{LP}).

Materials Used

Asphalt cement and stone aggregates were the major constituents of PFC mixes. The asphalt cement of 85–100 penetration grade, used in the present study, was supplied by the Mangalore Refinery and Petrochemicals Limited, Mangalore. Coarse and fine aggregates sourced from crushed granite stones obtained from local stone-crushing plants were used. The blend of stone dust and ordinary portland cement (OPC) was used as mineral filler, where, the quantity of OPC was 2% by mass of the total aggregates. The properties of asphalt cement and aggregates used are presented in Tables 3 and 4 respectively.

Laboratory Tests

Laboratory studies were carried on different PFC mixes. To prepare a cylindrical specimen of 100 mm diameter and thickness (h) in the range of 63–70 mm, 1000 g of blended aggregate (comprising coarse aggregate, fine aggregate and mineral fillers), and a selected quantity of binder were used. The mixing and compaction temperatures corresponded to the values for kinematic viscosities of 170 ± 20 cSt and 280 ± 30 cSt respectively (ASTM 2008). The Cantabro abrasion test, permeability test, and the unconfined static creep test were performed on separate cylindrical specimens.

Table 3. Properties of Asphalt Cement

Particulars of properties	Specification requirement[a]	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	Minimum 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)	Minimum 75	90
Retained penetration, % of original (after thin-film oven test)	Minimum 42	62

[a]ASTM D 946 (2005a).

The key volumetric properties considered in the present investigation include voids in coarse aggregates of the coarse aggregate only fraction (VCA_{DRC}), bulk specific gravity of compacted mix (G_{mb}), voids in coarse aggregate of compacted mix (VCA_{mix}), and the percent air voids (V_a) content. The VCA_{DRC} was calculated by using the bulk specific gravity of the coarse aggregate (G_{CA}), bulk density of coarse aggregate fraction (γ_s) in the dry-rodded condition, and the density of water (γ_w). The G_{mb} was determined based on the geometric measurements and the mass of the specimen. The V_a calculated corresponded to the G_{mb} and the G_{mm} (theoretical maximum density of the mixture determined according to AASHTO T209). The VCA_{mix} was calculated based on the G_{CA}, G_{mb}, and the P_{CA} (percentage of coarse aggregate fraction). The above volumetric properties were calculated using the following equations:

$$VCA_{DRC} = (G_{CA}\gamma_w - \gamma_s)/(G_{CA}\gamma_w) \quad (1)$$

$$VCA_{mix} = 100 - [(G_{mb}/G_{CA})P_{CA}] \quad (2)$$

$$V_a = 100[1 - (G_{mb}/G_{mm})] \quad (3)$$

The hydraulic-conductivity of compacted PFC specimens was evaluated in terms of the coefficient of permeability (K) determined according to the falling-head permeability concept (Bureau of Indian Standards 1986; Kandhal and Mallick 1999). The test-setup used was simple and economical. The curved surface of the cylindrical specimen was at first, coated with a thin layer of paraffin wax, and then inserted into the 101.6 mm diameter standard Marshall mold. Further, 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.

Table 4. Physical Properties of Aggregate

Particulars of physical properties	Specification requirement[a]	Test results
Flat and elongated particles, %	Maximum 10	8.1
Aggregate impact value, %	Not specified	20.1
Los Angles abrasion value, %	Maximum 30	26.6
Water absorption, %	Not specified	0.15
Soundness, magnesium sulfate solution, %	Not specified	0.21

[a]ASTM D 7064/D7064 M (2008).

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A collar was placed on the mold-specimen assembly that acted as a water reservoir. Water was allowed to flow through the specimen, and the mean time (t_m) taken for a drop in water level from 70 mm (h_1) to 30 mm (h_2), when measured from the top surface of the specimen, was recorded. The basic expression for determining the permeability using the falling-head approach is given below (Bureau of Indian Standards 1986)

$$K = 215.21(h/t_m)\log_{10}[(h+h_1)/(h+h_2)]T_C \tag{4}$$

where K=coefficient of permeability (m/day); h=mean thickness of the specimen (mm); h_1 and h_2=initial and final heads (mm); t_m=mean time (s); and T_C=temperature correction factor for viscosity of water.

