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A STUDY ON THE ECONOMIC USING OF STEEL SLAG AGGREGATE IN ASPHALT MIXTURES REINFORCED BY ARAMID FIBER

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ABSTRACT

Due to the urgent need to conserve natural resources, the researchers have been focused on using plant wastes as an alternative source of natural resources. On the other hand, increasing costs of material and rising consumption of natural resources prompted engineers and researchers to look for other materials to enhance asphalt mixture performance, thus minimizing maintenance and rehabilitation of roads as well as saving costs. In this regard, steel slag aggregate is a by product of steel manufacturing, and it is considered as one of the well-known plant wastes, which is suitable for pavements applications. Although it is useful in terms of improving the performances of asphalt mixtures, it has also disadvantages such as expansion volume and high density. However, fibers could be described as a distinct material in the enhancement of asphalt mixture. This study is aimed to evaluate electric arc furnace (EAF) steel slag aggregate replaced natural coarse aggregate in the asphalt mixture reinforced by aramid fiber in order to reduce asphalt layer thickness, and hence reduce transportation costs resulting from high density of the steel slag aggregate. In addition, steel slag aggregate was immersed in the water for 6 months in order to minimize free lime and free magnesia content, which leads to the expansion volume. Six mixtures with different proportion of aramid fiber by total weight of the aggregate were evaluated. Mix1, Mix2, Mix3, Mix4, Mix5 and Mix6 corresponding to 100% of granite aggregate, coarse steel slag aggregate, coarse steel slag and 0.025% aramid fiber, coarse steel slag and 0.05% aramid fiber, coarse steel slag and 0.1% aramid fiber and coarse steel slag aggregate and 0.3 aramid fiber, respectively. However, the fine granite aggregate kept fixed for all mixtures. Thermogravimetric and XRD tests were used to evaluate the benefit of treatment steel slag aggregate while resilient modulus and dynamic creep were the performed tests of the mixtures. Response surface Methodology (RSM) using design expert6 was used to analyze results obtained in order to investigate the interaction between factor and responses of the dynamic creep. Mechanistic empirical pavement design approach was used to examine the possibility of extend service life or reducing thickness of asphalt layer as well as to assess the benefit of ultra-thin asphalt overlay containing steel slag aggregate and aramid fiber in terms of improving service life of existing asphalt layer. The results indicated that method of treatment steel slag was successful in reducing free lime and free magnesia content. Introducing aramid fiber by 0.05% to the total weight of the aggregate into mixture significantly increased resilient modulus and dynamic creep compared to the other mixtures, and it was the optimum content. The results of Mechanistic empirical pavement design indicated that Mix4 have significantly reduced asphalt layer thickness by around 20% if the service life kept constant, or increased service life by 1.24 if the thickness kept constant. In addition, ultra-thin asphalt layer overlay with Mix4 dramatically improved service life of existing asphalt layer.

Keywords: asphalt, aramid fiber, steel slag aggregate, RSM, mechanistic empirical pavement design, thickness, ultra-thin asphalt layer, saving cost.

INTRODUCTION

Maintenance and rehabilitation of the roads has become a major concern for researchers. Therefore, there are serious trends to find appropriate and economic solutions to improve asphalt service life with effective costs (Johnson, 2000). In this regard, thin asphalt overlay can provides a distinct solutionin terms of increase asphalt layer service life with cost saving. A thin asphalt overlay is defined as a placing of thin asphalt layer (25-40 mm) on existing asphalt layer, as pavement preservation. Thin layer is used as layer treatment on existing asphalt layer that have been exposed to distress such as rutting, ravelling, longitudinal and transverse cracking (Newcomb, 2009). In contrast, there is an ongoing effort to find alternatives from plant wastes, which can be used as an aggregate in the asphalt mixtures, thereby reducing demand for the natural source, thus contributing to protect environment. In addition, one of the environmental problems getting rid of the steel slag caused by the iron industry (Tsakiridis and Papadimitriou, 2008; Drizo *et al.*, 2006). Steel slag can be considered as one of the famous wastes that can be used as an aggregate in asphalt mixture (Wen *et al.*, 2014; Yi *et al.*, 2012). Steel slag is a by product of steel manufacturing that can be produced by two manufacturing processes, either by Basic Oxygen Furnace (BOF) in this process iron is melted in the blast furnace after that converted into steel in the basic oxygen furnace. Alternatively, by melting of the recycled scrap in the Electric Arc Furnace (EAF), this process called Electric Arc Furnace (EAF), which represent the second method in producing of steel slag (Skaf *et al.*, 2017; Chesner *et al.*, 1998).Furthermore, the main disadvantages of using steel slag as an aggregate can be categories as follow: i) volume instability or expansion volume, changing in volume caused by free lime (free CaO) content and free magnesium oxide (MgO) (Emery, 2015).

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Free lime reaction with water causes expansion volume of the aggregate in short period, which means using steel aggregate containing a large quantity of free lime in the asphalt mixtures or concrete lead to cracking (Böhmer *et al*., 2008).Whereas, MgO take long period for hydration, sometimes takes several years, so it is contributes to long-term expansion volume (Grubeša *et al*., 2016). Thus, reducing the amount of free lime and free magnesia by aging of the aggregate using steam or hot water or by weathering for a period is necessary to avoid any problem associated with expansion volume (Gumieri *et al*., 2004). On the other hand, reaction between free lime and water generates hydrated lime ($Ca(OH)_2$) that can be beneficial in terms of increasing adhesion between aggregate and bitumen, and increasing resistance of the mixtures to stripping and provide greater durability. According to (Wang *et al*., 2010; Böhmer *et al*., 2008) the free lime content in the steel slag should be less than 4% to be suitable for asphalt layer and 7% in unbound layer. (ii the bulk density of the steel slag aggregate higher than conventional aggregate by around 15-20%, thereby increasing the transportation costs in road construction, this can be considered as a main concern on using of steel slag aggregate in civil application (Emery, 2015). Furthermore, using 100% of steel slag in the mixtures not recommended due to porosity and angular shape of the steel slag aggregate. Thus, mixtures are high susceptible to high void space and bulking, which generates compatibility problems due to the high bitumen content as well as flushing during compaction in the filed may occurred (Chen *et al*., 2015; Chesner *et al*., 1998). On the other side, increasing costs of material and rising consumption of natural resources prompted engineers and researchers to look for material to enhance asphalt mixture performance, thus minimizing maintenance and rehabilitation of roads as well as saving cost (Huang *et al*., 2007). Besides, introducing fiber in the asphalt mixture is one of the distinctive material in terms of raising the efficiency of asphalt mixtures to resist loads inflicted upon it (Abtahi *et al*., 2010; Mokhtari *et al*., 2012). Wherefore, adding fibers to asphalt mixtures are beneficial in reducing asphalt pavement thickness, and improves its services life (Al-Hadidy *et al*., 2009). However, the Mechanistic Empirical Pavement Design is an empirical method to determine thickness of the asphalt pavement based on the calculation of the stress, strain and deflection resulting of inputs such as loading, environmental condition and parameter of the road layers with regard to elastic modulus (AASHTO, 2008).

The objectives of this study are to provide novel solutions on using steel slag regarding to reducing free lime and magnesium oxide content in the steel slag aggregate, which are the main reasons for volume instability.In addition, saving costs transportation of steel slag due to its high density by reducing thickness of asphalt layer, or extend service life of asphalt layer, thence minimize maintenance costs. Additionally, using of steel slag aggregate in a thin asphalt overlay layer was evaluated using mechanistic empirical design to conclude the benefit of using steel slag aggregate and introducing fiber into asphalt mixtures in terms of extend service life of an existing layer. However, Steel slag aggregate were immersedin the water for 6 months as a treatment to reduce free lime and magnesium oxide content, respectively. The content of free lime was measured using thermogravimetry (TGA) test while magnesium oxide was detected by XRD. Over and above, Aramid fibers, which are a synthetic fiber chemically produced by the reaction between amine group and carboxylic acid group, were used as a reinforced material to enhance the performance asphalt mixtures, thus contributing to reducing the thickness of asphalt layer. Aramid fiber was chosen based on its ability in the enhancement of the performance of asphalt mixtures due to its high tensile strength and high melting point.

