The Role of Scrap Rubber, Asphalt and Manual Compaction against the Quality of Ballast Layer

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ABSTRACT

This research utilizes scrap rubber from outer motorcycle tires and asphalt of 60/70 penetration as a ballast layer mixture component. The objective of this study is to evaluate the characteristics of modified ballast with scrap rubber and asphalt mixtures and with two different numbers of manual compaction through a compressive strength test by analyzing elastic modulus, ballast material durability and vertical deformation. The most prominent finding to emerge from this study is that the more compaction times and the presence of asphalt, the higher the elastic modulus, the lower the ballast material abrasion and the lower the vertical deformation; hence, the stiffer the ballast layer and the higher the ballast durability. Furthermore, the percentage of ballast material abrasion shows a decrease along with the use of scrap rubber and asphalt. However, in the ballast layer with scrap rubber, the presence of 10% of 3/8” scrap rubber will reduce the ballast layer stiffness. Lastly, in the ballast layer with scrap rubber, the compaction works were unable to impact optimally the vertical deformation reduction, since the ballast materials in the sample with scrap rubber tend to bounce off each other, so that the sample does not have sufficient and proper density and stiffness.

KEYWORDS: 60/70 penetration asphalt, Ballast abrasion, Elastic modulus, Manual compaction, Scrap rubber, Vertical deformation.

INTRODUCTION

Ballast is one of the important components on the railroad to provide a stable and uniform foundation and to reduce the impact of loading to an acceptable level by subgrade (D'Angelo et al., 2016). At present, several studies have been carried out with the aim of reducing the impact of damage to the ballast layer, so that the cost of railroad maintenance can be decreased. The development of conventional railways the quality of which is close to the quality possessed by the slab track railroad is also an essential issue in railroad industry (Setiawan et al., 2013).

The addition of other materials to the ballast layer is one method that can improve the quality of the ballast structure. Woodward et al. (2012) through their research have applied a unique material called *in-situ* polyurethane polymer to enhance the stability of ballast layers. However, the use of this material needs to consider its availability in railway industry. On the other hand, the use of used rubber material (Asgharzadeh et al., 2018; Sol-Sanchez et al., 2014; Sol-Sanchez et al., 2015; Signes et al., 2016) and asphalt (Mino et al., 2012; D'Andrea et al., 2012; Lee et al., 2014; D'Angelo et al., 2017; Bressi et al., 2018) can be an alternative to the use of other materials on railroad structures, especially ballast layers.

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In Indonesia, data on the number of used tires every year has never been reported in detail (Satyarno, 2006). Several studies have been carried out regarding the use of scrap rubber as a mixture in ballast layers to improve the quality of the ballast. Sol-Sanchez et al. (2015) in their study used scrap rubber in the form of crumb as a mixture of ballast material. They concluded that excessive use of crumb rubber in the ballast layer not only can reduce stiffness, but also can increase the potential for deformation in the ballast layer. In their research, they also stated that the optimum content of crumb rubber as additional material in the ballast layer was 10%. Signes et al. (2016) also conducted a study of the characteristics of mixing rubber and aggregate materials in the ballast layer with a cyclic triaxial test to obtain a resilient modulus. In addition, modification of the ballast layer using a mixture of scrap tire rubber can minimize the degradation of ballast material while reducing the stiffness of the ballast layer and at the same time reducing vibration caused by dynamic loads received when the train is operated (D'Andrea et al., 2012; Asgharzadeh et al., 2018; Sol-Sanchez et al., 2014). Rubber has elastic properties that can be functioned as a protector and can minimize direct contact between materials separated by it. However, rubber is not resistant to temperature heating so that rubber can be classified as thermoplastic material (Hameed et al., 2016). According to Navaratnarajah et al. (2017), in the ballast layer overlaid with rubber at the bottom of the material ballast, deformation can decrease by around 35%-45% (Navaratnarajah et al., 2017). However, excessive use of rubber has an effect on reducing density values, the results of which directly affect the decreasing modulus of elasticity and instability of railroad lines (Abadi et al., 2016; Bressi et al., 2018; Sol-Sanchez et al., 2014; Signes et al., 2016).

Mixing ballast material with asphalt can increase the material durability of ballast, reduce vertical deformation and reduce energy due to load (D'Angelo et al., 2016). The addition of binding material to the ballast layer can shorten the duration of maintenance time so that it can reduce maintenance costs (D'Andrea et al., 2012). Besides, if the asphalt mingles with aggregate material, then the asphalt will make the aggregates more bound to one another (Soto et al., 2017) and can reduce the effect of dynamic loads as indicated by increasing stiffness modulus (Mino et al., 2012). Addition of asphalt material can reduce deformation in the ballast layer vertically, because it is influenced by the percentage and thickness of the asphalt (D'Angelo et al., 2016; Pirozzolos et al., 2017; Sol-Sanchez et al., 2015).

