Effect of the Densification of the Reinforced Asphalt Mixtures on the Permanent Deformation

M Y Aman*, A M Alnadish¹, M MD Rohani¹, D B Danial¹ and M N M Mohamad Tahir¹.

¹Smart Driving Research Centre, Faculty of Civil Engineering and Built Environment, Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Batu Pahat, Johor, MALAYSIA
*Corresponding author: mdyusri@uthm.edu.my

Abstract. This study aims to provide a better understanding for evaluating the resistance of the reinforced asphalt mixtures to permanent deformation. The resistance of asphalt mixtures to permanent deformation was assessed using dynamic creep test at a temperature of 40 °C. Four mixtures namely Mix1, Mix2, Mix3, and Mix 4 were evaluated, Mix1 corresponds to the control mixture that containing coarse steel slag aggregate while Mix2, Mix3, and Mix4 represent the reinforced mixtures with polyester fiber at the proportions of 0.05, 0.15, and 0.3%, respectively. The findings of this study showed that the elastic deformation occurred at the primary stage has a negative influence regarding the permanent deformation assessment. In addition, increasing the content of the polyester fiber has a positive relationship with the elastic stage; the higher the proportion of the fiber, the higher the deformation at the elastic stage, which have a negative effect on the evaluation of the mixtures resistance to permanent deformation, if the deformation occurred at the elastic stage is not excluded. On the other hand, the mixtures containing a high content of polyester fiber exhibited better resistance to the permanent deformation at the viscoelastic stage.

1. Introduction
Asphalt mixtures consist of coarse and fine aggregate and bitumen as binder [1]. The binder acts like a glue to the mixture that holds the aggregate in order to produce mixtures with stable and durable properties to resist the traffic loads. In some cases, the binder does not perform well due to the elevated temperature as well as the increase in the traffic loads. Thus, it is necessary to modify the binder with certain additives to enhance its physical properties [2-3]. In this regard, polymers and copolymers are common additives that have been used to improve the physical properties of the binder. It is proven that the polymers and copolymers enhance the mechanical properties of the mixtures regarding the resilient modulus, the resistance of the mixtures to permanent deformation and cracking [4-6]. The main disadvantage of modifying the binder with polymers and copolymers, that the storage stability of the binder becomes poor. In addition, modifying the binder with these additives requires a high mixing temperature and long period for mixing to produce a homogeneous modified binder. This in turn leads to energy consumption and toxic emissions. Furthermore, it is proven that these additives accelerate aging of the asphalt layer in the field. Subsequently, the service life of asphalt layer is decreased; this is because when the asphalt layer is aged it becomes too stiff. Thus, it is susceptible to rutting accompanying with longitudinal cracking [7-14].

Therefore, due to the sensitivity of the binder, the researchers tend to modify the asphalt mixtures to reduce the factors that may negatively affect the bitumen, which in turn affects the performance of the
Asphalt mixtures. Consequently, fibers are well-known materials that have been used for many decades to reinforce the mixtures due to their abilities to enhance the resistance of the asphalt layer to cracking, rutting and moisture sensitivity. Natural fibers, i.e. coconut, cellulose, sisal, wool, vegetable, cotton, flax, and asbestos have been utilized in the asphalt mixtures to improve the performance of the asphalt mixture concerning of resilient modulus, permanent deformation and cracking. Additionally, the high absorption rate of the natural fiber prevents the drainage of the binder during the production and placing of the stone mastic mixtures because it absorbs the bitumen [15-17]. In similar content, synthetic fibers, i.e. polypropylene, polyester, polyvinyl alcohol, polycrylonitrile, aramid, basalt, glass, and steel have been used in reinforcing the dense-graded asphalt mixtures to improve the performance of asphalt mixtures. It is proven that the reinforced asphalt mixtures with synthetic fibers have superior properties with regard to stiffness modulus, the resistance of the mixtures to rutting, cracking, and moisture susceptibility. [18-22]. In addition, reinforcing the dense-graded asphalt mixtures with synthetic fiber may increase the initial cost of the mixtures, but it increases the service life of asphalt layer and decreases the thickness of asphalt layer, and thus saving cost of the maintenance as well as costs of the transportation and reducing the demand for the natural aggregate [23-24]. The cost of the synthetic fibers depends on the optimum dosage. Reinforcing of the asphalt mixtures with the lightweight fibers may provide mixtures with low cost in comparison with the reinforced mixtures with the high-density fibers. In other words, introducing the high-density fibers at the optimum content may equal double of the optimum content of lightweight fibers.

