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THE USE OF MIXED WASTE RECYCLED PLASTIC AND GLASS AS AN AGGREGATE REPLACEMENT IN ASPHALT MIXTURES

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Graphical abstract

Abstract

One of the major problems with landfills is that they contain a large amount of solid wastes. Waste plastics and glasses contribute greatly to this problem, and these materials need to be managed or recycled to extend the life of landfill sites. Hence, this study was conducted to investigate the feasibility of using these waste materials in asphalt mixtures for pavement applications. Various types of recycled waste plastics and glasses were selected for this study and the mix containing these materials was designed by the Marshall method. Three types of glass were used: bottle glass, liquid-crystal display (LCD) glass, and sheet glass. In terms of the total weight of the asphalt mixtures, approximately 5% constituted of recycled materials used as an aggregate replacement. In this study, asphalt mixtures were aged in the laboratory to simulate the site conditions of short-term and long-term ageing. After the ageing process, samples were tested for asphalt mixture performance characteristics in terms of the following parameters: Marshall Stability and Flow, Marshall Quotient and resilient modulus. It was found that the replacement combining 1% recycled plastic and 4% recycled glass shows almost similar and satisfactory results compared to the control sample for all tests. Therefore, recycled plastic and recycled glass, when optimally blended, can be considered feasible to be used as an aggregate replacement in asphalt mixtures for flexible road pavements.

Keywords: Asphalt mixture, recycled glass, recycled plastic, ageing, resilient modulus

Abstrak

Salah satu masalah utama di tapak pelupusan adalah sisa pepejal yang dibuang adalah di dalam kuantiti yang agak banyak. Sisa plastik dan kaca paling banyak menyumbang kepada masalah ini dan bahan-bahan ini perlu diurus atau dikitar semula untuk memanjangkan hayat tapak pelupusan. Oleh itu, kajian ini telah dijalankan untuk mengkaji keberkesanan penggunaan bahan-bahan buangan di dalam campuran berasfalt untuk aplikasi turapan Jalan raya. Pelbagai jenis kaca dan plastik kitar semula telah dipilih di dalam kajian ini dan campuran yang mengandungi bahan-bahan ini telah direkabentuk menggunakan kaedah Marshall. Tiga jenis kaca iaitu: kaca botol, kaca *liquid-crystal display* (LCD) dan lembaran kaca dan plastik kitar semula telah digunakan. Dari segi jumlah berat campuran berasfalt, sekitar 5% merupakan bahan kitar semula yang telah digunakan sebagai pengganti agregat. Dalam kajian ini, campuran asfalt mengalami proses penuaan di makmal untuk mensimulasikan keadaan tapak untuk penunaan jangka pendek dan penuaan jangka panjang. Selepas proses penuaan, sampel telah diuji untuk ciri-ciri prestasi campuran asfalt dari segi parameter berikut: Marshall Kestabilan dan Aliran, Marshall Quotient, modulus kebingkasan dan rayapan dinamik. Didapati bahawa penggantian yang menggabungkan 1% plastik kitar semula dan 4% kaca kitar semula menunjukkan keputusan yang hampir sama dan memuaskan berbanding dengan sampel kawalan untuk semua ujian. Oleh itu, plastik dan kaca yang dikitar semula, apabila dicampur secara optimum, boleh digunakan sebagai pengganti agregat dalam campuran asfalt untuk turapan jalan raya boleh lentur.

Kata kunci: Campuran asfalt, kaca kitar semula, plastik kitar semula, penuaan, modulus kebingkasan

1.0 INTRODUCTION

Nowadays, the amount of solid waste that dumped into the landfill was rapidly increased. For example, the developing country like Malaysia produces over 23,000 tonnes of waste daily and less than 5% of waste is currently recycled. Hence, approximately 1,150 tonnes of waste, including plastic, metal, paper, and glass, are collected for recycling every day [1]. However, Al-Salem *et al*. [2] in their paper presented various recycling technologies for solid waste. They indicated that glass and plastic waste can be used as a secondary aggregate in mixtures for asphalt pavements, providing better dynamic behaviour, which will allow the pavements to withstand heavy traffic in the long term. Modarres and Hamedi [3] claimed that the addition of pieces of waste plastic bottles in asphalt mixtures improves the fatigue behaviour of the mixtures. This indicates that the modified mixtures will improve the ability of the pavement to enhance resistance to cracking and will exhibit higher flexibility than conventional mixtures. However, they also found that the resilient modulus decreases when the amount of waste plastic bottle material added is greater than 2%. In addition, the volume of the total mixture will increase as waste plastic is added in mixtures used for bituminous road construction [4].