According to Setiawan and Rosyidi (2018b), the use of 10% scrap rubber material can increase the value of vertical deformation significantly up to 84%, because it could enhance the elasticity of the ballast layer. On the other hand, the addition of 3% asphalt in the ballast mixture as a binder can improve the stiffness of the ballast layer up to 14%. Furthermore, Setiawan and Rosyidi (2018b) stated that in general, the use of 10% scrap rubber and 3% asphalt could reduce the percentage of material abrasion in the ballast layer significantly ranging from 47% to 80%. Besides, the use of 10% scrap rubber and 3% asphalt has a positive role against ballast durability in rail track structures, so that it has the potential to be used as a solution to increase service life and reduce rail track maintenance costs. Scrap rubber and asphalt have the potential to be used together on ballast layers and are expected to be a solution of the problems related to the service-life and ballast maintenance work.

According to Setiawan and Rosyidi (2018a), in the ballast layer with scrap rubber, an increase in compaction from 25 to 50 manual compaction times is only able to increase the elastic modulus of ballast layers by 6%. However, compaction plays a vital role in increasing ballast material durability up to 38% and ballast layer ability to withstand loads up to 70%.

In the ballast layer without scrap rubber, an increase in compaction works up to 100% will increase the modulus of elasticity of the ballast layer up to 72%. In the ballast layer uniformly sized scrap rubber, an increase in compaction work up to 100% is only able to increase the modulus of elasticity of ballast layers by 3%. In the ballast layer without scrap rubber, an increase in compaction works up to 100% will increase the ballast material durability up to 38%. In the ballast layer with uniformly sized scrap rubber, an increase in compaction works up to 100% is only able to increase the durability of the ballast material by approximately 10%. In ballast layers without scrap rubber, an increase in compaction works up to 100% will increase the ability of the ballast layer to withstand loads up to 70%. In the ballast layer with uniformly sized scrap rubber, an increase in compaction works up to 100% can only increase the ability of the ballast layer to withstand loads up to 14%.

When the compaction process with manual pounding is carried out, the ballast materials in the sample with scrap rubber tend to bounce off each other, so that the sample does not have sufficient and proper density and stiffness. Addition of scrap rubber can reduce the stiffness of the ballast layer, which is characterized by a decrease in elastic modulus and an increase in vertical deformation. But, on the other hand, the use of scrap rubber can minimize damage to the ballast material significantly, since the presence of scrap rubber can reduce the possibility of collision and friction between aggregates, so that the material durability could be increased and material degradation could be decreased.

In this study, the authors have used 10% scrap rubber from outer motorcycle tires with sizes of 3/8 inch and 2 % and 3% asphalt of 60/70 penetration as additional material in the ballast layer. Furthermore, two types of manual compaction number were applied, 25 and 50 compaction times. This study aimed to evaluate and validate the characteristics of modified ballast with scrap rubber and asphalt mixtures and with two different numbers of manual compaction through a compressive strength test by analyzing the elastic modulus, ballast material durability and vertical deformation. Thus, the effect of adding scrap rubber and asphalt on the ballast layer as well as the comparison of the characteristics between sample with 25 compaction times and sample with 50 compaction times can be seen.

RESEARCH METHOD

Material Preparation

Ballast

This research was conducted at the Laboratorium of Transportation and Laboratorium of Structure, Department of Civil Engineering, Universitas Muhammadiyah Yogyakarta. The ballast was obtained from Clereng, Kulon Progo, Special Region of Yogyakarta, as shown in Fig. 1. This study only uses oven-dried ballast which has undergone cleansing from the sludge content. The ballast had been put into the oven for 24 hours until the conditions achieved are completely dry so that they match the test plan that has been prepared beforehand. The ballast was then tested regarding specific gravity and water absorption according to the provisions of Indonesian National Standard (Badan Standardisasi Nasional, 2008a), followed by sludge content test (Indonesian National Standard, 1996), wear test (Indonesian National Standard, 2008b) and filter analysis (Indonesian National Standard, 2012).

Figure (1): Ballast material

The initial stage was carried out in the form of preparation of tools and materials. At the stage of material testing, the aggregate physical properties were tested to determine the material specifications. Regulations regarding testing of aggregate specifications are based on the Indonesian National Standard. Physical tests carried out on the ballast aggregates included specific gravity, absorption, sieve analysis, mud content analysis and Los Angeles analysis. The grain size of the ballast used is 2"- 3/4" based on the gradation requirements for ballast materials stated in Peraturan Dinas no. 10, 1986, Peraturan Menteri Perhubungan no. 60, 2012 and Undang-Undang no. 23, 2007. Moreover, this ballast material is classified as 2nd class in Indonesian railway systems.

