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Laboratory and theoretical evaluation of clogging behaviour of porous friction course mixes

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The clogging of porous friction courses (PFCs) plays a major role in their resulting performance. Clogging occurs due to deposition of external and internal materials, leading to the loss of permeability and drainage characteristics of PFCs. In this study, investigations were conducted to determine the effect of clogging and de-clogging on the permeability of PFC mixes. Tests were conducted to study the effect of three different clogging materials on PFC mixes prepared using four different aggregate gradations. Permeability tests were conducted using the falling-head concept on cylindrical PFC specimens. The influence of the particle size ratios and the effective air voids on the permeability of fresh, clogged and de-clogged PFC specimens was analysed. Experimental results on the permeability observed were compared with those predicted using theoretical models. Although, the theoretical models tend to overestimate the permeability values, statistical analyses indicate good correlations with the observed results.

Keywords: porous friction course; clogging; permeability; pavements; filter criteria

1. Introduction

1.1 *General*

Open-graded asphaltic mixes are composed of uniformly graded aggregates and asphalt cement or modified binders, and are mainly used to serve as drainage layers, either at the pavement surface or within the structural pavement section (FAA 2001). Different agencies around the world use various names to refer to these mixes (Fabb 1997, Suresha *et al.* 2007). The various terminologies used include porous friction course (PFC), open-graded asphalt, porous asphalt (PA), open-graded friction course, popcorn mixes, drain asphalt and so on. In the present investigation, the term PFC is used to refer to all open-graded mixes. PFCs are mainly recommended as surface courses for high-speed roads (Huber 2000) and runway pavements (FAA 1997). PFCs were found to improve skid resistance and night visibility, while minimising hydroplaning and splash and spray during wet weather conditions, in addition to reducing traffic tyre noise (Nicholls 1997, Huber 2000). PFCs are also considered to be effective in storm-water drainage, and are also recommended for paving parking lots (Cahill and Mann 2003, Hope *et al.* 2004, Boving *et al.* 2007, Dietz 2007, Martin *et al.* 2007). PFCs offer safe and quiet riding surfaces, and control the polluted surface runoff, benefiting the environment (Bohemen and Laak 2003).

The performance life or effectiveness of PFCs will depend mainly on its hydraulic conductivity or permeability. Field studies indicate that the loss of permeability of PFCs lessens their noise-attenuation characteristics when compared with newly laid surfaces (Bendtsen *et al.* 2002). Permeability of PFCs depends mainly on the effective void space available for drainage. A reduction in the effective air voids (V_a) content occurs mainly due to the clogging of voids, and also due to densification under heavy traffic.

Frequent clogging of PFCs over time is one of the major concerns for the deterioration in the performance of porous pavements (Dietz 2007). Research in Japan indicates that the clogging of porous pavements on urban PFC roads occurs generally after 3–4 years of construction (Nielsen *et al.* 2005). Based on the performance of porous pavements in parking lots within heavily trafficked areas, Boving *et al.* (2007) concluded that clogging occurred mainly due to the sand brought in from external sources.

Clogging may also occur due to the deterioration of internal materials such as mastic. The high percentage of air voids in PFCs will accelerate asphalt film aging, leading to a reduction in cohesion between the asphalt mastic and the aggregate. Studies on porous pavement test sections in The Netherlands and Denmark indicate that clogging of voids occurs due to the deterioration of mastic in pavements, resulting in reduced void sizes (Nielsen 2007a). It was also noticed that clogging increased with the age of the pavement, and was found to be more concentrated between the wheel tracks, and in areas with no or slow traffic (Nielsen 2007b).

The problem of clogging can be easily addressed with recent advancement in technology. Also, the use of modified binders and modifiers reduces mastic

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deterioration, minimising clogging due to internal materials. With the recent developments in de-clogging machines, it is possible to maintain the function of PFCs over the design life (Nielsen *et al.* 2005). But, while designing porous pavements or PFC mixes, it is very much essential to investigate the effect of clogging and de-clogging cycles on permeability (hydraulic conductivity).

1.2 *Literature review*

A number of theoretical and experimental studies on clogging in porous medium were reported by Schalchli (1992), Wu and Huang (2000), Tan *et al.* (2003) and Skolasinska (2006). However, only a few researchers have reported similar studies on PFCs (Fwa *et al.* 1999, Tan *et al.* 2000, Hamzah and Hardiman 2005).

Schalchli (1992) reported the results of laboratory investigations on the clogging behaviour of coarse-gravel river beds. It was observed that the deterioration of the hydraulic conductivity or permeability of the porous media with time followed a power model as shown below:

$$k = k_o t^{-\alpha}, \tag{1}$$

where k and k_o refer to the permeability at any instant t (h) and the initial permeability (mm/s), respectively, and α is a dimensionless quantity that depends on the shear stress (Θ), concentration of the suspended load (C) and the hydraulic gradient (i).