Earlier, Airey *et al*. [5] reported that compared to control samples, the stiffness modulus of an asphalt mixture containing glass cullet and an anti-stripping agent increases even after four moisture conditioning cycles, although the use of this mixture does lead to an increase in moisture susceptibility. Without the use of an anti-stripping agent, the binding strength between the glass particles and binder is weak. Su and Chen [6] recommended the addition of 2% lime to overcome this shortcoming. When a greater amount of lime is used, stronger deformation resistance can be produced in glass asphalt mixtures. They also stated that the required binder content varies according to the amount of recycled glass used and that less bitumen content is required when more glass is added to the asphalt mixture.

Arabani *et al*. [7] indicated that glass particles with greater angularity can increase the fatigue life of an asphalt pavement because the glasphalt creates a higher internal friction angle, improving the interlocking between different constituent particles. However, some problems can occur, such as inadequate friction and bonding strength when larger glass particles or a greater proportion of glass particles are used. Wu *et al*. [8] reported that increasing the amount of glass replacement leads to a decrease in the indirect tensile strength. Therefore, the appropriate amount of recycled glass to be used should be determined so that a good quality asphalt mixture can be produced. Ghasemi and Marandi [9] found that rutting parameters, stiffness, and thermal sensitivity are improved with the addition of recycled glass powder. Recently, Navarro *et al*. [10] showed that the reuse of waste glass as a substitute for the sand fraction in low dosages (8%) produced asphalt mixtures with mechanical properties that were suitable for road surfaces courses.

In addition to waste glass, many countries are seriously encountered with problems related to waste plastic materials as well. The presence of recycled waste plastic in asphalt mixture has a higher stability, reduced pavement deformation; increase fatigue resistance and provide better adhesion between the asphalt and the aggregate [11]. Moghaddam *et al*. [12] compared the stiffness and fatigue properties of recycled plastic modified asphalt mixtures with conventional mixture. The presence of 1% of plastic improves the fatigue life of modified asphalt mixtures compared to the control sample. However, the stiffness of modified mix was to some extent lower than conventional mixture. A study done by Ahmadinia *et al*. [11] found that the addition of recycled plastic to bitumen or asphalt mixture enhances the material rigidity and restricts the permanent deformations under heavy loading conditions particularly in upper pavement layers at higher temperatures. Modarres and Hamedi [3] found that the stiffness of recycled plastic modified mixture was acceptable and warranted the proper deformation characteristics of those mixtures at heavy loading conditions. At 5 and 25 °C, recycled plastic improved the fatigue behavior of studied mixtures.

Waste plastics and glasses contribute greatly to the problem of solid wastes in landfills, and these materials need to be managed or recycled to extend the life of landfill sites. However, most of the previous studies used asphalt mixtures containing either recycled glass or plastic separately. Therefore, this study was conducted to investigate the feasibility of using recycled glass and recycled plastic as an aggregate replacement in asphalt mixtures by using a dry process. Various percentages of the recycled materials, ranging from 0% to 5% by weight of the total mixture were used in this study. All the prepared samples were subjected to Marshall Stability and Flow, Marshall Quotient, resilient modulus and dynamic creep tests under unaged, short-term ageing, and long-term ageing conditions.

2.0 METHODOLOGY

Materials

The base binder used in this study was a 60/70 penetration grade bitumen, supplied by a factory at Port Klang, Malaysia. Table 1 lists the physical properties of the binder. It was found that the physical properties of the bitumen followed the minimum requirements as compared to the standard specifications as in Table 1.

Table 1 Physical properties of 60/70 penetration grade bitumen

Test	Unit	ASTM Test Method	Specification	Result
Specific Gravity @ 25°C	-	D-70	1.00-1.05	1.012
Penetration @ 25°C	0.1 mm	D-5	60-70	68
Softening Point	°C	D-36	47 Min	47.0
Ductility @ 25 °C. 5cm/min	Cm	D-113	100 Min	>100
Flash Point	°C	D-92	250 Min	326
Solubility in Trichloroethylene	wt.%	D-2042	99.5 Min	99.5
Wax Content	wt.%	DIN-52015	2.0 Max	1.86
Loss on heating	wt.%	D-6	0.2 Max	0.2
Penetration of Residue	% of original	D-5	75 Min	75.0
Thin Film Oven Test @ 163°C		D 1754		
Retained Penetration	%	D-5	50 Min	51
Ductility of Residue @ 25°C. 5cm/min	cm	D-113	100 Min	>100

Aggregates

The aggregates used in this study were excavated from a mine located in Kajang, in the eastern part of Selangor, Malaysia. The physical properties of the aggregates are listed in Table 2. The selected gradations of the aggregates and the specific gravity values are listed in Table 3. The specific gravity for both the coarse and fine aggregates was between 2.61 and 2.64. The aggregate gradations were selected according to ASTM D 3515-96 (D-4).