Asphalt

This study uses asphalt of 60/70 penetration, which is commonly used in the construction of highway pavements in Indonesia because of the absence of special asphalt for railroad construction. Asphalt comes from Pertamina which is stored in the Transportation and Highway Laboratory, Universitas Muhammadiah Yogyakarta. Asphalt was put into the oven for 5 hours to be heated to reach a temperature of 155° C. The asphalt was used in percentages of 2% and 3% of the total weight of the test object and is intended as a binding material. Asphalt physical testing was of the type of weight test according to the provisions of Indonesian National Standard (2011a), asphalt penetration (Indonesian National Standard, 2011b), ductility and oil loss (Indonesian National Standard, 1991a; Indonesian National Standard, 1991b) and asphalt softening point (Indonesian National Standard, 2011c). Asphalt used is shown in Fig. 2(a).

(a) (b) (c)

Figure (2): Asphalt (a), scrap rubber (b) and compressive strength test machine (c)

Used Rubber

This study uses rubber tires from unused vehicles. Rubber tires were cut into the size of 3/8 "using a 3/8" (9.52 mm) filter. The display of rubber pieces of used motorbike tires can be seen in Fig. 2(b).

The data needed in this test was the data of compressive strength test in the form of force, stress, strain and change in the height of the sample. Before testing the sample, first of all, physical testing was carried out on the ballast aggregates. Then, the compressive strength test results were analyzed to compare the modulus of elasticity, ballast material abrasion (durability) and vertical deformation of all specimens. This research was divided into several stages; namely, material preparation and testing, mixture planning and sample construction and compressive strength testing.

Mixture Planning and Sample Construction

The specimens were made in the ballast box with a size of 40 cm x 20 cm x 30cm. Mixing was accompanied by a manual compaction process with a pounder which has a manual load of 4.5 kg, a diameter of 6 cm and a falling height of 20 cm, distinguished by the amount of compaction by the pounder which is 25 times and 50 times (see Table 1).

Table 1. Sample design

Configuration	Sample
Ballast + 25 Compaction Times	S.1
Ballast + 50 Compaction Times	S.2
Ballast + 3/8" Scrap Rubber with 25 Compaction Times	S.3
Ballast + 3/8" Scrap Rubber with 50 Compaction Times	S.4
Ballast + 2% Asphalt + 25 Compaction Times	S.5
Ballast + 3% Asphalt + 25 Compaction Times	S.6
Ballast + 3% Asphalt + 50 Compaction Times	S.7
Ballast + 3/8" Scrap Rubber + 2% Asphalt + 25 Compaction Times	S.8
Ballast + 3/8" Scrap Rubber + 3% Asphalt with 50 Compaction Times	S.9

After the aggregates and asphalt material were known to meet the requirements, the samples can be made according to the planned mixture. The prepared samples are shown in Table 1. In each sample, the test material was inserted into the ballast box per 1/3 of the ballast box height. Then, the layer is compacted with a pounder at all sides and the middle part of the layer with a load height of ± 20 cm and then, the same thing was done with the second and third layers until the box was completely filled.

Compressive Strength Testing

At this stage, compressive strength testing was done using the Micro-Computer Universal Testing Machine (UTM) with a load plate area of 30 cm x 15 cm (Fig. 2c). The results of this test are the values of forces, stresses, strains and changes in the specimen's height. Furthermore, the relationship between stress and strain and the relationship between load and vertical deformation were analyzed in this stage.

Elastic Modulus Analysis

The modulus of elasticity (E) was obtained based on the test data of compressive strength, which was processed in the form of a stress-strain relationship curve with the trendline approach.

Vertical Deformation Analysis

Deformation is a change in the shape and size of a sample after testing. From this definition, it can be intended as a change in the height of a sample after being given a load. The examination of vertical deformation is obtained based on the number of changes in the height of the samples that occur due to the vertical loading process given by the Micro-Computer Universal Testing Machine. The vertical deformation value indicates the level of stiffness and the density of the ballast layer.

Ballast Material Abrasion Analysis

In this research, analysis was carried out by calculating the amount of aggregate material that was degraded or broken after the compressive strength test was completed. The investigation is carried out by taking a 5000 gr of sample material and putting it into sieve tools with sizes of 1" to no.4. Then, the calculation of material abrasion is based on the material that was passing the ¾" filter or, in other words, the ballast grain size is smaller than 25.4 mm. The ballast abrasion is obtained based on material damage, such as aggregate fracture or wear, due to compressive strength testing that leads to the reduction of ballast quality.

RESULTS AND DISCUSSION

Ballast Aggregate Examination Results

In Table 2, the results of aggregate physical tests are shown and these results have met the specifications determined by the regulations applied in Indonesia.

Table 2. Ballast aggregate examination results

No.	Examination	Specification	Result	Unit
1.	Specific Gravity-Bulk	≥ 2.60	2.63	-
2.	Specific Gravity-SSD	≥ 2.60	2.66	-
3.	Specific Gravity-Apparent	≥ 2.60	2.70	-
4.	Absorption	≤ 3.00	0.95	%
5.	Mud Content	≤ 0.50	1.85	%
6.	Los Angeles	≤ 25.0	17.70	%

Asphalt Examination Results

Physical testing of asphalt at the preparation stage of the test object was carried out to determine the feasibility of using 60/70 penetration asphalt. The results of physical asphalt testing have met Bina Marga specifications and are presented in Table 3.

