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Engineering properties of crumb rubber modified dense-graded asphalt mixtures using dry process

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Abstract. The development and production of high quality asphalt are crucial in the effort to meet current demands for the construction of roads. Crumb rubber is an industrial waste and one of the best ways to reduce the amount of this waste is by recycling it in the asphalt industry. Crumb rubber obtained from scrap tyres has been proven to be an effective additive for the modification of the properties of asphalt mixtures. This study presents a laboratory evaluation of the properties of crumb rubber modified asphalt mixture using the dry process method by adding three different sizes of crumb rubber, namely fine (≤ 1.18 mm), coarse (≥ 1.18 but ≤ 3.35 mm), and combination of both fine and coarse (50/50), at three different percentages of crumb rubber, 0, 1.5 and 2.5% of the total weight of the aggregate. Crumb rubber was used to modify the dense graded mixture of asphaltic concrete wearing course 14 (ACWC14). The effect of crumb rubber in the mixture was investigated in terms of the volumetric properties using the Marshall Mix Design and mixture performance testing was conducted by means of resilient modulus, dynamic creep, and abrasion loss. Results showed that fine crumb rubber improved most of the properties of asphalt mixtures compared to other types of mixtures; this could be due to the partial interaction between rubber particles and bitumen which simultaneously act as an elastic aggregate in the mixture.

1. Introduction

Road structures have been deteriorating at a faster rate over the years due to the increase in traffic load and improper maintenance service. In order to minimize pavement distress and increase the durability of flexible pavement, efforts have been made to improve certain aspects conventional asphalt mixtures, such as resistance to permanent deformation (rutting) and fatigue cracking. Over the past few decades, scholars and pavement engineers have been focusing their effort on developing modified asphalt mixtures as a way of improving the performance of asphalt mixtures [1]. Crumb rubber has been used in the asphalt industry since the late 1960s to reduce the amount of rubber accumulating in landfills. The use of crumb rubber in asphalt paving has been receiving increasing attention in many



parts of the world as this material has the potential to improve the mechanical and functional performance of mixtures in addition to providing an efficient way of dealing with scrap tyres. Crumb rubber obtained from used tyres has been the focus of several research which aims to overcome pavement problems and also to aid in the recycling of huge amount of scrap tyres in landfills. Previous studies have shown that 12% of the tyres generated are used in asphalt applications [1]. The process for using crumb rubber in asphalt was first developed in the 1960s as a method to improve the use of asphalt for surface treatments [2-3]. In the 1970s, crumb rubber began to be utilized in the production of hot mix asphalt known as rubberised asphalt.

In general, tyre rubber can be introduced into asphalt mixes through the wet process by reacting 10 to 30% crumb rubber by total weight of asphalt at an optimum temperature to induce physical and chemical changes which produce modified binder [4]. Crumb rubber could also be added to asphalt mixtures through the dry process in which 1 to 5% crumb rubber is blended with hot aggregate before being mixed with asphalt to produce a crumb rubber modified asphalt mixture [2]. The McDonald process and the continuous blending technology are the preferred methods of producing CRM mixes through the wet process. The PlusRide, Generic and Chunk-rubber technologies are associated with the preparation of CRM mixes through the dry process. Rubberised asphalt mixture is a general term used to describe a concept of incorporating scrap tyre rubber into asphalt paving materials. With so many studies conducted in this area, there are many terms associated with tyre rubber modified asphalt mixtures. Some of the commonly used terms are crumb rubber modifier (CRM), asphalt-rubber, rubber modified asphalt mixes (coarse and fine rubber), rubberised asphalt etc. These locutions refer to the uses of rubber in asphalt mixtures that are different in their mix composition, manufacturing or preparation method, and in their physical and structural properties.

The characteristics of rubberised asphalt depend on the type and size of rubber, asphalt composition, and the length of time and temperature of reaction [5]. Crumb rubber is used in asphalt paving to increase viscosity at high temperature, increase the flexibility and elasticity of binders at low temperature, improve adhesion to aggregates, and improve high thermos-stability and aging resistance. In addition to having excellent qualities in term of penetration, softening point and elastic recovery, research has shown that the use of rubber modified bitumen could reduce noise up to 85%. Swift *et al.* [6] studied the application of crumb rubber in noise barriers and concluded that the gradation of rubber and the type of binder used has an effect on noise absorption properties. Smaller rubber particle sizes reduce noise absorption, while larger sizes increase absorption. The use of the crumb rubber in binder course layer would reduce the impact of low stiffness modulus of the material while an increase in fatigue resistance would provide overall benefit to pavements [7].

