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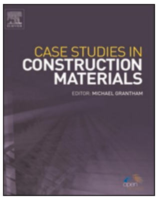

The mechanical response of dry-process polymer wastes modified asphalt under ageing and moisture damage

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ABSTRACT

The use of waste polymers for modifying asphalt has remarkable environmental and economic advantages. However, limitation still exists in the resistance of these mixtures against moisture damage and ageing. This paper aims to explore the impact of ageing and moisture damage on the mechanical properties of modified asphalt mixtures with polymer wastes (plastic waste and crumb rubber). Asphalt mixtures designated asphalt concrete (AC14) were prepared using granite aggregate, 60/70 PEN asphalt, and filler (hydrated lime). The properties of indirect tensile strength, resilient modulus, dynamic creep, and rutting were calculated to examine the effect of short-, long-term ageing and moisture damage. The results of the mechanical tests for the modified mixtures were compared to the conventional dense-graded asphalt mixture. The findings showed that asphalt mixtures containing both polymers presented superior properties after short-term ageing. In contrast, long-term ageing has enhanced the control and plastic waste mixtures' bonding properties while negatively impacting the rubberised asphalt. Long-term ageing has reduced the resistance of rubberised mixture against permanent deformation by about 33%. The moisture conditioning has significantly deteriorated the mixture's resistance to cracking and permanent deformation, particularly for the control and rubberised mixtures. The modulus and rutting resistance of the asphalt mixtures modified by crumb rubber and waste plastic has decreased by up to 9% and 17% after moisture conditioning.

1. Introduction

The high expenses of asphalt pavement maintenance and rehabilitation necessitate various potential ingredients to improve asphalt performance [1–3]. The utilisation of polymers waste to increase asphaltic mixture performance is promising in road construction. At intermediate and low temperatures, the least flexibility of conventional asphalt mixture leads to asphalt pavement deterioration [4]. The properties of the used polymers play a vital role in improving the performance of the modified asphalt mixtures. Polymer type and concentration, melting point, particle size, molecular weight, and asphalt type are important factors controlling the produced mixtures' performance and the energy consumed in mixture preparation and compaction [5,6]. High molecular weight can increase the

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number of flows needed to reach the required air void content. Moreover, a high melting point can lead to high mixing temperature resulting in deformation in the polymer and asphalt binder [7]. Using polymer can affect the viscosity and ductility of the asphalt binder at high and low temperatures. The polymer can increase the ductile behaviour of asphalt mixtures at low temperatures and the viscosity of the asphalt binder at high temperatures. As a result, numerous researchers have investigated modifying asphalt mixtures with the most commonly used polymers, crumb rubber and plastic waste [8–13]. Several studies have shown that fatigue life, rutting performance, and flexibility of asphalt mixtures can all be improved using these waste materials. Crumb rubber can be incorporated into asphalt mixtures using two different methods: dry and wet. The dry approach entails replacing the aggregate by weight with crumb rubber and mixing before compaction [14,15]. On the other hand, the wet approach involves mixing asphalt binder with crumb rubber before adding the aggregate [16]. Due to the interaction of asphalt binder and polymer particles in this technique, the modified asphalt can significantly increase the mixture performance [17–19]. However, Moreno [20] stated that using the dry method to modify the asphalt mixture can improve stiffness but reduce adhesion and indirect tensile strength [21]. Other research by Arabani [21] revealed that rubberised asphalt mixtures displayed high susceptibility to moisture damage than the conventional mixture. It was found that the time available for rubber- asphalt binder interaction contributed to controlling the sensitivity of asphalt mixtures to moisture deterioration. Furthermore, previous research has indicated that plastic waste was utilised to construct over 2500 km of roads that were determined to be free of potholes, ravelling, and rutting [4,22]. The same issues were also highlighted for the dry process modified asphalt mixtures by waste plastic. A previous study showed that the dry process has variable performance due to the inadequate plastic-binder interaction [8]. However, using crumb rubber and plastic waste to modify asphalt pavement has expanded in recent years due to the desired environmental impact [23–25]. Thus, more studies are required to demonstrate the desirable influence of plastic waste and rubber on the performance of conventional asphalt, particularly for moisture damage and ageing. Only a few studies in the literature support the resistance of these modified mixtures against ageing and moisture damage [21,26,27].

Accordingly, the mechanical performance of asphalt mixture is primarily affected by ageing due to the environmental impact [28]. This factor brings changes to asphalt characteristics [29]. Especially, it is well-known that asphalt viscosity increases during the asphalt pavement's service life [30]. Such a process can be related to physical and chemical ageing or steric hardening [31]. Physical ageing is mainly related to the reorganisation of asphalt molecules. Chemical ageing refers to the hardening of asphalt caused by oxidation and the loss of volatile components of asphalt. The volatilisation and oxidation process rates increase when asphalt binder is subjected to higher temperatures and decrease at ambient temperature. As a result, combining these processes leads to mixtures stiffening and a higher level of brittleness [32]. This chemical process is observed during the construction, transportation and laying of the asphalt mixtures. On the other hand, steric hardening is attributed to the reorganisation of molecular over an extended period by which asphalt aged at an average temperature at time elapse. It can be considered a physical process due to the transformation in the rheological characteristics of the asphalt binder without affecting its chemical composition. The long-term ageing (LTA) and short-term ageing (STA) procedures developed by SHRP is one of the most common procedures used for asphalt mixtures ageing conditioning [33]. Several researchers suggested conditioning the asphalt mixtures for 2 h at the compaction temperature to simulate field compaction [34–36]. This conditioning procedure represents the short-term ageing of asphalt mixtures and absorption during plant production. On the other hand, the LTA is used to simulate the ageing over many years the pavement is in service. The LTA includes conditioning the compacted mixtures for five days at 85 °C. The RILEM technical committee established other procedures proposed nine days at 85 °C [37]. Hardening due to LTA is caused mainly by evaporating the light components of the asphalt binder due to the oxidation process during pavement service life. The asphalt viscosity increases with age, as does stiffening the mixture, resulting in the brittleness of the asphalt and an increase of elastic modulus. Several studies found that the long-term ageing protocol varies depending on the laboratory ageing method, climatic conditions, and asphalt type [37–39].

Nevertheless, moisture damages are also considered a vital factor affecting asphalt mixtures' properties and contribute to the deterioration of pavement [40]. This factor can mainly impact the adhesion properties between asphalt binder and aggregate, leading to severe striping in the asphalt mixtures. Moisture damage starts by reaching the water to the interior of the asphalt mixtures, leading to various types of asphalt mixtures deterioration. The loss of adhesion or/and cohesion can occur when water penetrates between the aggregate surface and the asphalt film. The main three mechanisms for water penetration in the asphalt mixtures based on previous studies [41–43] are diffusion, capillarity, and permeability. Diffusion is when the water moves through the mixture components. In contrast, capillarity is the force formed by the phenomenon of surface tension of the fluid. These variables are influenced by the environment and the arrangement of the voids in the asphalt mixture. Last but not least, permeability represents the material aptitude to allow water to flow through its voids [44]. Asphalt mixture de-bonding can be caused by the following pavement mechanisms, which can act alone or in combination [45]: environment impact, detachment, displacement, spontaneous emulsification, hydraulic scouring, and pH instability are the problems that can occur. For mixture with moisture damage, the asphalt binder film is microscopically separated by a thin layer of water from the surface of the mineral particle, with no visible deformation in the asphalt film. The aggregate-asphalt bond is affected by the presence of water during the displacement phenomenon [46]. Therefore, a proper mix design is necessary to combat the stripping problem. However, sometimes a mixture is properly designed but not adequately compacted. In that case, it may still be vulnerable to moisture damage due to high air void content, which allows water to penetrate the asphalt mixture pavement. As a result, an asphalt mixture has to be evaluated in a condition where water could penetrate the mixture's air voids. For this reason, various experiments were conducted for asphalt samples with 7% air voids. The most common method of simulating the moisture damage of asphalt mixtures in the laboratory is to place samples in a 60 °C water bath for 24 h. The AASHTO

T283 specification requires immersing hot-mix asphalt samples in water after being air-vacuumed for various treatment periods [47]. A few studies reported the performance of asphalt mixtures could be effectively improved due to the interaction between asphalt and polymers, particularly when using the wet process[48–50].

Available studies about the modified asphalt mixtures using the dry method are limited and show opposed findings, particularly regarding the performance after moisture and ageing conditioning. Previous studies have shown that using the dry method for modifying the asphalt mixtures can improve the tensile strength and stiffness of the produced mixtures [20,51]. On the other hand, Moreno [52] conducted a study to examine the impact of crumb rubber on conventional asphalt mixtures. The findings revealed that the crumb rubber had decreased the resistance of materials to moisture damage due to the debonding effect of crumb rubber on the asphalt mixtures. The moisture susceptibility of rubberised asphalt mixtures was also investigated by Rahman et al. [53]. It was revealed that rubberised asphalt is more sensitive to moisture damage. Simultaneously, the analysis of the results of fatigue data revealed that, despite having marginally lower resistance to permanent deformation at 60 °C, rubberised mixtures have a better fatigue life than conventional asphalt mixtures. In contrast, several studies have reported improvement in the resistance of asphalt mixture against moisture damage when modified by plastic waste and crumb rubber [10,21,27].