Table 3. Asphalt physical test results

No.	Variable	Value	Specification
1.	Specific Gravity (gr/cm^3)	1.05	Min. 1.0
2.	Penetration	63.6	60 – 79
3.	Softening Point (ºC)	51 ºC	50 – 58
4.	Ductility (cm)	147	Min. 100
5.	Oil Losses (% weight)	0.397%	Max. 0.8

Scrap Rubber Examination Results

The basic testing of used rubber consists of 2 tests; namely, specific gravity test and absorption test, as shown in Table 4.

Table 4. Physical properties of used rubber

No.	Test	Results
1.	Specific Gravity	
	Specific Gravity-Bulk	2.64
	Specific Gravity-SSD	2.66
	Specific Gravity-Apparent	2.7
2.	Absorption	0.85%

Modulus of Elasticity

The modulus of elasticity can be known by comparing stress and strain values. Elastic modulus is the assessment of a material that is in an elastic condition resulting from the relationship between two axes; namely, the Y-axis that denotes the stress (σ) and the X-axis which presents the strain (ε). In this study, the elastic modulus value is obtained using the trendline method, assuming that the sample is still elastic until peak stress and strain are reached. In other words, the stress-strain curve is considered to be in a linear elastic condition. The trendline method was used, because there are only nine readings of stress and strain relationships and the maximum testing load is only 3,000 kg. This condition causes difficulties in determining the elastic and plastic area limits on the curve, because there is a possibility for each sample to receive more significant stress and because of the possibility of the stress-strain curve to increase.

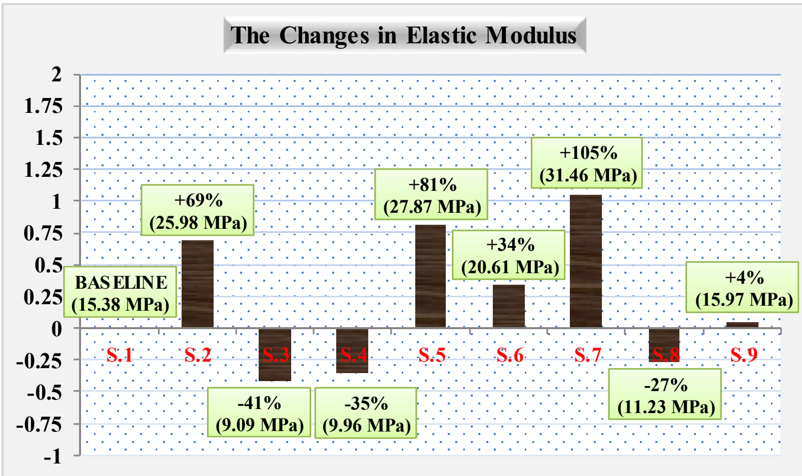
The obtained elastic modulus from each sample shows different values due to the nature of the material from the mixture, which also has different levels of elasticity. As presented in Table 5 and Fig. 3, the highest modulus of elasticity is shown by sample 7 (ballast with 3% asphalt and 50 compaction times), which is equal to 31.46 MPa, with an increase of 21% compared to sample 2 (ballast with 50 compaction times) or 105% compared to sample 1 (ballast with 25 compaction times). Furthermore, when compared to sample 1 (ballast with 25 compaction times), it is known that the modulus of elasticity shows an increase along with the use of asphalt. As described in Fig. 3, sample 5 (ballast with 2% asphalt and 25 compaction times), sample 6 (ballast with 3% asphalt and 25 compaction times) and sample 9 (ballast with 3/8” scrap rubber, 3% asphalt and 50 compaction times) have elastic modulus values of 81% (27.87 MPa), 34% (20.61 MPa) and 4% (15.97 MPa) higher compared to sample 1. These results were due to the application of bitumen as a binder material in the ballast layer. However, when compared to sample 1 (ballast with 25 compaction times), it is known that the modulus of elasticity shows a decrease along with the use of scrap rubber.

