PROPERTIES OF CELLULOSE FIBRES AND WASTE PLASTIC MODIFIED POROUS FRICTION COURSE MIXES

Subbarao Nagabhushanarao Suresha[1], George Varghese[2], Ayyalasomayajula Udya Ravi Shankar[3]

[1]*Dept of Civil Engineering, Dayananda Sagar College of Engineering, S. M. Hills, K. S. Layout, Bangalore – 560 078, India*
E-mail: sureshasn@rediffmail.com
[2, 3]*Dept of Civil Engineering, National Institute of Technology Karnataka, Surathkal, Mangalore, 575025, India*
E-mails: [2]*varghese-g@lycos.com;* [3]*aurshankar@yahoo.com*

Abstract. This paper summarises the laboratory investigation on porous friction course mixes that were modified with cellulose fibres and waste plastics. Porous friction course mixes of three different aggregate gradations were tested for predetermined binder content. The influence of each modifier on the volumetric properties, permeability, aged abrasion loss, and moisture susceptibility of porous friction course mixes were evaluated. In order to determine the significance level of effect of modifiers on the above properties, the tests for analysis of variance (ANOVA) and Tukey's multiple mean comparisons were performed. Results of statistical analyses indicate that the gradations are major source of variations in all response properties. However, modifiers too appreciably contributed in reducing the moisture-induced damages. The findings suggest that shredded waste plastics are potentially useful as modifiers to porous friction course mixes.

Keywords: porous friction course (PFC), modifiers, waste plastics (WP), cellulose fibres (CF), volumetric properties, permeability, aging, abrasion loss, moisture susceptibility.

1. Introduction

According to some projections (Mutha *et al.* 2006) in India the consumption of plastics will increase about six-fold between the year 2000 and 2030. While, in the year 2030, plastic wastes for disposal (excluding recycled plastics) will increase 10 times compared to the situation in the year 2000–2001. A huge percentage of post-consumer plastic wastes are sent to landfill, while remaining is subjected to the process of incineration and recycling. The recovery of plastic bags from older landfills may increase the cost of resource recovery operations and landfill reuse options. But, potential use of waste plastics (WP), specifically in porous friction courses (PFCs), and generally in road construction industry can address these problems.

PFCs are typical open-graded mixes characterized by a high percentage of interconnected air voids that can ease the drainage of surface water. PFCs are also called by different names by various agencies around the world, like porous asphalt (PA), open-graded friction course (OGFC), open-graded asphalt (OGA) etc. (Suresha *et al.* 2007). PFCs are found to offer multiple benefits like better skid-resistance, reduced splash and spray, and improved night-visibility during wet weather conditions, in addition to mitigation of hydroplaning. Moreover, the negative-texture of PFC surfaces enables considerable reduction in traffic tyre-noise. Hence, these are generally recommended for surfacing high-speed road-corridors, streets with wide carriageways and runway pavements. PA layers can also be used as drainage layer sandwiched between water-proofing layer and wearing course, over bridge decks (Kim *et al.* 2009).

The lower surface area due to the use of uniformly graded aggregates, and the low quantity of filler materials used result in the draining of bitumen-mastic (draindown) from PFC mixes during mixing, storage, transport, and laying operations. To mitigate the problem of draindown, the use of fibres as modifiers (stabilizers) to mixes is widely recommended. The use of fibres consequently requires an increase in the binder content which further improves the durability of the mix. Further, it increases the stiffness of bitumen-mastic minimizing the amount of draindown.

1.1. Review on utilization of fibres

Many researchers have reported the use of various types of fibres in different types of bituminous mixes. Some of the findings related to use of fibres in PFC mixes are summarised below.

