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Effects of Geometrically Cubical Shaped Aggregate on the Engineering Properties of Porous Asphalt

(Kesan Agregat Berbentuk Kubus Secara Geometri ke Atas Sifat Kejuruteraan Asfalt Berliang)

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ABSTRACT

Porous asphalt (PA) is predominantly made up of coarse aggregates. The coarse aggregate is instrumental in providing the strength and stability of the mix. The aggregate properties including shape is expected to greatly influence the performance of PA. In this study, five different proportions of geometrically cubical shaped (GCS) aggregate and normal shape aggregate combinations were introduced and designated as mix M0, M25, M50, M75 and M100. Further laboratory tests were carried out to determine the properties of PA including air voids, coefficient of permeability, abrasion loss, indirect tensile strength, resilient modulus and resistance to permanent deformation. The results obtained showed that mix M100 which consists of 100% GCS aggregate performed the best in all tests. Statistical analyses of one-way ANOVA and Duncan's Post Hoc test results showed that the introduction of GCS aggregate has a significant effect on air voids, coefficient of permeability, abrasion loss and resistance to permanent deformation of the mixes. However, the results showed that GCS aggregate do not gave significant effect on indirect tensile strength and resilient modulus of the PA mixes tested.

Keywords: Abrasion loss; air voids; geometrically cubical aggregate; indirect tensile strength; permanent deformation; permeability; porous asphalt; resilient modulus

ABSTRAK

Asfalt berliang (PA) kebanyakannya terdiri daripada agregat kasar. Agregat kasar memainkan peranan penting dalam membekalkan kekuatan dan kestabilan campuran. Ciri agregat termasuk bentuk agregat, dijangka mempengaruhi prestasi campuran PA. Dalam kajian ini, lima peratusan kandungan berbeza agregat geometri berbentuk kubik (GCS) dan kombinasi agregat berbentuk normal telah dikaji dan dinamakan sebagai campuran M0, M25, M50, M75 dan M100. Ujian makmal telah dijalankan untuk menentukan sifat PA termasuk lompang udara, pekali kebolehtelapan, kehilangan lelasan, kekuatan tegangan tidak langsung, modulus kebingkasan dan rintangan terhadap ubah bentuk kekal. Keputusan yang diperoleh menunjukkan bahawa campuran M100 yang terdiri daripada 100% agregat GCS adalah yang terbaik bagi semua ujian yang dijalankan. Analisis statistik ANOVA sehala dan ujian Duncan Post Hoc menunjukkan bahawa agregat GCS memberikan kesan yang besar terhadap lompang udara, pekali kebolehtelapan, kehilangan lelasan dan rintangan kepada ubah bentuk kekal campuran PA. Walau bagaimanapun, keputusan menunjukkan bahawa agregat GCS tidak memberi kesan yang signifikan terhadap kekuatan tegangan tidak langsung dan modulus kebingkasan campuran PA yang diuji.

Kata kunci: Agregat berbentuk kubus secara geometri; asfalt berliang; kebolehtelapan, kehilangan lelasan; kekuatan tegangan tak langsung; modulus kebingkasan; rongga udara; ubah bentuk kekal

INTRODUCTION

The highway construction industries consume a huge amount of aggregates annually causing considerable loss of depleting raw material. The aggregates are usually produced by blasting and crushing of naturally occurring rock mass in quarries or from other natural sources. As a result of the increasing demands for new aggregate, the general texture of earth's surface has been steadily deteriorating, causing environmental concerns (Akbulut & Gürer 2007). One way to reduce the consumption of naturally occuring aggregate is by design and construction of more durable, if not, long lasting or perpetual pavements.

According to Singh et al. (2013), the significant amount of aggregates used, their shape characteristics, namely angularity, texture, two-dimensional (2D) form and sphericity (3D form) have a direct influence on the asphalt performance and service ability. The 2D form represents the overall shape of a particle, whereas the 3D characteristics of a particle are captured using sphericity measurements. Kandhal and Mallick (2001)mentioned that the rough-textured surfaces result in stronger mixes by providing more friction between aggregate particles. Similarly, angular aggregates provide better interlock, consequently increasing the rut resistance.