Table 5. Elastic modulus

Sample Name	Stress (kPa)	Strain (%)	Elastic Modulus (MPa)
S.1	352.72	2.29	15.38
S.2	730.88	2.81	25.98
S.3	282.53	3.11	9.09
S.4	303.89	3.05	9.96
S.5	482.96	1.73	27.87
S.6	750.38	3.64	20.61
S.7	764.47	2.43	31.46
S.8	687.33	6.12	11.23
S.9	359.24	2.25	15.97

As shown in Fig. 3, the most significant reduction in the modulus of elasticity was found in sample 3 (ballast with scrap rubber 3/8” and 25 compaction times), followed by sample 4 (ballast with scrap rubber 3/8” and 50 compaction times) and sample 8 (ballast with scrap rubber 3/8”, asphalt 2% and 25 compaction times), with values of 41% (9.09 MPa), 35% (9.96 MPa) and 27% (11.23 MPa), respectively. This result is due to the addition of scrap rubber with uniform size that can fill the cavities in the ballast layer, enabling to reduce the stiffness of the ballast mixture, thus reducing the modulus of elasticity. This result is in line with the results of the studies conducted by Setiawan and Rosyidi (2018b), Setiawan and Rosyidi (2018a), Sol-Sanchez et al. (2014), Sol-Sanchez et al. (2015) and Signes et al. (2016), which show that the addition of an elastic material can reduce the ballast layer stiffness.

Besides, the results in Table 5 and Fig. 3 show that in the same mix configuration, the elastic modulus values of the samples with 50 compaction times are higher than those of the samples with 25 compaction times. For example, the elastic modulus of sample 2 (ballast with 50 times of compaction) is higher than that of sample 1 (ballast with 25 times of compaction) and the elastic modulus of sample 7 (ballast with asphalt 3% and 50 times of compaction) is higher than that of sample 6 (ballast with asphalt 3% and 25 times of compaction). So, it can be concluded that good, proper compaction is an essential factor to increase the stiffness of the ballast layer. However, there was only a slight improvement of elastic modulus in sample 4 (ballast with scrap rubber 3/8” and 50 times compaction) compared to sample 3 (ballast with scrap rubber 3/8” and 25 times compaction). This result is in line with the output of a previous study conducted by Setiawan and Rosyidi (2018a). They stated that in the ballast layer with scrap rubber, an increase in compaction works up to 100% can only increase the ballast layer ability to withstand loads up to 14% and 18%, respectively and can only increase the elastic modulus of ballast layers by 3% and 6%, respectively. Furthermore, the results in Table 5 and Fig. 3 indicate that at the same amount of compaction, samples with asphalt 3% have lower moduli of elasticity compared to samples with asphalt 2%. This result is in line with the results of a previous study conducted by D'Angelo et al. (2017), which stated that the optimum asphalt content is 2%.



Figures (3): The changes in elastic modulus

There were also several results that can be obtained based on the analysis:

1. Even though there was an increase in compaction times (from 25 to 50), the addition of scrap rubber 10% still could reduce the elastic modulus of the ballast layer (sample 1 *vs.* sample 4).
2. Even though there was an increase in compaction times (from 25 to 50), increasing asphalt from 2% to 3% and the addition of scrap rubber 10% at the same time still could reduce the elastic modulus of the ballast layer (sample 5 *vs.* sample 8).
3. The effect of scrap rubber 10% on reducing ballast layer elastic modulus becomes more dominant compared to the influence of bitumen utilization on improving ballast layer elastic modulus.
4. However, the combination of compaction time improvement and the use of asphalt in the ballast layer could help increase the elastic modulus far outweighing the domination of scrap rubber 10%.
5. Even though there was a decrease in compaction times (from 50 to 25), the addition of asphalt 2% still could enhance the ballast layer elastic modulus (sample 2 *vs.* sample 5).
6. In the sample with scrap rubber 10%, the reduction in compaction times from 50 to 25 followed by the addition of asphalt 2% still could enhance elastic modulus of ballast layer (sample 4 *vs.* sample 9).
7. In the sample with scrap rubber 10%, the change in asphalt from 2% to 3% and the change in compaction times from 25 to 50 could enhance elastic modulus of ballast layer (sample 8 *vs.* sample 9).

Ballast Material Abrasion (Durability)

Percentage of ballast that experienced abrasion can be analyzed based on the changes in aggregate grain size that becomes smaller making the grains able to pass sieve ¾". In other words, the ballast grain size becomes smaller than 25.4 mm. As shown in Fig. 4 and Fig. 5, the highest percentage of the ballast material abrasion was demonstrated by sample 1 as a baseline (ballast with 25 times of compaction), which is 3.24% (162.1 gr). Furthermore, when compared to sample 1 (as the baseline) and sample 2 (ballast with 50 times of compaction), it is found that the percentage of ballast material abrasion shows a decrease along with the use of scrap rubber and asphalt. The most significant reduction in the percentage of the ballast material abrasion was shown by sample 9 (ballast with scrap rubber 3/8”, asphalt 3% and 50 times of compaction), followed by sample 7 (ballast with asphalt 3% and 50 times of compaction), sample 4 (ballast with scrap rubber 3/8” and 50 times of compaction), sample 8 (ballast with scrap rubber 3/8”, asphalt 2% and 25 times of compaction), sample 6 (ballast with asphalt 3% and 25 times of compaction) and sample 5 (ballast with asphalt 2% and 25 times of compaction), with a decrease of 87%, 80%, 77%, 77%, 76% and 71%, respectively. Lower percentage of ballast material abrasion in the sample indicates that the sample has a higher level of durability, so that it can minimize the occurrence of rupture and wear on ballast aggregates due to a reduction in friction or direct contact between aggregates. Scrap rubber and asphalt can fill the cavities or pores in the mixture of the samples, so that the modification of ballast with scrap rubber, asphalt or both materials can reduce the level of ballast damage.