Generally, the particle size ratios corresponding to the permeability criteria (R_{15}) and the clogging criteria (R_S) are often used in the design of pavement filters (Huang 2004). These are determined based on the particle sizes D_{15} and D_{85} that refer to particle diameters below which 15 and 85% of finer particles exist, respectively, for the drainage PFC and clogging materials (CMs), as shown in Equations (2) and (3). In the case of aggregates used as filter materials and drainage layers, R_S and R_{15} are required to satisfy the conditions $R_S \leq 5$ and $R_{15} \geq 5$.

$$R_{15} = \frac{D_{15}^{\mathrm{PFC}}}{D_{15}^{\mathrm{CM}}}, \tag{2}$$

$$R_S = \frac{D_{15}^{\mathrm{PFC}}}{D_{85}^{\mathrm{CM}}}. \tag{3}$$

Wu and Huang (2000) reported a formulation to illustrate the relationship for the permeability of a porous medium after clogging (k_C) as presented in Equation (4), based on the initial permeability (k_o), specific deposit (σ) of the CM (or sediment) and the permeability criteria (R_{15}). Here, σ represents the ratio of the volume of sediment to the bulk volume of the porous medium:

$$k_C = k_o(5.626)((0.4 - 5\sigma/3)^3/(0.4 - 5\sigma/3)^2) \times ((R_{15})^2(\sigma/0.24)). \tag{4}$$

Tan *et al.* (2003) performed experimental studies to evaluate the clogging of permeable bases, and the results were validated using Equation (4), excluding the second term $((R_{15})^2(\sigma/0.24))$.

Fwa *et al.* (1999) proposed a laboratory test procedure to evaluate the clogging potential of PFCs. Studies were conducted on 500 mm square slab specimens, of 100 mm thickness. It was observed in these studies that there existed a linear relationship between the initial permeability (k_o, mm/s) and the percent air voids (V_a) content as in Equation (5), with an R^2 value of 0.72. Based on further studies on slabs of 50 and 75 mm thickness, the authors proposed a revised form of Equation (5) as given in Equation (6), which had a higher R^2 value of 0.93 (Tan *et al.* 2000). The authors also proposed conversion factors for effective permeability values with due consideration to the geometry of the specimen.

$$k_o = -89.1 + 5.840(V_a), \tag{5}$$

$$k_o = -28.583 + 1.9807(V_a). \tag{6}$$

Hamzah and Hardiman (2005) made a comparative study on the clogging behaviour of single-layer and double-layer PA. Experimental results indicated that the double-layer PA performed better than the single-layer in resisting clogging. The use of cylindrical specimens in this study is considered to be more economical in performing laboratory tests for the evaluation of clogging behaviour when compared with the use of slab specimens, as adopted by Fwa *et al.* (1999) and Tan *et al.* (2000).

Skolasinska (2006) carried out laboratory and field studies on microstructures caused owing to clogging of pores in the vadose zone. The author used the term 'clogging index' (η), which is the ratio of the initial permeability (k_o) to the permeability after clogging (k_C), to express the reduction in permeability over time for each dosage of CM. However, it is difficult to distinguish the clogging behaviour of different filter materials based on this index.

1.3 *Research objectives and scope*

In the above studies, it was observed that clogging affected the performance of single-layer PFCs. However, it is also required to study the effect of de-clogging on PFC mixes in order to simulate de-clogging operations performed in the field, in view of the widespread use of modern equipment for the same. In this context, it was felt that investigations need to be focused on assessing the

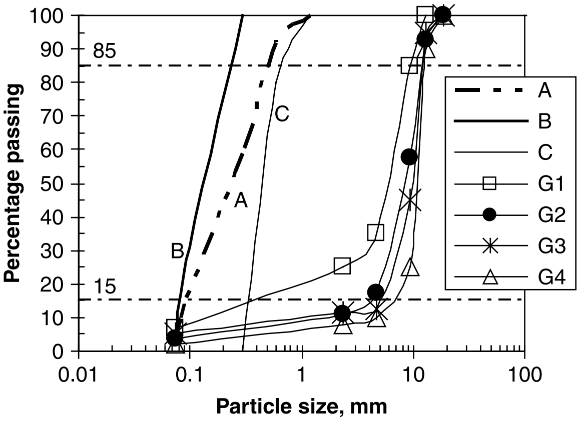

Figure 1. Gradation curves of CMs and PFC mixes.

hydraulic conductivity of PFCs due to clogging and de-clogging, for the design of PFC mixes. The research objectives of the present study are as follows:

1. to carry out laboratory studies on the PFC mixes when subjected to clogging and de-clogging operations,
2. to verify the interrelationships among various test results and
3. to verify the test results with available theoretical approaches.