Decoene (1990) discussed the possibility of using cellulose fibres (CF) as anti-draining agent in PFC mixes and his findings suggested that the quantity of CF of more than 0.3% by weight of total mix is not beneficial. Cooley *et al.* (2000) investigated the moisture sensitivity behaviour of PFC mixes modified with cellulose and mineral fibres. Based on laboratory and field data the authors concluded that the performance of both the stabilizers were comparable. Similar findings were reported by Mallick *et al.* (2000). Their findings indicated that PFC mixes with slag-wool failed to satisfy the min tensile strength ratio (TSR) of 80%. Hassan *et al.* (2005) observed that the draindown performance of PFC mixes with fibres was better compared to that of mixes with modified bitumen. The experimental results of Wu *et al.* (2006) showed that the mixes modified with CF performed better than that of mixes modified with polyester fibres, in all respect. Tayfur *et al.* (2007) reported that the bituminous mixes modified with cellulosed fibres coated with bitumen exhibited better rutting resistance than the mixes modified with uncoated cellulosed fibres. Wu *et al.* (2008) used polyester fibres to modify the bitumen, and their findings indicate that the viscosity of bitumen was significantly influenced at lower temperatures (60–135 °C).

1.2. Review on utilization of WP

The disposal of WP is one of the major problems causing environmental degradation and is of worldwide concern. Environmental hazards due to WP can be addressed to a large extent by using these effectively in road construction. A number of studies were performed on exploring the possibility of using such as, high-density polyethylene (HDPE), low-density polyethylene (LDPE), polyethylene terephthalate (PET) etc., in cement/bituminous concrete mixes (Siddique *et al.* 2008). The following section summarizes the findings on utilization of WP in the form of replacements to a part of the aggregates in the bituminous mixes, or as bitumen modifiers.

Research on the use of WP as replacements to aggregate indicated that there is a reduction in the bulk density of compacted mix, accompanied by an increase in the stability, strength, and improved deformation capacities, in comparison to mixes of similar nature where WP were not used. Based on the findings of various researchers (Hinislioglu, Agar 2004; Panda, Mazumdar 2002; Punith, Veeraragavan 2007), the major advantages of using polyethylene-modified bitumen in bituminous mixes when compared to that of plain bitumen mixes included an increase in the Marshall-quotient, indicating increased stiffness and greater ability to spread the load; an increase in the resilient modulus and fatigue life; an improved resistance to moisture susceptibility; a decrease in the plastic deformation; and an increased shear resistance. Ho *et al.* (2006) were of the opinion that LDPE with lower molecular weights and wider molecular weight distributions were more suitable as bitumen modifiers when compared to that of high molecular weight with narrow molecular weight distributions. Fuentes-Audén *et al.* (2008) suggested that the concentration of recycled polyethylene in bitumen should not exceed 5% for paving applications, while,

Al-Hadidy and Yi-qiu (2009) reported that the flexible pavement with high performance, durability, and more economic can be obtained with 6% pyrolysis LDPE.

2. Objectives and scope of the study

The literature review indicates that investigations need to be performed on the use of WP as modifiers to PFC mixes. The present study was carried out with an objective of investigating the potential use of WP as modifiers in PFC mixes, and on performing a comparative study on the behaviour of PFC mixes modified with WP and CF. Laboratory studies were performed on WP and CF modified PFC mixes and the results were compared to that of mixes without modifiers. The mixes were evaluated for their volumetric properties, permeability measured using the falling-head method, aged abrasion loss determined using the Cantabro abrasion test method, and the test for moisture susceptibility based on the tensile strength ratio method. To study the significance of WPs as modifiers, the test results corresponding to the properties of PFC mixes were statistically analysed.

3. Materials

The PFC mixes corresponding to three different aggregate gradations (G1, G2, and G3) as shown in Fig. 1 were investigated.
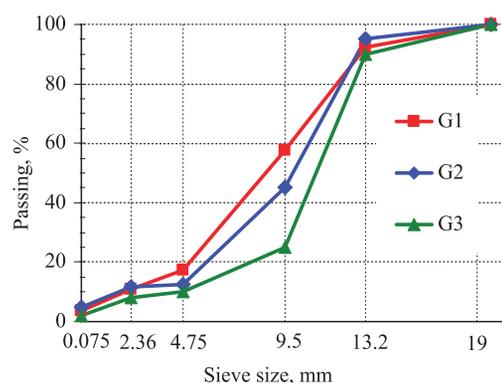