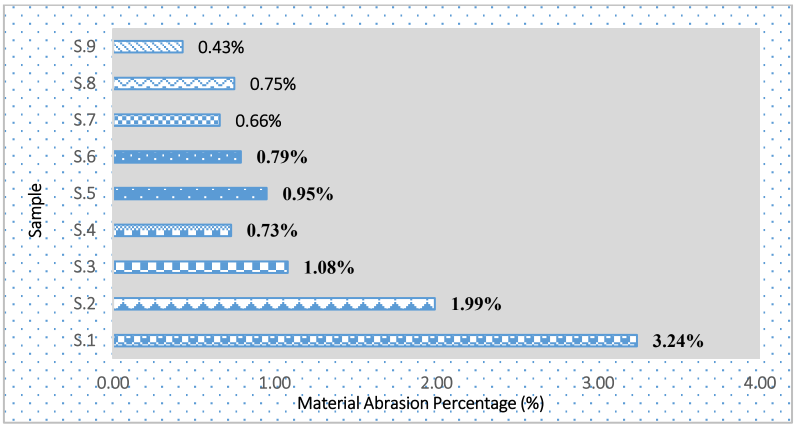


Figure (4): Percentage and weight of degraded ballast material

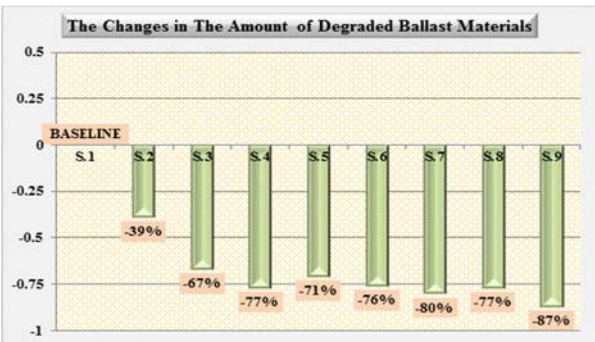


Figure (5): The changes in the amount of ballast material abrasion

Also, the results in Fig. 4 and Fig. 5 show that in the same mixture configuration, the percentage of ballast material abrasion in the samples with 50 compaction times is lower than that in the samples with 25 compaction times. For example, the abrasion of the material of sample 2 (ballast with 50 times of compaction) is smaller than in sample 1 (ballast with 25 times of compaction), the material abrasion of sample 7 (ballast with asphalt 3% and 50 times of compaction) is lower than in sample 6 (ballast with asphalt 3% and 25 times of compaction) and the material abrasion of sample 4 (ballast with scrap rubber 3/8” and 50 times compaction) is lower than in sample 3 (ballast with scrap rubber 3/8” and 25 times of compaction). It can be concluded that good, proper compaction is one of the crucial factors to minimize material abrasion. This result is in line with the results of a previous study conducted by Setiawan and Rosyidi (2018a), which stated that in the ballast layer with scrap rubber, an increase in compaction works was able to increase the durability of the ballast materials.

Moreover, the results in Fig. 4 and Fig. 5 indicate that at the same amount of compaction, samples with asphalt 3% produce higher ballast durability than samples with asphalt 2%. This result is in line with the output of a study conducted by D'Angelo et al. (2017), which states that the optimum asphalt content is 2%.

Furthermore, the results in Fig. 4 and Fig. 5 show that at the same number of compaction, samples with asphalt produce a lower ballast material abrasion percentage compared to samples with scrap rubber 3/8". This result is in line with the results of a previous study conducted by Setiawan and Rosyidi (2018b) which stated that asphalt can fill the cavity between ballast layers better and more evenly compared to scrap rubber, thereby reducing friction between ballast aggregates.

Vertical Deformation

Vertical deformation values were obtained from the graph of the relationship between loads and changes in the height of the specimens. Based on Fig. 6, the difference in the height of a sample at a particular load can be seen.