There are countless benefits of utilising plastic waste and crumb rubber in asphalt mixture using a dry method, such as using a high amount of waste, subsequently decreasing environmental issues. However, utilising the dry method in modifying asphalt mixtures revealed uncertain results on the asphalt performance against moisture damage and ageing conditioning. The current study aims to provide a mechanical assessment for the impact of moisture damage and ageing on asphalt mixtures modified by plastic waste and crumb rubber using the dry method. Laboratory evaluation in this study includes performance and mechanical tests: the resilient modulus, indirect tensile strength, dynamic creep, and rutting potential. Two levels of ageing and moisture damage were considered with the addition of 1% of plastic waste and 1% of crumb rubber by the total weight of aggregate. The selected polymers content is based on the previous studies' recommendations [8,26]. This study provides significant findings regarding the effect of moisture damage and ageing on the performance of asphalt mixtures modified with crumb rubber and plastic waste.

2. Materials and test method

2.1. Materials preparation

Three different asphalt mixtures of AC14, with granite aggregate of nominal maximum (NMAS) size of 14 mm, were prepared according to JKR specification [54]. A total of 1% plastic waste and 1% crumb rubber from the total weight of aggregate were added to the mixtures. In this study, 60/70 penetration grade asphalt was utilised as a binder. This material was supplied from Kemaman Bitumen Company (KBC) Malaysia Ltd. Table 1 lists the tests and results of the asphalt binder used.

The plastic waste bags were segregated from the municipal waste and shredded into a size of approximately 5–10 mm (see Fig. 1). The rubber used in this study was taken from car and truck tyres and was shredded mechanically to the desired size (see Fig. 1). The size of rubber particles retained on sieve size 1.18 mm was utilised in this study. The specific gravity of the crumb rubber used in the study is 1.3896. In this study, 1% of Low-density polyethylene (LDPE) in the form of shredded plastic bags were designated for modification by the total weight of aggregate. The specific gravity of the plastic bags used in the study is 0.908. The aggregate grading for AC14 is confirmed with the upper and lower limits specified in the JKR standard, as shown in Fig. 2.

2.2. Test method

The test methodology of this study consists of three phases. The first phase is to design the control and modified asphalt mixture. The Marshall design method was used to design each asphalt mixture individually. Five blends (with 4%, 4.5%, 5%, 5.5% and 6% asphalt binder contents) were used to determine the optimum asphalt content. This study adopted the dry process method to prepare the modified mixtures. The rubberised asphalt mixture was produced by substituting 1% of the total weight of aggregate with the aggregate retained on 1.18 mm sieve size. Then, the binder, aggregate, and crumb rubber are blended at 170 ± 5 °C [10]. On the other hand, the plastic waste was incorporated into the asphalt mixtures based on the enhanced dry process method developed by Radeef

Table 1
Asphalt binder tests.

Tests	Units	Results	Standard test method
Asphalt Density	(gm/cm^3)	1.020	ASTM D70
Softening Point	(°C)	51.5	ASTM D36
Viscosity @ 165 °C	(mPa s)	200	ASTM D4402
Viscosity @ 135 °C	(mPa s)	650	ASTM D4402
Ductility	(cm)	116	ASTM D113
Penetration (dmm) at 25 °C	(dmm)	64	ASTM D5

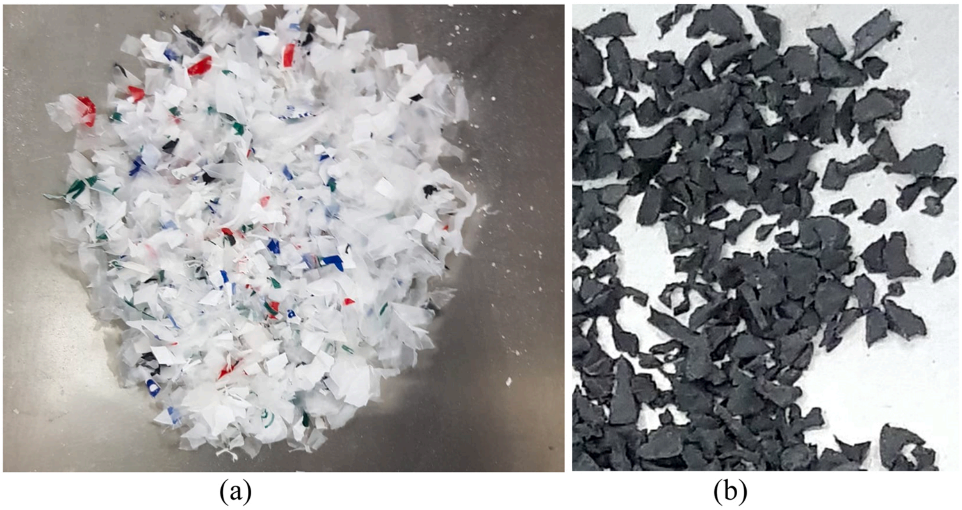

Fig. 1. Shredded wastes (a) plastic and (b) crumb rubber.

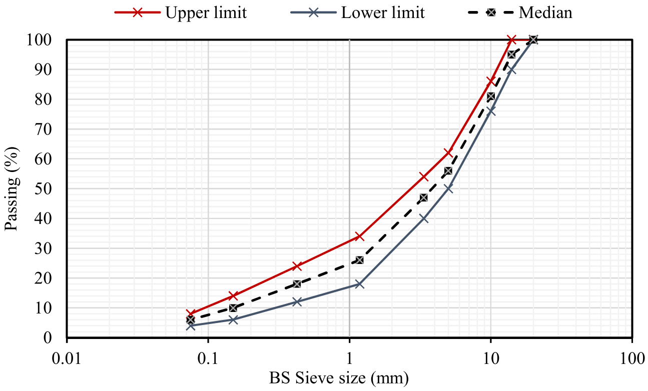

Fig. 2. Aggregate gradation of AC14.

et al. [8]. This method involves mixing coarse aggregate and plastic waste at 180 °C until the melted plastic coated the aggregate. Then, the fine aggregates were blended with the resulting mixture, and the combination was mixed until a homogeneous asphalt mixture was generated. Marshall hammer was utilised for compacting the asphalt mixtures.

After compaction, the samples were cooled and extruded from the moulds to determine their volumetric properties. The Marshall properties were obtained and plotted to determine the optimum asphalt content. The second phase includes preparing and conditioning the asphalt samples. Air void of 7 ± 0.5 was selected to investigate the impact of moisture damage on the performance properties of asphalt mixtures. After that, all samples were divided into four groups; unconditioned, short-term ageing, long-term ageing, and moisture condition, as listed in Table 2. The sample has been labelled according to the type of modifiers and conditioning. Whereas the third phase includes performing the mechanical and performance test. The indirect tensile strength, resilient modulus, dynamic creep, and wheel tracking tests were performed for the unconditioned and conditioned samples. For both control and modified mixtures, the results were analysed and discussed for evaluating the impact of moisture and ageing conditioning on the mechanical response of control and modified mixtures.

Table 2
Mixtures names according to the type of modifier and conditioning.

Mixture Label	Description
C-UN	Unaged Control Mixture
C-STA	Short-Term Ageing of Control Mixture (STA)
C-LTA	Long-Term Ageing of Control Mixture (LTA)
C-MD	Moisture Conditioning of Control Mixture (MD)
PLW-UN	Unaged Plastic Mixture
PLW-STA	Short-Term Ageing of Plastic Mixture (STA)
PLA-LTA	Long-Term Ageing of Plastic Mixture (LTA)
PLW-MD	Moisture conditioning of Plastic Mixture (MD)
CRM-UN	Unaged Rubber Mixture
CRM-STA	Short-Term Ageing of Rubber Mixture (STA)
CRM-LTA	Long-Term Ageing of Rubber Mixture (LTA)
CRM-MD	Moisture Damage of Rubber Mixture (MD)

2.2.1. *Marshall properties*

All the Marshall properties have been evaluated as described in JKR (2008) specifications to calculate the optimum asphalt content (OAC) [38] of the control and modified mixtures. Using Marshall Compactor, all samples were compacted using 75 blows on both sides. The density of the compacted samples was determined following ASTM D 2726 [38]. The theoretical maximum density of ASTM D2041 / D2041M-11 [39] was determined for the loose mixes. Next, the samples after compaction were placed in water at 60 °C for 45 min to assess the Marshal parameters according to ASTM D1559 [40]. Table 3 displays the Marshall test results of the control and the modified mixtures [8,26]. The CRM mixture showed the lowest stability value; meanwhile, the PLW mixture demonstrated the highest stability. The stiffness results showed that the CRM mixture has the lowest stiffness value due to the rubber particles impact on reducing the friction force between the aggregate particles, leading to high flow under loading. On the other hand, despite its high stability value, the PLW mixture displayed a comparable stiffness to the control mixture. These features are attributed to the PLW and CRM mixtures that displayed high air void content and flow. The high flow value of the PLW mixture could be attributed to the low workability of the produced mixtures during the compaction process [55]. The total voids in the mix (VTM) for the control mixture was 3.5%, and the value increased by about 15% for the PLW and CRM mixtures. The VFA values of mixtures modified with plastic waste and crumb rubber were lower than the control mixture but still within the specification (70–80%). Moreover, the OAC of the plastic mixture is lower than the control mixture. Meanwhile, the CRM mixture showed the highest OAC because rubber particles absorb part of the light fraction of the asphalt binder [56].