Arasan et al. (2011) pointed out that the importance of the shape of aggregate particles on their mechanical behaviour of bituminous materials is well recognized. In asphalt concrete, the shape of aggregate particles affects the durability, workability, shear resistance, tensile strength, stiffness, fatigue response and optimum binder content of the mixture. The research investigated the shape characteristics such as aspect ratio, elongation, flatness, form factor, roundness, shape factor and sphericity. The test results indicated that there is a good correlation between some shape indexes of aggregate and asphalt concrete properties.

Among road surfacing materials available, PA is the most effective material to mitigate hydroplaning, improves visibility during wet weather and mitigating traffic noise. Unfortunately, the performance of PA is hampered by its poor resistance to disintegration and raveling. The service life of PA in general, depends predominantly on its air voids. The more possibilities for oxidation, as in the case of high air voids mix, the less durability can be achieved (Choubane et al. 1998). It can be expected that the service life of PA pavement is shorter than that of an impermeable pavement due to deterioration by runoff, air infiltration, and subsequent stripping and oxidation, as well as hardening of the binder (Mallick et al. 2003).

Porous asphalt (PA) is predominantly made up of coarse aggregate which provides the much needed strength and stability of the mix. The aggregate properties including shape is expected to greatly influence the performance of PA. This paper attempted to evaluate the use of GCS aggregates to improve performance of PA mix in terms of permeability, abrasion loss, indirect tensile strength, resilient modulus and rutting.

MATERIALS AND METHODS

Two granite aggregate used were normal shaped (NS) aggregate and GCS aggregate. Hydrated lime was the filler type used in quantity not more than 2.0%. The conventional bitumen penetration grade 60/70 used was supplied by PETRONAS. The aggregate and binder properties have been tested and the results are shown in Table 1.

The aggregate gradation used was similar to the grading developed by Mohd Hasan et al. (2012). This gradation was based on the Dutch porous asphalt standard mix PA16 but modified to suit local standard sieve sizes. The aggregate gradation incorporated a gap between sieve sizes 2.36 to 5.00 mm and graphically presented in Figure 1.

The mixing and compaction temperatures were determined using the Brookfield Viscometer in accordance with the Asphalt Institute (2007) procedures. The mixing and compaction temperatures adopted were 165°C and 155°C, respectively, corresponding to binder viscosities 0.17±0.02 and 0.28±0.03 Pa.s. All raw materials and

TABLE 1. Aggregate and binder properties

Material	Standard	Properties	Value
100% Geometrical cubical shape aggregates	BS EN 812	Elongation index	10.9%
	BS EN 812	Flakiness index	6.1%
	BS EN 812	Aggregate crushing value	16.3%
	BS EN 812	Aggregate impact value	17.9%
100% Normal shape aggregates	BS EN 812	Elongation index	24.4%
	BS EN 812	Flakiness index	21.6%
	BS EN 812	Aggregate crushing value	20.3%
	BS EN 812	Aggregate impact value	23.7%
Bitumen 60/70	ASTM D5-97	Penetration at 25°C (× 0.1 mm)	63
Pen. Grade	ASTM D36-95	Softening Point	49°C
	ASTM D11	Ductility at 25°C	>100 cm
Hydrated lime	ASTM C110	Specific Gravity	2.350