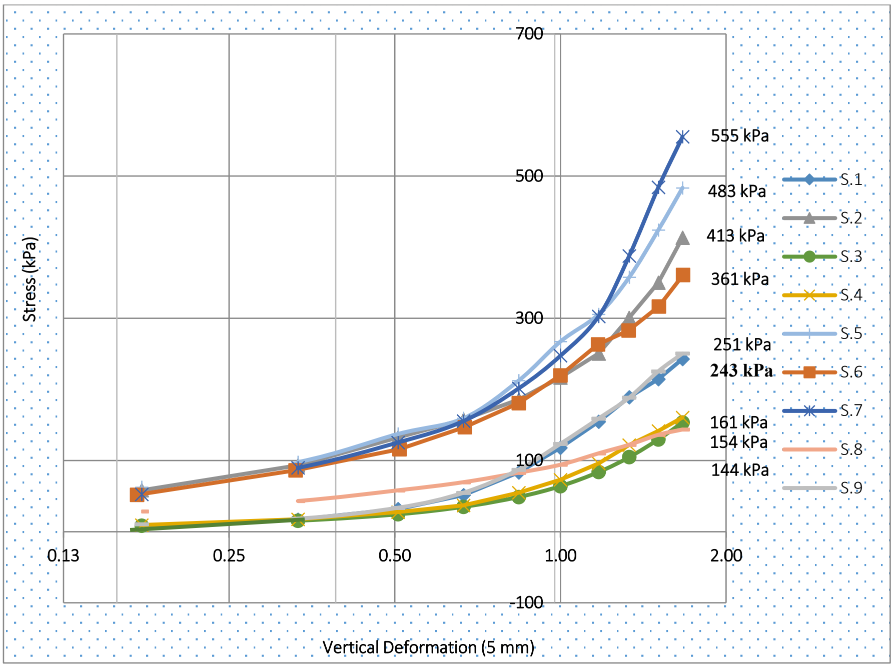


Figure (6): Vertical deformation (mm) and stress (kPa)

As presented in Fig. 6 and Fig. 7, at the same vertical deformation value (1.67 inches), the highest load received is shown by sample 7 (ballast with asphalt 3% and 50 compaction times), which is 555 kPa. In other words, there is an increase by 1.29 times compared to sample 1 as the baseline (ballast with 25 compaction times) or an increase by 34% compared to sample 2 (ballast with 50 times of compaction). Furthermore, when compared to sample 1 (ballast with 25 compaction times), it is known that there is an increase in the load needed to achieve 1.67-inch vertical deformation along with the use of asphalt. As described in Fig. 6, sample 5 (ballast with asphalt 2% and 25 compaction times), sample 6 (ballast with asphalt 3% and 25 compaction times) and sample 9 (ballast with scrap rubber 3/8", asphalt 3% and 50 compaction times) have the loads needed to achieve 1.67- inch vertical deformation by 99% (483 kPa), 49% (361 kPa) and 3% (251 kPa) higher compared to sample 1. This condition was due to the application of bitumen as a binder material in the ballast layer.

However, when compared to sample 1 (as the baseline), it is known that there is a decrease in the load needed to achieve 1.67-inch vertical deformation along with the use of scrap rubber 3/8". As shown in Fig. 7, the most significant reduction in the load required to produce 1.67-inch vertical deformation is found in sample 8 (ballast with scrap rubber 3/8", asphalt 2% and 25 compaction times), followed by sample 3 (ballast with scrap rubber 3/8" and 25 compaction times) and sample 4 (ballast with scrap rubber 3/8" and 50 compaction times), with values of 41% (144 kPa), 37% (154 kPa) and 34% (161 kPa), respectively. This result is due to the addition of scrap rubber with uniform size that can fill the cavities in the ballast layer and is able to reduce the stiffness of the ballast mixture, thus reducing the modulus of elasticity. The elastic material in the form of scrap rubber added to the ballast mixture can improve the elastic properties of the ballast layer. In ballast with scrap rubber (samples 3, 4, 8 and 9), loads needed to achieve the same vertical deformation value, for example, 5 mm, are much lower compared to ballast without scrap rubber (samples 1, 2, 5, 6 and 7). The elastic properties possessed by scrap rubber cause significant changes in the height of the ballast layer given the load as shown in samples 3, 4, 8 and 9. This result is in line with the results of previous studies conducted by Setiawan and Rosyidi (2018b), Setiawan and Rosyidi (2018a), Sol-Sanchez et al. (2014), Sol-Sanchez et al. (2014) and Signes et al. (2016), which stated that the use of scrap rubber can increase permanent deformation in ballast and sub-ballast layers.

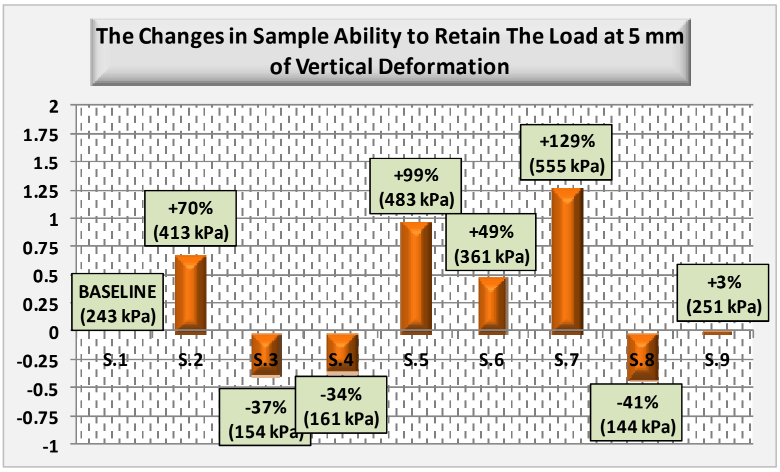


Figure (7): The changes in sample capability to retain the load at 5-mm of vertical deformation