However, rubberised asphalt mixes require higher mixing and compacting temperatures, which bring about problems with emissions [8]. Crumb rubber modified asphalt mixtures are also more susceptible to moisture damage compared to conventional asphalt mixtures, with approximately 30% and 75% reduction in stiffness for mixtures containing 3% and 5% crumb rubber respectively [7]. Airey *et al.* [9] investigated the mechanical properties of crumb rubber modified asphalt mixtures using the dry process. Results showed a large reduction in the stiffness of asphalt mixture, that is approximately 25% for 3% CRM asphalt mixtures and 45% for 5% CRM asphalt mixtures. However, the fatigue performances of CRM mixtures were superior than those of the control mixtures, while the permanent deformation performance was only marginally worse, particularly at high void contents.

These findings show that the performance of asphalt mixtures modified with crumb rubber through the dry process is not consistent as it is influenced by mixing process, binder types, rubber content, and aggregate gradation. There is also a lack of comprehensive guidelines for achieving good mixture design. Hence, there is a need to conduct a study to evaluate mixture design and the performance of asphalt mixtures modified with crumb rubber. The aim of this study is to evaluate the effect of adding different percentages of crumb rubber with varying rubber sizes on the performance of dry rubberised asphalt mixtures.

2. Materials and methods

2.1 Materials properties

This study used bitumen with 80/100 penetration grade and average softening point of 47°C. Table 1 lists the physical properties of the base bitumen. Crushed granite aggregate was mixed with the mixture in accordance with the gradation limits for Asphaltic Concrete 14 (AC14) with a nominal maximum aggregate size of 14 mm as stated in the Malaysian Public Works Department (PWD), 2008 specification [10]. Figure 1 shows the gradation limits for AC14. Three different sizes of crumb rubber were sieved, namely fine (<1.18mm), coarse (≥ 1.18 and ≤ 3.35 mm) and a 50:50 combination of fine and coarse. Different proportions of crumb rubber (size and quantity) were used in this study to understand the suitability of singular size (fine or coarse) and mixture of a combination between fine and coarse crumb rubber, and the suitability and homogeneity of the composite mixtures. The density of rubber is approximately 1.15 g/cm³. The crumb rubber was mechanically shredded at ambient temperature from truck tyres.

Table 1. Physical properties of bitumen.

Bitumen test	Result	Standard
Penetration @ 25°C (dmm)	82	ASTM D5
Softening point (°C)	45	ASTM D36
Viscosity @ 135°C (mPa·s)	300	ASTM D4402
Specific gravity @ 25°C	1.02	ASTM D70

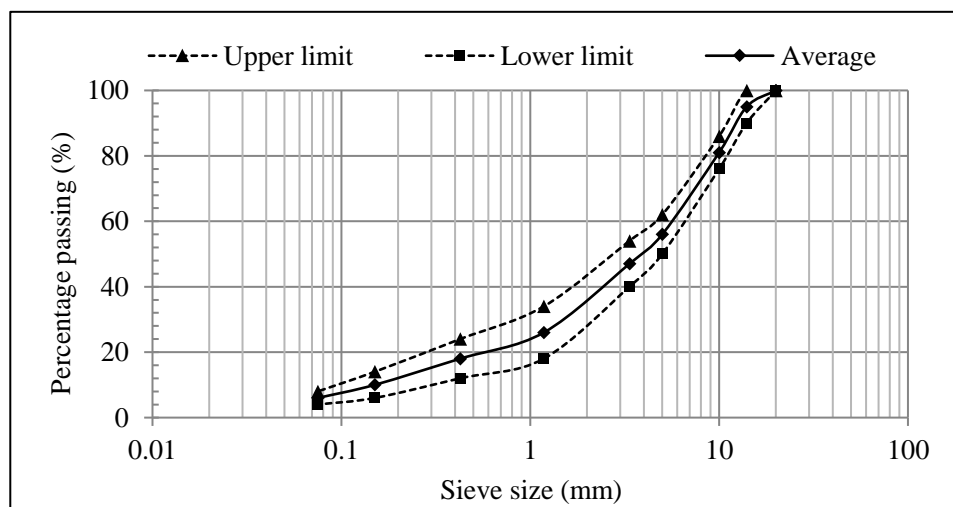


Figure 1. Aggregate gradations for ACWC14.