Table 2 The aggregate properties

Aggregate Test	Result (%)	Specification (%)	Method
Aggregate Crushing Value (ACV)	22.57	<30	BS EN 812 : Part 110 :1990
Aggregate Impact Value (AIV)	15.10	<30	BS EN 812 :Part 112 : 1990
Flakiness Index (FI)	6.00	<20	BS EN 812 : Section 105.1 :1989
Elongation Index (EI)	12.00	<20	BS EN 812 :Part 1: 1975
Los Angeles Abrasion Value (LAAV)	32.13	<45	ASTM C: 131-81

Table 3 The gradation of aggregates and their specific gravity (SG) values

Sieve Size	Percent Passing (%)			
	Upper Limit	Lower Limit	Design	SG (g/cm^3)
19 mm	100	90	95	2.61
9.5 mm	80	56	68	2.64
4.75 mm	65	35	50	2.64
2.36 mm	49	23	36	2.54
300 µm	19	5	12	2.53
75 µm	8	5	5	2.64
Dust	0	0	0	2.65

Recycled Materials

In addition to bitumen and the aggregates, the raw materials used in this study were lime, mixed recycled plastic, and three types of recycled glass, namely, bottle glass, LCD glass, and sheet glass, as shown in Figure 1. The recycled plastic and recycled glasses were used as the aggregate replacement in the asphalt mixtures. The gradations of the recycled materials are listed in Table 4. In this study, all available particle sizes were used to make it more convenient for commercial application and to avoid the additional cost of processing the recycled material. The different types of glass were mixed to represent the real condition of the recycled materials in landfills. The specific gravity was found to be between 2.26 and 2.64 for recycled glass, 0.95 for recycled plastic, and 2.24 for lime.

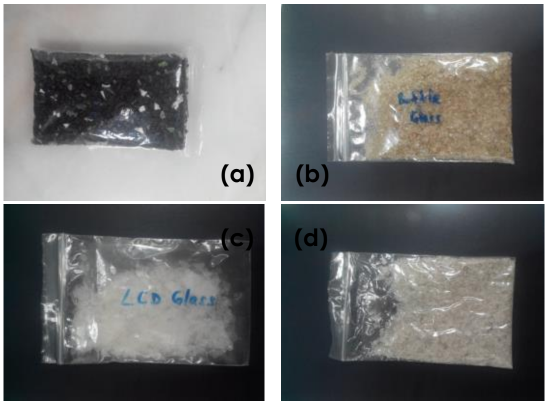

Figure 1 (a) Recycled plastic, (b) bottle glass, (c) LCD glass and (d) sheet glass

Table 4 The gradation of waste materials

Sieve Size	Percent Passing (%)			
	Bottle glass	LCD glass	Sheet glass	Plastic
19 mm	0	1	0	0
9.5 mm	0	8.96	0	0
4.75 mm	1.27	23.22	3.48	21.69
2.36 mm	37.73	26.51	29.94	75.14
300 µm	56.39	29.40	56.20	3.17
75 µm	3.54	1.37	7.56	0
Dust	1.07	9.54	2.82	0

Sample Preparation

In this study, dense-graded asphalt mixtures using conventional and modified raw materials were designed by the Marshall and Superpave methods. Three different mixture groups were prepared: a conventional asphalt mixture, which was used as the control design; asphalt mixtures containing either recycled plastic or recycled glass; and a mixture containing a combination of recycled plastic and glass. The different combinations were as shown in Table 5.

A dry process was used for sample preparation: the recycled materials were mixed with the aggregate before adding the binder. Sangita and Verinder [3] stated that because of its low specific gravity and non-uniform size, plastic was not suitable for blending with bitumen (wet process) and could not act as a modifier. In addition, lime was added during sample preparation for bonding purposes and for retaining the stripping resistance [13-15]. Some samples were prepared according to the Marshall mix design method with impact compactor used was 75 blows of hammer and the diameter of the sample is 100 mm (4 in). On the other hand, the procedures adopted to develop the Superpave specimens used in this study were in accordance with AASHTO T312 and PP-28-200 procedures. The design gyration number used was 125, the consolidation pressure was set as 600 kPa with a speed of 30 rpm, the angle of gyration was 1.25°, and the specimen diameter was 100 mm. The mixing temperature for all the samples containing recycled plastic was not allowed to exceed 140 °C to prevent the plastic from melting and coating the aggregates.