The abrasion resistances of the specimens were evaluated using the Cantabro abrasion test (Ruiz et al. 1990; ASTM 2008). The compacted specimen was placed in the Los Angeles abrasion (LAA) drum without any abrasive charge, and the machine was operated at a speed of 30–33 rpm for 300 revolutions. The percentage of loss in the weight of the specimen when compared to its initial weight was expressed as the UAL. The temperatures recorded during the test procedure were within the range of 25±5°C as specified in ASTM (2008). Three replicates of such specimens were tested separately, and the mean values were noted.

The permanent deformation characteristics of the PFC mixes were evaluated by the static unconfined creep test method (Zhang et al. 2005). The influence of aggregate gradations on the permanent strain, strain recovery, and the creep stiffness were evaluated. A static load of 150 kPa was applied over the cylindrical specimen for one hour, and the deformation of the specimen was noted every 60 s. The static load was removed immediately after one hour, and the recovery in strain was noted for the next one hour period. The tests were conducted at a temperature of 30°C. The creep stiffness of the mix was calculated as the ratio of the applied stress to the total strain.

Results and Discussion

Aggregate Locking Point

The influence of gyration levels on various mixes corresponding to the six gradations (G1 to G6) and for the BC of 4.5 and 5.0% by mass of the total mix were evaluated. In addition, Gradation G4 to Gradiation G6 were also tested for a BC of 4.0%. In total, 15 different PFC mixes with 3 replicates for each, were compacted using the SGC to a maximum gyration level of 120 (N_{120}). The locking point (N_{LP}) for each mix was identified. The individual plot of N_{LP} values for different mixes is shown in Fig. 2. It can be seen that there is no clear trend that describes the variations in the N_{LP} in relation to the gradations and the BCs. The N_{LP} of most of PFC mixes tested were found to vary between 50 and 75. Similar studies performed by Varadhan (2004) on friction course mixes with granite-aggregates has reported N_{LP} values in the range of 76–96, where the N_{LP} values were identified according to the recommendations of Vavrik and Carpenter (1998). It may be observed that in the present study, the LAA value of aggregates used was lesser than 30%, while Varadhan (2004) adopted aggregates with LAA values up to 50%. The difference in the results of the N_{LP} is inferred to be mainly due to the above reason.

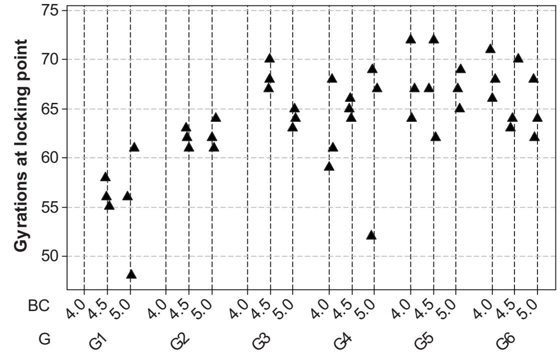

Fig. 2. Gyrations at aggregate locking point for different mixes

Volumetric Properties

Table 5 shows the mean values of VCA_{DRC}, G_{mb}, V_a, and VCA_{mix}, for all the 15 different PFC mixes, at the gyration levels of N_{50}, N_{LP}, N_{80}, and N_{120}. The mixes corresponding to Gradation G3 to Gradiation G6 satisfied the requirement of stone-on-stone contact condition ($VCA_{mix} \leq VCA_{DRC}$) even at the lowest gyration level (N_{50}). In the case of mixes with Gradation G2, this requirement was satisfied, when the mix was compacted beyond N_{LP}. But, the mixes corresponding to gradations-G1 failed to exhibit stone-on-stone contact in the coarse aggregate skeleton. This is mainly due to higher quantities of fine aggregates that result in an increase in the density, keeping coarse aggregate afloat between the fine aggregates (Qiu and Lum 2006).