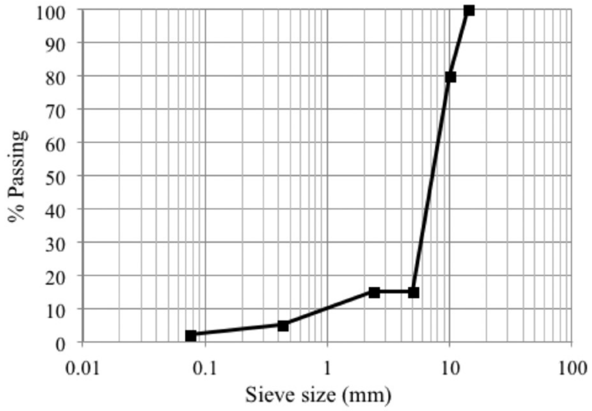

FIGURE 1. Modified Dutch gradation incorporating a gap in the fine aggregate gradation

equipments were heated to the mixing temperature prior to mixing. Then, the specimens were compacted by applying 50 blows on each face using the standard Marshall hammer. However, compaction of specimens for the wheel tracking test was accomplished by applying 100 gyrations of the gyratory compactor.

Four different proportions of GCS aggregate mixture and a mixture with 100% NS aggregate were prepared. The aggregates proportions are shown in Table 2 which also shows the mix designations. Mixes are designated based on the proportion of GCS aggregate used. Thus, mix M25 refers to a mixture incorporating 25% GCS and 75% NS aggregates.

The design binder content of the proposed aggregate mix combination was determined based on the binder drainage and Cantabro testing results. The design binder content was equivalent to the mean value of the upper and lower limits obtained from both 0.3% of binder drainage and 18% of abrasion loss values, respectively. The design binder contents of each aggregate mix combinations are shown in Table 2. The GCS aggregate exhibits lower surface area, hence require less bitumen to coat.

LABORATORY TESTS

The specimens were tested for volumetric properties, permeability, abrasion loss, indirect tensile strength, resilient modulus and wheel tracking tests. Permeability tests on un-extruded sample were conducted using a falling head water permeameter. The permeability test measured the time taken for a fixed volume of water to permeate through a specimen. The coefficient of permeability was calculated using the following equation:

$$k = 2.3\frac{aL}{At}\log_{10}\left(h1/h2\right), \qquad (1)$$

where k is the coefficient of permeability (cm/s), A is the cross section area of specimen(cm^2), a is the cross section area of standpipe (cm^2), L is the height of specimen (cm), t is the time taken for water in the standpipe to fall from h_1 to h_2 (s), h_1 is the head at the beginning of time measurement (cm) and h_2 is the head at the end of time measurement (cm).

The Cantabro test was conducted according to BS EN 12697-17 (BSI 2004) procedures. The test simulated the impact and friction at the pavement-tyre interface. The test involved subjecting a Marshall specimen to 300 rotations at 30 to 33 revolutions per min in the Los Angeles drum without steel balls. The abrasion loss was expressed in terms of percentage of mass loss after drum rotations relative to its original mass.

The indirect tensile strength (ITS) test is used to assess the cracking potential of an asphalt mix. The test was carried out at 25°C according to ASTM D4123 (ASTM 2005a) procedures. According to Nunn and Smith (1996), the elastic indirect tensile stress modulus is a measure of its resistance to bend and hence of its load spreading ability.

The resilient modulus test was conducted in the indirect tension loading mode at 25°C according to ASTM D4123-82 (ASTM 2005b) procedures. During the test, approximately 10 to 15% of compressive load of the ITS were applied vertically on the vertical diametrical plane of the cylindrical PA specimen. The specimen was then rotated 90 degree for the second testing to obtain an average value for the resilient modulus of the specimen.

The wheel tracking test evaluated the rutting behaviour of the specimens. The test was conducted on immersed specimens at 35°C using the Hamburg wheel tracking machine. The test procedures were conducted according to a British Standard BS EN 12697-22 (BSI 2003) on cylindrical specimens of 150 mm diameter.

EFFECTS OF GEOMETRICALLY CUBICAL SHAPED AGGREGATE

AIR VOIDS

The effect of GCS aggregate on the air voids of PA mixes is graphically presented in Figure 2. The mean air voids for mixes M0, M25, M50, M75 and M100 are 19.83, 19.97, 20.47, 20.54 and 21.44%, respectively. The results indicated that mix M0 and M100 has respectively the lowest and highest air voids. In addition, the results also showed that the air voids increase as the proportion of GCS aggregate increases. Introducing GCS aggregates creates more stone on stone contact between aggregate's faces. This creates more faces that are in contact with air hence producing more air voids. A sketch of the stone on stone contact of aggregates are shown in Figure 3.