Table 3
Results of Marshall test.

Marshall properties	Mixture type			Requirement as in MPWD specification
	Control	CRM	PLW	
Stability (N)	16,410	12,930	19,319	> 8000
Flow (mm)	3.1	3.48	3.83	2.0–4.0
Stiffness (N/mm)	5293	3715	5044	> 2000
VTM (%)	3.5	4.1	4.5	3.0–5.0
VFA (%)	74.9	76	71.9	70.0–80.0
OAC	5	5.4	4.9	–

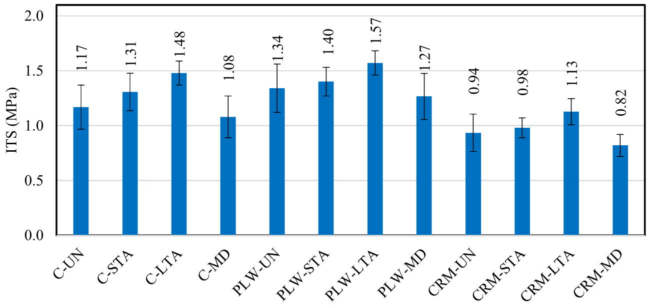

Fig. 3. Indirect tensile strength of different mixtures.

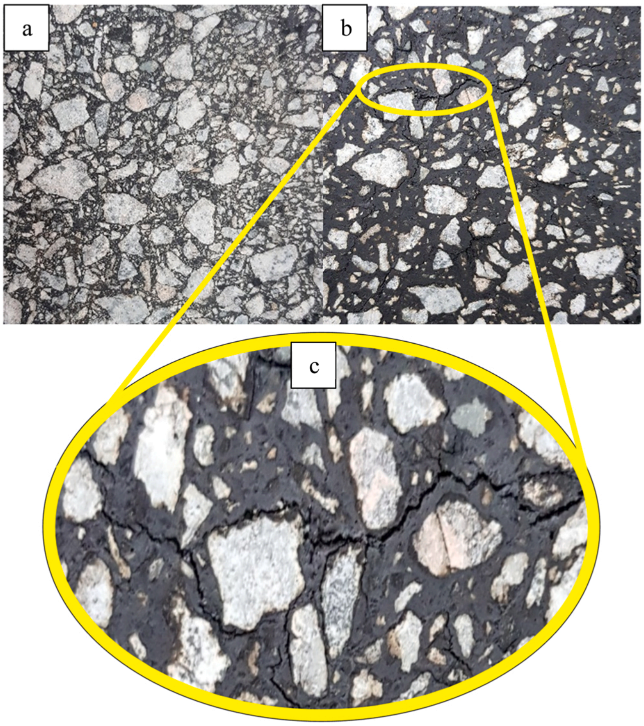

Fig. 4. Rubberised asphalt mixture a) before ageing, b) after ageing, c) cracks developed in the sample after LTA ageing.

2.2.2. *Samples conditioning*

After verifying the Marshall properties, more than 150 samples were produced for investigating the influence of moisture damage and ageing on the control and modified mixtures. The moisture damage includes conditioning the samples according to D4867M 2014 [57]. The standard requires partial saturation by vacuuming the samples under 30HQ for less than 5 min based on the required saturation level. Next, the samples were sent to a hot water bath of 60 °C for 24 h and then to a cold water bath of 25 °C for 2 h before conducting the performance and mechanical test. The moisture conditioning was conducted on mixtures after mixtures conditioned for STA. On the other hand, two ageing conditioning levels were adopted in this study: short-term ageing for simulating asphalt production and transportation and long-term ageing conditioning, which simulate asphalt ageing during the service life of asphalt pavement. The STA involves heating the loose mixtures for 2 h in the oven at the compaction temperature 154 °C before the compaction process according to AASHTO R30 standard [58]. The LTA was performed on the samples after compaction. The procedure involves placing the samples in an oven at 85 °C for five days or 120 h before sending the sample to the testing process.

2.2.3. *Indirect tensile strength (ITS)*

The (ITS) is usually employed to determine the fracture and fatigue performance of the asphalt mixture following UNI EN 12697–23. The cylindrical sample was placed between the load strips in the compression testing equipment and loaded diametrically along the cylindrical axis direction with a constant displacement. The value of ITS represents the average highest stress reached from the peak load as described in Eq. (1):

$$\mathrm{StD} = 2000\mathrm{P}/\pi \mathrm{hD} \tag{1}$$

where, StD is indirect tensile stress (MPa); P is the max load (kN); h and D are the sample height and diameter accordingly (mm), respectively. The tensile strength ratio (TSR) was calculated by dividing the (StW) for wet samples by the (StD) for dry samples [59], as presented in Eq. (2):

$$\mathrm{TSR} = \mathrm{StW}/\mathrm{StD} \tag{2}$$

2.2.4. *Resilient modulus (MR) test*

The resilient modulus represents the ability of asphalt mixtures to sustain the dynamic loading and related stresses. The resilient module relates the stress imposed at a specific load and temperature to the recoverable strain. In this research, the samples were tested according to a standard method for indirect tensile resilient test ASTM-D4123–82, 1995 [60] using a universal testing machine (UTM). This equipment has a close loop system for testing samples at 25 and 40 °C. The samples were exposed to repetitive loading at a frequency of 1 $\mathrm{H_Z}$. Linear differential transducers were used to collect the deformations in the horizontal axis, which is needed to analyse and determine the resilient modulus.

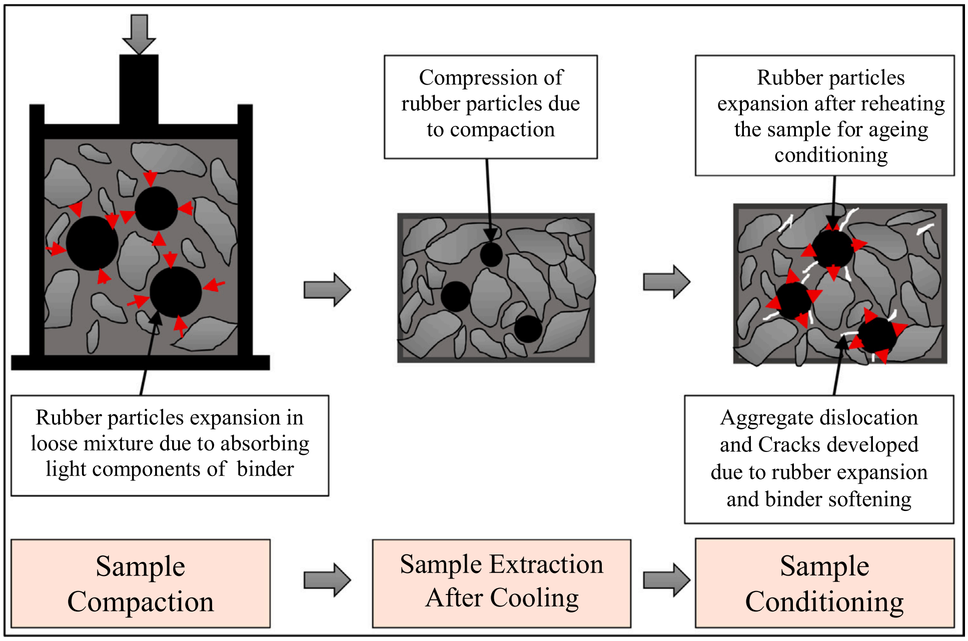

Fig. 5. Rubber particles expansion after ageing conditioning.

2.2.5. *Dynamic creep test*

The dynamic creep test was conducted to assess the resistance of the asphalt mixtures against permanent deformation. The test was conducted according to BS EN 12697-25 (British Standards Institution, 2005) [61] with three replicates for each mixture. A maximum number of cycles of (3600 cycles) were set up according to the specification to examine the deformation trends of the asphalt mixture sample under repetitive axial load stresses. The following test conditions were used for conducting the dynamic creep test: pulse width of 300 ms, pulse duration of 500 ms, stress testing termination ratio of 5%, pulse terminal count 3600 cycles, pre-loading stress of 150 kPa, stress testing 300 kPa and test temperature of 40 °C. The creep slope and creep stiffness module were determined using Eqs. (3) and (4).

$$\mathrm{CSS} = (\log\varepsilon 3600 \quad - \quad \log\varepsilon 1200)/(\log 3600 \quad - \quad \log 1200), \tag{3}$$

$$\mathrm{E} = \sigma/\varepsilon, \tag{4}$$

where, CSS = creep strain slope, ε3600 and ε1200 represent the amount of strain at 3600 cycles and 1200 cycles accordingly, σ = applied stress (kPa), E = creep stiffness modulus (MPa), ε = total strain at the end of the test (mm),

2.2.6. *Wheel tracking test*

This test was utilised to assess the rutting potential of the control and modified asphalt mixtures following EN 12697-22 standard [62]. Typically, asphalt mixture samples (150 mm diameter and 64 mm thickness) have been produced based on the optimum asphalt content. After that, the samples were conditioned at a controlled temperature of 50 ± 2 °C and subjected to 26.5 cycles/min compression loading using a steel wheel. The failure criteria of the test were set based on a total rut depth of 2 cm or the number of load cycles of 10,000.