In addition, the results in Fig. 7 show that with the same mixture configuration, the loads needed to achieve a 5-mm vertical deformation in the sample with 50 times of compaction are higher than in the samples with 25 times of compaction. For example, the load needed to achieve a 5-mm vertical deformation in sample 2 (ballast with 50 times of compaction) is higher than in sample 1 (ballast with 25 times of compaction), while the load needed to achieve a 5-mm vertical deformation in sample 7 (ballast with asphalt 3% and 50 times of compaction) is higher than in sample 6 (ballast with asphalt 3% and 25 times of compaction). Therefore, it can be concluded that good, proper compaction is an essential factor to minimize vertical deformation and increase the stiffness of the ballast layer. However, there was only a slight improvement of the load needed to achieve a 5-mm vertical deformation in sample 4 (ballast with scrap rubber 3/8" and 50 times of compaction) compared to sample 3 (ballast with scrap rubber 3/8" and 25 times of compaction). This result is in line with the results of a previous study conducted by Setiawan and Rosyidi (2018a), which stated that when the compaction process with manual pounding is carried out, the ballast materials in the sample with scrap rubber tend to bounce off each other, so that the sample does not have sufficient and proper density and stiffness.

Furthermore, the results in Fig. 6 and Fig. 7 indicate that at the same number of compaction, samples with asphalt 3% require lower loads to achieve a 5-mm vertical deformation when compared to samples with asphalt 2%. This result is in line with the results of a previous study conducted by D'Angelo et al. (2017), which stated that the optimum asphalt content is 2%.

There were also several results that can be obtained based on the analysis:

1. Even though there was an increase in compaction times (from 25 to 50), the addition of scrap rubber 10% still could increase the vertical deformation of the ballast layer (sample 1 *vs.* sample 4).
2. Even though there was an increase in compaction times (from 25 to 50), increasing of asphalt from 2% to 3% and the addition of scrap rubber 10% at the same time still could increase the vertical deformation of the ballast layer (sample 5 *vs.* sample 8).
3. The effect of scrap rubber 10% on enhancing ballast layer vertical deformation becomes more dominant compared to the influence of bitumen utilization on reducing ballast layer vertical deformation.
4. However, the combination of compaction time improvement with the use of asphalt in the ballast layer could help minimize vertical deformation far outweighing the domination of scrap rubber 10%.
5. Even though there was a decrease in compaction times (from 50 to 25), the addition of asphalt 2% still could reduce the vertical deformation of ballast layer (sample 2 *vs.* sample 5).
6. In the sample with scrap rubber 10%, the reduction in compaction times from 50 to 25 followed by the addition of asphalt 2% still could reduce the vertical deformation of ballast layer (sample 4 *vs.* sample 9).
7. In the sample with scrap rubber 10%, the change in asphalt from 2% to 3% and the change in compaction times from 25 to 50 could enhance elastic modulus (sample 8 *vs.* sample 9).

CONCLUSIONS

Based on the research that has been conducted, it can be concluded that:

1. The more compaction times, the higher elastic modulus and hence the stiffer the ballast layer. However, in the ballast layer with scrap rubber, compaction works are unable to impact optimally the ballast layer stiffness improvement.
2. The presence of 2% and 3% asphalt in the ballast layer will enhance the ballast layer stiffness, which will increase the elastic modulus. However, the presence of 10% of scrap rubber 3/8" in the ballast layer will reduce the ballast layer stiffness and hence will decrease the elastic modulus.
3. The more the compaction times, the lower the ballast material abrasion and hence the higher the ballast durability.
4. The percentage of ballast material abrasion shows a decrease along with the use of scrap rubber and asphalt, since scrap rubber and asphalt can fill the cavities or pores in the mixture of the samples, so that it can reduce friction between ballast aggregates and hence reduce the level of ballast damage.
5. The more the compaction times, the lower the vertical deformation and hence the higher the ballast stiffness. However, in the ballast layer with scrap rubber, compaction works are unable to impact optimally the ballast layer vertical deformation reduction, since the ballast materials in the sample with scrap rubber tend to bounce off each other, so

that the sample does not have sufficient and proper density and stiffness.

6. The presence of 2% and 3% asphalt in the ballast layer will minimize the vertical deformation of ballast layer and hence will increase the elastic modulus. However, the presence of 10% of scrap rubber 3/8" in the ballast layer will decrease the ballast layer stiffness and hence reduce the elastic modulus.

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