Table 5 Type of asphalt mixture

Number	Type of Samples
1	Control (without recycled materials)
2	5% glass
3	5% plastic
4	2.5% glass and 2.5% plastic
5	4% plastic and 1% glass
6	1% plastic and 4% glass

Ageing Procedures

All samples underwent mixture conditioning. For the volumetric mixture design procedure, mixture conditioning was applied to laboratory-prepared, loose mixtures only. Mixture conditioning was not required for conditioning quality control or quality assurance testing of a plant-produced mixture, which was placed in a pan and spread to an even thickness ranging between 25 and 50 mm. The pan containing the mixture was placed in a forced-draft oven for 2 h ± 5 min at a temperature equal to the mixture's compaction temperature ± 3 °C. The mixture was stirred after 60 ± 5 min to maintain uniform conditioning.

The short-term and long-term ageing process were conducted according the AASHTO-R30 and SHRP-A-383. For the short-term ageing, the mixture (loose mixture) was placed in a pan and spread to an even thickness ranging between 25 and 50 mm. The pan containing the mixture was placed in the conditioning oven for 4 h ± 5 min at a temperature of 135 ± 3 °C. The mixture was stirred every 60 ± 5 min to maintain uniform conditioning. After 4 h ± 5 min, the mixture was removed from the forced-draft oven. In the oven aging method, forced-draft ovens were used to ensure that the temperature was constant throughout the oven. Finally, for the long-term ageing, long-term conditioning was applied to laboratory-prepared mixtures that had earlier been subjected to short-term conditioning. Compacted test specimens were placed in the conditioning oven for 120 ± 0.5 h at a temperature of 85 ± 3 °C. After 120 ± 0.5 h, the oven was turned off, the doors were opened, and the specimens were allowed to cool to room temperature.

Marshall Stability and Flow Test

The mechanical properties obtained from the Marshall test are Marshall Stability and Flow and the Marshall Quotient. Marshall Stability indicates the maximum load that a sample can carry when being tested at 60 °C, and Marshall Flow is the deformation that a sample undergoes during loading until the maximum load is reached. An increase in the Marshall Stability value indicates an improvement in the ability of an asphalt mixture to resist shoving and rutting under heavy traffic load [16]. The Marshall Quotient is the ratio of the stability to flow and is generally known as stiffness. At each value of the optimum binder content (OBC), three new identical samples were prepared for each mix type and then tested using the Marshall testing machine. The average results were reported and used in the analysis. This Marshall stability and flow test was conducted in accordance to the procedure of ASTM D6927.

Resilient Modulus Test

The resilient modulus test was carried out using the procedure outlined in ASTM D4123. This test was performed by placing the test samples in a controlled temperature cabinet and bringing them to the specified test temperatures at least 24 h before testing. A sample was placed into the loading apparatus, and the loading strips were positioned parallel and centered on the vertical diametric plane. The electronic measuring system was adjusted as necessary. Horizontal and vertical deformations were monitored and measured during the test. If the total cumulative vertical deformations were greater than 0.025 mm during the test, the applied load, the temperature, or both were reduced. Each resilient modulus determination procedure should be completed within 4 min from the time the samples are removed from the temperature-controlled cabinet. The specimens were subjected to conditioning loading pulses. The applied force was automatically adjusted to achieve the required horizontal strain or deformation value. Force and deformation data were charted and tabulated as the conditioning stage proceeded. At the conclusion of the conditioning stage, the level display was automatically invoked. Any out-of-range linear variable differential transformers (LVDTs) were adjusted, and the level display was then shut off to continue with the test. The test was performed at two temperatures, 25 and 40 °C, on all samples.

Dynamic Creep Test

The dynamic creep test was developed to determine the rutting potential of asphalt mixtures. In this study, the samples were conditioned at the provided chamber at a temperature of 40 °C for at least four hours before testing is initiated. During the initial stage of testing, sample was pre-loaded with conditioning stress at 10 kPa for 120 seconds to ensure that the platen is loaded flat on the sample. Then, the sample was applied with a haversine wave load cycle which consists of 100 kPa stress pulse with 100 ms pulse width followed by a 900 ms rest period. The test was terminated when the accumulative strain reached 10000 micro-strains or until 10000 cycles (whichever comes first). This testing was conducted in accordance with protocol developed by NCHRP 9-19 Superpave Models [17].