Fig. 1. Gradations investigated for PFC mixes

Coarse and fine aggregates obtained from local stone crushing plants were used in this study. Ordinary Portland cement (OPC) blended with stone dust, was used as the mineral filler. The quantity of OPC was limited to 2% by mass of the total aggregates. Straight-run paving grade bitumen used in the present investigation, was supplied by the Mangalore Refinery and Petrochemicals Limited (MRPL), Mangalore. The physical properties of coarse aggregates, and paving-grade bitumen were determined in accordance with Indian Standard test methods. The test results are presented in Table 1.

Commercially available CF in loose (CFL) and their pellet (CFP) forms were used as modifiers. The CFL are similar to cotton, in feel. The CFP used had been coated with a bitumen content of 36% and a CF content of 64%, as claimed by the suppliers. The WPs used in this study was made available in the form of shredded plastic fibres of size

Table 1. Properties of coarse aggregate and bitumen

Material	Properties	Test method	Test results
Coarse aggregate	Combined flakiness and elongation index, %	IS 2386 P(1)	28.1
	Aggregate impact value, %	IS 2386 P(4)	20.1
	Los Angles abrasion value, %	IS 2386 P(4)	26.6
	Water absorption, %	IS 2386 P(3)	0.15
	Soundness: magnesiun sulphate, %	IS 2386 P(5)	0.21
Bitumen	Specific gravity, at 27 °C	IS 1202	1.01
	Penetration at 25 °C, 100 g, 5 s, 1/10 mm	IS 1203	89
	Penetration at 4 °C, 200 g, 60 s, 1/10 mm	IS 1203	43
	Softening point (ring and ball), °C	IS 1205	46
	Loss on heating, thin-film oven test, % by mass	IS 1212	0.2
	Ductility at 27 °C, cm after thin-film oven test	IS 1208	90
	Retained penetration after thin-film oven test, % of original	IS 9382	62
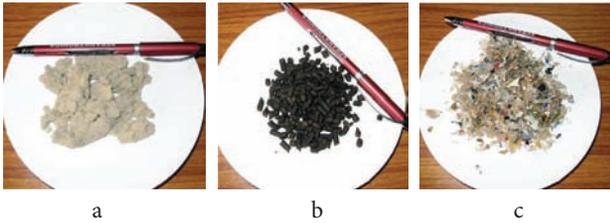
Fig. 2. Samples of cellulose: a – fibres-loose; b – cellulose fibres-pellets; c – WP

smaller than 9×3 mm, obtained from shredded plastic bags reclaimed from domestic and commercial wastes. Fig. 2 shows the samples of CFL, CFP and WP, respectively.

4. Experimental design

PFC mixes corresponding to different gradations with or without modifiers were prepared for pre-determined binder content (BC) of 5% by weight of the total mix. The selection of gradations and binder content were based on the findings of the previous study (Suresha *et al.* 2009, 2010). Table 2 shows the details of mix combinations and coding. The dosage of CFL and CFP were fixed as 0.3% and 0.45% by weight of total mix respectively, based on the earlier research findings (Cooley *et al.* 2000; Mallick *et al.* 2000). The dosage of WP was fixed as 0.4% by weight of the total mix. This is in agreement with the dosages recommended for modifiers like fibres and polymers, to be used in hot asphalt mixes (Al-Hadidy, Yi-qiu 2009; Fuentes-Audén *et al.* 2008; Ho *et al.* 2006; Punith, Veeraragavan 2007).