2.2 Marshall mix design and laboratory performance tests

The Marshall Mix Design procedure adopted in this study was as standardised by the American Society for Testing Materials. A total of 119 Marshall samples were prepared for the conventional and dry mixed rubberised asphalt mixtures to determine the optimum bitumen content (OBC). Six different rubberised asphalt mixtures with varying crumb rubber contents and sizes, including optimum bitumen content, were designed as shown in Table 2. The dry process method was used to incorporate crumb rubber into the aggregate prior to being mixed with bitumen. Previous research has shown that the optimum quantity of crumb rubber for dry rubberised asphalt is approximately 1 to 5% [2]. Hence, two different percentages of crumb rubber were selected and added into the mixture, i.e. 1.5% and 2.5% (by weight of the aggregate) for 100% fine (F), 100% coarse (C) and a combination of 50% coarse and 50% fine crumb rubber (M) as shown in Table 2. Due to the large difference in density, aggregate

replacement was done by substituting the aggregate with the same volume of measured crumb rubber content in order to avoid massive sample expansion after compaction. The aggregates were heated to 110°C and were then mixed with crumb rubber at ambient temperature. The mixture was compacted according to ASTM D 1559 specification with 75 blows of compaction on each side of the sample [11]. The mixture was mixed at 160°C and compacted at $135 \pm 5^\circ\text{C}$.

Table 2. Conventional and rubberised asphalt mixtures.

Mixture type	Rubber (%)	Rubber size, x (mm)	OBC (%)
Conventional	-	-	5.25
100% Fine Crumb Rubber	1.5	x < 1.18 mm	5.58
	2.5		5.63
100% Coarse Crumb Rubber	1.5	1.18 ≤ x ≤ 3.35 mm	5.50
	2.5		5.66
Mix (50% fine + 50% coarse) Crumb Rubber	1.5	x ≤ 3.35 mm	5.63
	2.5		5.73

A total of 42 samples were fabricated for performance tests, namely the resilient modulus, dynamic creep tests and abrasion loss, with three replicates for each testing condition. Resilient modulus was measured in indirect tensile mode which represents the elastic properties of asphalt mixtures under repeated load. The test was conducted according to the ASTM D 4123-82 and tested at 25°C and 40°C [12]. The dynamic creep test assessed the permanent deformation characteristics of asphalt mixtures at 40°C as stated in BS EN 12697-25 [13]. The main parameter derived from the test is the permanent compressive strain versus loading cycles curve. The Cantabro test was conducted to evaluate asphalt mixture's resistance against abrasion loss as specified in the ASTM D 7064 [14]. The compacted sample was placed in a Los Angeles abrasion machine for 300 revolutions. Abrasion loss is expressed as a percentage of the ratio of mass loss during the test to the initial mass of the compacted sample and is considered as an index of the mixture's resistance to stripping and ravelling.

3. Results and discussion

3.1 Marshall stability

Marshall stability is defined as a measurement of mixture's susceptibility to deformation resulting from frequent and heavy traffic load. Figure 2 shows the relationship between Marshall Stability and rubber content. The stability value refers to the maximum load in indirect tensile position tested at 60°C. In general, the addition of rubber into asphalt mixture increase the mixture's stability when compared to that of the control mixture. The graph in Figure 2 shows that the stability value decreased with the increase in crumb rubber content and sizes. However, the addition of 1.5% fine crumb rubber into the mixture resulted in a stability that is comparable to that of the control mixture, which is in contrast to the result of adding other sizes of crumb rubber. This could be attributed to the rubber-bitumen interaction which stiffens the binder and ability of fine rubber particles to distribute well within the mix during compaction, thus producing a mixture with greater stability compared to other rubberised mixtures. When rubber content was increased to 2.5%, the high elasticity of rubber particles caused the asphalt mixture to become too flexible. A good asphalt mixture must have a good balance between flexibility and strength. A mixture that is too flexible could cause instability under loading condition. However, the stability value is a very direct measurement and does not fully describe the ability of the rubberised asphalt mixtures to recover after deformation. For this particular mixture, further evaluation of sample recovery under post loading condition should be conducted to better characterize its behaviour under loading action.