The results are then statistically interpreted using ANOVA with a confidence level of 95% (α = 0.05) and further analysed using Duncan's post hoc test analysis. The results are shown in Table 3. From the statistical analysis, the p-value is less than 0.05 which indicates that the means

TABLE 2. Aggregate mix proportion and designation

Mix designation	Geometrically cubical aggregates proportion (%)	Normal shape aggregate proportion (%)	Design binder content (%)
M0	0	100	5.39
M25	25	75	5.24
M50	50	50	5.09
M75	75	25	4.93
M100	100	0	4.78

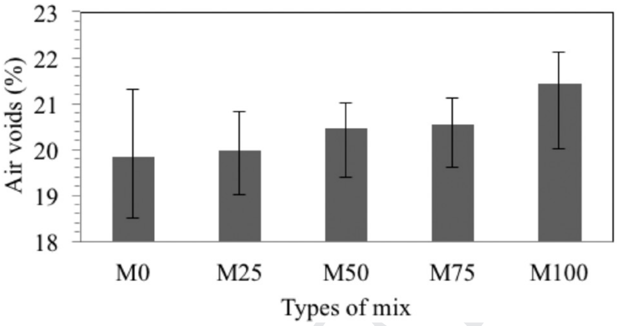

FIGURE 2. Air voids results of mixes tested

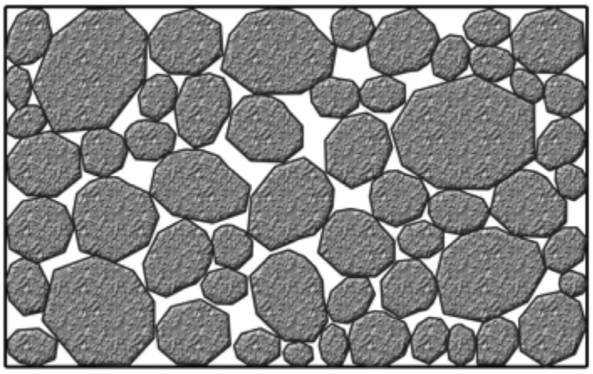

FIGURE 3. Sketch of stone on stone contact of GCS aggregates

TABLE 3. One-way ANOVA and Duncan's post hoc analysis on effects of air voids

Source	DF	Sum of squares	Mean square	F	*p*-value
Types of mix	4	9.701	2.425	4.46	0.007
Error	25	13.602	0.544		
Total	29	23.303			

Duncan's post hoc

Mix	Group 1	Group 2
M0	19.8267	21.4433
M25	19.9667	
M50	20.4717	
M75	20.5367	
M100		

of specimens is significantly different and therefore GCS aggregate has an effect on air voids. Compared with all other mix combinations, mix M100 exhibits the highest mean air voids.

COEFFICIENT OF PERMEABILITY

The effect of GCS aggregate on the coefficient of permeability is presented in Figure 4. The mean coefficient of permeability for mixes M0, M25, M50, M75 and M100 are 0.153, 0.220, 0.258, 0.307 and 0.379 cm/s, respectively. Mixes M0 and M100 exhibit the lowest and highest coefficient of permeability, respectively. In addition, the coefficient of permeability increases linearly with the proportion of GCS aggregate. Increasing GCS aggregate proportion increases air voids, which subsequently increases the specimen drainage capability.

The test result is also investigated statistically using one-way ANOVA and Duncan's post hoc test analysis. The results are shown in Table 4. The results showed that the *p*-value obtained is less than 0.05 and therefore the mean of the specimen is significantly different. This shows that the proportion of GCS aggregate has a significant effect on the mix coefficient of permeability. The test result of Duncan's post hoc test analysis showed that the highest mean coefficient of permeability 0.379 cm/s occurs at mix M100, while the mean coefficient of permeability of mixes M75 and M100 is not significantly different.