The procedure adopted for the preparation of cylindrical PFC specimens was the same as that followed for

Table 2. Details of experimental mix combinations

Gradations	Mix for each modifier			
	Nil	CFL	CPF	WP
G1	M1	M2	M3	M4
G2	M5	M6	M7	M8
G3	M9	M10	M11	M12

dense graded asphalt, as suggested in the Asphalt Institute Manual Series-2. To prepare a cylindrical specimen of Ø101.4 mm, loose hot PFC mix was compacted by applying 50 blows on each end of the specimen, using a standard Marshall hammer. Each specimen thus prepared constituted 1000 g of the aggregate in addition to pre-defined quantity of BC and one of the modifiers. It may be noted that modifier was first blended with pre-heated aggregates and then hot bitumen was introduced to produce PFC mix. Totally, 144 cylindrical PFC specimens that constituted 12 replicate specimens for the 12 experimental mixes (Table 2) were prepared to evaluate the volumetric properties, coefficient of permeability (K), aged abrasion loss (AAL) and moisture susceptibility. The detailed test plan is given in Table 3.

Table 3. Test plan

Particulars of tests	No. of replicates	
	No. of experiments	Total
Volumetric properties	3 × 12 = 36	36
Permeability	3 × 12 = 36	36
Aged abrasion loss	3 × 12 = 36	72
Moisture susceptibility	6 × 12 = 72	144

5. Evaluation of PFC mixes

5.1. Volumetric properties

The volumetric properties of compacted specimens tested included the bulk specific gravity (G_{mb}), percent air voids (V_a), and the voids in coarse aggregate (VCA_m). The G_{mb} was determined using the geometric measurements of the diameter and mean length, and the mass of the specimen in air. The theoretical max density (G_{mm}) of the uncompacted mix was determined in accordance with ASTM D 2041. The V_a was then determined using the corresponding values of G_{mb} and G_{mm} using Eq (1). The presence of stone-on-stone contact condition in the compacted PFC mix was evaluated based on the VCA_m and the percentage of voids in coarse aggregate of the coarse aggregate alone (VCA_d) determined using the dry-rodded test pro-

cedure. The VCA_d and VCA_m values were computed using Eqs (2) and (3), respectively. The stone-on-stone contact condition was confirmed when the ratio of VCA_m to VCA_d was found to be lesser than unity.

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

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

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

where G_{CA} – bulk specific gravity of the coarse aggregate; γ_w – density of water, kg/m³; γ_s – bulk density of the coarse aggregate fraction in the dry-rodded condition, kg/m³; P_{CA} – percentage of coarse aggregate in the total mixture, %.

For tests conducted on 12 mix combinations, with three replicate tested for each mix, the results corresponding to the G_{mb}, V_a, and the stone-on-stone-contact condi-

Fig. 3. Individual plot for volumetric properties of all 12 mixes

tion ($\frac{VCA_m}{VCA_d}$) are presented by an individual plots, as shown in Fig. 3. The bulk specific gravity of compacted mixes (G_{mb}) ranged between 2.038 and 2.155. The presence of modifiers resulted in variation of ±4% when compared to the mixes without modifiers. The use of modifiers in the PFC mixes resulted in higher densities, especially for mixes with the CFL and the CFP. In general, the mixes with gradation-G3 exhibited low G_{mb}, relative to that of mixes with other gradations (G1 and G2). This is mainly due to higher quantity of coarse aggregates. Consequently, these mixes exhibited higher V_a. The individual values of V_a for entire experimental mixes varied from 13.0% to 17.6%. While, the mean values of V_a for each experimental mix varied from 13.4% to 16.9%. The ratios of VCA_m to VCA_d presented as stone-on-stone-contact, shown in Fig. 3, confirm the presence of stone-on-stone contact condition in the coarse aggregate skeleton in all the experimented mix combinations tested. Thus, all the experimented mixes are expected to exhibit adequate stability to resist the plastic deformation. However, field performance of these mixes can be assessed by frequent inspection using any kind non-destructive testing methods; like non-nuclear density gauges (Praticò et al. 2009).