The laboratory tests on clogging and de-clogging processes were conducted on cylindrical single-layer PFC specimens prepared using the standard Marshall method. The falling-head concept was used to determine the permeability.

2. Research approach

2.1 *Experiment design*

To study the effect of clogging on the permeability of PFCs, three different CMs were selected based on a study on dust samples collected from dust-prone sections of National Highway-17 (NH-17), India. These CMs were designated as A, B and C, respectively. PFC mixes of four aggregate gradations (G1–G4) and two binder contents (BC) of 4.5 and 5.0% were investigated in this study. Figure 1 shows the gradation curves of the CMs, and the aggregate gradations (G) used for PFCs. A total of 10 experiments were conducted with different combinations of G, BC and CMs as indicated in Table 1.

Table 1. Experimental design.

Experiment code	Gradation (G)	BC (%)	CM
M1	G1	4.5	A
M2	G1	5.0	B
M3	G2	4.5	A
M4	G2	5.0	B
M5	G3	4.5	A
M6	G3	5.0	B
M7	G4	4.5	A
M8	G4	5.0	B
M9	G4	5.0	B
M10	G4	4.5	C

2.2 *Specimen preparation*

Cylindrical specimens were prepared in standard Marshall moulds of 101.6 mm diameter, by applying 50 blows on each face using the standard Marshall hammer. Each test specimen thus prepared constituted 1000 g of blended aggregates and a specified quantity of binder. The other specifications related to the preparation of the specimens are similar to those specified in ASTM D 7064 (2004) and ASTM D 6926 (2004).

2.3 *Evaluation of permeability*

The coefficients of permeability (K) of the PFC mixes were obtained using the falling-head permeability concept. The experimental set-up for this test comprises the PFC specimen compacted in the standard Marshall mould as described above, along with the collar assembly, a graduated centimetre scale with least count of 1 mm, a digital stop watch of 0.1 s accuracy and a measuring jar of 1000 cm^3 capacity. A thin coating of paraffin wax was applied on the inner circumference of the mould at the top and bottom faces of the compacted specimen. The collar was mounted on the mould-specimen assembly, by applying a thin layer of petroleum jelly along the grooves of the collar to avoid water leakage. The entire mould-specimen collar assembly was then placed on a tripod.

The graduated metallic scale was placed over the centre of the specimen, and water was poured into the collar so as to maintain a head of 85 mm above the top surface of the specimen. In the first instance, water was poured into the collar and allowed to drain out to keep the specimen wet. The collar was once again filled with water to the brim of the collar, and was allowed to drain out again. The time (t, s) taken for a drop in water level from a height of 70 to 30 mm was recorded. The trial was repeated thrice, and the mean value of the time taken (t_{m}) was determined. The permeability (K, m/day) of the specimen was then calculated based on the thickness of the specimen (L, mm), and the value of t_{m}, using Equation (7), a simplified form of the basic falling-head permeability relationship (BIS 1986).

$$K = 208.49(L/t_{\mathrm{m}})\log_{10}((L+70)/(L+30)). \tag{7}$$

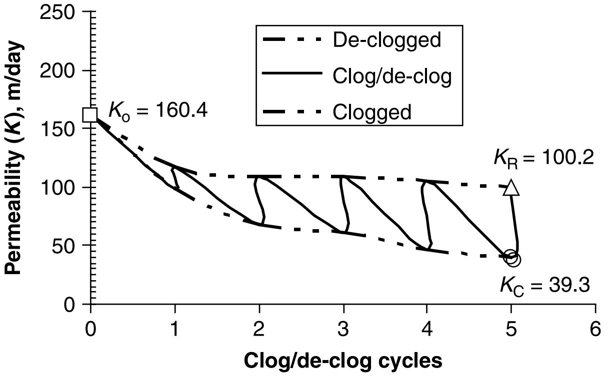

Figure 2. Typical plot of variations in permeability for clogging and de-clogging cycles.

2.4 *Experimental procedure for performing clogging and de-clogging*

Generally, the clogging of PFCs results in the loss of permeability, whereas the subsequent de-clogging restores the same to a considerable extent. The present study was aimed at simulating the frequent clogging of PFCs, and the de-clogging operations performed on them. The test procedure for performing investigations on the effect of clogging was adopted from that proposed by Fwa *et al.* (1999) and Hamzah and Hardiman (2005). Minor changes in the test procedure, with respect to the geometry of the specimen, and the method of application of the CM were also incorporated. After the application of each dose of the CM, the permeability of the PFC specimen was measured, and the same was then subjected to a simple backwash to de-clog the voids, in order to simulate de-clogging operations in the field.