LITERATURE REVIEW

Many studies have been investigated using of steel slag as a partial or total replacement to the natural aggregate of asphalt mixtures, most of study found that asphalt mixtures containing steel slag as a coarse aggregate performed better than other proportion in terms of the mechanical properties of the mixtures. According to their studies, it has been proven that asphalt mixtures containing coarse steel aggregate is the preferable substitution. Ahmedzade and Sengoz (2009) investigated using of steel slag as a coarse aggregate and limestone as fine aggregate in the asphalt mixtures. Their study showed enhancement in the mechanical properties of the mixtures that containing steel slag aggregate in connection with Marshal Stability, indirect tensile strength, stiffens modulus and dynamic creep. Similarly, Arabian and Azarhoos (2012), evaluated of asphalt mixtures containing steel slag aggregate (EAF) as a coarse aggregate. They concluded that mixtures containing coarse steel slag aggregate performed better than reference mixtures in terms of marshal stability, flow, permanent deformation and indirect tensile strength, and the mixtures containing fine steel slag aggregate were worse. Additionally, Ameri *et al* (2013), studied feasibility of using steel slag (EAF) as a coarse aggregate in the warm mix asphalt. They reached that steel slag in asphalt mixtures enhanced the performance of the asphalt mixtures with regard to resilient modulus, moisture susceptibility, and permanent deformation. In similar content, Hesami *et al* (2014) assessed of warm mix asphalt mixtures incorporated with coarse steel slag aggregate (EAF). Their study indicated that asphalt mixtures containing steel slag as coarse aggregate increases its resistance to moisture damage and permanent deformation. In addition, Kavussi and Qazizadeh (2014), examined fatigue resistance of asphalt mixtures substituting with coarse steel slag (EAF) aggregate. They found that asphalt mixtures replaced with coarse steel slag presented greater fatigue life, this attributed by the angularity of the steel slag which contribute to preventing cracking by angle friction. In the relevant, Masoudi *et al* (2017), conducted a Marshal Stability, resilient modulus, indirect tensile strength, moistures sensitivity and permanent deformation tests on the warm mix asphalt containing (EAF) steel slag aggregate as replacement to the natural coarse aggregate. They have found that WMA with (EAF) coarse steel slag aggregate exhibited higher than control mixtures. Thenceforward, the asphalt mixtures replaced natural aggregate by steel slag aggregate exhibited greater performance than control mixture with natural aggregate regarding to resilient modulus, marshal stability, dynamic creep and rutting resistance (Hainin *et al*., 2013; Hainin *et al*., 2014). According to the researchers mentioned above, enhancement of the mixtures containing coarse steel slag (EAF) aggregate was attributed to the mechanical properties of the steel slag with reference to angularity, roughness, hardness, bulk specific gravity, and porosity of the steel slag that requires high content of bitumen, and this course improve durability of the mixtures by providing thicker film. Otherwise, using steel slag as a coarse aggregate offers better interlocking and durability, while using of steel slag as a fine aggregate produces mixtures sensitive to water as well as it is expensive in terms of crushing due to the hardness of steel slag aggregate (Skaf *et al*, 2017). On the side of reduce asphalt layer thickness, the researchers have in depth investigated the possibility of reduce asphalt layer thickness using mechanistic empirical design. Al-Hadidy and Tan (2009), studied effect of pyrolysis polypropylene modified asphalt binder on the mixture. In their study, MEPD was used to evaluate benefits of adding PP with regard to reduce asphalt thickness and improve of the service life of asphalt layer. They found that modified asphalt binder have increased properties of the mixtures in terms of Marshal Stability, indirect tensile strength. Moreover, output of the MEPD showed improvement of the service life by 1.359 time, if the pavement thickness was same to the unmodified asphalt mixtures. However, the SMA thickness has reduced. Similarly, Mokhtari and Nejad (2012) examined of different additive mineral fiber, cellulose fiber and SBS in stone mastic asphalt. MEPD was employed in their study to estimate improvement of the service life or reduction the thickness of asphalt pavement. They observed that modified mixtures performed better than reference mixtures in connection with resilient modulus, moisture susceptibility and permanent deformation. Moreover, outputs of the Mechanistic Empirical Pavement Design showed that best enhancement was on the SMA mixtures modified by SBS, which improved the service life of asphalt layer by 1.243 time, if the thickness kept constant. Thickness of the SMA could be reduced by around 30% if the service life kept fixed.

MATERIALS AND EXPERIMENTS

Materials

A penetration grade of 80/100 produced by Petronas, Malaysia was used; table1 shows the physical properties of the binder. Electric arc furnace (EAF) steel slag aggregate supplied by NSL, Singapore and crushed granite aggregate were used. Table-2 represents properties of the EAF and granite aggregate. Aramid fibers supplied by Surface Tech, Portland, USA were used, Table-3 shows the physical properties of the Aramid fiber and Figure-1 presents shape of the aramid fibres, respectively. Additionally, the dense fine graded with 12.5 nominal maximum size aggregate was adopted. Figure-2 shows the designed gradation of the aggregate based on the Superpave specification.

Table-1. Physical properties of bitumen.

Properties	Test value	Standard
Penetration at 25°C, 1/10 mm	87	ASTM D 36 - 06
Ductility at 25°C (cm)	> 100	ASTM D 113 - 07
Softening point	49	ASTM D 36 - 06
Specific gravity at (25°C) (g/cm3)	1.02	ASTM D 70 - 09
Viscosity @ 135 °C (cP) Viscosity @ 165 °C (cP)	487 144	ASTMD44
Mixing temperature Compaction temperature	160 °C 150 °C	ASTM D4402

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Table-2. Physical properties of the aggregate.

Properties	EAF	Granite	Specification	Standard
Loss Angeles Abrasion	17.8	19.75	≤ 25 %	ASTM C 131
Aggregate Crushing Value	22.6	25.4	≤ 25 %	IS: 2386 (Part IV)
Bulk S.G	3.22	2.75	n/a	ASTM C127
Water absorption (%)	2.75	0.843	≤ 3%	ASTM C127
Free CaO content (%)	1.1733	n/a	Variable	

Table-3. Aramid fibers physical properties.

Material property	Measure
Material	Para-Aramid Fiber (50-52% by weight)
Density	1.44-1.45 (g/cm3)
Tensile Strength	> 2.758 (GPa)
Modulus	> 95 (GPa)
Decomposition Temperature	> 450 °C
Treatment Type	Sasobit Wax (48-50% by weight)
Treatment Melting Temperature	> 80 °C
Length	19 mm

Figure-1. Aramid fiber.