5.2. Permeability

The hydraulic conductivity of compacted specimens tested is expressed in terms of the coefficient of permeability (K) determined using the falling-head method. The test setup used was simple and economical. Compacted PFC specimens prepared in the standard Marshall mould were subjected to this before extruded. To prevent water leakage through the joints, the circumferential contact area between the specimen and the mould was covered using paraffin wax on either side. Care was taken to avoid clogging of voids due to paraffin wax in the specimen. The collar placed on the mould-specimen assembly, acted as a water reservoir. Water was then allowed to flow through the specimen, and the average time (t_m, s) taken for a drop in water level from 70 mm to 30 mm was recorded. The typical setup for permeability test using falling-head method is shown in Fig. 4. The coefficient of permeability (K, m/day) of the cylindrical specimen of Ø101.4 mm diameter (D) and of mean length (L, mm) was calculated, by applying the temperature correction factor (T_C) for the viscosity of water, using the expression as in Eq (4).

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

The individual permeability (K) values for the 12 mix combinations tested varied in the range of 30–133 m/day. Thus, all the mix combinations satisfied the permeability criteria that K should be more than 8.7 m/day (0.01 cm/s) for good drainage condition. Fig. 5 shows the individual plot K values of all the 12 mixes tested. It is generally accepted that the permeability is directly proportional to the porosity (percent air voids, V_a). Here too, the variations in the per-
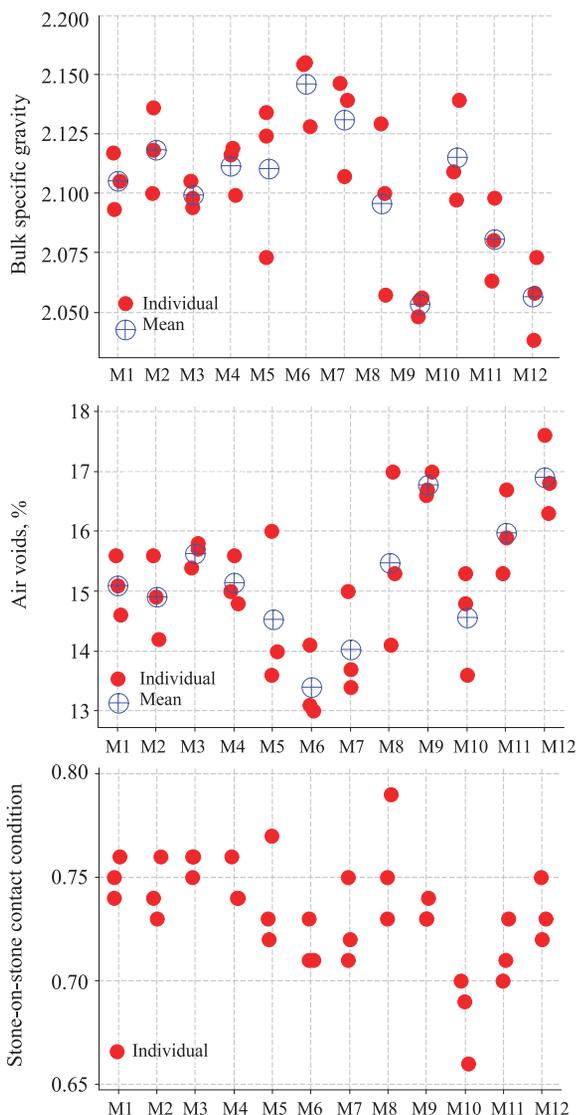
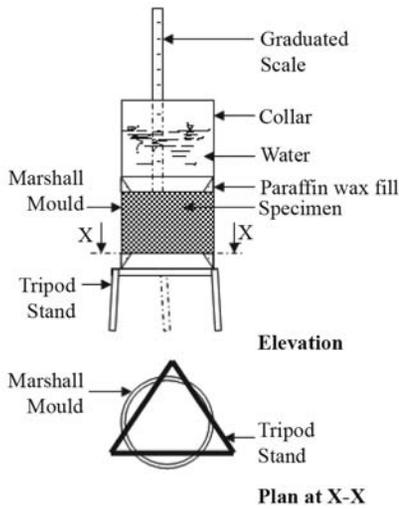**Fig. 4.** Typical permeability test setup

Fig. 5. Results of permeability tests on all 12 mixes

meability seem to be similar to that of trends of air voids. The variations in *K* values of CFL, CFP and WP modified mixes were respectively in the ranges of 0.38–1.50, 0.52–1.68, and 0.81–2.62 times that of the respective unmodified mixes. It may be observed that mixes modified with WP exhibited higher *K* values compared to that of other mixes, similarly, the mixes of gradation-G3 exhibited higher *K* values compared to the mixes with other gradations.