The dosage of 2 mg/mm^2 of the CM was arrived at based on a study of the quantity of dust deposited over a unit area of pavement surface, as observed along NH-17. The clogging and de-clogging were performed in the following manner:

(1) The initial permeability (K_o) of fresh PFC specimen was determined using the falling-head concept as described in the previous section.
(2) The CM was spread uniformly over the upper face of the cylindrical specimen.
(3) Water was poured into the collar up to its brim and was then allowed to drain off completely. The process was repeated until the time taken for the discharge of water reached a constant value. The permeability corresponding to this discharge time was denoted as the clogged permeability (K_C) that represents the permeability of a clogged PFC.
(4) The clogged specimen was then subjected to backwash in order to perform the de-clogging operation. The backwash was performed by inverting the specimen with the mould. The specimen with the mould was then inverted back to its original position, and the permeability of the de-clogged specimen (K_R) was determined.
(5) The cycle of clogging and de-clogging as mentioned in steps (2), (3) and (4) was repeated until K_C and K_R reached fairly stable values. Figure 2 shows the typical plot of variations in the permeability during each clogging and de-clogging cycles.

3. Results and discussion

3.1 *Effect of clogging and de-clogging on permeability*

The effects of clogging and de-clogging on permeability of PFC mixes were evaluated for all the 10 experiments (M1–M10), and the variations in the permeability observed are shown in Figure 3. The initial permeability (K_o) values were found to vary between 5 and 226 m/day. The studies showed that clogging of PFC mixes resulted in the deterioration of permeability, while de-clogging resulted in significant recovery of the permeability. The stable values of K_C and K_R were found to be in the range of 0.9–52.9 and 1.1–128.8 m/day, respectively.

The stable values of K_C and K_R determined from the clogging and de-clogging operations performed on PFC mixes were compared with the initial permeability (K_o). A clogging index (η) that refers to the ratio K_o/K_C, and a clog-recovery index (η_r) that refers to the ratio K_o/K_R were used for this purpose. The indices with values closer to unity indicate mixes that are clog resistant.

Figure 4 shows the test results corresponding to K_o, η and η_r for the experimental mixes shown in Table 1. The mixes corresponding to experiments M7–M10 exhibited higher permeability values of more than 100 m/day, with the η_r values indicating better clog resistance. But, mixes corresponding to experiments M1 and M2 exhibited very low permeability values, and higher susceptibility to clogging. Regression equations correlating K_C to K_o, and K_R to K_o were obtained based on this study, as shown in Equations (8) and (9), respectively. The scatter plot diagram, along with the line of equality and the regression lines, is presented in Figure 5.

$$K_C = 0.1236 K_o^{1.0301}, \quad R^2 = 0.80, \tag{8}$$

$$K_R = 0.1017 K_o^{1.3192}, \quad R^2 = 0.94. \tag{9}$$

3.2 *Relationships between permeability and particle size ratios*

In the design of aggregate drainage layers, the particle size ratios R_{15} and R_S are considered as the basic criteria to satisfy the requirements of permeability and clogging resistance, respectively (Huang 2004). In the present study, this concept was used to assess the behaviour of PFCs