On the other hand, Permanent deformation (rutting) is one of the significant distresses that negatively affects the service life of asphalt layer, in some cases, it requires full-depth rehabilitation for the asphalt layer due to the significant rut depth. However, rutting depth may occur due to the densification of the mixtures (change in volume) and improper compaction as well as excessive in the air voids content, the level of this rut depth is considered as low. Similarly, the moderately level of rutting depth caused by the lateral flow, which is generated by the applied traffic loads on the surface layer. Additionally, the significant/high level of rutting depth is occurred the subsistence in the subgrade layer, this rutting might be accompanied by a longitudinal cracking, if the asphalt layer become too stiff [25-26]. Furthermore, there is a lack of information in terms of illustrating the effect of the densification of the reinforced mixtures on the permanent deformation. Introducing synthetic fibres decrease the density of the mixtures because some fibers are characterized by their light weight. This is observed through the slight decrease in the specific gravity of the reinforced mixtures [27-28]. However, the slight decrease in the density is due to the slight increase in the height of the sample. In other words, introducing the fibers at high content increases the volume of the sample, while the change in the weight of the sample still small in comparison with the change in volume. Therefore, the higher the content of the lightweight fibers, the lower the specific gravity. The densification is occurred because of the decreasing in the thickness of the sample/layer after applying the load/traffic densification; hence, the density of the sample/layer is increased. Consequently, the reinforced mixtures with the lightweight fibers are highly affected by the densification.

Otherwise, Steel slag is considered as a waste material because it is a by-product of steelmaking. Utilizing steel slag aggregate in the civil applications is viewed as sustainable practice because it depreciates the need for the raw material. However, one of the disadvantages of using steel slag aggregate is its high density, which increases the transportation costs. It is proven that replacing the natural aggregate with the coarse steel slag aggregate improves the mechanical properties of the mixtures in terms of resilient modulus, permanent deformation, and cracking resistance. In addition, introducing the synthetic fiber may reduce the thickness of the asphalt layer because the enhancements on the performance of the mixtures; thus, the transportation cost may minimize [20]. Lastly, the objective of this study is to evaluate the performance of the asphalt mixture incorporating coarse steel slag aggregate and reinforced with polyester fiber in terms of permanent deformation. In addition, to study the effect of the densification on the assessment.
2. Materials and method

2.1. Materials
Conventional bitumen 80/100 penetration grade were used, which is equivalent to PG 64, produced by Petronas (M) Sdn. Bhd. The natural coarse aggregate (granite) were replaced with coarse Electric Arc Furnace (EAF) steel slag. Steel slag aggregate was supplied by NSL Chemicals Ltd., Singapore, while the granite aggregate provided by Hanson quarry, Johor, Malaysia. The polyester fiber used in this study was supplied from Mainland, China. Figure 1 and Table 1 displays the polyester fiber shape and the physical properties of the fiber (provided by the supplier), respectively. Denes-graded with nominal maximum size aggregate of 12.5 mm was adopted, the finer gradation shown in Figure 2 was selected to decrease the effect of the porosity of steel slag aggregate on the bitumen content.

![Polyester fibers](image)

**Figure 1.** Polyester fibers.

| Material Property       | Measure                  |
|-------------------------|--------------------------|
| Material                | polyester                |
| Density                 | 1.36 (g/cm³)             |
| Tensile Strength        | >500 Mpa                 |
| Young Modulus           | >7 Gpa                   |
| Melting Point           | > 240 °C                 |
| Color                   | white                    |
| Length                  | 6 mm                     |
| Diameter                | 10-25 um                 |

**Table 1.** Polyester fiber physical properties

![Gradation of designed aggregate](image)