5.3. Aged abrasion loss

Aging of PFC specimens were simulated in the laboratory. The Cantabro abrasion tests were then conducted on the aged specimens to evaluate the aged abrasion loss (AAL). Compacted PFC specimens of a particular mix, in triplicate, were stored in a forced draft oven at a temperature of 60 °C for a period of 168 h. The specimens were then taken out from the oven, allowed to cool to the ambient temperature, and stored for a period of 4 h at a temperature (25±5 °C) corresponding to the Cantabro abrasion test. The aged specimen was then placed in a Los Angeles abrasion drum without any abrasive charge, and the machine was operated at a speed of 30–33 revolutions per minute for 300 revolutions. The loss in the specimen was expressed as a percentage of the ratio of weight of disintegrated particles to the initial weight of the specimen. Fig. 6 shows pictures of the aging process of cylindrical specimens and the specimen to be subjected into Los Angeles drum.

For tests performed on 12 mix combinations, with three replicates tested for each mix, the AAL values ranged between 5.6% and 32.7%. The mean and individual AAL values were found not exceeded the 30% and 50% respectively, satisfying the ASTM D 7064 requirements. This is evident from the Fig. 7, shows the individual plot of aged abrasion losses. The results of AAL tests show that the use of modifiers resulted in an improvement in the resistance to AAL. The mixes corresponding to gradation-G1 exhibited high resistance to AAL followed by mixes with gradations G2 and G3.
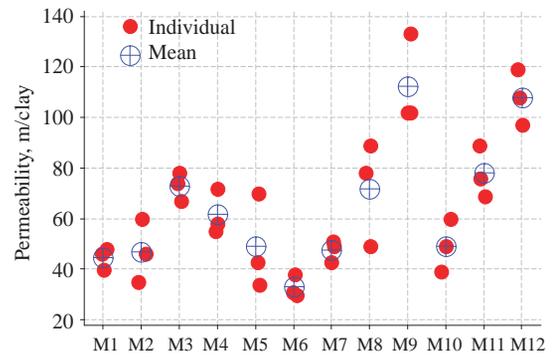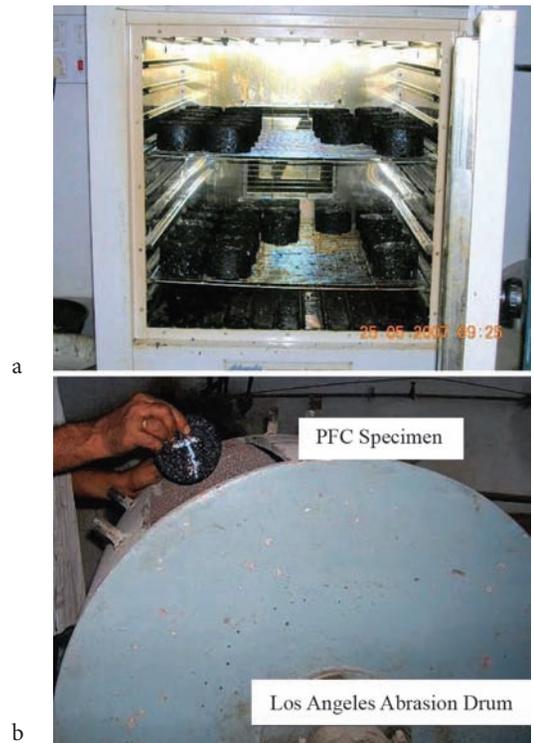