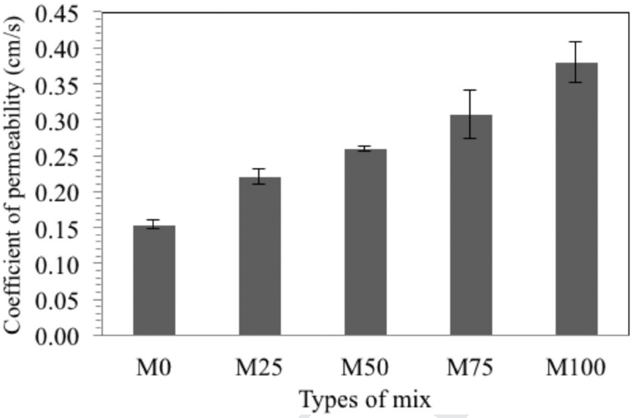

FIGURE 4. Coefficient of permeability results of mixes tested

TABLE 4. One-way ANOVA and Duncan's post hoc analysis on effects of coefficient of permeability

Source	DF	Sum of squares	Mean square	F	*p*-value
Types of Mix	4	0.05905	0.01476	18.11	0.004
Error	5	0.00408	0.00082		
Total	9	0.06413			

Duncan's post hoc

Mix	Group 1	Group 2	Group 3	Group 4
M0	0.1525			
M25	0.2195	0.2195		
M50		0.2575	0.2575	
M75			0.307	0.307
M100				0.379

ABRASION LOSS

The effect of GCS aggregate on the abrasion loss of PA mixes is shown in Figure 5. The mean abrasion loss for mixes M0, M25, M50, M75 and M100 are 3.21, 2.74, 2.23, 2.00 and 1.86%, respectively. The results showed that the abrasion loss decreases almost linearly with the proportion of GCS aggregates. Mixes M100 and M0, respectively, exhibit the lowest and highest abrasion loss. This implies that mix M100 is the most resistant to impact and disintegration. This may be attributed to better toughness properties of the GCS aggregates and the buildup of a more stable aggregate matrix by the GCS aggregate.

Then, statistical analyses are conducted on the test result. The result of the one-way ANOVA and Duncan's post hoc test analysis are presented in Table 5. The one-way ANOVA analysis showed the type of mix that has effect on the abrasion loss of the mixes with the *p*-value of 0.038. The Duncan's Post Hoc test showed the mean abrasion loss between mixes M100, M75, M50 and M25 is not significantly different. Therefore, the results showed that by replacing the normal shaped aggregates in PA mix with at least 50% or more of GCS aggregate, can potentially improve its resistance to abrasion loss.

INDIRECT TENSILE STRENGTH

The effect of GCS aggregate on the ITS results is shown in Figure 6. The mean ITS values for mixes M0, M25, M50, M75 and M100 are 764, 771, 776, 778 and 779 N/mm^2, respectively. The results showed that these ITS values do not differ significantly. Though mix M100 exhibits the highest ITS, the percentage difference between the highest and lowest values is less than 2%.

The detailed ANOVA result is shown in Table 6 with *p*-value equals to 0.948. Therefore, the mean of the specimen is not significantly different and the incorporation of GCS aggregate into PA has no effect on its ITS. In the ITS test, the aggregate matrix is subject to an indirect tensile force. The strong aggregate matrix build-up by the GCS aggregate appears to be less beneficial to resist tensile forces.