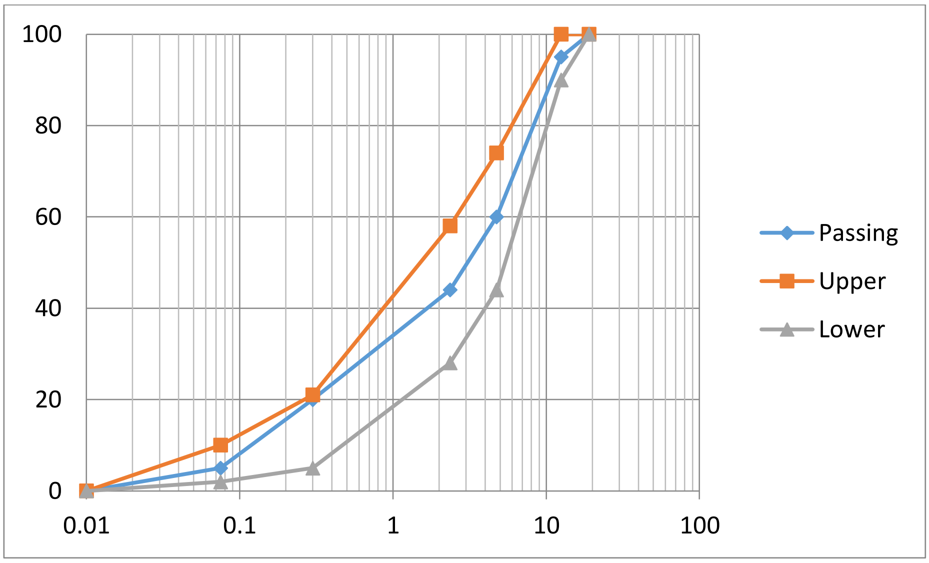

Figure-2. Gradation of designed aggregate.

Thermo gravimetry

The TGA was used to quantitatively determine free lime content in the steel slag before and after treatment by immersing in the water for six months.

Mineralogical compositions

X-ray diffraction (XRD) was used to determine the mineralogical phases of the steel slag.

Mixture design

In this study, Aramid fibers were introduced to the asphalt mixture containing coarse (EAF) steel slag aggregate at different proportions; i.e. 0.025, 0.05, 0.1 and 0.3% by total weight of the aggregate to produce reinforced mixtures. However, 0.025, 0.05, 0.1 and 0.3 of aramid fiber corresponding to Mix3, Mix4, Mix5 and Mix6, Respectively. While Mix1 containing 100% of

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granite and Mix 2 containing steel slag as a coarse aggregate represents the references mixes without fiber. The gradation of 12.5 nominal maximum size aggregate was adopted; fig2 shows design gradation. Prior mixing, the dried aggregate were kept in the oven at mixing temperature (160 °C) for four hours to be equilibrated with test temperature, mixing temperature was determined based on the viscosity of the binder. Thereafter, the heated binder were added to the heated aggregate, and then they were mixed in auto mixer for 3 minute. Subsequently, the Aramid fibers were introduced to the mixtures and they mixed for another three minutes, this method called composite mixing. After mixing, the mixtures were kept in the oven at compaction temperature (150 °C) for two hours to simulate short-term aging. Afterwards, the samples with 100 mm in diameter and 65 mm in height were produced using Superpave gyratory compactor with 100 gyrations, the number of gyrations were selected based on the level traffic <30 million ESALs. The dimensions of the produced samples were adopted for the performances tests. Thence, the volumetric properties of the mixtures were determinein order to meet the requirements of Superpave specifications. Table-4 shows the volumetric properties of the mixtures.

Table-4. Volumetric properties of the mixtures.

Mixtures properties	Mix1	Mix2	Mix3	Mix4	Mix5	Mix6	Requirement
OBC	4.78	4.9	4.9	4.9	4.9	4.9	4-7
AV	4	4	3.98	3.70	4.20	4.50	3.5-5
VMA	15.91	14.7	15.3	14.85	16.8	17.95	14 minimum
VFA	74.85	72.8	74	75	75	74.9	65-75
Bulk specific gravity	2.343	2.56	2.543	2.522	2.49	2.446	n/a

Resilient modulus

Resilient modulus can be defined as stress divided by strain at quickly applied load, which refers to the ability of martial to absorb energy in the elastic range. Resilient modulus of the materials used as an estimate for its elasticity modulus (E), which is the most important input in the Mechanistic Empirical Pavement Design to measure stiffens and strain of the material under applied load in the asphalt layer (Papagiannakis and Masad, 2017). This test was carry out in accordance with ASTM D7369 using IPC UTM-5P. This test is nondestructive, prior testing the specimens were kept in the climate chamber for two hours at testing temperature, to ensure that temperature within specimens have been equilibrated with the test temperature, testing temperature in this study was 25 °C. The applied force with have sine wave pulse was 1000 N, which is 10% of indirect tensile strength, and the frequency of the applied load was 1HZ with a load width 0.1 s and rest period of 0.9s this to simulate at high-speed of vehicle in the road were adopted. Every sample per every mixture was tested at two angle (0 and 90°) and results obtained averaged. Two of Linear Variable Displacement Transducers (LVDTs) were used to measure horizontal deformation.

Dynamic creep

Permanent deformation occurs due to the accumulation of non-recoverable strain, which generates by repeated load of the vehicles. Additionally, permanent deformation in the asphalt layer caused by the lateral movement of layer due to the applied load by vehicles, this occurs at the top 100 mm of the asphalt surface layer (Brown *et al*., 2001). Dynamic creep test was used to evaluate resistance of asphalt mixtures to permanent deformation. This test was carry out in accordance with British standard BS DD 226. The samples were conditioned in the environmental chamber for 4 hours before testing at test temperature, which was 40 °C to ensure that temperature of equilibrium is reached within the specimen. This test was assessed using Universal Testing Machine (UTM-5P). A stress of 10 Kpa was applied as a preload for 120s; thereafter the specimens were subjected to repeated axial stress of 100 Kpa for 3600 second with squared wave pulse, the pulse loading consists 1second for loading and 1second for rest period. Total of the load application is 1800 cycles.

Statistical analysis

In this paper, response surface methodology (RSM), which is a statistical tool using Design expert 6 software, was used to investigate how different properties related to each other, with regard to factor and responses of the dynamic creep test. However, one factor and two responses were analyzed. The factor represents the aramid fiber content proportion while the responses are the axial strain and the dynamic creep modulus. Moreover, Aramid fiber was selected as the only factor because other factors are fixed concerning loading (100 Kpa) and testing temperature (40 °C) whilst aramid fiber content is variable. In order to correlate the outcome of dynamic creep test three model regressions were used to fit data, which are linear, cubic and quadratic. The appropriate model was selected based on the Prob>F, the lower Prob>F the suitable model. In addition, the suitable equation based on the model analysis, which is corresponding to the factor and responses was provided.

Mechanistic-empirical design approach

A mechanistic-empirical design has been used to evaluate the benefit of introducing Aramid fiber into the asphalt mixtures that containing coarse steel slag aggregate under applied load in terms of reduction asphalt thickness and extension in service life of the asphalt mixtures during its service life. The layer thickness reduction (LTR) concept represents an aspect of mechanistic–empirical design, which used to determine the possibility of reduce asphalt layer thickness, taking into account that the service life of the asphalt layer kept constant for the asphalt concrete layer with and without fiber. The second aspect of the mechanistic–empirical design is described as the Traffic Benefit Ratio (TBR) that shows the potential of extension service life of asphalt layer; this can be concluded if the thickness of the asphalt layer kept fixed for the asphalt concrete layer with or without fiber. Similarly, ultra-thin asphalt overlay was evaluated using MEPD to investigate its ability in terms of improve the service life of existing asphalt layer. The resilient modulus of existing layer was selected as 2500 Mpa, based on the assume that existing pavement with Mix1 lost 40% of its service life in order to evaluate the benefit of ultra-thin asphalt overlay in terms of increase the service life of existing layer. Whereas, Bisar software was used to analyse responses of the pavement section to the applied load in terms of the horizontal tensile strain at the bottom of asphalt concrete layer and vertical compressive strain at the top of the subgrade layer. These strains could be described as the most important responses, which used to calculate fatigue and rutting behavior of the asphalt section under applied load. In this study, super single axle of 898 Kpa was adopted as applied load on the surface layer, this load was selected to evaluate the asphalt mixture under heavy load. The thickness of the pavement section layers and its elastic modulus described in the Figures 12 and 13, respectively.