In the case of open-graded mixes like PFCs, the internal resistance developed is mainly contributed by the single-sized coarse aggregates that ensure rutting resistance. This observation has been corroborated by investigations performed by Mallick et al. (2000), where it has been observed that in order to ensure stone-on-stone contact in the coarse aggregate skeleton, PFC mixes should not have more than 20% of aggregates passing 4.75 mm sieve.

It is quite evident from the test results shown in Table 5 that (i) the G_{mb} of mixes will increase with an increase in the gyration level, resulting in a decrease in the V_a and VCA_{mix}, (ii) at lower gyration levels, there is a lesser probability of satisfying the stone-on-stone contact condition, and (iii) at higher gyration levels, the probability of maintaining a minimum air voids content of 18% is lesser.

To study the effects of the main treatment factors [gradations (G) and BC], and the interaction between the main factors (G*BC) on the response properties (G_{mb}, V_a, and VCA_{mix}), the observations were subjected to ANOVA test, using a two-factor model with interaction (Montegomery 2004), as shown in Eq. (5). Statistical analyses were carried out using MINITAB (Release 15, trial version)

$$y_{ijk} = \mu + \tau_i + \beta_j + (\tau\beta)_{ij} + \varepsilon_{ijk} \tag{5}$$

where y_{ijk} is considered as the kth observation of a response, for a mix of ith G and jth BC; μ=mean value of the response; τ=variation due to G; β=variation due to BC; $(\tau\beta)$=variation due to the interaction between G and BC; ε=error term; i and j=number of levels in G and BC respectively; k indicates the trial number of the experiment. Here, the null hypothesis (H_0) was that the mean value of the response for a particular source of variation (G, BC, or G*BC) is the same at each level. A confidence level of 95% was selected to test the H_0. If, the F-static (F) of the response for a particular source of variation was found to be lesser

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Table 5. Volumetric Properties of Different PFC Mixes at Four Gyration Levels

G	VCA_{DRC} (%)	BC (%)	G_{mb} at N_{50}	N_{LP}	N_{80}	N_{120}	V_a (%) at N_{50}	N_{LP}	N_{80}	N_{120}	VCA_{mix} (%) at N_{50}	N_{LP}	N_{80}	N_{120}
G1	40.3	4.5	2.071	2.082	2.107	2.136	17.1	16.7	15.7	14.6	44.5	44.2	43.5	42.7
		5.0	2.065	2.075	2.104	2.133	16.8	16.4	15.3	14.1	44.9	44.7	43.9	43.1
G2	39.8	4.5	2.010	2.031	2.052	2.083	19.7	18.9	18.1	16.8	40.7	40.0	39.4	38.5
		5.0	2.028	2.047	2.066	2.096	18.5	17.7	16.9	15.7	40.5	39.9	39.3	38.5
G3	39.1	4.5	1.907	1.935	1.946	1.975	23.9	22.8	22.3	21.2	36.9	36.0	35.6	34.6
		5.0	1.931	1.954	1.971	2.001	22.4	21.5	20.8	19.6	36.4	35.7	35.1	34.1
G4	40.0	4.0	1.974	1.994	2.014	2.042	21.7	21.0	20.2	19.1	36.8	36.1	35.5	34.6
		4.5	1.974	1.998	2.015	2.044	21.2	20.2	19.6	18.4	37.1	36.3	35.8	34.9
		5.0	1.972	1.992	2.011	2.041	20.4	19.6	18.8	17.6	37.5	36.8	36.2	35.3
G5	40.7	4.0	1.966	1.994	2.006	2.040	21.8	20.7	20.2	18.8	37.3	36.4	36.0	34.9
		4.5	1.960	1.989	2.003	2.034	21.4	20.3	19.7	18.5	37.8	36.9	36.5	35.5
		5.0	1.971	1.998	2.011	2.044	20.5	19.4	18.8	17.5	37.8	36.9	36.5	35.5
G6	39.8	4.0	1.896	1.924	1.936	1.966	24.4	23.4	22.9	21.7	37.1	36.2	35.8	34.8
		4.5	1.899	1.924	1.940	1.970	23.8	22.8	22.2	21.0	37.3	36.5	36.0	35.0
		5.0	1.911	1.936	1.952	1.983	22.8	21.8	21.1	19.9	37.2	36.4	35.9	34.9

Note: Volumetric properties presented above are the mean values of three replicates of the each mix tested; G=gradation; VCA_{DRC}=voids in coarse aggregate of only coarse aggregate fraction (dry-rodded technique); BC=binder content (% by mass of total mix); $G_{mb,}$=bulk, specific gravity of the compacted mix; V_a=percent air voids; and VCA_{mix}=voids in coarse aggregate of the compacted mix.

or equal to F-critical (F_C), then H_0 was accepted.