RESILIENT MODULUS

The effect of GCS aggregate on the stiffness of PA mixes is shown in Figure 7. The results showed an approximately similar trend as the test result of ITS. The mean resilient modulus for mixes M0, M25, M50, M75 and M100 are 1996.25, 2140.75, 2210.50, 2248.50 and 2281.50 MPa,

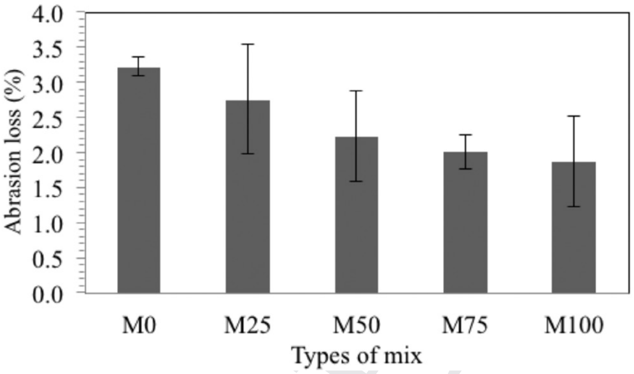

FIGURE 5. Cantabro test results of mixes tested

TABLE 5. Result of one-way ANOVA and Duncan's post hoc analysis on abrasion loss

Source	DF	Sum of squares	Mean square	F	*p*-value
Types of Mix	4	3.565	0.891	5.994	0.038
Error	5	0.743	0.149		
Total	9	4.308			
		Duncan's post hoc			
Mix	Group 1	Group 2			
M100	1.86				
M75	2.00				
M50	2.23				
M25	2.74	2.74			
M0		3.21			

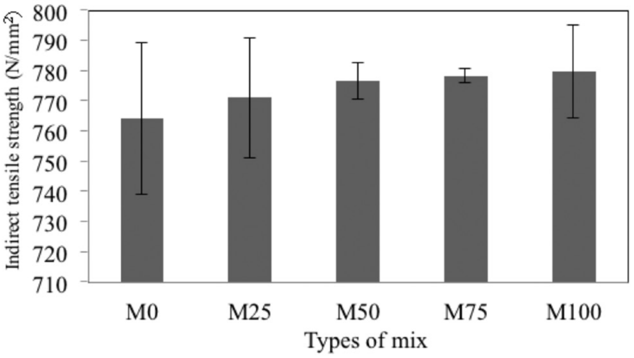

FIGURE 6. ITS test results of mixes tested

TABLE 6. One-way ANOVA effects of mix types on ITS

Source	DF	Sum of squares	Mean square	F	*p*-value
Types of Mix	4	336.69	84.17	0.164	0.948
Error	5	2573.71	514.74		
Total	9	2910.4			

respectively. The mix resilient modulus slightly improves as the proportion of GCS aggregate increases which indicates incorporation of cubically shape aggregate may result in stiffer PA mixtures. However, this improvement is not statistically significant as evidenced from the ANOVA statistical analysis results shown in Table 7.

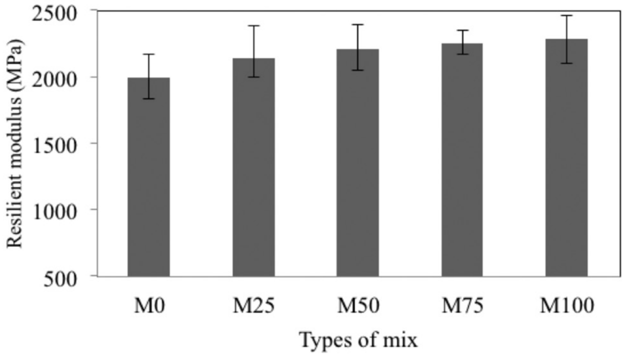

FIGURE 7. Resilient modulus test results of mixes tested

TABLE 7. One-way ANOVA on resilient modulus result

Source	DF	Sum of squares	Mean square	F	*p*-value
Types of Mix	4	204513	51128	2.33	0.103
Error	15	328449	21897		
Total	19	532961			

RESISTANCE TO PERMANENT DEFORMATION

The curves depicting the development of rutting as a function of number of wheel passes are shown in Figure 8. The results showed the rut development curves exhibits the same trends but to a different extent depending on the proportion of GCS aggregate incorporated in the mix. Since the wheel tracking test was carried out up to 20000 passes, the rutting curves can be divided into two stages. During the early stage, the rut development is exceptionally high. This stage of rutting is attributed to over-compaction of the specimen along the tracked path. In the second stage, the rutting appears to increase linearly with the number of wheel passes. Rutting at this stage is due to the re-orientation of aggregate matrix into a progressively more stable mass. Permanent deformation due to specimen over-compaction is described as short term rutting, while rutting due to re-orientation of the aggregate matrix is analyzed as rutting that takes place in the long term after the onset of short term rutting.