3.0 RESULTS AND DISCUSSION

Optimum Binder Content (OBC)

The optimum binder content (OBC) is the most important criterion in preparing a sample because any error in obtaining the OBC will influence the result. It was found that the OBC values for all samples are in the range of 4.20% to 5.40% as shown in Table 6. This range is very important to ensure that the samples produce reliable results when conducting the performance tests for asphalt mixtures.

Table 6 Optimum binder content for all samples

Samples	OBC (%)
Control	4.43
5% glass	4.78
5% plastic	4.20
2.5% glass and 2.5% plastic	4.20
4% plastic and 1% glass	5.20
1% plastic and 4% glass	5.40

Marshall Stability and Flow and Marshall Quotient

Table 7 indicates that the asphalt mixture containing 5% recycled glass and the one containing 4% recycled plastic and 1% recycled glass exhibit higher values of Marshall stability compared to the control sample, indicating that these asphalt mixtures have high load-withstanding strength. The addition of fine-sized recycled plastic to the asphalt mixture increases Marshall Stability [18]. The table also indicates that an asphalt mixture containing a high content of recycled plastic (around 5% or higher) exhibits a lower value of stability because the presence of coarse plastic particles causes the adhesion among the asphalt binder, aggregates, and recycled plastic to be weak [19]. The value of Marshall Flow for all cases is almost similar to that for the control sample; except for the asphalt mixture containing 1% recycled plastic and 4% recycled glass. The maximum Marshall Flow value is observed for the asphalt mixture sample containing 4% recycled plastic and 1% recycled glass. A high value of flow will produce a mixture that has low resistance to rutting; therefore, a good asphalt mixture should have a low flow value.

Table 7 Marshall Stability and Flow and Marshall Quotient

Samples	Stability (KN)	Flow (mm)	Quotient (KN/mm)
Control	13.42	5.64	2.41
5% glass	6.67	5.92	1.13
5% plastic	14.66	5.62	2.62
2.5% glass and 2.5% plastic	11.56	5.61	2.03
4% plastic and 1% glass	14.81	6.26	2.36
1% plastic and 4% glass	11.24	4.08	2.79

The Marshall quotient values for different asphalt mixtures having different types and percentages of recycled materials were determined and are also listed in Table 7. The highest Marshall Quotient indicates that the asphalt mixture has the highest stability and the lowest flow. Two asphalt mixtures, one containing 5% recycled glass and the other containing 1% recycled plastic and 4% recycled glass, show higher Marshall Quotient values compared to the control mixture. Hinislioglu and Agar [20] reported that the addition of recycled plastic would increase the Marshall quotient by approximately 50% compared to the control sample. The Marshall Quotient values for the asphalt mixture containing 5% recycled glass and the one containing 1% recycled plastic and 4% recycled glass are 1.08 and 1.16 times higher, respectively, than those of the conventional mixes. However, it is observed that the asphalt mixtures containing high percentages of recycled plastic have a lower Marshall Quotient value compared to the asphalt mixtures containing high percentages of recycled glass.

Observations indicate that a higher content of recycled plastic produces a sample with a higher number of air voids because less filler material exists in the asphalt mixture owing to the size of the recycled plastic itself; that is, almost 75% of the particles sizes are 2.36 mm and only 3% of the particles are 300 μm. This implies that the voids in asphalt mixture depend on the filler from the aggregate. Consequently, this problem leads to low resistance of asphalt mixtures to permanent deformation, thus decreasing their stiffness. Vasudevan *et al*. [21] found that the strength of mixtures improved when plastic waste was coated over the aggregate. Moreover, the use of limestone in the asphalt mixtures containing recycled glass resulted in good performance in terms of the Marshall Quotient [22]. From the Marshall Stability and Flow test, it can be inferred that the value of the Marshall Quotient increases in the following order of the mixtures: 5% recycled plastic < 2.5% recycled plastic and 2.5% recycled glass < 4% recycled plastic and 1% recycled glass < control sample < 5% recycled glass < 1% recycled plastic and 4% recycled glass.