The ANOVA tests were carried out in two batches. Three volumetric properties (G_{mb}, V_a, and VCA_{mix}) at four gyration levels (N_{50}, N_{LP}, N_{80}, and N_{120}) were considered. In the first batch (Batch-I), responses corresponding to mixes of all the six gradations (G1–G6) and two BCs (4.5 and 5.0%) were analyzed. In the second batch (Batch II), responses corresponding to mixes of three gradations (G4–G6) and three BCs (4.0, 4.5, and 5.0%) were analyzed. The results of ANOVA for Batch-I and Batch-II are presented in Tables 6 and 7 respectively.

The results of ANOVA presented in Table 6 indicate that the volumetric properties G_{mb}, V_a, and VCA_{mix} were significantly influenced by G. The increase in the BC from 4.5 to 5.0% seems to have a significant effect only on V_a, at all the gyration levels, and also on G_{mb} corresponding to N_{50}. The effect of interaction between G and BC does not seem to be significant. Similar observations can be made based on results provided in Table 7. It may be observed that the R^2 values for correlations between the assumed model [Eq. (5)] and the laboratory results corresponding to G_{mb} and V_a as presented in Tables 6 and 7 are higher than 0.96 and 0.90 respectively. Also, there exists a good correlation between the assumed model [Eq. (5)] and laboratory results corresponding to VCA_{mix} with R^2 values of 0.99 as observed in Table 6. However, in Table 7, the R^2 values for the same seem to be much lower. This is because, the variations in VCA_{mix} due to the treatment factors (G, BC, and G*BC) are not statistically significant as indicated by the low F-test values.

Unaged Abrasion Loss

The UALs of PFC mixes corresponding to all the six gradations, at a BC of 5.0% were evaluated. In addition, the UAL at a BC of 4.0% were also evaluated for mixes with Gradation G4 to Gradiation G6. The specimens for the mixes used in these tests were prepared at the respective locking points (N_{LP}). The individual and mean UAL values for all the mixes and the 95% confidence interval for each mean UAL values are shown in Fig. 3. The mixes corresponding to Gradation G6 exhibited poor resistance to abrasion, with mean UAL values more than 25%, and wide confidence intervals. But, the mean UAL values of all other mixes were found to be lesser than 20%, while the maximum UAL values corresponding to 95% confidence interval were found to be

Table 6. Results of ANOVA for Responses of 12 Different Mixes (Batch-I)

Response property	Source of variation	DF	F_C	at N_{50} F	R^2	at N_{LP} F	R^2	at N_{80} F	R^2	at N_{120} F	R^2
G_{mb}	G	5	2.62	142.0	0.96	98.0	0.95	131.0	0.96	116.0	0.96
	BC	1	4.26	5.1		2.4		4.0		4.3	
	G*BC	5	2.62	1.3		1.0		1.1		1.0	
V_a	G	5	2.62	143.0	0.97	98.0	0.96	126.0	0.97	109.0	0.96
	BC	1	4.26	34.8		24.6		31.4		29.2	
	G*BC	5	2.62	1.0		0.7		0.8		0.7	
VCA_{mix}	G	5	2.62	361.0	0.99	336.0	0.99	353.0	0.99	352.0	0.99
	BC	1	4.26	0.0		0.37		0.1		0.0	
	G*BC	5	2.62	1.1		0.95		1.1		0.9	

Note: The results provided above are for gradations G1 to G6, tested for the BCs 4.5 and 5.0%; DF=degree of freedom; F_C=critical F-statistic at confidence level of 95%; F=F-static of responses; G*BC=interaction between gradation and BC; and R^2=coefficient of determination.