Yang considered a rut depth of 12.7 mm with the reliability of 85% for the asphalt failure. Eq1 is used to determine Nd:

$$Nd = 1.365 \times 10^{-9} \varepsilon\nu^{-4.477} \quad (1)$$

Where Nd =the allowable number of repetition standard axles to produce a rut of 12.7 mm, while $\varepsilon\nu$ is the vertical compressive strain at the top subgrade layer.

Additionally, fatigue-cracking failure due to the repeated load of the axles can be calculated as follow:

$$Nf = 1.66 \times 10^{-10} \varepsilon t^{-4.32} \quad (2)$$

Where Nf is the allowable number of reparation load to avoid failure, and εt is the horizontal tensile strain at the bottom asphalt layer.

Equation (3) and (4) are used to determine the extension in the service life of the pavement (TBR) and the possibility of reduce asphalt layer thickness (LTR), respectively.

$$TBR = \frac{Ndm}{Ndu} \quad (3)$$

Where Nd is the number passes of axels to produce rut depth of 12.7mm; m and u the mixture with and without Aramid fiber, respectively.

$$LTR = \frac{Tu - Tm}{Tu} \times 100 \quad (4)$$

Where Tu and Tm = Thickness of the asphalt layer with and without fiber, respectively.

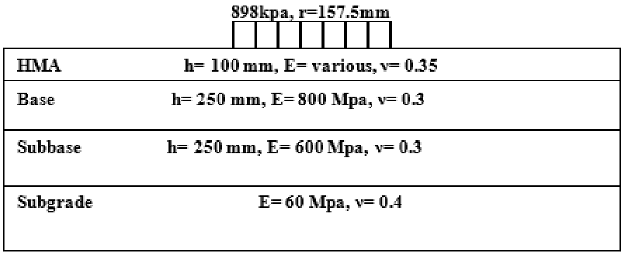

Figure-3. Pavement section with a single axial load (898 Kpa) and radius of 157.5 mm.

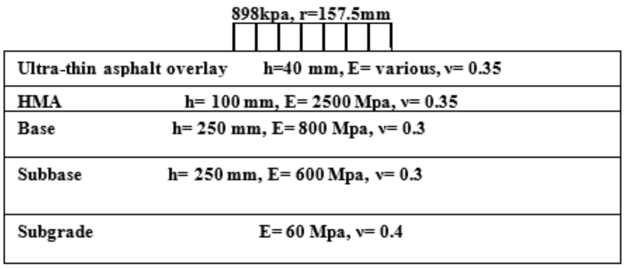

Figure-4. Pavement section with a single axial load (898 kpa) and ultra-thin asphalt layer.

RESULTS AND DISCUSSIONS

Thermo gravimetry

TGA is used to measure losing weight of the material at specific reactions, which occur due to the heating with increase temperature at constant rate. These reactions are used to identify the constituents of the material at specific temperature by knowing lose weight of material at the beginning and ending of the reaction (Moon *et al*., 2002; Kneller *et al*., 1994). In this study, thermogravimetry analysis was used in terms of determine free lime content of steel slag that were immersed in water for 6 months. However, a 50 mg of fine steel slag

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aggregate that pass sieve size 0.075mm, heating rate 20 °C/min and water flow rate 30ml/min were adopted. The samples preheated at 350 °C to relegation the remaining water. The first stage reaction is started at 400 °C and ending at 460°C by evolution of hydroxyl water. The second stage has evolved of carbon dioxide, which occurred at 490 °C and end at 785 °C. The percentage of free lime in steel slag is determined from dissociation of Ca(OH)2 and $CaCO_3$ which occurred at first and second stage, respectively. These reactions are detailed below:

Ca (OH)2 + heat→ CaO + H2O (1)

CaCo3 + heat → CaO + CO2 (2)

The equations below are used to determine percentage of free lime in the slag:

$$\frac{\text{CaO}}{56} = \frac{\text{H2O wt. loss}}{18} \quad (5)$$

$$\frac{\text{CaO}}{56} = \frac{\text{CO2 wt. loss}}{44} \quad (6)$$

Where 56, 18and 44are the molecular weight of the CaO, H_2O and CO_2, respectively. While H_2O wt loss and CO_2 loss are the percentages of losing weight, which occurred at first stage and second stage.

It can be seen in the Figure-5 that losing (H_2O wt . loss) weight of the treated steel slag at first stage was 0.12 % and 0.63% at the second stage (CO_2), while the losing weight of the steel slag before the aging were 0.868% and 0.7% for the first stage and second stage, respectively. Amount of free lime is calculated as follow:

$$\frac{\text{CaO}}{56} = \frac{0.12}{18}$$

$$\frac{\text{CaO}}{56} = \frac{0.63}{44}$$

Total free lime of the treated steel slag = 0.3733 +0.8 = 1.1733%

Total free lime of steel slag before treatment = 2.73 +0.89= 3.62%

The amount of free lime in the steel slag significantly decreased by around 68%, which indicates that method of treatment, was very useful in reducing free lime content.

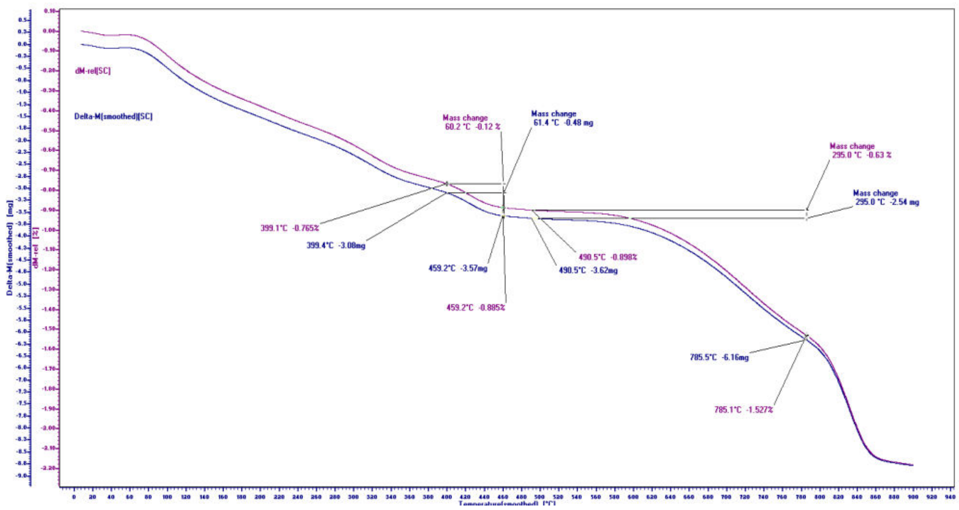

Figure-5. TGA plot.

Mineralogical compositions

X-Ray Diffraction testing is considered as the most widely method that used to determine the crystalline structure of the steel slag (Xie *et al*., 2012). In this study, XRD was used to detect the Periclase (MgO) for the treated steel slag aggregate by immersing in water for 6 months. Figure-6 shows mineralogical compositions of the steel slag prior treatment, while Fig7 represents mineralogical compositions after treatment. As can be seen in Figure-6 that Periclase have been detected in the peak of 2θ, which located at 75°. Periclase can be described as the main cause of the long-term expansion due to its hydration reaction with water, this expansion generates a stress, which leads to cracking of the pavement and reduce its performance. This reaction is described as follow:

MgO + H2O ⟶ Mg (OH)2 (3)

On the other hand, it can be observed in Figure-7 that periclase was not detected, and this was attributed to the long period of the treatment, which was successful in reducing free (MgO) by the hydration between periclase and water. However, treatment of steel slag does not completely means eliminate the percentage of periclase, this is because if the content of periclase less than 20%, it is difficult to discrimination, in other words the peak will not be appeared (Rojas and De, 2004). Therefore, it can be

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said that treatment of the steel slag by immersing in the water was effective and significantly reduced the amount of periclase/ free MgO in the steel slag.