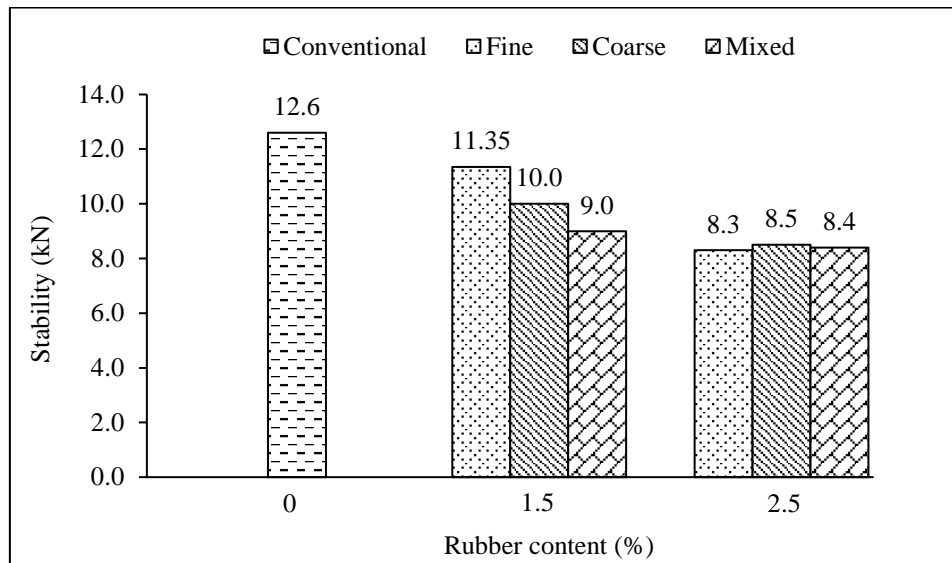


Figure 2. Stability for different mixture types and rubber contents.

3.2 Plastic flow

As shown in Figure 3, the plastic flow result shows that the mixture with coarse crumb rubber gives the highest plastic flow compared to other mixtures. This is in contrast with the mixtures containing fine and mixed crumb rubber sizes where the plastic flow decreases with the increase in rubber content. However, the plastic value for conventional mixture and mixture with fine crumb rubber stays within the permissible limit of 2–4 mm accordingly to JKR specifications [10]. The mixture with coarse size of crumb rubber results in the plastic value above the upper limit which are 5.1 mm and 6.1 mm at 1.5% and 2.5% rubber contents respectively. In this case, the mixture can be considered as too plastic or unstable. Meanwhile, the mixture with a combination of fine and coarse aggregate shows the lowest flow value of 1.0 mm which is below the lower limit and this mixture can be considered as too brittle.

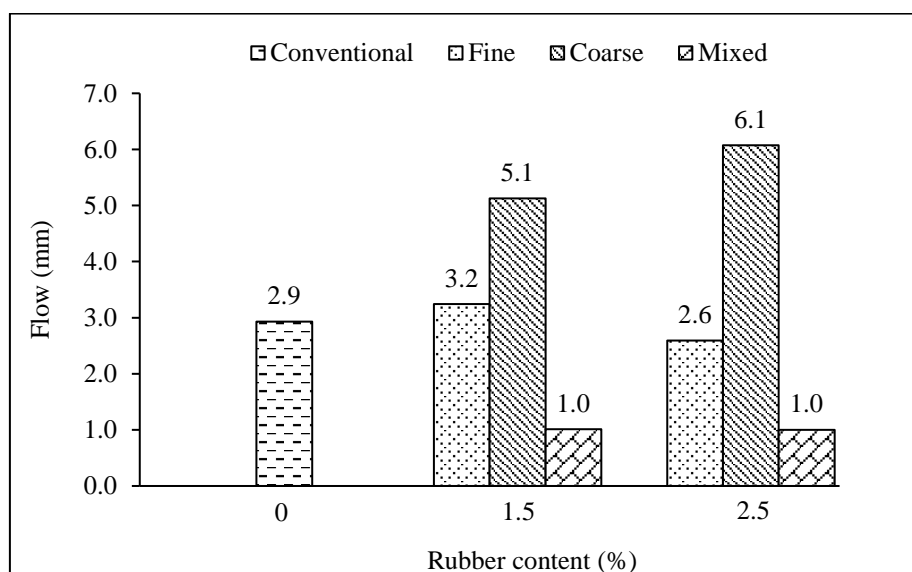


Figure 3. Flow analysis for different mixture types and rubber contents.