**Figure 2.** Gradation of designed aggregate.
2.2. Samples preparation
In this study, polyester fibers were introduced to the asphalt mixture that incorporating coarse steel slag aggregate at the proportions of 0.05, 0.15 and 0.3% by total weight of the aggregate. The prepared mixtures namely Mix1, Mix2, Mix3, and Mix4. Mix1 represents the control mixture, while Mix2, Mix3, and Mix4 correspond to the reinforced asphalt mixtures with polyester fiber at the dosages of 0.05, 0.15 and 0.3%, respectively. The mixtures were fabricated based on the specification of Superpave. The dried aggregate was heated at mixing temperature of 160°C for four hours; the mixing and compaction temperatures were determined based on the viscosity of the bitumen to ensure that the bitumen is able to coat the aggregate. Thereafter, the heated bitumen and aggregate, as well as the polyester fiber, were mixed for three minutes in the automatic mixer. The prepared mixtures were kept in an oven at the compaction temperature of 150°C to simulate the short-term aging. The Superpave Gyratory Compactor with 100 revolutions were adopted to produce the compacted samples. Prior testing, the volumetric properties of the compacted specimens were determined in order to meet the requirements of Superpave.

The content of the air voids of Mix1, Mix2, and Mix3 were 4, 4, and 4.35%; respectively, at the optimum bitumen content of 4.9%. The content of air voids and optimum bitumen content for Mix4 were 4.3 and 5.2%. In addition, adding polyester fiber have decreased the specific gravity (density) by around 0.25, 0.64, and 0.76% for Mix2, Mix3, and Mix4 compared to Mix1. This is attributed to the slight increment in the thickness of the compacted sample, which decreased the weight of the compacted samples in the water.

2.3. Dynamic creep test
The permanent deformation of the mixtures is measured through the dynamic creep test. The deformation depends on the applied compressive strength as well as type of the wave pulses loading. The pulse wave of have sine and square are the common types used in the dynamic creep test, due to its abilities to simulate the pulses loads of the vehicles on the pavement layer. In addition, the width and rest period of the pulse loading is the most important parameter, which directly affects the deformation. In other words, increasing the pulse loading width/reducing the rest period is offset by an increase in the deformation.

However, there are no limitations for this test to be as a criterion for evaluating asphalt mixtures. The main use of the dynamic creep test is to create a comparison among various types of asphalt mixtures. In this study, dynamic creep was performed in accordance with British standard BS DD 226. Prior testing, the samples of the test were kept in an oven at a temperature of 40°C for four hours to ensure that the equilibrium temperature is reached. The selected temperature is appropriate to evaluate the permanent deformation because at this temperature the bitumen becomes soft, and thus the aggregate loses the bonding with bitumen. Thereafter, the mixtures are susceptible to the deformation when it is subjected to compressive strength. A servo-hydraulic machine called UTM-5P was used to evaluate the permanent deformation. The stress of 12 kPa was applied on the specimens for two minutes as preload to ensure the contacting between the load and the sample. Thereafter, the samples were subjected to a repetitive compressive strength of 200 kPa for 3600 seconds (1 hour); the compressive strength was applied with a wave pulse of square, the pulse load consists of 1-second width and 1-second rest period, the total number of the cycles was 1800. The deformation of the sample was measured using a Linear Variable Displacement Transducer (LVDT) sensor.

3. Results and discussions
3.1. Permanent deformation of the asphalt mixtures
The ultimate permanent deformation of the reinforced mixtures that occurred after 1800 cycles is shown in Figure 3. As observed from the figure the reinforced mixtures with 0.05% of the polyester fiber have reduced the permanent deformation by approximately 11% compared to Mix1. While adding the fibers at the proportion of 0.15% (Mix3) exhibited slightly lower permanent deformation than the control mixture by approximately 4%. This is attributed to the fact that permanent deformation is highly affected by the aggregate matrix (interlocking) and the viscous of the bitumen. In other words, the higher the viscosity of the bitumen the higher the softening point. Thus, introducing the fibers at the proportions
of 0.05 and 0.15% have increased the bitumen softening point due to the slight absorption by the fiber as well as coating fibers with binder may enhance the hardness of the bitumen at the elevated temperature. Furthermore, Mix4 showed the highest permanent deformation compared to the other mixtures. This is because the increase in the fiber dosage has increased the height of the sample, and thus the sample is highly affected by the densification that occurred at the primary stage, which corresponds to the elastic deformation.