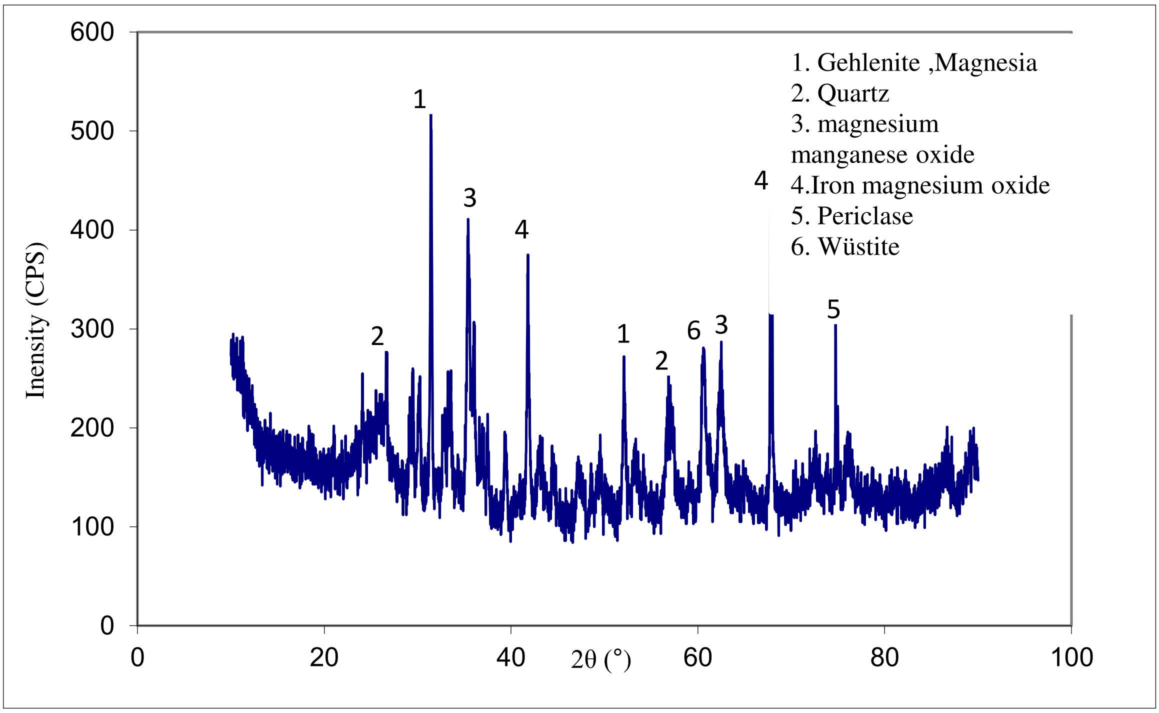

Figure-6. XRD pattern of the steel slag before treatment.

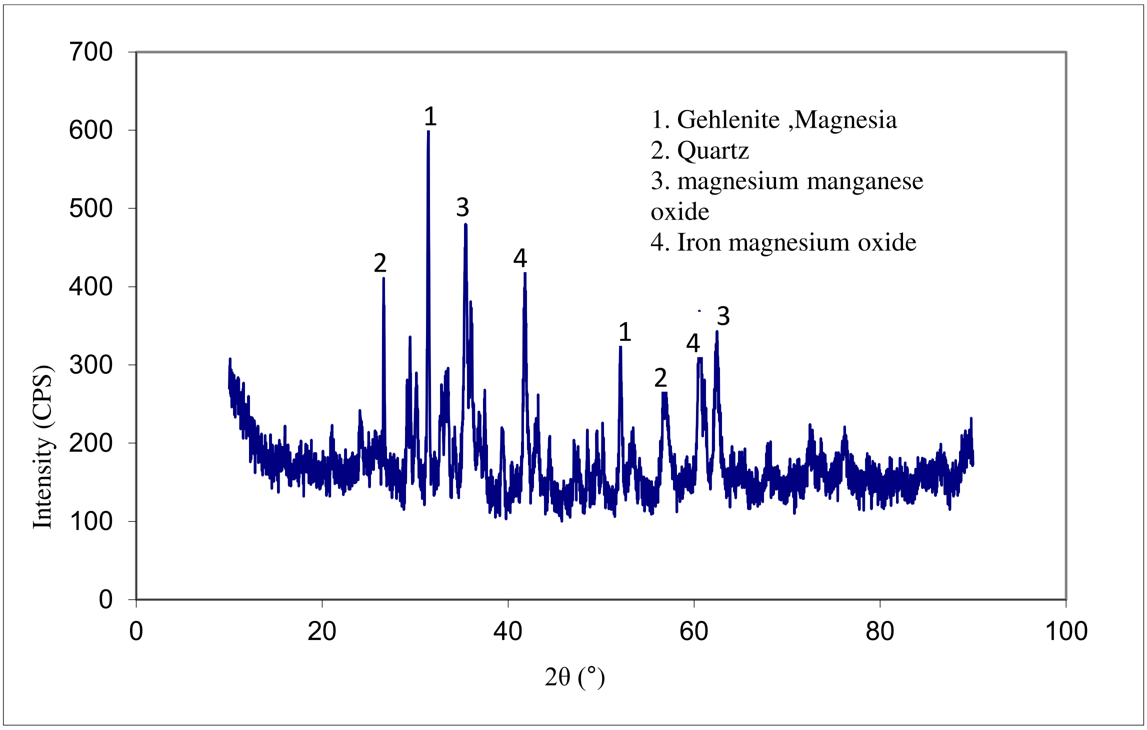

Figure-7. XRD pattern of the steel slag after treatment.

Resilient modulus

Resilient modulus of the mixtures was conducted in accordance with ASTM D4123. The resilient modulus of the mixtures was calculated automatically using UTM-5P software based on the recoverable vertical and horizontal deformations, which measured using a set of

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two LVDTs aligned in the diametric plane. Otherwise, resilient modulus of mixture considered as an important parameter, which used as inputs in the design of the asphalt layer thickness. Figure-8 illustrates the average resilient modulus per every mixture, as could be seen Mix6 has the lower value of resilient modulus while Mix4 has the highest value of resilient modulus. On the other hand, Mix2 exhibited better than Mix1 (control). Moreover, the resilient modulus of Mix1 (control), Mix2, Mix3, Mix4, Mix5, Mix6 are 5760, 6211, 6527, 8336, 5825 and 5784 Mpa, respectively.

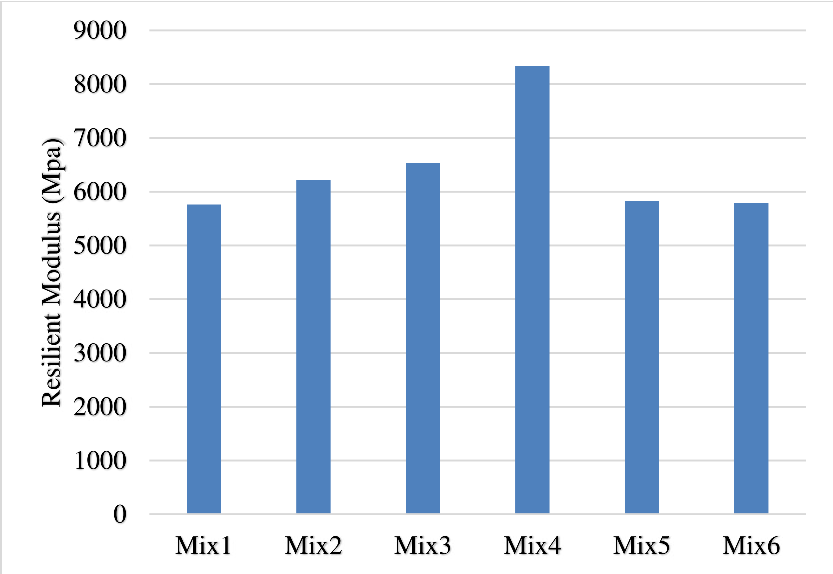

Figure-8. Resilient modulus.