3. Results

3.1. *Moisture damage*

The main concern of asphalt pavement construction is the sensitivity against moisture damage, i.e. the reduction in strength, stiffness, and durability due to water damage. Fig. 3 illustrate the average value of ITS with three replicates per asphalt mixture. In general, the ITS results of the asphalt mixtures before conditioning have shown higher performance than the conditioned modified and control mixtures. The low values of ITS for the samples conditioned for moisture damage are mainly attributed to the impact of water on the adhesion properties of the asphalt binder. However, the PLW mixture showed the best performance, followed by the control and CRM mixtures, which indicates that plastic has reduced mixture susceptibility to moisture damage. These findings are attributed to the new characteristics of plastic-coated aggregate on enhancing bonding with asphalt film and decreasing the aggregate affinity with water, consequently lowering the susceptibility to moisture damage [22]. The findings of ITS are in line with results obtained by

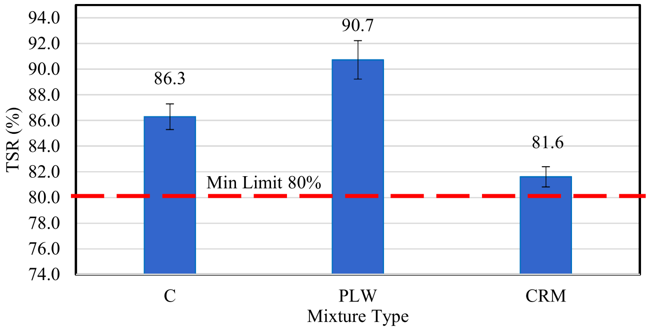

Fig. 6. Tensile strength ratio for different mixtures.

Suaryana et al. [22]. Suaryana declared that mixtures modified by plastic had high resistance to water damage. The CRM mixture displayed the lowest tensile strength, which could be due to the deterioration in the adhesive force of the rubberised asphalt. Such findings were revealed by a previous study conducted by Wang [63]. The study proposed method for evaluating the interfacial adhesion between asphalt and rubber. The results showed lower adhesive between rubber particles and asphalt binder than the mineral aggregate.

The impact of long- and short-term ageing showed an increasing trend, whereas the CRM mixture showed slight enhancement for the CRM-STA and the lowest value of ITS for the CRM-LTA mixtures. This demonstrates that LTA can increase the bonding properties of control and plastic waste mixtures while having a destructive effect on the rubberised asphalt. Such results can be attributed to the expansion phenomenon of rubber particles, resulting in the rubberised samples' deformation after ageing conditioning, as seen in Fig. 4. This phenomenon can be explained by referring to the production stages of the rubberised asphalt, as shown in Fig. 5. At the mixing stage, the rubber particles tend to swell after absorbing the maltene content of the asphalt binder. The rubber particles are compressed during compaction and remain in this state after cooling to the ambient temperature. The hardness of the asphalt binder at ambient temperature keeps the rubber particles compressed. When the sample was reheated for the age conditioning, it softened the asphalt binder. Thus, rubber particles tend to swell due to their flexibility or recovery action and, consequently, develop cracks within the asphalt mastic.

Fig. 6. shows the TSR value of the control and modified samples. It was understood that a higher TSR value indicated high-performance asphalt mixtures while a lower value of TSR (< 80%) demonstrated the fail criteria [59]. However, the PLW mixture showed the highest TSR value than the control and rubberised asphalt mixtures. This demonstrated that mixtures modified by plastic waste lead to a reduction in the susceptibility to moisture damage. In contrast, the CRM mixture revealed the lowest value of TSR (81.6%), followed by the control (C) mixture (86.3%). These results could be attributed to the heating process involving moisture conditioning, which increases the size of the rubber particles inside the mixtures. The swollen particles induce more air voids in the mixture, resulting in weak cohesiveness and high susceptibility to moisture damage [26,64]. Exposing According to Poulikakos et al. [65], An increase in interfacial moisture content caused by increased asphalt film surface area will allow for the destructive impact of moisture and an oxidative action of air, consequently losing the adhesion and adhesive properties of asphalt binder.

3.2. *Resilient modulus (MR)*

The result of resilient modulus was tested at two test temperatures (25 °C and 40 °C) for the control and modified asphalt with three replicates per mixture, as shown in Fig. 7. At 25 °C, the resilient modulus reflected the mechanical performance of the pavement to dynamic loading, whereas the MR at 40 °C refers to the mixture's resistance to permanent deformation. It is apparent that modified asphalt mixture with plastic waste consistently increases the MR. Meanwhile, the CRM mixture showed the lowest MR. The impact of moisture damage on the asphalt mixture has the same trend as the unconditioned sample, where the value of MR of the control, PLW,

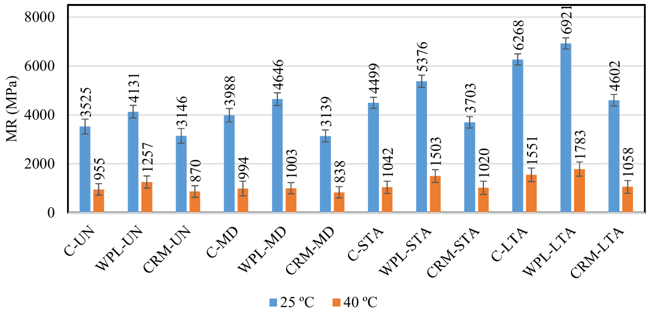

Fig. ↱7. M_R results.

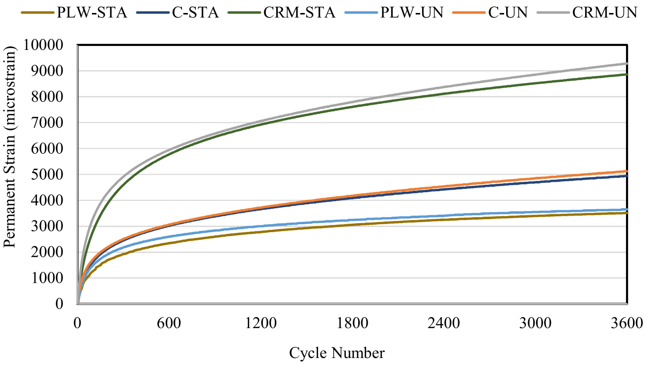

Fig. 8. Cumulative creep strain result for unaged and after short-term ageing.

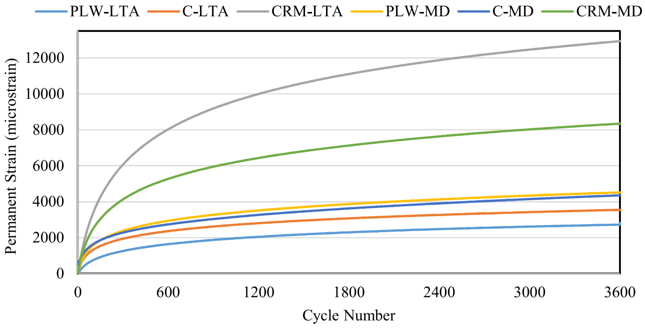

Fig. 9. Cumulative creep strain result after long-term ageing and moisture damage.

and CRM was decreased by 11%, 13%, and 15%, respectively. Although the PLW-MD displayed relatively great influence by the moisture damage compared with the control mixture, the MR value of PLW-MD was higher than the CRM and control mixtures. In contrast, the impact of ageing on the MR was expected to increase the stiffness of the control and modified mixtures, thus improving the mixture ability against plastic deformation under loading. The short-term ageing has increased the MR for all mixtures by about 15%. The same trend was observed for the long-term ageing impact where the C-LTA, PLW-LTA, and CRM-LTA showed a higher value of MR by 40%, 22%, and 24%, respectively, compared to unaged samples. On the other hand, the samples tested at 40 °C showed the same trend, with the PLW mixture exhibiting the highest MR value. This shows the mixture has the greatest rutting resistance, whereas the CRM showed the poorer performance at this temperature. The effect of moisture damage on the control and modified mixtures showed that the plastic displayed the lowest influence by the moisture conditioning and the highest MR value compared to the C-MD and CRM-MD. For long-term ageing impact (tested at 40 °C), all the mixtures showed an increase in the MR value by 70%, 18%, and 1% for C-LTA, PLW-LTA, and CRM-LTA, respectively. This fact is attributed to the influence of ageing on increasing the stiffness of the CRM-LTA. The MR results align with the previous study by Farouk et al. [66], which proved that rubber decreases the MR value of modified asphalt. In contrast, using plastic waste in asphalt mixture has increased the MR values, and the results agree with previous findings [4,22].

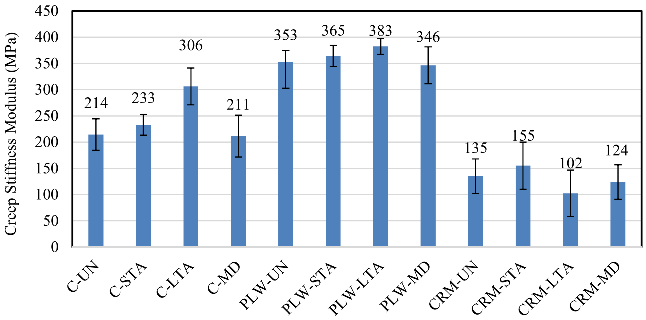

Fig. 10. Creep stiffness of asphalt mixture.