Resilient Modulus

The resilient modulus at 25 °C indicates the asphalt mixture's resistance to fatigue, whereas the resilient modulus at 40 °C indicates the mixture's resistance to rutting. The trends for the three different frequencies considered in this study (0.33, 0.5, and 1.0 Hz) were all similar in shape, and therefore, the results are presented only for the frequency of 0.33 Hz, as shown in Figure 2, with the understanding that the discussion applies to all the samples. As seen in the Figure 2, at 25 °C, the asphalt mixture containing 4% recycled glass and 1% recycled plastic is the least susceptible to fatigue and has the highest resilient modulus of 2691 MPa. According to Airey *et al*. [23] and Zakaria *et al*. [24], the presence of glass improve the strength of the modulus of the asphalt mixture. The melted plastic in the asphalt mixture also contributed to this phenomena. This is followed by the mixture containing 5% recycled glass (1915 MPa), the mixture containing 2.5% recycled plastic and 2.5% recycled glass (1744 MPa), the control sample (1728 MPa), the mixture containing 4% recycled plastic and 1% recycled glass (1464 MPa), and finally the mixture containing 5% recycled plastic (1123 MPa). A similar trend can be observed for the samples subjected to both short-term and long-term ageing as reported in Figure 3 and Figure 4 respectively.

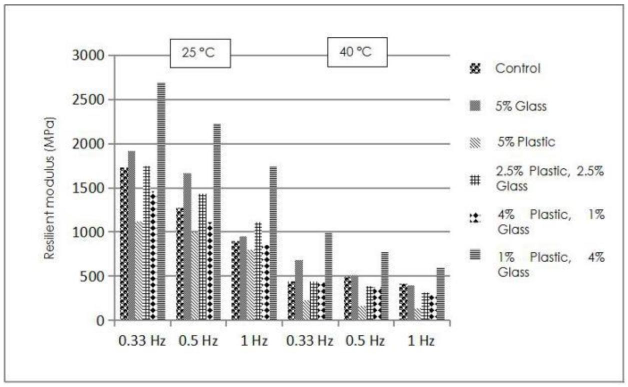

Figure 2 Resilient modulus of unaged samples

As the temperature increases, the difference in the resilient modulus is more notable, with a decline in stiffness at 40 °C. At a frequency of 0.33 Hz, the results of the resilient modulus test show that the greatest resistance to rutting is obtained for the asphalt mixture containing 1% recycled plastic and 4% recycled glass, and this mixture has the highest resilient modulus of 997 MPa. This is followed by the asphalt mixture containing 5% recycled glass, the control sample, the mixture containing 2.5% recycled plastic and 2.5% recycled glass, the mixture containing 4% recycled plastic and 1% recycled glass, and the mixture containing 5% recycled plastic with the resilient modulus value of 680 MPa, 444 MPa, 442 MPa, 437 MPa and 226 MPa respectively .

However, for short-term ageing (see Figure 3), the control sample shows the best resistance to rutting, followed by the mixtures containing 5% recycled glass, 4% recycled glass and 1% recycled plastic, 5% recycled plastic, and 2.5% recycled plastic and 2.5% recycled glass. For long-term ageing (see Figure 4), the mixture containing 5% recycled glass shows the best resistance to rutting with the highest resilient modulus of 1324 MPa. This is followed by the control sample (774 MPa), the mixture containing 1% recycled plastic and 4% recycled glass (653 MPa), the mixture containing 5% recycled plastic (472 MPa), the mixture containing 2.5% recycled plastic and 2.5% recycled glass (368 MPa) and the mixture containing 4% recycled plastic and 1% recycled glass (360 MPa). This finding is in good agreement with that of a previous study by Airey *et al*. [5], who found that the presence of glass increases the stiffness modulus of asphalt mixtures at high temperatures. On the other hand, Modarres and Hamedi [3] found that the resilient modulus reduces when the amount of recycled plastic added is more than 2%. The addition of recycled plastic could satisfy the standard requirements for asphalt mixture and exhibit acceptable trends [11]. The performance of long term ageing is better compared to short term ageing because ageing conditions increase the stiffness of asphalt mixture. This finding is in line with previouse study done by Yao *et al*. [25].