Dynamic creep

Dynamic creep test have been conducted in order to determine permanent deformation, or in other words rutting resistance. On the other hand, the ultimate axial strain, which presents recoverable elastic strain during primary stage, is calculated automatically by dividing axial deformation (permanent deformation in mm) with the original thickness of the specimens before applying load (mm). However, the higher axial strain indicates that mixtures have high permanent deformation and susceptible to rutting. As can be observed in Figure-9, Mix2 exhibited better resistance to permanent deformation than Mix1 (control), this was attributed to the mechanical properties of the steel slag. Furthermore, Mix6 and Mix5 exhibited the worst permanent deformation compared to other mixes, this is because the high content of aramid fiber that increased thickness of the samples tests by around 1-1.5 mm, thus requires increasing number of the applied load (cycles) to exhibit its usefulness in enhancement of permanent deformation resistance. In other words, permanent deformation of Mix6 was in the stage of compaction and this was for Mix5. Moreover, Mix4 showed the lowest axial strain, this indicates that aramid fiber have increased permanent deformation resistance. Similarly, dynamic creep modulus is another aspect in terms of evaluates permanent deformation resistance, which is calculated by dividing applied stress (100 Kpa) to the ultimate axil strain after 1800 cycles. Anyway, the higher dynamic creep modulus, the lower permanent deformation. As can be seen in Figure-10, the dynamic modulus of mixture of Mix1, Mix2, Mix3, Mix4, Mix5 and Mix6 are 21.44, 24, 28.95, 41.3, 21.8 and 11.49Mpa, respectively.

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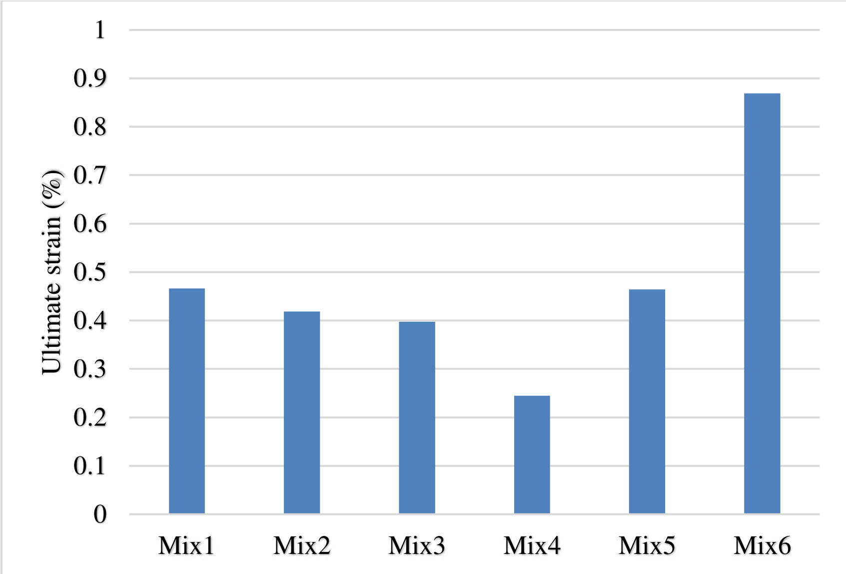

Figure-9. Ultimate axial strain after 1800 cycles.

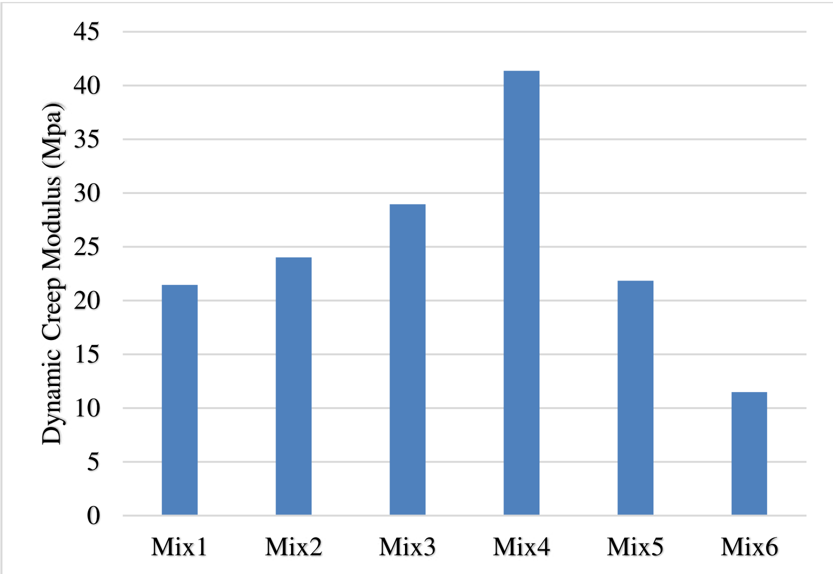

Figure-10. Dynamic creep modulus after 1800 cycles.

Statistical analysis

RSM is a statistical tool, which gives an indication about the correlation and interaction between factors and response as well as provides a mathematical equation to predict the responses, which represents the results of experiments (Dean *et al*., 2017). However, 15 runs with one factor and two responses were analyzed, in other words three specimens were tested per every proportion of aramid fiber. The factor corresponding tothe aramid fiber content, while the responses represents the ultimate axial strain and dynamic creep modulus. Additionally, three model linear, quadratic and cubic were used to analyze data in order to find the suitable model in terms of describe the suitable correlations. Table6 represents factor and responses, which are the results of the dynamic creep test used as input in the design expert6 software. However, the appropriate model was selected based on some important parameter, such as Prob> F, lack of fit and R-squired. Otherwise, Prob>F value that less than 0.05 indicates considerable correlation between the factors and responses, in other words the least Prob>F, the appropriate model. In addition, the higher R-squared and the lower lack of fit means the data fit well (Golchin and Mansourian, 2017). As can be absorbed in table7, all models were significant, but the cubic model was the best in terms of fit data than other with respect to Prob>F, lack of fit and R-squared, which were 0.0009, 1 and 0.9573, respectively. Table8 displays the ANOVA analysis between factor and dynamic creep modulus (response), it is clearly shown that cubic model was the appropriate model based on the values of Prob>F, lack of fit and R-squared that were 0.0008, 1 and 0.833, respectively. However, the correlation between aramid fiber content (factor) and ultimate axil strain (response) exhibited better correlation than aramid fiber and dynamic creep modulus in terms of lack of fit and R-squared, in other words the aramid fiber and ultimate axial strain fit well than dynamic creep. On the other side, it can be seen in Figure-11 that when aramid fiber (factor) increased the ultimate axial strain (response) increased. Similarly, Figure-12 shows the interaction between aramid fiber (factor) and dynamic creep modulus (response). As it can be inferred from Figure-12 the high aramid fiber content, the low response (dynamic creep modulus). Figure-13 illustrates how data fit, as could be seen the analyzed data approximately linear, which indicates the data fit well and the model is appropriate. Furthermore, suggested equation for the prediction of ultimate axial strain and dynamic creep modulus based on the suggested model, as follow:

Ultimate Axial Strain (%) = 0.43367 - (7.56470$\times x$) + (101.83961$\times x^2$) – (239.26886$\times x^3$)(7)

Dynamic Creep Modulus (Mpa) = 22.17699 + (696.43846$\times x$) - (9134.74082$\times x^2$) + (22323.07386$\times x^3$)(8)

Where,x is the Aramid fiber content (%).

Table-5. Experiment matrix and obtained Dynamic creep test results.