3.3. Dynamic creep

Figs. 8 and 9 present the permanent strains of control and modified mixtures after 3600 cycles. Generally, the PLW mixture displayed the lowest deformation, whereas the CRM mixture displayed high deformation under the dynamic creep test. The CRM-UN showed the highest permanent strain (12,923 μs) among all. The control mixture shows higher permanent strain than the PLW mixture. For the moisture-damaged sample, the results showed that C-MD and CRM-MD mixtures were more affected by the moisture conditioning than the PLW-MD mixture. The moisture impact increases the permanent strain of the control, PLW-MD, CRM-MD by 8%, 7%, and 10%, respectively. The long-term ageing seems to harden and decrease the permanent strain of the C-LTA and PLW-LTA mixtures. This could be due to the hardening impact of ageing on the control and plastic waste mixtures. In contrast, for the CRM-LTA mixture, the long-term ageing significantly increased the permanent deformation, which could be attributed to the minor increase in the size of the rubber particles and leads to partial disintegration of the mixture component as discussed in Section 3.1 [15,66,67].

Consequently, the creep stiffness was determined and presented in Fig. 10. Based on the results of creep stiffness, the trend of results was correlated with indirect tensile strength and resilient modulus. The creep stiffness was increased by 100% for PLW mixtures and decreased by 33% for CRM compared to the control mixtures. Moreover, the short-term ageing and long-term ageing have increased creep strain value for the control mixture by 10% and 30% for C-STA and C-LTA accordingly. Consequently, the ageing conditioning has increased the stiffness for the plastic waste modified mixtures by 10% and 20% for PLA-STA and PLW-LTA mixtures. The results indicate that mixtures modified by plastic waste are less affected by the ageing effect than the control mixtures. The effect of ageing is mainly associated with changing the asphalt's physical and chemical characteristics. These properties are responsible for the behaviour of the overall performance of produced mixtures [68]. In contrast, dissimilar behaviour was detected for the impact of ageing on the creep stiffness values of rubberised asphalt mixtures. The short-term ageing has slightly increased the stiffness of CRM-STA by 8%, while the long ageing has decreased the value by 5%. This behaviour is in contrast to the impact of long-term ageing on the control and plastic waste asphalt mixtures. Conversely, the influence of moisture damage on the control and modified mixtures are shown in the same figure. The moisture conditioning slightly decreased the creep stiffness for C-MD, PLW-MD by about 2%, whereas the moisture condition has decreased the stiffness value for CRM-MD by about 23%.

Simultaneously, the CSS was determined by calculating the slope of the second part of the permanent strain curve to assess the mixture's resistance to permanent deformation at the secondary creep stage. This stage reflects the constant deformation rate under cyclic loading. As shown in Fig. 11, the trend of CSS was in contrast with the creep stiffness for all conditioned and unconditioned mixtures except for C-LTA and PLW-LTA. These mixtures have presented a high value of creep stiffness and creep strain slope. In contrast, it is crucial to declare that the CSS result for the rubberised mixture show that most of the permanent deformation occurs at the initial stage. Such results are in line with the discussion of the results of cumulative permanent strains regarding the impact of samples expansion on the performance of rubberised asphalt mixture. When the loading was applied to the rubberised sample during the creep test, the expanded rubber particles will absorb most of the applied energy in the first stage of creep deformation. Thus, it is logical to have comparable CSS values for the rubberised asphalt mixtures compared to the control and plastic waste modified asphalt mixtures. The long-term ageing increased the deformation of the control and plastic waste mixtures. In contrast, mixtures exposed to moisture conditioning have almost similar CSS, particularly for control and modified mixtures. This indicates that moisture conditioning has the least impact on the secondary creep stage.

3.4. Rutting potential

The asphalt deformation under rutting is associated with the viscous behaviour of the asphalt mixtures at the range of high temperatures. The thermal viscoelastic properties determine the severity of permanent deformation in asphalt mixtures. Thus, changes in test temperature, loading time, and frequency are contributed to the amount of deformation that specific asphalt mixtures can sustain, which indicates the susceptibility of asphalt mixtures against temperature increment. The results of rutting depth for the unconditioned and conditioned samples are shown in Figs. 12 and 13. As can be seen from the plots, the deformation increases with the increment of passes (time). At the initial loading stage, a sudden increase in the rutting was observed for the control and modified mixtures. This condition was expected due to the mixture components' densification (compression stress) and aggregate interlocking under the loading action. The second stage of the curve signifies the stable shear deformation (mainly due to shear stress), which represents the constant rutting rate (see Fig. 12) [69]. The mixture modified with plastic waste showed the lowest rutting rate at both stages, indicating higher compression and shear strength than other mixtures.

Moreover, Fig. 14 illustrates the average value of rutting depths for two replicates per asphalt mixture after being subjected to 10,000 test cycles. After 10,000 cycles, the rut depth for the control mixture is 3.36 mm. Meanwhile, the modified mixtures with plastic waste showed significant enhancement in the resistance against plastic deformation. The plastic mixtures have a 0.93 mm rut depth after 10,000 cycles. This could be attributed to the effect of plastic in reducing the asphalt mixture's susceptibility to thermal liquefaction. Such impacts are directly related to the low thermal sensitivity of plastic to the increment in temperatures. In other words, the interaction between melted plastic and asphalt binder enhances the viscous flow behaviour of the binder. Consequently, the produced asphalt binder will have lower susceptibility to deformation at high service temperatures.

As observed, the failure in asphalt mastic or loss of adhesion properties directly contributes to mixtures' resistance to plastic deformation [70]. Accordingly, the asphalt binder and adhesion with aggregate play a vital role in improving the rutting performance of the mixture [8]. On the other hand, the rubberised mixture has a high rutting depth of 5.8 mm. The same result can be observed for the rubberised mixture under the creep test. After sample extraction, the minor expansion of rubber particles is responsible for the low

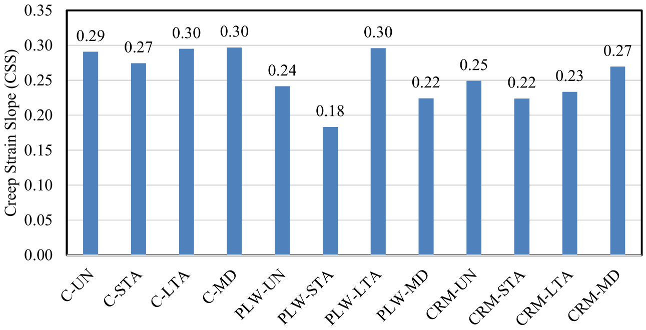

Fig. 11. Creep strain slope (CSS) of asphalt mixture.

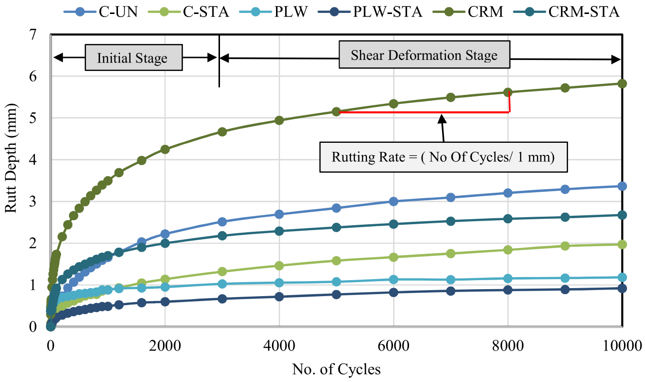

Fig. 12. Wheel tracking test of unconditioned and short-term aged conditioned samples.

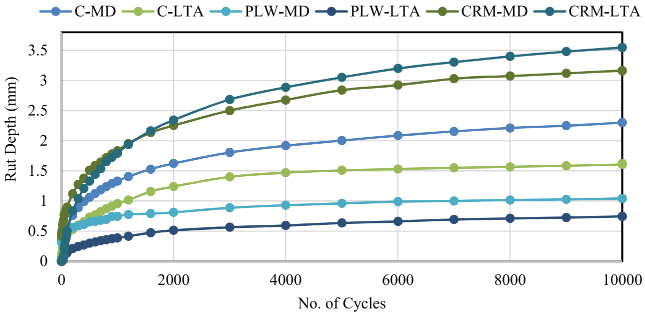

Fig. 13. Wheel tracking test of samples after moisture and long-term ageing conditioning.

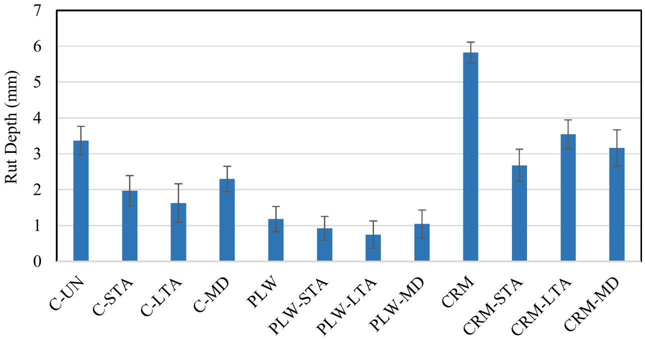

Fig. 14. Total rutting depth of the conditioned and unconditioned samples.

resistance of rubberised mixtures to plastic deformation. The same finding was observed by previous research showing that rubberised mixture exhibited higher rutting potential than conventional mixture [71]. Accordingly, the results of STA showed that the rutting of mixtures modified by plastic waste and crumb rubber have decreased by about 22% and 51%, respectively. In contrast, the control mixture showed a decrement in the rutting depth of about 42%. Such findings are related to the effect of STA on improving the interlocking force between the mixture components. Moreover, short-term ageing has enhanced the interaction between asphalt binder, crumb rubber, and plastic particles. As revealed by a previous study, the bonding properties were observed to improve after exposure to short-term ageing, resulting in high adhesion between the mixture components [72]. The rutting results align with the MR (as presented in Section 3.2), indicating that the PLW mixture demonstrated the least rut depth under wheel tracking.