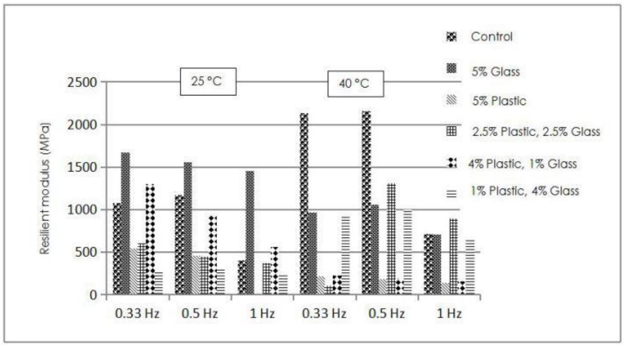

Figure 3 Resilient modulus of short term ageing samples

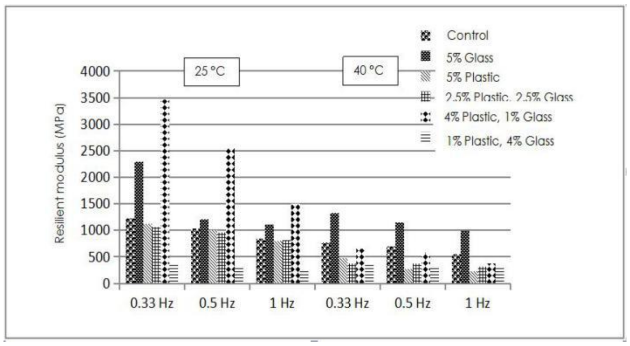

Figure 4 Resilient modulus of long term ageing samples

Table 8 lists the values of the resilient modulus index (MRI), which was obtained by dividing the resilient modulus of the recycled material mixture with that of the control mixture. MRI index show that the higher the index value, the higher is the value of the resilient modulus. According to the table, the sample containing 1% recycled plastic and 4% recycled glass shows the highest MRI for the unaged and long-term ageing conditions with values of 1.56 and 2.82, respectively. However, the sample containing 5% recycled glass shows the highest value of 1.55 for the short-term ageing condition. The sample having a high value of the MRI is much less prone to fatigue problems when used in the asphalt mixture. Moghaddam *et al*. [12] found that the addition of higher amounts of recycled plastic in asphalt mixtures would decrease the stiffness but considerably improve the fatigue properties of asphalt mixtures compared to the control mixture.

Table 8 Resilient modulus index (MRI)

Samples	Resilient Modulus Index		
	Unaged	Short-term ageing	Long-term ageing
Control	1.00	1.00	1.00
5% glass	1.11	1.55	1.87
5% plastic	0.64	0.51	0.91
2.5% glass and 2.5% plastic	1.01	0.56	0.87
4% plastic and 1% glass	0.85	0.26	0.29
1% plastic and 4% glass	1.56	1.21	2.82

Table 8 also shows the MRI at 40 °C. The sample containing 1% recycled plastic and 4% recycled glass shows the highest MRI value of 2.26 for the unaged condition. However, for short-term and long-term ageing, the control sample and the sample containing 5% recycled glass show the best MRI values of 1.00 and 2.82, respectively. It is inferred that the recycled plastic melts during the ageing procedure and subsequently reduce the resilient modulus of asphalt mixtures.

Dynamic Creep

The strength of the asphalt mixtures to resist plastic deformation can be determined by the dynamic creep test. The dynamic creep values for unaged, short term ageing and long term ageing samples are presented in Figure 5, 6, and 7 respectively. As shown in the Figure 5, the asphalt mixture sample containing 1% recycled plastic and 4% recycled glass is the least susceptible to rutting deformation at high temperatures, followed by the control sample, the sample containing 5% recycled glass, the sample containing 2.5% recycled glass and 2.5% recycled plastic, the sample containing 1% recycled plastic and 4% recycled glass, the sample containing 4% recycled plastic and 1% recycled glass, and the sample containing 5% recycled plastic. Previous studies by Jeong *et al*. [25] and Moghaddam *et al*. [26] found that asphalt mixtures containing waste plastic had greater resistance against permanent deformation.