Runs	**Factor**	**Responses**	
	Aramid fiber content (%)	**Ultimate axial strain** (%)	**Dynamic creep modulus** (MPA)
1	0	0.38	26.32
2	0	0.4469	22.37
3	0	0.4295	23.28
4	0.025	0.307	32.57
5	0.025	0.375	26.67
6	0.025	0.3612	27.62
7	0.05	0.2793	35.8
8	0.05	0.2258	44.29
9	0.05	0.2282	43.821
10	0.1	0.3905	25.6
11	0.1	0.4769	20.97
12	0.1	0.5239	19.1
13	0.3	0.85	11.76
14	0.3	0.8393	11.914
15	0.3	0.919	11.49

Table-6. Summary on ANOVA analysis of Aramid fiber vs Ultimite axil strain.

Sequential model sum of squares						
Model type	**Sum of squares**	**DF**	**Mean square**	**F Value**	**Prob > F**	**Performance**
Linear	0.574893	1	0.574893	57.97302	< 0.0001	significant
Quadratic	0.044171	1	0.044171	6.254694	0.0279	significant
Cubic	0.054757	1	0.054757	20.08644	0.0009	Suggested
Residual	0.029987	11	0.002726			
Total	4.000879	15	0.266725			
Lack of Fit tests						
Model type	**Sum of squares**	**DF**	**Mean square**	**F Value**	**Prob > F**	
Linear	0.109196	3	0.036399	18.45874	0.0002	significant
Quadratic	0.065025	2	0.032513	16.48802	0.0007	significant
Cubic	0.010268	1	0.010268	5.20716	0.0456	Suggested
Pure Error	0.019719	10	0.001972			
Model summary statistics						
Model type	**Std. Dev.**	**R-Squared**	**Adjusted R-Squared**	**Predicted R-Squared**	**PRESS**	
Linear	0.099582	0.816832	0.802742	0.769303	0.162366	
Quadratic	0.084036	0.879592	0.859524	0.820393	0.126409	
Cubic	0.052212	0.957393	0.945773	0.920489	0.05596	Suggested

Table-7. Summary on ANOVA analysis of Aramid fiber vs Dynamic creep modulus.

Sequential model sum of squares						
Model type	**Sum of squares**	**DF**	**Mean of squares**	**F Value**	**Prob > F**	**Performance**
Linear	689.8974	1	689.8974	11.11053	0.0054	significant
Quadratic	81.35571	1	81.35571	1.344969	0.2687	Not significant
Cubic	476.6274	1	476.6274	21.03561	0.0008	Suggested
Residual	249.2394	11	22.65813			
Total	11305.77	15	753.7181			
Lack of Fit tests						
Model type	**Some of squares**	**DF**	**Mean of Square**	**F Value**	**Prob > F**	
Linear	710.5613	3	236.8538	24.50347	< 0.0001	significant
Quadratic	629.2056	2	314.6028	32.54692	< 0.0001	significant
Cubic	152.5781	1	152.5781	15.78482	0.0026	Suggested
Pure Error	96.6613	10	9.66613			
Model summary statistics						
Model type	**Std. Dev.**	**R-Squared**	**Adjusted R-Squared**	**Predicted R-Squared**	**PRESS**	
Linear	7.879977	0.460816	0.419341	0.350818	971.9038	
Quadratic	7.777461	0.515158	0.434351	0.321289	1016.111	
Cubic	4.760055	0.833521	0.788117	0.731857	401.4424	Suggested

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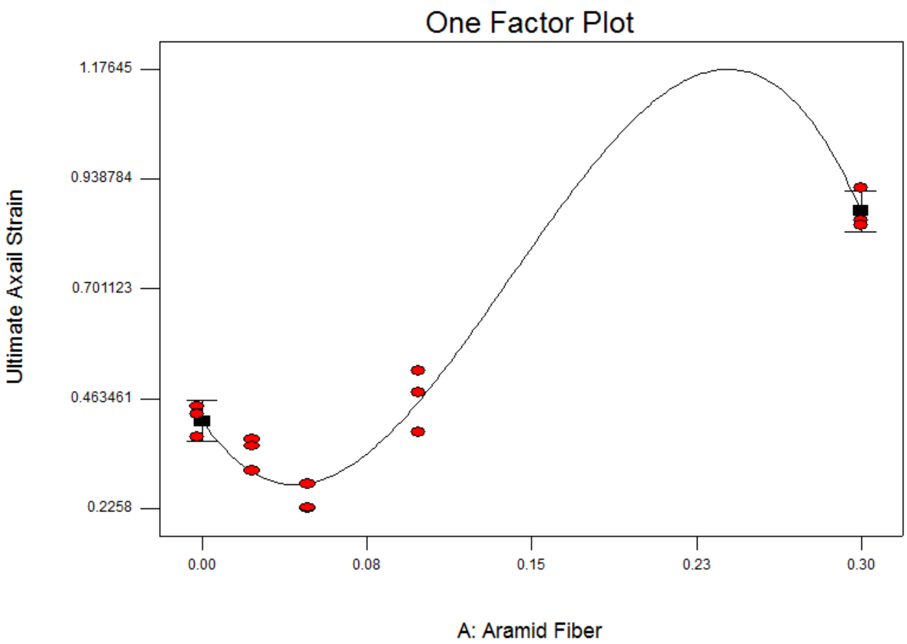

Figure-11. Counter plot of Ultimate axial strain versus Aramid fiber content.

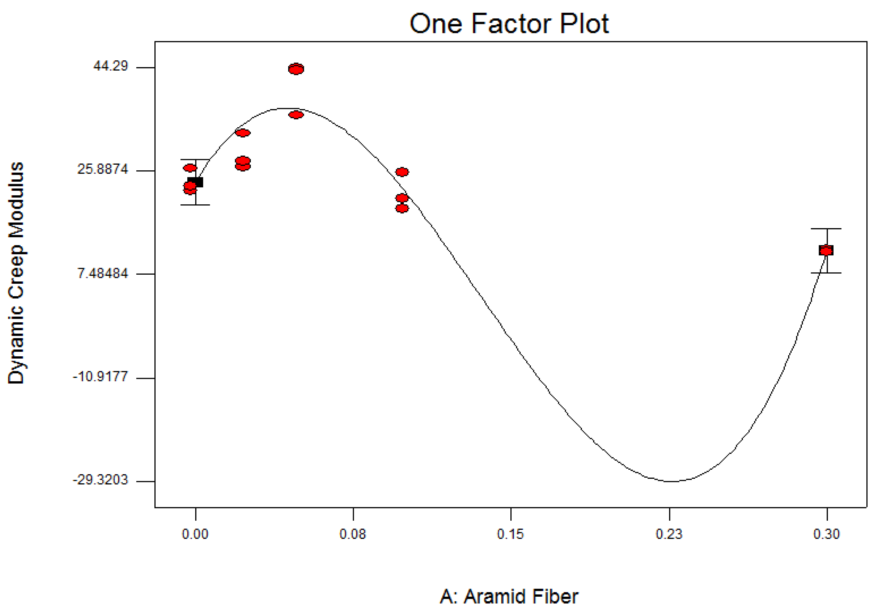

Figure-12. Counter plot of Dynamic creep modulus VS Aramid fiber content.