The short and long term resistances to permanent deformation of the mixes are evaluated based on four parameters; namely wheel tracking rate (WTR), rut depth (RD), proportional rut depth (PRD) and dynamic stability (DS). WTR refers to the mean increase in rut depth obtained from the slope of the lines at the rutting curve using statistical linear regression analysis with a coefficient of determination (R^2) above 95%. The results obtained for short term and long term WTR are reported in Table 8. Steeper slopes indicate mixtures that are more susceptible to rutting. The results showed that the rate of rutting reduces with proportion of GCS aggregates in both instances. Mix M100 is the least susceptible to rutting with short term and long term WTRs equivalent to 0.00020 and 0.000044 mm/passes, respectively.

The performance of short term and long term rutting resistance is further investigated based on RD and PRD. The average RD and PRD for short term and long term rutting of the specimens are also shown in Table 8. In both instances, mix M100 is the most resistant to permanent deformation. The results showed that the short term and long term PRD for the least rut resistant mix M0 are the highest at 2.9 and 7.9%, respectively. The corresponding values for the most rut resistant mix M100 is 1.6 and 3.9%, respectively.

The DS of the mix is determined from the rut development curve. DS is defined as the number of wheel passes to induce 1 mm permanent deformation during the steady state. The effects of GCS aggregates on the DS of PA mixes are presented in Figure 9. The results indicated that the DS increases with the proportion of GCS aggregate. Mix M100 exhibits the highest DS value of 9920 passes/mm which is almost double the DS value of mix M0. Therefore, this indicates mix M100 is most resistant towards plastic deformation.

The wheel tracking test results analyzed in terms of WTR, RD, PRD and DS consistently indicate that mix M100 is least susceptible to short term and long term rutting. This is due to the stable skeleton of stone on stone contact of aggregate of mix M100 that gives an excellent resistance to rutting.

The results are then statistically interpreted using ANOVA with a confidence level of 95% ($\alpha = 0.05$). The results of one-way ANOVA are shown in Table 9. The statistical analysis showed that the *p*-value for the DS, RD and PRD for short term rut resistance and long term rut resistance is less than 0.05. This indicates that the means of mixes are significantly different. Therefore, the introduction of GCS aggregate into PA has considerable effects on DS, RD and PRD for short-term and long-

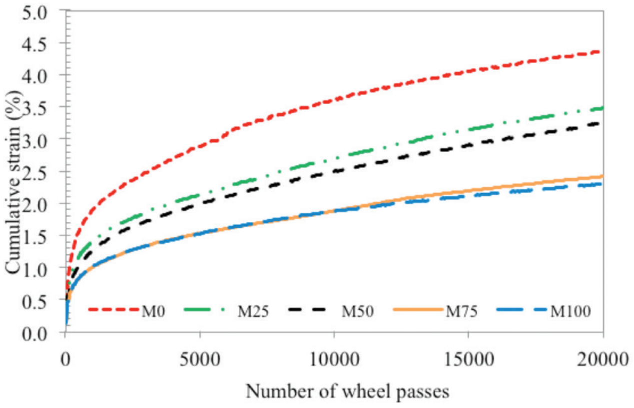

FIGURE 8. Rut development curves for mixes with different proportions of CGS aggregate in mix

TABLE 8. Coefficients of the linear relationships between short term and long term rut depth and number of wheel passes