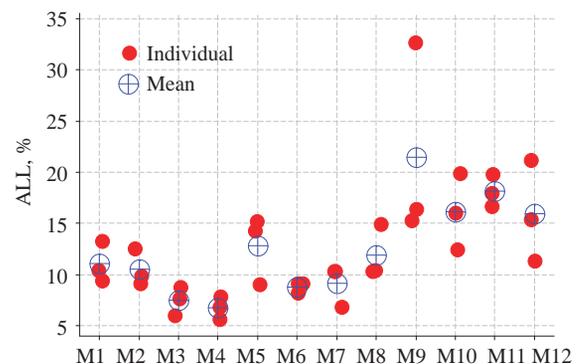**Fig. 6.** Specimens subjected to aging in a hot air oven (a) and abrasion test (b)

Fig. 7. Results of ALL tests on all 12 mixes

5.4. Moisture susceptibility

The moisture susceptibility of PFC mixes was evaluated using the retained tensile strength or tensile strength ratio (*TSR*) method. Totally six replicate specimens were prepared for each mix as per the experimental design. Three of the six replicates, were subjected to indirect tensile strength tests in dry-condition (ITS_d). The remaining, three specimens of each mix was then subjected to wet-conditioning, and the indirect tensile strengths (ITS_w) were evaluated. The wet-conditioning of the compacted PFC specimens was performed as per AASHTO T 283 with minor modifications. The specimens were first saturated by submerging in water, and kept at water freezing temperature for about 15 h. The frozen specimens were immediately transferred into the hot water bath for thawing to a temperature of 60 °C for 24 h. After two such cycles of moisture-conditioning, the specimens were kept in a cold water bath to bring down the temperature to 25 °C before testing. The mean *ITS* values of each mix for the dry- and wet-conditioned specimens were used to compute the *TSR*. The following relations were used to compute *ITS* and *TSR*.

$$ITS = \frac{2 \times P_u}{\pi \times L \times D} \times 1000 , \qquad (5)$$

$$TSR = \frac{ITS_w}{ITS_d} \times 100, \qquad (6)$$

where P_u – ultimate load required to fail specimen in the indirect tension test, N; *TSR* – tensile strength ratio; ITS_w – mean indirect tensile strengths of wet-conditioned specimens, kPa; ITS_d – mean indirect tensile strengths of dry-conditioned specimens, kPa.

The mean indirect tensile strengths (*ITS*) of dry- and wet-conditioned PFC specimens and the *TSR* of the respective mixes are provided in Table 4.

Table 4. Moisture susceptibility test results

Mix code	ITS_d, kPa	ITS_w, kPa	TSR, %
M1	447.7	406.0	91
M2	473.7	446.3	94
M3	445.3	431.3	97
M4	448.3	411.3	92
M5	536.0	318.7	59
M6	537.0	426.7	79
M7	540.3	391.7	72
M8	540.7	439.3	81
M9	372.7	227.7	61
M10	379.7	313.3	83
M11	378.7	298.0	79
M12	384.3	306.7	80

The individual values of ITS_d for tests on the 12 mix combinations were found to be in the range of 314–561 kPa. When, replicate specimens were subjected to wet conditioning, the individual ITS_w value was found varied between 202 kPa and 498 kPa. It may be observed in these tests, variations in ITS_d of modified mixes were in the range of 0.96–1.16 times that of mixes without modifiers. Similarly, variations in ITS_w of modified mixes were in the range of 0.97–1.82. According to ASTM D 7064, the TSR of PFC mixes should be at least 80%, so as to ensure resistance to moisture susceptibility. The modified and unmodified mixes corresponding to gradation-G1 satisfied this requirement, while, mixes of gradations-G2 and G3 failed to satisfy the requirement, except in the case of M8, M10 and M12.