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Table 7. Results of ANOVA for Responses of Nine Different Mixes (Batch-II)

Response property	Source of variation	DF	F_C	at N_{50}		at N_{LP}		at N_{80}		at N_{120}	
				F	R^2	F	R^2	F	R^2	F	R^2
G_{mb}	G	2	3.55	92.0	0.91	67.0	0.88	86.0	0.91	78.0	0.90
	BC	2	3.55	0.9		0.4		0.6		0.8	
	G*BC	4	2.93	0.5		0.4		0.5		0.5	
V_a	G	2	3.55	79.0	0.91	59.0	0.89	75.0	0.91	66.7	0.91
	BC	2	3.55	19.7		20.2		20.2		18.2	
	G*BC	4	2.93	0.2		0.2		0.2		0.3	
VCA_{mix}	G	2	3.55	4.5	0.50	2.0	0.40	4.1	0.47	3.1	0.43
	BC	2	3.55	3.3		3.1		2.7		2.9	
	G*BC	4	2.93	0.6		0.5		0.5		0.4	

Note: The results provided above are for gradations G4, G5, and G6, tested for the BCs 4.0, 4.5, and 5.0%.

lesser than 30%. Also, the extreme limits of the 95% confidence intervals for the mean UAL values were found to be lesser than 50%.

Permeability

Generally, over a period of time, the hydraulic-conductivity of PFCs gets reduced due to the clogging of voids or densification under traffic (Huber 2000). Thus, in order to evaluate the permeability (K), PFC mixes for each gradation were prepared for a maximum BC of 5.0% and compacted to the maximum gyration level (N_{120}). Fig. 4 shows the individual and mean permeability of all the mixes tested. The 95% confidence interval for the mean values of K for each mix is also presented. The mixes corresponding to Gradation G6 exhibited more variations, although the individual K value was more than 100 m/day. The upper and lower limits of the 95% confidence interval for mixes of gradation-G6 were found to vary between 300 m/day and 1 m/day. However, the K values of all other mixes seem to be more consistent. The mixes corresponding to gradation-G1 exhibited relatively poor permeability, with no individual values more than 25 m/day, while in the case of all other mixes, the minimum individual permeability observed was 40 m/day. Also, the mean permeability in such cases was found to be higher than 50 m/day.