Figure 3. The ultimate permanent deformation of the reinforced mixtures.

The permanent deformation consists of three stages; the primary stage, which represents the recoverable elastic deformation that causes by the densification due to the change in the volume. While the second stage corresponds to the irrecoverable viscoelastic deformation that occurs by the actual deformation after exceeding the elasticity stage. The third stage depicts the failure of the sample [28-30]. However, since the elastic deformation is recoverable; hence, when the applied load is removed, the deformation may recovery and the sample may back to its original state. He et al. [29] suggested that the deformation that occurs at the primary stage should be excluded from the evaluation, because the deformation at the primary stage is recoverable, which occurs by the densification and not by the actual strain. In addition, the deformation occurs at the viscoelastic stage is the critical damage because the deformation at the secondary stage is irrecoverable. He et al. [29] proposed that the primary stage occurs at the first third of the number of cycles. Consequently, the deformation occurred at the 1/3 of the number of cycles should be neglected in the evaluation. The number of the cycles in this study were 1800 cycles, and the number of cycles to overcome the primary stage (elastic deformation) are 600 cycles.

However, the deformation occurs at the first 600 cycles is excluded in order to evaluate the permanent deformation at the viscoelastic stage, through neglecting the deformation causes by the densification. Figure 4 presents the permanent deformation of the reinforced mixtures at the viscoelastic stage that excluded the deformation at the primary stage. As concluded from the Figure 4, Mix2, Mix3, and Mix4 have reduced the permanent deformation in comparison with Mix1 by approximately 14, 9, and 4%, respectively. It can be said that the densification of the reinforced mixtures has negative influences in the evaluation for the resistance of the mixtures to the permanent deformation, if it is not excluded from the assessment while the resistance of the reinforced mixtures to the permanent deformation at the viscoelastic stage have improved.
3.2. Estimation of the rut depth

The permanent deformation of mixtures common used in the dynamic creep test was used to investigate the rut depth. Van de Loo [31] developed a method to estimate the rut depth in the asphalt layer. The estimated rut depth is determined based on the permanent deformation that occurs by the lateral flow/plastic movement, which is generated by the traffic loads at the elevated temperature. The estimated rut depth excludes the permanent deformation caused by the subsistence of subgrade layer. The rutting depth is calculated from equation 1, where $C_m$ is a correction factor with a value ranging from 1-2 depending on the mixtures.

$$ \text{Rut depth (mm)} = C_m h_1 \left( \frac{\sigma_{av}}{\sigma_{mix}} \right) $$

Finn et al. [32] suggested that $C_m$ should be 1 if the resilient modulus of the mixture was obtained from the dynamic creep test outputs at the viscoelastic stage. Whereas $h_1$ represents the thickness of the asphalt layer, while $\sigma_{av}$ corresponds to the average vertical stress on the asphalt layer, and $\sigma_{mix}$ is the resilient modulus of mixtures that obtained from dynamic creep test. However, the number of the load applications in-place equal to the number of the load cycles of the dynamic creep test multiplied by 10. To determine the rut depth; the thickness of the asphalt layer was assumed as 100 mm and a load of the standard dual wheel was adopted as the vertical stress (compressive strength) with a stress of 577 kPa and a radius of 10.5 mm. Therefore, $\sigma_{mix}$ is calculated as $577/2 = 288.5$ kPa.

Figure 5 illustrates the resilient modulus of the mixtures, which obtained from the dynamic creep test outputs at the viscoelastic stage as well as the estimated rutting depth. As clearly shown in the Figure 5 the estimated rut depth after 18000 of load applications for Mix1, Mix2, Mix3, and Mix4 were 0.069, 0.0645, 0.0661, and 0.0674 mm, respectively. Mix2 exhibited the lowest rut depth compared to all mixtures, which indicates that adding the fiber have enhanced the resistance of the mixture to permanent deformation. In addition, Mix3 and Mix4 showed lower rut depth than Mix1 by 4.2 and 2.4%.