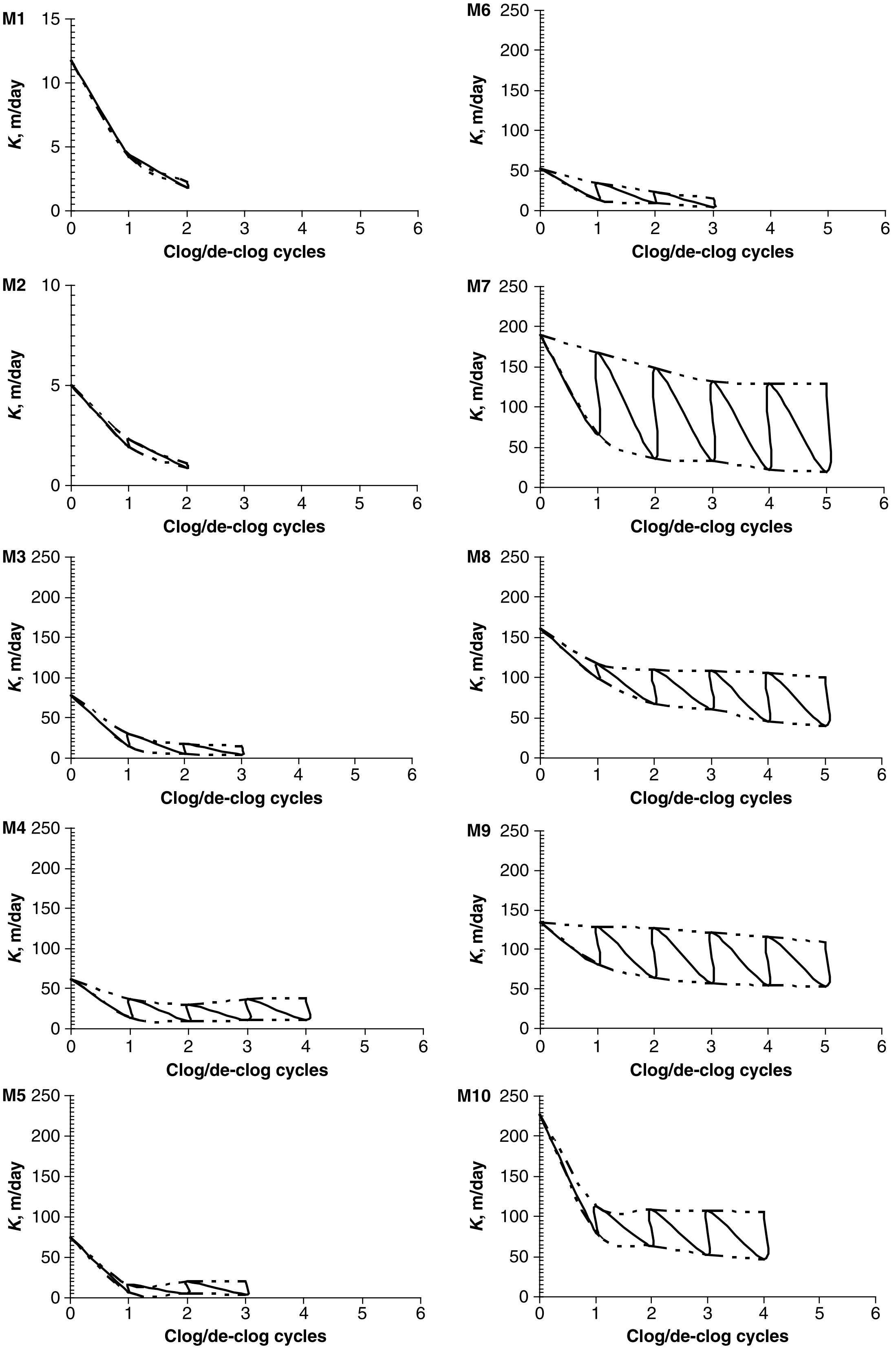

Figure 3. Variations in permeability for clogging and de-clogging cycles for experiments M1–M10.

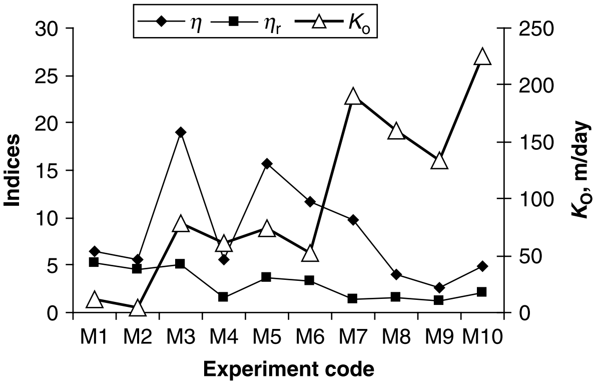

Figure 4. Variations in the clogging index (η), recovery index (η_r) and the initial permeability (K_o).

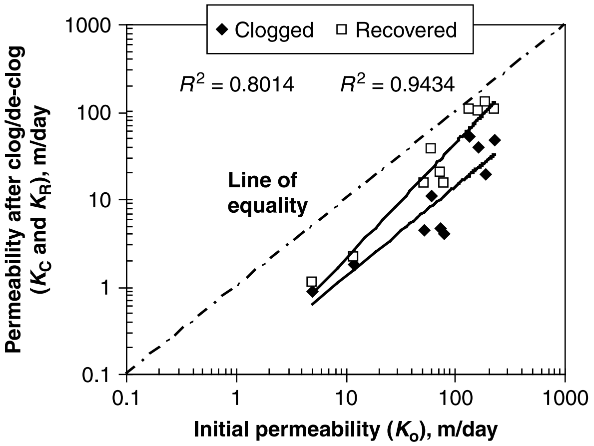

Figure 5. Regressions between K_C and K_o, and K_R and K_o.

under clogged and de-clogged conditions for the selected CMs tested.

Table 2 shows the particle size ratios (R_{15} and R_S) for different combinations of gradations for the PFC mixes, and for different gradations of CMs used. Additionally, the coefficients of curvature (C_u) for each of the gradations of the PFC mixes and CMs tested are also provided.