The findings were also in line with observations by Radeef et al. [8], which showed a decrease in the rutting potential for mixture modified by plastic waste. Accordingly, Fig. 14 shows the rutting depth values after conditioning the control and modified mixtures for moisture damage and long-term ageing. It can be seen that the moisture conditioning has decreased the mixture's resistance against deformation compared to the conditioned mixtures under short-term ageing. However, the plastic waste modified mixture showed the highest resistance to moisture damage. The rutting depth after moisture damage was increased by 16%, 12%, and 18% for the control, PLW-MD, and CRM-MD accordingly. The effects of moisture damage on rutting depth align with the result of creep. Furthermore, a previous study found that plastic waste has good resistance to moisture damage than the rubberised mixture [21]. On the other hand, the same figure also shows the result of rutting after long-term ageing. The control and plastic waste modified mixtures have shown decrement in the rutting depth due to the hardening of the asphalt binder. Asphalt hardening increases the shear resistance of materials by restricting aggregate displacement under the compressive force. The shear properties of asphalt directly influence the mixture's resistance to compression failure. Thus, improving the asphalt binder stiffness will enhance the mixture's resistance to creep and rutting deformation.

On the other hand, the rubberised mixture showed a different trend, where the exposure to LTA has increased the rutting depth of the tested sample. As earlier declared, the rubberised mixture showed minor expansion in the form of cracks developed in the asphalt mastic between the aggregate particles, which increased the rutting potential of rubberised mixtures when exposed to LTA conditioning. Fig. 15 depicts the failure of asphalt mastic in the images of the cross-section of the control and modified mixtures under the wheel path. ImageJ software was used to process the images to threshold the deformation within the asphalt mastic. The red colour reflects the cracks and cavities due to the densification impact of wheel load in the asphalt mastic after 10,000 cycles. As shown in the figure, asphalt mixtures modified by plastic waste showed lower deformation in the asphalt mastic than the control and rubberised mixtures. On the other hand, significant deformation was observed in the upper half of the cross-section for the mixtures modified by crumb rubber as circled in Fig. 15 (c,f), which justify the least resistance of rubberised asphalt against permanent deformation.

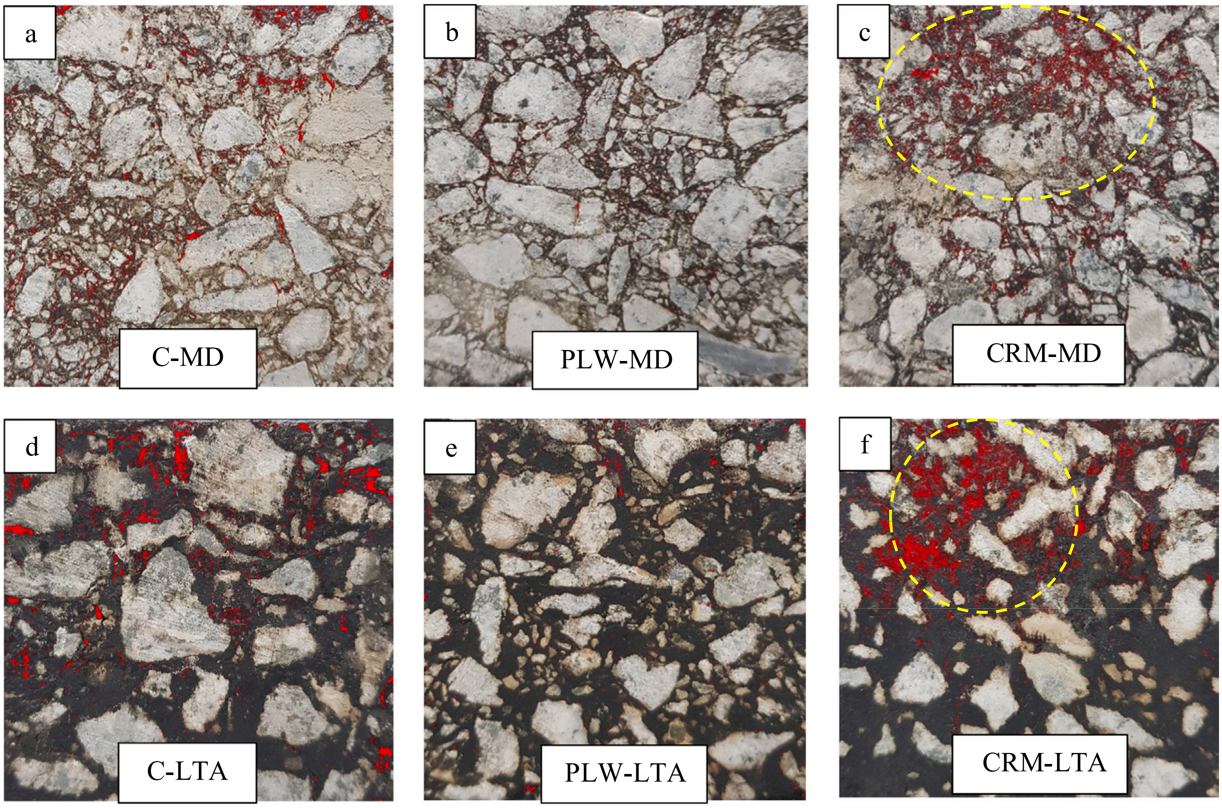

Fig. 15. Deformation in asphalt mixtures under wheel path.

4. Conclusion

This study aimed to assess the impact of ageing and moisture damage on conventional and modified asphalt's performance through laboratory experiments. Based on the results, the optimum binder content to reach 4% air voids is higher for the CRM asphalt mixture than the control mixture, while the PLW mixture has the least. Both modified mixtures require more compaction effort to achieve the specified density than the control mixture. The addition of crumb rubber into asphalt decreases the mixtures' performance in terms of the indirect tensile, resilient modulus, dynamic creep, and rutting potential due to the elasticity of rubber particles. Although the performance of the conventional asphalt deteriorated after adding crumb rubber, the results comply with the required specification and seem to be applicable for the road industry. In contrast, plastic waste has increased the mechanical performance of the asphalt compared to the conventional mixture. The moisture conditioning has significantly decreased the modulus and rutting resistance of the rubberised mixture. Such results could be attributed to the decrement in the cohesion and adhesion properties for the rubberised mixture. On the other hand, plastic waste seems to be an ideal additive to improve the mechanical properties and durability of the asphalt. The plastic mixture showed lower susceptibility to moisture damage due to the plastic coating on the aggregate surface, making it hydrophobic. The STA plays an essential role in enhancing the properties of modified mixtures, particularly for the rubberised mixture owing to the stiffening effect, which results in a better performance against elastic and plastic deformation. Incorporating crumb rubber in asphalt seems to have a detrimental impact on the mixtures' durability due to the substantial decrement in the resistance to permanent deformation after LTA. In contrast, the LTA has increased the indirect tensile strength and resilient modulus of rubberised asphalt by 17% and 31% accordingly. Such results indicate that rubberised mixture resistance to compressive stresses is lower than tensile stresses, which could be attributed to the minor increase in the size of the rubber particles after LTA conditioning. On the other hand, the asphalt containing plastic waste showed a significant enhancement in the mechanical performance after LTA due to improved adhesion properties. Overall, the results indicate that the asphalt mixture containing plastic waste has better ageing and moisture damage resistance than the rubberised mixture. The rubberised mixture was found to have a high susceptibility to moisture damage and long-term ageing, which require further studies on the applicability of crumb rubber over the long-term service of asphalt pavement.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] C. Fang, C. Wu, J. Hu, R. Yu, Z. Zhang, L. Nie, S. Zhou, X. Mi, Pavement properties of asphalt modified with packaging-waste polyethylene, J. Vinyl Addit. Technol. 20 (2014), https://doi.org/10.1002/vnl.21328.

[2] E. Romeo, B. Birgisson, A. Montepara, G. Tebaldi, The effect of polymer modification on hot mix asphalt fracture at tensile loading conditions, Int. J. Pavement Eng. (2010), https://doi.org/10.1080/10298436.2010.488735.

[3] X. Xu, Z. Leng, J. Lan, W. Wang, J. Yu, Y. Bai, A. Sreeram, J. Hu, Sustainable practice in pavement engineering through value-added collective recycling of waste plastic and waste tyre rubber, Engineering 7 (2021) 857–867, https://doi.org/10.1016/j.eng.2020.08.020.