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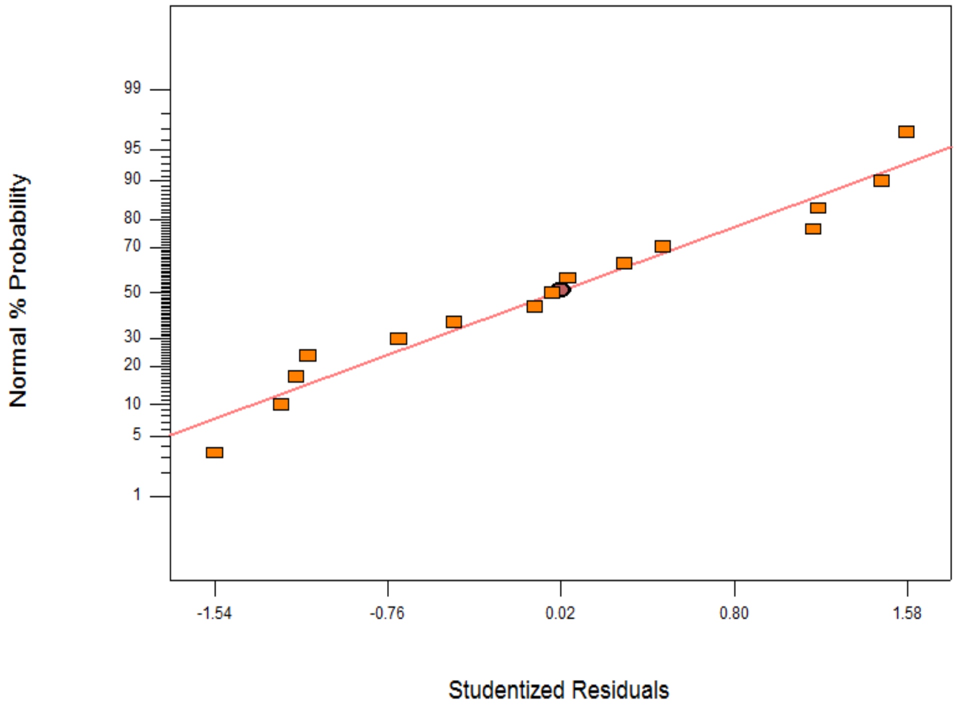

Figure-13. Normal probability of Ultimate axial strain and Dynamic modulus creep VS Aramid fiber content.

Benefits of reinforced mixtures

Fatigue cracking and rutting are the major failure in asphalt pavement.Fatigue cracking generally developed at the bottom asphalt layer due to the repeated load, the horizontal tensile strain at the bottom asphalt layer used to indicate fatigue cracking by mechanistic empirical pavement design. On the other hand, rutting developed at the top of subgrade layer due to the accumulation of permanent deformation in the various layer. The vertical compressive strain at the top of subgrade layer used to indicate rutting depth depending on the number of standard axles (Yang, 1994). However, the mechanistic empirical pavement design approach using Bisar software was used to assess the benefit of reinforced asphalt mixture by aramid fiber in terms of reduce asphalt layer thickness or extension its service life. Moreover, the mixtures that were assessed are Mix1, Mix2 andMix4, which represents the mixtures consisted of100% granite aggregate, coarse steel slag aggregate and coarse steel slag aggregate reinforced by aramid fiber, respectively. In addition, Mix1 and Mix2 represent the control mixtures while Mix4 presents the optimum content of aramid fiber. However, the outputs of the mechanistic empirical pavement for pavement sections in Figures 3 and 4 are presented in Tables 9 and 10. It can be seen in table9 that service life of the pavement system with Mix2 improved by around 4% than pavement system life with Mix1. On the other hand, pavement system with Mix4 exhibited the higher extension service life than others, which enhanced by around 20% and 16% compared to the pavement system with Mix1 and Mix2, respectively. However, if the service life kept constant the thickness of the pavement system with Mix4 can be reduced by around 20%. On the other side, Table-11 shows the benefit of adding extra thin layer (ultra-thin asphalt overlay) as a pavement preservation in terms of increase existing layer service life. As can be seen in the table11, thin asphalt overlay with Mix1, Mix2 and Mix4 have dramatically increased the service life of existing layer by 2.8, 2.93and 3.33 time, respectively. In other words, thin asphalt layer with Mix4 exhibited better service life by around 16% and 12% than Mix1 and Mix2, respectively. Moreover, if the service life kept fixed the thin layer thickness with Mix4 can be reduced by around 20%, with same service life of thin layer system with Mix1.Overall, the thin asphalt overlay with Mix4 on existing layer exhibited a significant improvement in the service life of existing layer; the service life was higher than service life of the system asphalt pavement in Figure-3 with Mix1, Mix2 and Mix4 by 2.1, 2 and 1.7 time, respectively.

Table-8. Outputs of mechanistic empirical design for pavement section in Figure-3.

Mixture type	**Thickness** (mm)	**LTR** (%)	**εt**	**εν**	**Nf** (10^5)	**Nd** (10^5)	**TBR**
Mix1	100	0	151	353.8	53.33	38.6	1
Mix2	100	0	149.6	350.5	55.51	40.23	1.04
Mix4	100	0	138.8	337.3	76.74	47.77	1.24
Mix4	90	10	143	346.6	67.46	42.3	1.1
Mix4	85	15	144.4	351.2	64.68	39.9	1.03
Mix4	80	20	145.2	355.8	63.2	37.62	0.975

Table-9. Outputs of mechanistic empirical design for pavement section with Ultra-thin asphalt.

Mixture type	**Thickness** (mm)	**LTR** (%)	**εt**	**εν**	**Nf** (10^5)	**Nd** (10^5)	**TBR**
Existing	100	0	160.4	392.7	41	24.18	0.63
Overlay-Mix1	40	0	167.2	312	34.33	67.73	2.8
Overlay-Mix2	40	0	167.6	309	34	70.72	2.93
Overlay-Mix4	40	10	169	300	32.78	80.73	3.33
Overlay-Mix4	36	10	171	306	31.15	73.9	3.06
Overlay-Mix4	34	15	172	310	30.38	69.71	2.88
Overlay-Mix4	32	20	173	313	29.63	66.76	2.76

CONCLUSIONS

Based on the outputs of this study, the following concluded were made:

a) The treatment method of steel slag aggregate was successful in terms of reduce free lime and free magnesia content, which reduced by 68%.
b) Using steel slag (EAF) as a coarse aggregate in the asphalt mixture have improved the performance of the mixtures with regard to resilient modulus and dynamic creep.
c) Introducing aramid fibre to the mixtures that containing coarse steel slag aggregate have significantly enhanced the resilient modulus and dynamic creep. Moreover, the optimum content of aramid fibre was at 0.05% by total weight of the aggregate.
d) RSM outputs showed a very strong interaction between the factor (aramid fiber) and responses of dynamic creep.
e) The Mixture containing coarse steel slag (EAF) aggregate and optimum content of aramid fiber (Mix4) can reduce the thickness of asphalt layer by 20%, if the service life kept constant. While it can extend the service life of asphalt layer 1.24 time, if the thickness kept constant.
f) The bulk specific gravity of the compacted asphalt mixture containing coarse steel slag aggregate was higher than conventional asphalt mixture with 100% of granite aggregate by around 10%. However, system asphalt layer with Mix4 can reduces the thickness by 10% and extend the service life by 1.1 time. In other words, it is possible to reduce the quantity of steel slag aggregate by 10% in order to be equal with the quantity of the conventional aggregate (granite)for certain thickness, and above that it can increase the service life of asphalt layer by 1.1 time compared to the pavement layer with natural aggregate (Mix1).
g) The mechanistic empirical design outputs showed that ultra-thin asphalt layer have dramatically extend the service life of existing pavement layer by 2.8, 2.93 and 3.33 time with Mix1, Mix2 and Mix4, respectively. However, Mix4 have significantly increased the service life of asphalt layer as well as it can reduce the thickness of thin-asphalt layer by around 20% with same service life of ultra-thin asphalt layer with natural aggregate (Mix1).
h) Using of steel slag aggregate can reduce the demand for the natural source, thus it is considered as a sustainable practice. However, introducing fiber in the mixture can reduce cost transportations of the aggregate as well as it can provide an asphalt layer

with long service layer than asphalt layer with conventional mixture.

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