The R_{15} values corresponding to gradation G1 for all the CMs tested were calculated, and found to be lesser than 5, indicating insufficient permeability. The results of the tests for permeability performed on mixes with gradation G1 also revealed that these mixes had permeability values lesser than 12 m/day. Moreover, the R_S values computed for PFCs of gradations other than G1 exceeded the limiting value of 5, indicating higher susceptibility to clogging. Thus, R_{15} and R_S were considered as indices to assess the clogging behaviour of PFC mixes.

Figure 6(a) provides details of the scatter plot between the values of R_{15} and K_o, K_C and K_R. Similarly, Figure 6(b) gives details of the scatter plot between the values of R_S, and K_o, K_C and K_R. It can be observed that in these scatter plots, the regressions using the power models fit the given data reasonably well, as illustrated in Table 3. An examination of this table shows that the prediction of permeability values using R_S is more reliable than the predictions obtained using R_{15}. Also, K_R values show a better fit with the power model than those of K_o and K_C. However, the R^2 values obtained through the analyses indicate moderate correlation due to the reason that permeability values also depend upon other factors like the void structure and the volume of CM trapped in the pores.

3.3 *Relationship between permeability and air voids*

The air voids (V_a) content in freshly compacted PFC mixes tested were in the range of 9.8–20% in all the experiments. However, when the PFC mixes were subjected to clogging and de-clogging cycles, the air voids content reduced. The effective air voids in mixes after the clogging and de-clogging cycles (corresponding to stable values of K_C and K_R) were found to be in the range of 7.1–15.3 and 6.9–18.6%, respectively.

The relationship between the K values for the mixes tested under the initial, clogged and de-clogged conditions, and the corresponding effective values of V_a, are plotted as shown in Figure 7. This relationship follows a power model as shown in Equation (10) with a high R^2 value of 0.98, in a manner similar to Kozney's Equation (Bear 1972):

$$K = 0.00004(V_a)^{5.182}. \tag{10}$$

Table 2. Particle size ratios.

		R_{15}			R_S		
		A	B	C	A	B	C
Gradation of PFC (G)	C_u ↓ →	3.7	2.0	1.7	3.7	2.0	1.7
G1	58.3	4.1	4.6	1.0	0.7	1.7	0.6
G2	5.8	45.6	51.3	11.1	8.2	18.6	6.6
G3	10.0	56.7	63.8	13.8	10.2	23.2	8.2
G4	2.3	77.8	87.5	18.9	14.0	31.8	11.3

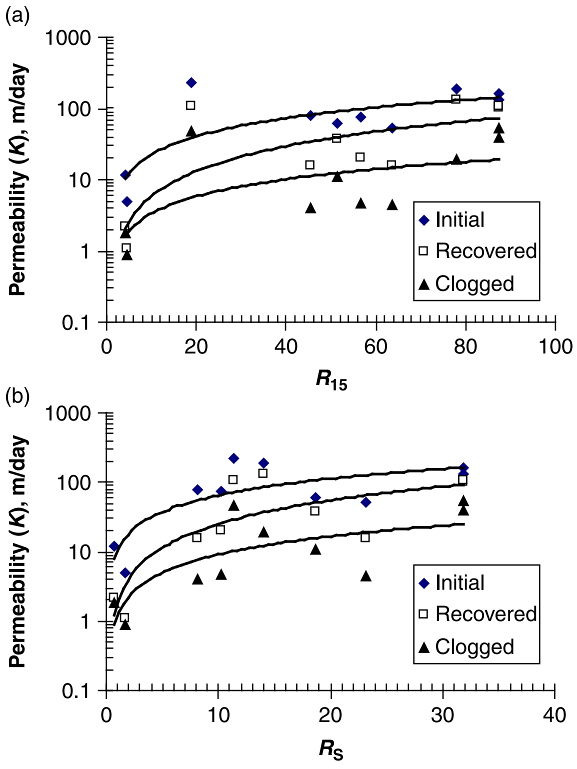

Figure 6. Regressions between permeability and particle size ratios: (a) R_{15} and (b) R_S.

3.4 *Verification of clogging behaviour using theoretical models*

In order to predict the permeability in the clogged and de-clogged mixes (K_C and K_R, respectively), the theoretical formulation vide Equation (4), as reported by Wu and Huang (2000), was adopted. However, in the study of the clogging behaviour of modified permeable bases, Tan *et al.* (2003) used this equation by excluding the second term, $(R_{15})^2(\sigma/0.24)$. In the present study, an attempt was made to verify the significance of the second term in Equation (4) in predicting the values of K_C and K_R.