3.3 Resilient modulus

The resilient modulus test evaluates the ability of compacted sample to recover under repeated load with constant compressive stress without the sample reaching failure conditions [16-17]. The results for this test are shown in Figures 4 and 5. They show that when the temperature increased, resilient modulus decreased regardless of rubber size and content. Increasing the temperature dramatically reduced the resilient modulus of the samples. Adding a larger amount of crumb rubber decreased the resilient modulus of the mixtures. At 25°C, the mixture with fine crumb rubber performs better than both the mixture with coarse crumb rubber and the mixture with a combination of fine and coarse crumb rubber regardless of the quantity of the crumb rubber. When the temperature was increased to 40°C, the difference in the resilient modulus between the control and rubberised asphalt mixtures is very slight. The resilient modulus for all rubberised asphalt mixtures with 1.5% crumb rubber is comparable to the value for the control sample. However, with the exception of the sample with fine crumb rubber, samples containing high percentages of crumb rubber show a slightly lower resilient modulus compared to that of the control mixture. This shows that the sample with crumb rubber has the potential to perform as well as conventional mixture at elevated temperature with the advantage of recycling crumb rubber. This could be due to the properties of crumb rubber itself as it is recycled from truck tyres which are composed of natural and synthetic rubber [2]. A combination of these two materials could improve the thermal stability of the tyre compound. Natural rubber consists of linked monomers called isoprene. It provides greater elastic recovery and excellent physical strength as well as resilience and high resistance to tearing and abrasion. Natural rubber has a working temperature range of approximately -50°C to 100°C, making it ideal for anti-vibration applications and use in large tyres where excessive heat build-up could be disastrous. Hence, one of the clear benefits of adding crumb rubber in asphalt mixtures is that the mixtures will be less susceptible to extreme temperature. According to Hassan *et al.* [18-19], the dispersion of coarse crumb rubber in rubberised asphalt mixtures is not as uniform the dispersion of fine crumb rubber in the mixture since coarse rubber tends to form clusters in the vicinity of the aggregate particles. As a result, samples with fine crumb rubber are able to better recover uniformly throughout the sample from repeated loading compared to samples with coarse rubber.

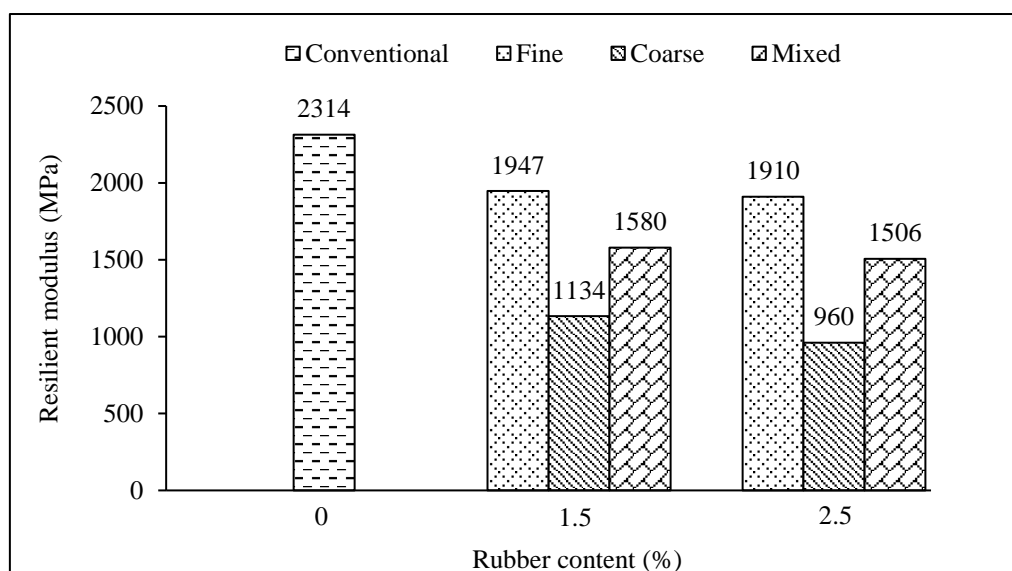


Figure 4. Resilient Modulus at 25°C.