[4] E. Ahmadinia, M. Zargar, M.R. Karim, M. Abdelaziz, E. Ahmadinia, Performance evaluation of utilisation of waste polyethylene terephthalate (PET) in stone mastic asphalt, Constr. Build. Mater. (2012), https://doi.org/10.1016/j.conbuildmat.2012.06.015.

[5] M.M. Rahman, G.D. Airey, A.C. Collop, I. Rodríguez Fernández, M.C. Cavalli, L. Poulikakos, M. Bueno, M.M. Rahman, G.D. Airey, A.C. Collop, Moisture susceptibility of high and low compaction dry process crumb rubber–modified asphalt mixtures, Transp. Res. Rec. 2180 (2010) 121–129, https://doi.org/10.3141/2180-14.

[6] A. Behnood, M. Modiri Gharehveran, Morphology, rheology, and physical properties of polymer-modified asphalt binders, Eur. Polym. J. 112 (2019) 766–791, https://doi.org/10.1016/j.eurpolymj.2018.10.049.

[7] L. Brasileiro, F. Moreno-Navarro, R. Tauste-Martínez, J. Matos, M. del, C. Rubio-Gámez, Reclaimed polymers as asphalt binder modifiers for more sustainable roads: a review, Sustainability 11 (2019) 1–20, https://doi.org/10.3390/su11030646.

[8] H.R. Radeef, N. Abdul Hassan, A.R.Z. Abidin, M.Z.H. Mahmud, N.I.M. Yusoffa, M.K. Idham Mohd Satar, M.N.M. Warid, Enhanced dry process method for modified asphalt containing plastic waste, Front. Mater. 8 (2021) 247, https://doi.org/10.3389/fmats.2021.700231.

[9] M.B. Khurshid, N.A. Qureshi, A. Hussain, M.J. Iqbal, Enhancement of hot mix asphalt (HMA) properties using waste polymers, Arab. J. Sci. Eng. 44 (2019) 8239–8248, https://doi.org/10.1007/s13369-019-03748-3.

[10] H.R. Radeef, N. Abdul Hassan, M.Z.H. Mahmud, A.R. Zainal Abidin, C.R. Ismail, H.F. Abbas, Z.H. Al-Saffar, Characterisation of cracking resistance in modified hot mix asphalt under repeated loading using digital image analysis, Theor. Appl. Fract. Mech. (2021), 103130, https://doi.org/10.1016/j.tafmec.2021.103130.

[11] S. Noura, A.M. Al-Sabaeei, G.I. Safaeldeen, R. Muniandy, A. Carter, Evaluation of measured and predicted resilient modulus of rubberised stone mastic asphalt (SMA) modified with truck tire rubber powder, Case Stud. Constr. Mater. 15 (2021), e00633, https://doi.org/10.1016/j.cscm.2021.e00633.

[12] J.K. Appiah, V.N. Berko-Boateng, T.A. Tagbor, Use of waste plastic materials for road construction in Ghana, Case Stud. Constr. Mater. 6 (2017) 1–7, https://doi.org/10.1016/j.cscm.2016.11.001.

[13] H.R. Radeef, N. Abdul Hassan, M.Z.H. Mahmud, A.R. Zainal Abidin, C.R. Ismail, H.F. Abbas, Mixture design and test parameter effect on fracture performance of asphalt: a review, ASEAN Eng. J. (2021), https://doi.org/10.13140/RG.2.2.14832.79363.

[14] S.A. Tahami, A.F. Mirhosseini, S. Dessouky, H. Mork, A. Kavussi, The use of high content of fine crumb rubber in asphalt mixes using dry process, Constr. Build. Mater. 222 (2019) 643–653, https://doi.org/10.1016/j.conbuildmat.2019.06.180.

[15] N.A. Hassan, G. Airey, R.P. Jaya, M.Z.H. Mahmud, N. Mashros, Use of imaging techniques for viewing the internal structure of rubberised asphalt mixtures, Appl. Mech. Mater. 695 (2014) 8–11, https://doi.org/10.4028/www.scientific.net/amm.695.8.

[16] D.Lo Presti, Recycled tyre rubber modified bitumens for road asphalt mixtures: a literature review, Constr. Build. Mater. 49 (2013) 863–881, https://doi.org/10.1016/j.conbuildmat.2013.09.007.

[17] Z.N. Kalantar, M.R. Karim, A. Mahrez, A review of using waste and virgin polymer in pavement, Constr. Build. Mater. (2012), https://doi.org/10.1016/j.conbuildmat.2012.01.009.

[18] M. Khalili, K. Jadidi, M. Karakouzian, S. Amirkhanian, Rheological properties of modified crumb rubber asphalt binder and selecting the best modified binder using AHP method, Case Stud. Constr. Mater. 11 (2019), e00276, https://doi.org/10.1016/j.cscm.2019.e00276.

[19] A. Chegenizadeh, B. Peters, H. Nikraz, Mechanical properties of stone mastic asphalt containing high-density polyethene: an Australian case, Case Stud. Constr. Mater. 15 (2021), e00631, https://doi.org/10.1016/j.cscm.2021.e00631.

[20] F. Moreno-Navarro, M. Gámez, Influence of crumb rubber on the indirect tensile strength and stiffness modulus of hot bituminous mixes, J. Mater. Civ. Eng. 24 (2012), https://doi.org/10.1061/(ASCE)MT.1943-5533.0000436.

[21] M. Arabani, S.A. Tahami, G.H. Hamedi, Performance evaluation of dry process crumb rubber-modified asphalt mixtures with nanomaterial, Road Mater. Pavement Des. 19 (2018) 1241–1258, https://doi.org/10.1080/14680629.2017.1302356.

[22] N. Suaryana, E. Nirwan, Y. Ronny, Plastic bag waste on hotmixture asphalt as modifier, Key Eng. Mater. 789 (2018) 20–25, https://doi.org/10.4028/www.scientific.net/KEM.789.20.

[23] H. Zhou, S. Holikatti, P. Vacura, Caltrans use of scrap tires in asphalt rubber products: a comprehensive review, J. Traffic Transp. Eng. Engl. Ed. 1 (2014) 39–48, https://doi.org/10.1016/S2095-7564(15)30087-8.

[24] A.V. Tiwari, Y.R.M. Rao, Study of plastic waste mixed bituminous concrete using dry process for road construction, Sel. Sci. Pap. J. Civ. Eng. 13 (2019) 105–112, https://doi.org/10.1515/sspjce-2018-0024.

[25] H.R. Radeef, N. Abdul Hassan, A.R. Zainal Abidin, M.Z.H. Mahmud, H.F. Abbas, Z. al Saffar, S. Redha, Impact of ageing and moisture damage on the fracture properties of plastic waste modified asphalt, in: Proceedings of the InFInID 2021. ⟨https://doi.org/10.13140/RG.2.2.29093.42728⟩ (In press).

[26] H.R. Radeef, N. Abdul Hassan, A.R. Zainal Abidin, M.Z.H. Mahmud, H. Yaacob, N. Mashros, A. Mohamed, Effect of aging and moisture damage on the cracking resistance of rubberised asphalt mixture, Mater. Today Proc. (2021) 2853–2858, https://doi.org/10.1016/j.matpr.2020.12.734.

[27] D. Movilla-quesada, A.C. Raposeiras, L.T. Silva-klein, P. Lastra-González, D. Castro-fresno, Use of plastic scrap in asphalt mixtures added by dry method as a partial substitute for bitumen, Waste Manag. 87 (2019) 751–760, https://doi.org/10.1016/j.wasman.2019.03.018.

[28] Z. Arega, A. Bhasin, T. Kesel, Influence of extended aging on the properties of asphalt composites produced using hot and warm mix methods, Constr. Build. Mater. 44 (2013) 168–174, https://doi.org/10.1016/j.conbuildmat.2013.02.081.

[29] Asphalt Institute, Principles of Construction of Hot-Mix Asphalt Pavements, Manual Ser, 1983.

[30] I.A. Tonial, Influência do envelhecimento do revestimento asfáltico na vida de fadiga de pavimentos, Rio Janeiro Diss. Mestr. Apresentada à Univ. Fed. Do Rio Janeiro/COPPE, 2001.

[31] G. Ramond, C. Such, Bitumens and modified bitumens: relationships, structures, properties and composition. Bitumes et bitumes modifies, Bull. Liaison Lab. Chaussees (1990) 65–88.

[32] D. Lesueur, The colloidal structure of bitumen: consequences on the rheology and on the mechanisms of bitumen modification, Adv. Colloid Interface Sci. 145 (2009) 42–82, https://doi.org/10.1016/j.cis.2008.08.011.

[33] C.A. Bell, Y. AbWahab, M.E. Cristi, D. Sosnovske, Selection of Laboratory Aging Procedures for Asphalt-aggregate Mixtures, Strategic Highway Research Program, 1994.

[34] R.N. Hunter, A. Self, J. Read. The Shell Bitumen Handbook, sixth ed., ICE Publishing, 2015 https://doi.org/10.1680/tsbh.58378.

[35] S.H. Khanghahi, S.J. Zakavi, M. Montasheri, Study of The Effect of Aging on Hot-Mix Asphalt Using Indirect Tensile Strength Test, 2021, pp. 1–5.

[36] T.R. Board of Sciences Engineering, Medicine, Short-Term Laboratory Conditioning of Asphalt Mixtures, The National Academies Press, Washington, DC, 2015. ⟨https://doi.org/10.17226/22077⟩.