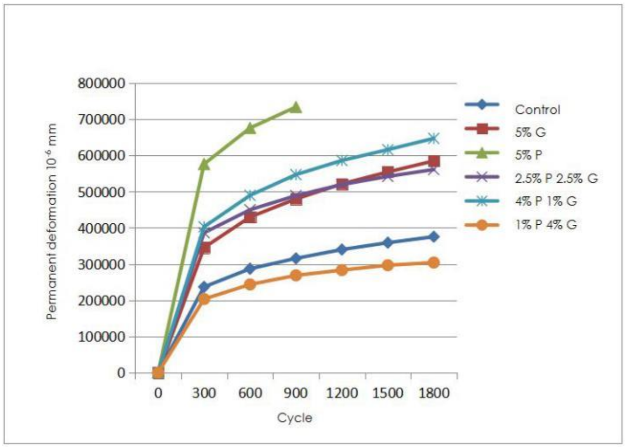

Figure 5 Dynamic creep of unaged samples

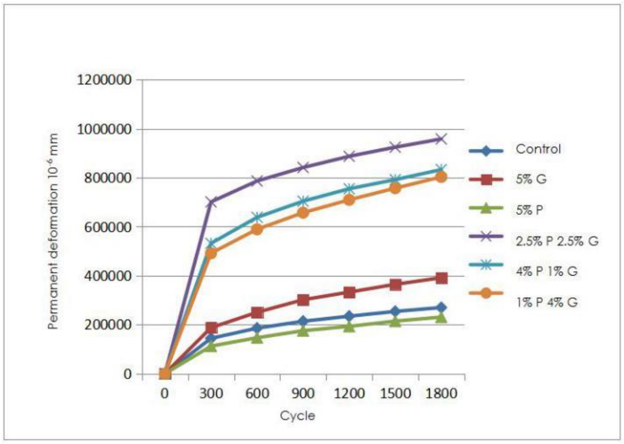

Figure 6 Dynamic creep of short term ageing samples

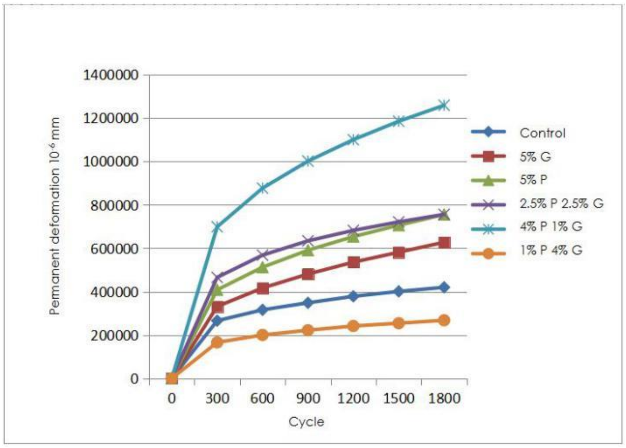

Figure 7 Dynamic creep of long term ageing samples

Table 9 lists the values of the dynamic creep index (DRI), which was obtained by dividing the dynamic creep of the recycled material mixture with that of the control mixture. For the unaged samples, the asphalt mixture sample containing 1% recycled plastic and 4% recycled glass shows the highest DRI value, followed by the control sample, the sample containing 5% recycled glass, the sample containing 2.5% recycled glass and 2.5% recycled plastic, the sample containing 1% recycled plastic and 4% recycled glass, the sample containing 4% recycled plastic and 1% recycled glass, and the sample containing 5% recycled plastic. For short-term ageing, the asphalt mixture sample containing 2.5% recycled glass and 2.5% recycled plastic shows the highest dynamic creep values with a DRI value of 3.55, followed by the sample containing 4% recycled plastic and 1% recycled glass, the sample containing 4% recycled plastic and 1% recycled glass, the sample containing 5% recycled glass, the control sample, and finally the sample containing 5% recycled plastic. For long-term ageing, the sample containing 1% recycled plastic and 4% recycled glass shows the least deformation, followed by the control sample, the sample containing 5% recycled glass, the sample containing 5% recycled plastic, the sample containing 2.5% recycled glass and 2.5% recycled plastic, and finally the sample containing 4% recycled plastic and 1% recycled glass. The long-term ageing conditions cause the recycled plastic to melt, which subsequently results in a decrease in the stiffness of the asphalt mixtures. Even though the results obtained are not consistent, the sample containing 1% recycled plastic and 4% recycled glass produces the most consistent results in terms of dynamic creep of asphalt mixtures.

Table 9 Dynamic creep index (DRI)

Samples	Dynamic Creep Index		
	Unaged	Short-term ageing	Long-term ageing
Control	1.00	1.00	1.00
5% glass	1.52	1.45	1.49
5% plastic	2.32	0.86	1.80
2.5% glass and 2.5% plastic	1.55	3.55	1.80
4% plastic and 1% glass	1.73	3.09	3.00
1% plastic and 4% glass	0.85	2.98	0.64

4.0 CONCLUSION

The study found that recycled plastic and glass have a good possibility of replacing aggregate in asphalt mixtures. Based on the laboratory works conducted in this study, it is found that the asphalt mixture sample containing 1% recycled plastic and 4% recycled glass shows almost similar and satisfactory results compared to the control sample in all tests. For short-term and long-term ageing conditions, satisfactory and consistent results are found for the sample containing 1% recycled plastic and 4% recycled glass. Therefore, it can be concluded that recycled plastic and recycled glass, when optimally blended, can be considered feasible to be used as an aggregate replacement in asphalt mixtures for flexible road pavements.

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