Types of mix	STWTR* (mm/passes)	R^2	PRD** (%)	RD*** (mm)
Short term				
M0	RD=0.00040WP+1.48	0.9872	2.9	1.709
M25	RD=0.00033WP+1.10	0.9882	2.2	1.277
M50	RD=0.00031WP+0.94	0.9888	1.9	1.134
M75	RD=0.00022WP+0.77	0.9917	1.8	1.010
M100	RD=0.00020WP+0.78	0.9887	1.6	0.913
Long term				
M0	RD=0.000078WP+2.91	0.9917	7.9	4.683
M25	RD=0.000076WP+1.96	0.9924	5.7	3.342
M50	RD=0.000074WP+1.77	0.9964	5.0	2.912
M75	RD=0.000054WP+1.39	0.9901	4.2	2.409
M100	RD=0.000044WP+1.47	0.9951	3.9	2.306

*Short Term Wheel Tracking Rate; ** Proportion Rut Depth; ***Rut Depth

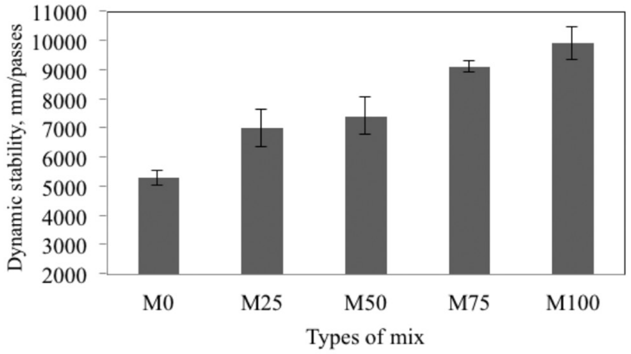

FIGURE 9. Dynamic stability of mixes

TABLE 9. One-way ANOVA on short term and long term rut resistance test results

Test condition	Evaluated parameter	*p*-value
Short term	Wheel tracking rate	<0.001
	Rut depth	0.03
	Proportional rut depth	0.039
Long term	Wheel tracking rate	0.023
	Rut depth	0.001
	Proportional rut depth	<0.001
	Dynamic stability	0.015

TABLE 10. Duncan's post hoc test analysis on short term, long term and dynamic stability of mixes

Mix type	WTR*			RD**			PRD***		
Groups	1	2	3	1	2	3	1	2	3
				Short term					
M100	0.0002			0.913			1.55		
M75	0.0002			0.903			1.60		
M50		0.0003		1.134			1.95		
M25		0.0003		1.278	1.278		2.20	2.20	
M0			0.0004		1.709			2.90	
				Long term					
M100	0.00004			2.245			3.90		
M75	0.00005	0.00005		2.290			4.10		
M50		0.00007	0.00007		3.080			5.30	
M25			0.00007		3.415			5.90	
M0			0.00007			4.195			7.25
				Dynamic stability					
Mix	Group 1	Group 2	Group 3						
M0	5274.5								
M25	7005.0	7005.0							
M50	7401.5	7401.5							
M75		9111.5	9111.5						
M100			9920.0						

term rutting. The experimental data is further analyzed statistically using Duncan's post hoc test analysis as shown in Table 10. Generally, the results of Duncan's post hoc test analysis indicate mix M100 is the most resistance to permanent deformation.

CONCLUSION

The effects of GCS aggregate on the performance of PA mixes were assessed from the air voids, coefficient of permeability, abrasion loss, indirect tensile strength, resilient modulus, and resistance to permanent deformation. Analysis of the results showed that mix M100 which consists of 100% GCS aggregate, performed the best in all the test parameters.The statistical analysis results obtained indicate that the GCS aggregate significantly affect air voids, coefficient of permeability, abrasion loss and resistance to permanent deformation of the PA mix. The strong aggregate matrix buildup by the GCS aggregate appears to be less beneficial to resist tensile forces. This is evident when the incorporation of GCS aggregate did not significantly affect the indirect tensile strength and resilient modulus of the PA mixes tested.

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