[37] C. de la Roche, M. de Ven, et al., Development of a laboratory bituminous mixtures ageing protocol, in: Advanced Testing and Characterization of Bituminous Materials, Two Volume Set, CRC Press, 2009, pp. 347–362.

[38] B.E. Ruth, R. Roque, B. Nukunya, R. Davis, M. Marasteanu, W. Vavrik, F. Fee, M. Taylor, E. Dukatz, Li, Aggregate gradation characterisation factors and their relationships to fracture energy and failure strain of asphalt mixtures, Asphalt Paving Technology: Association of Asphalt Paving Technologists-Proceedings of the Technical Sessions, 2002, p. 71.

[39] M.D. Elwardany, F.Y. Rad, C. Castorena, Y.R. Kim, Evaluation of asphalt mixture laboratory long-term ageing methods for performance testing and prediction, Road. Mater. Pavement Des. 18 (2017) 28–61, https://doi.org/10.1080/14680629.2016.1266740.

[40] G.D. Airey, State of the Art Report on Ageing Test Methods for Bituminous Pavement Materials, 4 September 2003, pp. 165–176.

[41] S. Caro, E. Masad, A. Bhasin, D.N. Little, Moisture susceptibility of asphalt mixtures, part 1: mechanisms, Int. J. Pavement Eng. (2008), https://doi.org/10.1080/10298430701792128.

[42] E.R. Hunter, K. Ksaibati, Evaluating Moisture Susceptibility of Asphalt Mixes (MPC-02-138), 2002.

[43] T.M. Breakah, J.P. Bausano, R.C. Williams, Integration of moisture sensitivity testing with gyratory mix design and mechanistic-empirical pavement design, J. Transp. Eng. 135 (2009) 852–857, https://doi.org/10.1061/(ASCE)0733-947X(2009)135:11(852).

[44] E. Arambula, Influence of Fundamental Material Properties and Air Voids Structure on Moisture Damage of Asphalt Mixes, Texas A&M University, College Station, TX, 2007.

[45] M.C.F. Jr, P.G. Manke, C.E. O'Bannon, Quantitative evaluation of stripping by the surface reaction test, Transp. Res. Rec. (1974) 40–54.

[46] T. López-Montero, R. Miró, Differences in cracking resistance of asphalt mixtures due to ageing and moisture damage, Constr. Build. Mater. 112 (2016) 299–306, https://doi.org/10.1016/j.conbuildmat.2016.02.199.

[47] AASHTO T283, Standard Method of Test for Resistance of Compacted Bituminous Mixture Against to Moisture Induced Damage, Washington, DC Am. Assoc. State Highw. Transp. Off., 2014.

[48] A. Ghavibazoo, M. Abdelrahman, Composition analysis of crumb rubber during interaction with asphalt and effect on properties of binder, Int. J. Pavement Eng. 14 (2013) 517–530, https://doi.org/10.1080/10298436.2012.721548.

[49] B. Hill, W.G. Buttlar, Evaluation of polymer modification in asphalt mixtures through digital image correlation and performance space diagrams, Constr. Build. Mater. (2016), https://doi.org/10.1016/j.conbuildmat.2016.06.108.

[50] J. Peralta, H.M.R.D. Silva, A.V. Machado, J. Pais, P.A.A. Pereira, J.B. Sousa, Changes in rubber due to its interaction with bitumen when producing asphalt rubber, Road. Mater. Pavement Des. (2010), https://doi.org/10.3166/RMPD.11.1009-1031.

[51] S. Angelone, M. Cauhapé Casaux, M. Borghi, F.O. Martinez, Green pavements: reuse of plastic waste in asphalt mixtures, Mater. Struct. 49 (2016) 1655–1665, https://doi.org/10.1617/s11527-015-0602-x.

[52] F. Moreno, M.C. Rubio, M.J. Martinez-Echevarria, The mechanical performance of dry-process crumb rubber modified hot bituminous mixes: the influence of digestion time and crumb rubber percentage, Constr. Build. Mater. 26 (2012) 466–474, https://doi.org/10.1016/j.conbuildmat.2011.06.046.

[53] M. Rahman, G. Airey, A. Collop, Laboratory investigation to assess moisture sensitivity of dry process CRM asphalt mixtures, in: Proceedings of the Sustainable Waste Management and Recycling: Used/Post-Consumer Tyres, 2004, pp. 151–162.

[54] Jabatan Kerja Raya Malaysia (JKR), Standard Specification for Road Works, 50580 Kuala Lumpur, 2008.

[55] H.R. Radeef, Effect of lab. Compaction effort on evaluation of modified HMA specimens, Civ. Environ. Res. 7 (2015) 112–125.

[56] S. Bressi, N. Fiorentini, J. Huang, M. Losa, Crumb rubber modifier in road asphalt pavements: state of the art and statistics, Coatings 9 (2019), https://doi.org/10.3390/COATINGS9060384.

[57] ASTM D4867, Standard Test Method for Effect of Moisture on Asphalt Concrete Paving Mixtures, West Conshohocken PA ASTM Int., 2014.
[58] AASHTO R30, Standard Practice for Mixture Conditioning of Hot Mix Asphalt (HMA), Provisional Stand. Am. Assoc. State Highw. Transp. Off. Washington, DC, USA, 2002.
[59] A. D4867, ASTM D4867, Standard Test Method for Effect of Moisture on Asphalt Concrete Paving Mixtures, West Conshohocken PA ASTM Int., 2014.
[60] ASTM D4123-82, Standard Test Method for Indirect Tension Test for Resilient Modulus of Bituminous Mixtures, West Conshohocken, 1995. ⟨https://doi.org/10.1520/D4123-82R95⟩.
[61] BS EN 12697-25, Bituminous Mixtures – Test Methods for Hot Mix Asphalt-Part 25: Cyclic Compression Test, UK BSI Stand. Inst., London, 2013.
[62] BS EN 12697-22, Bituminous Mixtures – Test Methods for Hot Mix asphalt, Part 22 Wheel Tracking, UK BSI Stand. Institution, London, 2013.
[63] X. Wang, Z. Fan, Li, H. Wang, M. Huang, Durability evaluation study for crumb rubber-asphalt pavement, Appl. Sci. 9 (2019), https://doi.org/10.3390/app9163434.
[64] N. Abdul Hassan, A. Abdulhussein Abdulridha Almusawi, M. Zul Hanif Mahmud, N. Asniza Mohamed Abdullah, N. Athma Mohd Shukry, N. Mashros, R. Putra Jaya, N.I.Md Yusoff, Engineering properties of crumb rubber modified dense-graded asphalt mixtures using dry process, IOP Conf. Ser. Earth Environ. Sci. 220 (2019), https://doi.org/10.1088/1755-1315/220/1/012009.
[65] L. Poulikakos, M. Partl, Evaluation of moisture susceptibility of porous asphalt concrete using water submersion fatigue tests, Constr. Build. Mater. 23 (2009) 3475–3484, https://doi.org/10.1016/j.conbuildmat.2009.08.016.
[66] A.I.B. Farouk, N.A. Hassan, M.Z.H. Mahmud, J. Mirza, R.P. Jaya, M.R. Hainin, H. Yaacob, N.I.M. Yusoff, Effects of mixture design variables on rubber–bitumen interaction: properties of dry mixed rubberised asphalt mixture, Mater. Struct. Constr. 50 (2017) 1–10, https://doi.org/10.1617/s11527-016-0932-3.
[67] Y.A. Almaali, S. Al-Busaltan, Effect of aggregate gradation on rutting of thin asphalt overlay, IOP Conf. Ser. Mater. Sci. Eng. (2020), https://doi.org/10.1088/1757-899X/745/1/012114.
[68] F. Xiao, W. Zhao, S.N. Amirkhanian, Aging influence on fatigue characteristics of RAC mixtures containing warm asphalt additives, Adv. Civ. Eng. (2010), https://doi.org/10.1155/2010/329084.
[69] F. Zhou, T. Scullion, L. Sun, Verification and modeling of three-stage permanent deformation behavior of asphalt mixes, J. Transp. Eng. J. Transp. Eng. ASCE 130 (2004), https://doi.org/10.1061/(ASCE)0733-947X(2004)130:4(486).
[70] H.R. Radeef, N.A. Hassan, A.R.Z. Abidin, M.Z.H. Mahmud, M.K.I.M. Satar, M.N.M. Warid, Z.H.Al Saffar, Determining fracture energy in asphalt mixture: a review, IOP Conf. Ser. Earth Environ. Sci. (2021) 12069, https://doi.org/10.1088/1755-1315/682/1/012069.
[71] H.T. Tai Nguyen, T. Nhan Tran, Effects of crumb rubber content and curing time on the properties of asphalt concrete and stone mastic asphalt using dry process, Int. J. Pavement Res. Technol. 11 (2018) 236–244, https://doi.org/10.1016/j.ijprt.2017.09.014.
[72] J.P. Aguiar-Moya, J. Salazar-Delgado, A. Baldi-Sevilla, F. Leiva-Villacorta, L. Loria-Salazar, Effect of aging on adhesion properties of asphalt mixtures with the use of bitumen bond strength and surface energy measurement tests, Transp. Res. Rec. 2505 (2015) 57–65, https://doi.org/10.3141/2505-08.