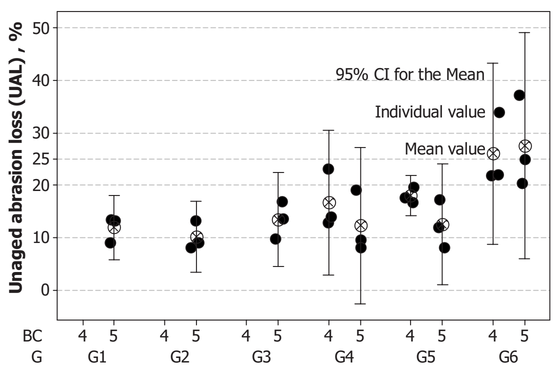

Fig. 3. UALs of different mixes at N_{LP}

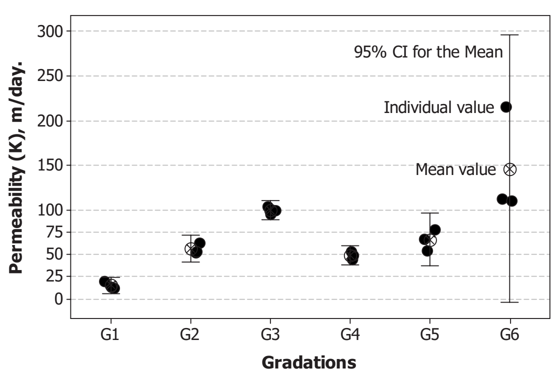

Fig. 4. Permeability of different PFC mixes at N_{120}

Permanent Deformation Characteristics

The permanent deformation characteristics for PFC mixes of all the six gradations for BCs of 4.5 and 5.0% were studied based on the static unconfined creep tests. The specimens tested were compacted to the respective locking points (N_{LP}). The results of the static creep tests are presented in Table 8. The permanent strains of all the PFC mixes were found to be in the range of 0.0013–0.0043, and the values of creep stiffness in the range of 29.84–86.82 MPa. One of the important findings in this study is that the mix that failed to satisfy the stone-on-stone contact condition, exhibited relatively good strain recovery and good resistance to permanent deformation, compared to all other mixes. The mixes with Gradation G1 failed to develop the stone-on-stone contact due to the presence of higher quantities of finer particles (<4.75 mm). However, these mixes had a comparatively denser aggregate structure that contributed to higher resistance to defor-

Table 8. Unconfined Static Creep Test Results at N_{LP}

G	BC (%)	Permanent strain	Recovered strain (%)	Creep stiffness (MPa)
G1	4.5	0.0013	41	86.82
	5.0	0.0013	50	73.46
G2	4.5	0.0028	49	33.51
	5.0	0.0029	47	36.04
G3	4.5	0.0042	31	31.31
	5.0	0.0043	33	29.84
G4	4.5	0.0034	43	32.93
	5.0	0.0033	39	34.11
G5	4.5	0.0041	23	36.04
	5.0	0.0041	23	36.04
G6	4.5	0.0025	31	53.06
	5.0	0.0027	29	50.26

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mation. The presence of sufficient amount of asphalt mortar too, must have provided the necessary lateral restraint for maintaining higher creep stiffness (Zwan et al. 1990).

Of all the gradations tested, the mixes prepared with G1, and G6 exhibited highest creep stiffness values. Also, the mixes prepared with gradations G3 and G4 gave relatively low resistances to permanent deformation. Furthermore, it can also be observed that the PFC mixes tested have better resistance to permanent deformation, when compared to that observed in dense graded asphalt mixes as reported (Abo-Qudais 2007; Abo-Qudais and Al-Shweily 2007; Aravind and Das 2007).

Conclusions

The prime objective of the present investigation was to evaluate the effect of gyration levels and gradations on the properties of PFC mixes. The laboratory studies were performed using six aggregate gradations with selected BCs for PFC mixes. The results were statistically analyzed, and the following conclusions were made:

- The locking points (N_{LP}) of most of the PFC mixes tested were found to be between 50 and 75. The mixes compacted at N_{LP} were found to provide consistent responses. Also, it may be observed that in the case of mixes compacted at the corresponding locking points, the dry-rodded test for ensuring stone-on-stone contact condition need not be performed. In the light of the above finding, it is recommended that tests for PFC mixes may be performed at the locking points (N_{LP}) in place of the existing design gyration levels of N_{50} and N_{80} recommended by different agencies.
- The aggregate gradations were found to have a significant effect on all the volumetric properties, while variations in the BC resulted in a significant change in the air voids (V_a) content only. The interaction between gradations and BCs seems to have lesser significance on the volumetric properties.
- The mean UAL values of all the mixes were well below 30%, while the upper limits of the 95% confidence interval for the mean UAL values were lesser than 50%.
- The mix corresponding to Gradation G1 exhibited poor permeability, while that with Gradation G6 gave the highest permeability.
- The mixes corresponding to Gradation G1 exhibited good resistance to permanent deformation, although it failed to satisfy the stone-on-stone contact condition.
- Overall, by observing all the properties it can be concluded that the mixes with Gradation G2 to Gradiation G4 can be considered as the master aggregate band for PFC mixes that are most likely to produce consistent results, satisfying all the design requirements of PFC mixes.

Acknowledgments

The writers gratefully acknowledge the financial support extended by the Ministry of Science and Technology (Government of India) under the Scheme: Fund for improvement of Science & Technology Infrastructure (FIST)-2005 for the research, and the National Institute of Technology Karnataka for having provided the basic infrastructure, human resource, and other timely assistance. The writers would like to thank Mr. Hiroo Oda, Senior Counselor, Infrastructure Development Institute-Japan, for having provided the necessary details on the use of porous asphalt mixes in Japan and Malaysia.

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