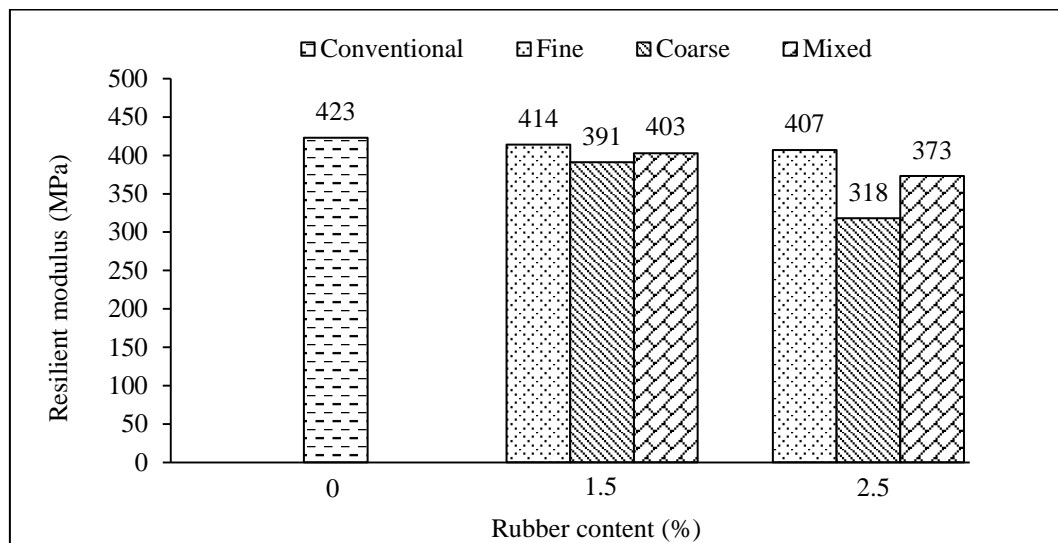


Figure 5. Resilient Modulus at 40°C.

3.4 Abrasion loss

The Cantabro test was conducted to evaluate mixture's resistance against abrasion loss. Figure 6 shows the relationship between abrasion loss and the various mixtures with different rubber contents and sizes. It shows that, compared to the conventional asphalt, samples with coarse rubber are the least durable against abrasion loss, followed by those with mixed crumb rubber size. Similar observation was made when a high percentage of crumb rubber was added to the mixture. This could be due to the discontinuity in the bitumen film reducing its bonding capacity and weakening the cohesive and adhesive properties of the mixtures. However, the degree of particle loss in asphalt mixtures seems to be very minimal as fine rubber was added to the mixture. In other words, fine rubber is better able to increase mixture's resistance against abrasion loss compared the abrasion loss experienced by conventional mixture. This could be due to the greater mobility of the fine rubber particles within the mixture during mixing and compaction which allow the particles to form a homogenous blend and therefore produce a uniform asphalt mixture. Fine rubber particles also have a larger surface area and therefore require a larger amount of bitumen to completely coat all particles; this accelerates the rate of rubber-bitumen interaction which stiffens the binder. As a result, the value for abrasion loss decreased with the addition of fine rubber. However, in general, the values for abrasion loss for all mixtures are considered acceptable as they are very minimal.

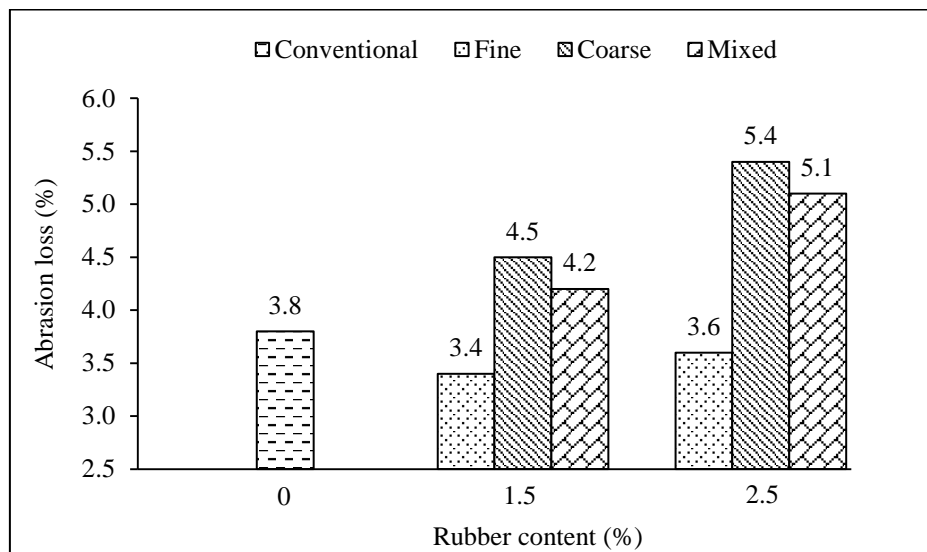


Figure 6. Cantabro test result for different mixture type.