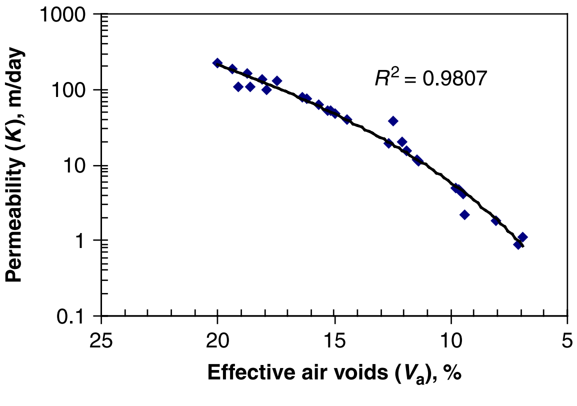

Figure 7. Regression between permeability and air voids.

Table 3. Details of permeability prediction models based on particle size ratios R_S and R_{15}.

	$K = m(R_S)^n$			$K = m(R_{15})^n$		
K (m/day)	m	n	R^2	m	n	R^2
K_o	10.424	0.7951	0.65	3.155	0.8529	0.65
K_C	1.242	0.8667	0.59	0.524	0.8045	0.44
K_R	1.866	1.1296	0.72	0.403	1.1646	0.66

Note: *m* and *n* are regression coefficients for the power models.

Thus, the permeability values irrespective of the clogging or recovery ($K_{C/R}$) values were predicted using three alternate Equations (11)–(13) in addition to Equation (4).

$$K_{C/R} = K_o(5.626)((0.4 - 5\sigma/3)^3/(0.4 - 5\sigma/3)^2) \times (R_{15})(\sigma/0.24), \tag{11}$$

$$K_{C/R} = K_o(5.626)((0.4 - 5\sigma/3)^3/(0.4 - 5\sigma/3)^2) \times (\sigma/0.24), \tag{12}$$

$$K_{C/R} = K_o(5.626)((0.4 - 5\sigma/3)^3/(0.4 - 5\sigma/3)^2). \tag{13}$$

Among the results of the 10 experiments conducted, the initial permeability values (K_o) for the individual tests were in the range of 5–226 m/day. Also, the specific deposits (σ) in clogged and de-clogged mixes were found to be in the ranges of 2.66–6.92 and 0.32–4.47%, respectively. The experimental results of K_C and K_R were compared with that determined using the theoretical models (Equations (4) and (11)–(13)). The relationships between these are shown in Figure 8.

It is clear from the plots that all the permeability points corresponding to the experimental and theoretical results fall below the line of equality. This indicates that the theoretical models have a tendency to overestimate the permeability compared with the experimental results. Statistical analyses were carried out to compare the experimental and theoretical permeability values, for K_C and K_R, and the results are presented in Table 4. The tests for analysis of variance (ANOVA) based on the linear model indicate that the theoretical permeability values computed using Equation (4) have a mild correlation with the experimental values, while the values computed using Equations (11)–(13) exhibited good correlations with high R^2 value. But, it seems that the use of the power model will further improve the R^2 values as shown in Figure 8.

4. Conclusions

This investigation was aimed at evaluating the clogging behaviour of PFC mixes. Four aggregate gradations and two BC were considered for the preparation of PFC mixes. Three different CMs were used in the experiments