5.5. Statistical analysis

In order to determine the significance of main effects of modifiers (MF) used and gradations (G), and interaction of modifiers and gradations (MF×G), the test for analysis of variance (ANOVA) was performed using MINITAB® (Release 15, trial version). The details of the *F*-static corresponding to each source of variation on each property obtained using the ANOVA test, while F_0 values correspondent to the respective degree of freedom (DF) and 95% confidence interval ($\alpha = 0.05$) are presented in Table 5. If $F > F_0$, then it indicates that each source of variation will have a significance effect on the mean value. In order to identify the specific differences among the mean values, the Tukey's tests were conducted for 95% simultaneous confidence intervals.

Based on the results of the ANOVA and the Tukey's tests, the following inference can be made:
- the effect of modifiers (MF) on AAL and ITS_d were not significant;
- the interaction of modifiers and gradations (MF×G) on the G_{mb}, V_a, AAL, ITS_d, and the ITS_w were not significant;
- the mean G_{mb} and the mean V_a values of mixes corresponding to CF were found to be different from that of mixes without modifiers and also, of mixes with WP;
- the mean *K* values of mixes with CF were found to be significantly lower when compared to that of other mixes;
- the mean ITS_w values of modified mixes were significantly higher when compared to that of mixes without modifiers;
- except the mean values of ITS_d, the mean values of G_{mb}, V_a, *K*, and ITS_w of the mixes corresponding to the gradation G1 and G2 remained the same.

6. Conclusions

The laboratory studies were conducted on PFC mixes with and without modifiers with view to reuse the WP in road constructions. The experiment results corresponding to different properties of PFC mixes were statistically analysed. In addition to the inferences of ANOVA and Tukey's tests, the following conclusions are made.

It was found that the use of CFL and CFP contributed in improving moisture susceptibility but resulted in reduced air voids content and lower permeability.

Table 5. F-statistics from ANOVA test

Parameter	Source	DF	Adj. SS	Adj. MS	F_0	F	P	R^2	Adj. R^2
G_{mb}	MF	3	0.0085602	0.0028534	3.01	7.18	0.001		
	G	2	0.0125927	0.0062963	3.40	15.85	0.000		
	$MF \times G$	6	0.0038284	0.0006381	2.51	1.61	0.189	72.38%	59.72%
	Error	24	0.0095327	0.0003972					
V_a	MF	3	11.7222	3.9074	3.01	6.20	0.003		
	G	2	17.1717	8.5858	3.40	13.63	0.000		
	$MF \times G$	6	6.3328	1.0555	2.51	1.68	0.170	69.98%	56.22%
	Error	24	15.1133	0.6297					
K	MF	3	6619.6	2206.5	3.01	15.07	0.000		
	G	2	9161.6	4580.8	3.40	31.29	0.000		
	$MF \times G$	6	5051.8	842.0	2.51	5.75	0.001	85.57%	78.96%
	Error	24	3513.3	146.4					
AAL	MF	3	81.66	27.22	3.01	1.93	0.151		
	G	2	545.81	272.90	3.40	19.36	0.000		
	$MF \times G$	6	54.82	9.14	2.51	0.65	0.691	66.86	51.66%
	Error	24	338.25	14.09					
ITS_d	MF	3	32 915	10 972	3.01	5.64	0.005		
	G	2	125 331	62 665	3.40	32.19	0.000		
	$MF \times G$	6	10 765	1794	2.51	0.92	0.497	81.81%	73.47%
	Error	24	46 715	1946					
ITS_w	MF	3	639	213	3.01	0.15	0.930		
	G	2	153 154	76 577	3.40	53.33	0.000		
	$MF \times G$	6	1220	203	2.51	0.14	0.989	78.35%	68.42%
	Error	24	34 465	1436					

Note: Adj. *SS* – adjusted sum of squares; Adj. *MS* – adjusted mean square; *P* – *p*-value

While, the mixes modified with WP exhibited improved moisture susceptibility with no significant reduction in the air voids content and the permeability.

Thus, WP can be effectively reused as a modifier to PFC mixes. This will enable to consume nearly about 20–35 kg of WP/100 m^2 area of PFC surfacing for a thickness varying between 25–40 mm.

Acknowledgements

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