3.5 Rut depth

The dynamic creep test was used to evaluate the mixture's resistance against permanent deformation. Figure 7 shows the relationship between rut depth and rubber content for different crumb rubber sizes. Permanent deformation, which results from high shear stress in the upper portion of the bituminous layer, seems to be the primary cause of rutting in flexible pavements. Repeated loading of this stress under comparatively low mix stiffness leads to the accumulation of permanent deformation on the surface of pavements. Results show that the addition of crumb rubber improves mixture's resistance towards rutting. When compared to the control sample, the sample with fine crumb rubber shows the most resistant towards rutting followed by the samples with mixed rubber size and coarse rubber. Interestingly, the increase in crumb rubber content to 2.5% resulted in a reduction of rut depth by almost half compared to samples with 1.5% crumb rubber. It seems that higher rubber content has a significant effect on the elastic recovery by providing more elasticity to the mixture, which improves their recovery properties under dynamic loading. It should be noted that rubber particles act as elastic aggregate which provides elastic contacts within the asphalt mixture. As highlighted by Abdul Hassan *et al.* [20], the elastic contacts will give mixtures higher ability to absorb energy under imposed stress (through repetitive loading) and help in decelerating the rate of permanent deformation

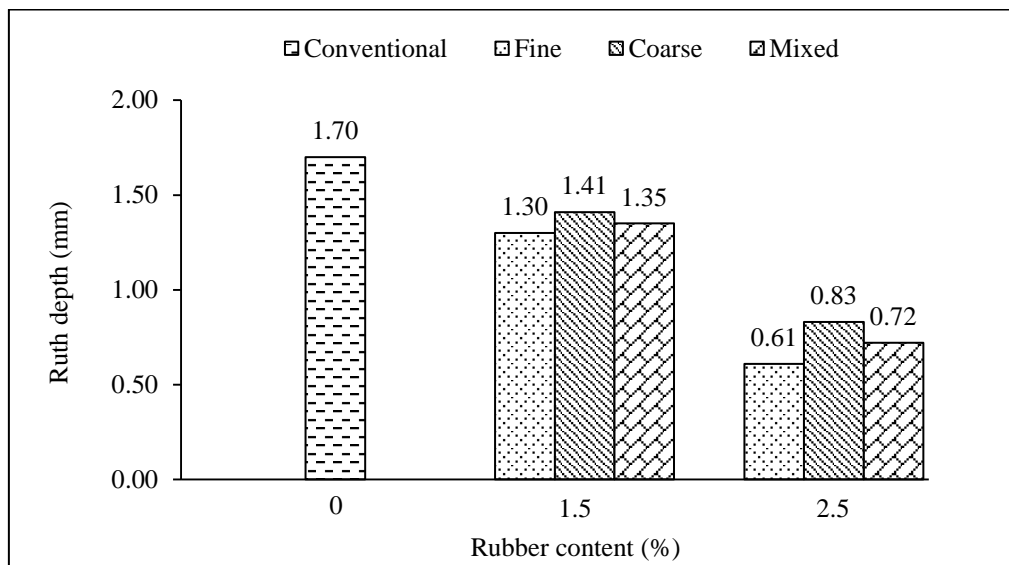


Figure 7. Dynamic creep test.

4. Conclusion

Based on the results of this study, it can be concluded that the addition of crumb rubber into asphalt mixture through the dry process method affect the mix design and its performance. Mixture stability and density decrease when the percentage of crumb rubber increased. Furthermore, the addition of rubber reduced the mixtures' resilient modulus, however, the result is comparable to that of the control mixture when tested at high temperature. This finding shows that there exists some potential resistance against temperature susceptibility, which improves the recovery of the samples under extreme temperature. In terms of abrasion loss, fine rubberised mixtures with both crumb rubber contents showed better result than the control mixture. However, all types of mixtures showed very minimal abrasion loss, and this is considered acceptable. The addition of crumb rubber particularly those with finer rubber size at higher rubber content seemed to show better rutting resistance compared to the conventional mixture.

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