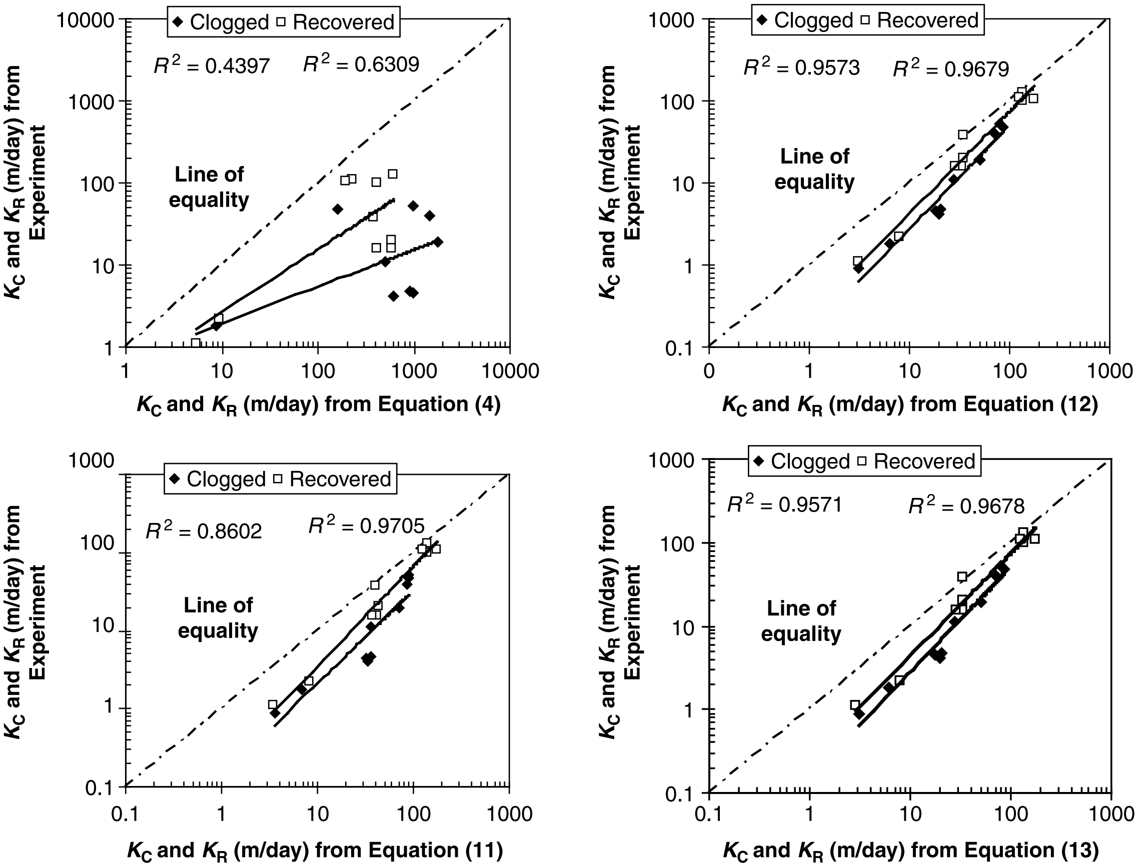

Figure 8. Regressions between experimental and theoretical permeability (K_C and K_R) values.

performed. The permeability values of the PFC specimens were determined using the falling-head method. The effects of clogging and de-clogging on the PFC mixes were performed by conducting 10 experiments (M1–M10). The variations in the permeability values due to clogging and de-clogging were recorded. The interrelationships between the permeability of the freshly prepared, clogged and de-clogged specimens were evaluated. The relationships between the permeability and the influencing factors such as the particle size ratios, and the air voids were also investigated. The test results were verified with the results obtained using available theoretical formulations. Based on the above investigations, the following conclusion can be made:

- The test procedure adopted to evaluate the clogging of PFC was made simpler by adapting methods proposed by other researchers (Fwa *et al.* 1999, Tan *et al.* 2000, Hamzah and Hardiman 2005).
- It was observed that the PFC mixes with initial permeability values of more than 100 m/day ensured good drainage potential ($K > 8.64$ m/day) even after

Table 4. Statistical details of comparisons between experimental permeability values and values predicted using various theoretical models.

	Comparison of K_C based on equations				Comparison of K_R based on equations			
Particulars of statistics	(4)	(11)	(12)	(13)	(4)	(11)	(12)	(13)
Results of linear ANOVA								
Multiple-*R*	0.29	0.93	0.98	0.98	0.23	0.96	0.96	0.96
R^2	0.08	0.86	0.95	0.95	0.050	0.92	0.92	0.92
Adjusted R^2	−0.03	0.84	0.95	0.95	−0.07	0.91	0.91	0.91
SE	20.52	8.12	4.71	4.67	52.61	15.48	15.55	15.54
Adjusted mean square	304	3146	3496	3499	1177	21402	21385	21387
F	0.072	48	157	160	0.43	89	88	89
R^2 based on power model	0.44	0.864	0.957	0.957	0.631	0.971	0.968	0.968

reaching stable clogged conditions. Such mixes also had low clogging (η) and clog-recovery (η_r) indices.

- The particle size ratios (R_{15} and R_S) and filter design criteria are seen to be of use in understanding the clogging behaviour of PFCs. The statistical model presented in Table 3 can be used in making rough estimates of the permeability.
- The relationship between the permeability (K) and effective air voids (V_a) followed a power model, resulting in a high R^2 value. The nature of the relationship is in agreement with Kozeny's equation (Bear 1972).
- The theoretical formulation presented by Wu and Huang (2000) even after eliminating the additive term consisting of R_{15} as recommended by Tan *et al.* (2003) overestimated the permeability of PFC specimen in clogged and de-clogged conditions. But, there existed a good correlation (adjusted $R^2 > 0.90$) between the experimental and theoretical results with a minimum SE of about 15.55 m/day for the entire experiment.

The trends observed in the variations of K_C and K_R will provide the necessary basis for highway maintenance personnel in the scheduling of de-clogging operations. However, the actual permeability trends represented by K_C and K_R will mainly depend upon factors such as the characteristics of the CM, rate of deposition, frequency of cleaning operation and the efficiency of the de-clogging machine. Further studies need to be performed to address the influence of variations in these factors on K_C and K_R values.

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Notes

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