![Figure 4: The permanent deformation of the reinforced mixtures at the viscoelastic stage.](image-url)
4. Conclusions

Based on the results and discussions, the following conclusions were made:

- Introducing polyester fibers to the mixtures have greatly enhanced the elasticity behavior of the asphalt mixtures.
- Adopting the ultimate deformation as the main parameter to evaluate the resistance of the asphalt mixtures to permanent deformation without taking into account the deformation occurred in the elastic stage may be an inadequate assessment, particularly for the flexible mixtures.
- Regarding the optimum fiber content, the outputs of the dynamic creep test at the viscoelastic stage (non-recoverable deformation) showed that there is an improvement in terms of the resistance of the reinforced mixtures with the high content of polyester fibers to the permanent deformation in comparison with the unreinforced mixture. Thus, adding the polyester fiber at the content of 0.3% by total weight of the aggregate represents the optimum content due to its capability to improve the flexibility of the asphalt layer. Therefore, it offers rapid recovery for the deformation as well as it may enhance the service life of asphalt layer because it requires higher traffic densification than the unreinforced mixtures to fall to the final air voids (4-3%) during the service life of asphalt layer.
- Increasing effort of the compaction in the laboratory to control the change in volume may densify the mixtures; thus, the content of the air voids in the mixture may decrease because the optimum bitumen content produces samples with air voids content of approximately 4%. Thereafter, the asphalt mixtures become unstable and highly susceptible to permanent deformation. However, increasing the effort of the compaction depends on the amount of the change in volume. In other words, the slight change in volume is desirable because it increases the initial service life of asphalt layer.

5. References

[1] John R and David W 2003 The Shell Bitumen Hand Book, 5th edition (Thomas Telford Publishing)
[2] Cortizo M S, Larsen D O, Bianchetto H and Alessandrini J L 2004 Effect of the Thermal Degradation of SBS Copolymers During the Ageing of Modified Asphalts Journal of Polymer Degradation and Stability 86(2) 275–282
[3] Yildirim Y 2007 Polymer Modified Asphalt Binders Journal of Construction and Building Materials 21(1) 66–72
[4] Polacco G, Muscente A, Biondi D and Santini S 2006 Effect of Composition on the Properties of SEBS Modified Asphalts Journal of European Polymer Journal 42(5) 1113–1121
[5] Mitchell M R, Link R E, Ghaffarpour Jahromi S, Andalibizade B and Khodaii A 2010 Mechanical Behavior of Nanoclay Modified Asphalt Mixtures Journal of Testing and Evaluation 38(5) 102-196
[6] Pamplona T F, De C, Amoni B, De Alencar A E B, Lima A P D, Ricardo N M P S, Soares J B and De A Soares S 2012 Asphalt Binders Modified by SBS and SBS/Nanoalloys: Effect on Rheological Properties Journal of the Brazilian Chemical Society
[7] Ouyang C, Wang S, Zhang Y, and Zhang Y 2006 Low-Density Polyethylene/Silica Compound Modified Asphalts with High-Temperature Storage Stability Journal of Applied Polymer Science 101(1) 472–479
[8] Cortizo M S, Larsen D O, Bianchett H and Alessandrimi J L 2004. Effect of The Thermal Degradation of SBS Copolymers During the Ageing of Modified Asphalts Polymer Degradation and Stability 86(2) 275–282
[9] Ragab M and Abdelrahman M 2018 Enhancing the Crumb Rubber Modified Asphalt’s Storage Stability Through the Control of its Internal Network Structure International Journal of Pavement Research and Technology 11(1) 13–27
[10] Sienkiewicz M, Borzędowska-Labuda K, Wojtkiewicz A and Janik H 2017 Development of Methods Improving Storage Stability of Bitumen Modified with Ground Tire Rubber: A Review Journal of Fuel Processing Technology 159 272–279
[11] Paul D K, Sirin O and Kassem E 2016 Laboratory Investigation of Asphalt Mixture Aging, Proceedings of 6th Eu asphalt and Eurobitume Congress Jun 2016
[12] Pérez-Lepe A, Martínez-Boza F J and Gallegos C 2006 High Temperature Stability of Different Polymer-Modified Bitumens: A Rheological Evaluation Journal of Applied Polymer Science 103(2) 1166–1174
[13] Kim S, Lee S H, Kwon O, Han J Y, Kim Y S and Kim K W 2015 Estimation of Service-Life Reduction of Asphalt Pavement Due to Short-Term Ageing Measured by GPC from Asphalt Mixture Journal of Road Materials and Pavement Design 17(1) 153–167
[14] Wu S, Zhao Z, Li Y, Pang L, Amirkhanian S and Riara M 2017 Evaluation of Aging Resistance of Graphene Oxide Modified Asphalt Journal of Applied Sciences 7(7) 702.
[15] Panda M, Suchismita A and Giri J 2013 Utilization of Ripe Coconut Fiber in Stone Matrix Asphalt Mixes International Journal of Transportation Science and Technology 2(4) 289–302
[16] Vale A C, Casagrande M D T and Soares J B 2014 Behavior of Natural Fiber in Stone Matrix Asphalt Mixtures Using Two Design Methods Journal of Materials in Civil Engineering 26(3) 457–465
[17] Abiola O S, Kupolati W K, Sadiku E R and Ndambuki J M 2014 Utilisation of Natural Fibre as Modifier in Bituminous Mixes: A Review Journal of Construction and Building Materials 54 305–312
[18] Park P, El-Tawil S, Park S Y and Naaman A E 2015 Cracking Resistance of Fiber Reinforced Asphalt Concrete at −20°C Journal of Construction and Building Materials 81 47–57 .
[19] Chen Z, Wu S, Zhu Z, and Liu J 2008 Experimental Evaluation on High Temperature Rheological Properties of Various Fiber Modified Asphalt Binder Journal of Central South University of Technology 15(1) 135–139
[20] Alnadish A M and Aman Y M 2018 Mechanistic Approach for Reducing the Thickness of Asphalt Layer Incorporating Steel Slag Aggregate Journal of Civil Engineering 4(2) 334
[21] Alnadish A and Aman M Y 2018 Evaluation of Aramid Fibre-Reinforced Asphalt Mixtures Lecture Notes in Civil Engineering.
[22] Alnadish A and Aman M Y 2018 A study on the Economic Using of Steel Slag Aggregate in Asphalt Mixtures Reinforced by Aramid Fiber, ARPN Journal of Engineering and Applied Sciences 13(1) 276-292.
[23] Al-Hadidy A I and Yi-qiù T 2009 Mechanistic Approach for Polypropylene-Modified Flexible Pavements Journal of Materials and Design 30(4) 1133–1140.
[24] Mokhtari A and Moghadas Nejad F 2012 Mechanistic Approach for Fiber and Polymer Modified SMA Mixtures Journal of Construction and Building Materials 36 381–390
[25] Zhang J, Ray Brown E, Kandhal P and West R 2005 An Overview of Fundamental and Simulative Performance Tests for Hot Mix Asphalt (HMA), Journal of ASTM International 2(5)
[26] Chen H, Xu Q, Chen S and Zhang Z 2009. Evaluation and Design of Fiber-Reinforced Asphalt Mixtures Journal of Materials and Design 30(7) 2595–2603
[27] Xu Q, Chen H, and Prozzi J A 2010 Performance of Fiber Reinforced Asphalt Concrete Under Environmental Temperature and Water Effects Journal of Construction and Building Materials 24(10) 2003–2010
[28] Zhou F and Scullion T 2002 Discussion: Three Stages of Permanent Deformation Curve and Rutting Model International Journal of Pavement Engineering 3(4) 251–260
[29] He G and Wong W 2007 Laboratory Study on Permanent Deformation of Foamed Asphalt Mix Incorporating Reclaimed Asphalt Pavement Materials Journal of Construction and Building Materials 21(8) 1809–1819
[30] Katman H Y, Ibrahim M R, Karim M R, Salim Mashaan N and Koting S 2015 Evaluation of Permanent Deformation of Unmodified and Rubber-Reinforced SMA Asphalt Mixtures Using Dynamic Creep Test Journal of Advances in Materials Science and Engineering 2015 1–11
[31] Van de Loo P J 1978 Creep Test: A Key Tool in Asphalt Mix Design and in the Prediction of Pavement Rutting, In Association of Asphalt Paving Technologists Proceedings (Vol. 47)
[32] Finn F N, Monismith C L and Markevich N J 1983 Pavement Performance and Asphalt Concrete Mix Design (With Discussion), In Association of Asphalt Paving Technologists Proceedings (Vol. 52)

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