Research Article

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Utilization of 60/70 penetration grade asphalt on ballast structures with the variation of percentage and the number of pouring layers

<https://doi.org/10.1515/jmbm-2019-0013>

Received Sep 21, 2019; accepted Nov 02, 2019

Abstract: Railroad ballast structure layer may experience a decline in mechanical and geometrical performance due to heavy train and environmental loads. In order to improve the quality of ballast structure, the addition of asphalt to ballast layer can be considered as a solution. Therefore, this research utilizes 60/70 penetration grade asphalt for ballast layer binding and stabilization. The objective of this study was to evaluate and analyze the mechanical behavior of clean-ballast and fouled-ballast layers with 2% and 4% penetration grade 60/70 asphalt poured in one (ballast surface layer) and three ballast surface layers. Compressive strength test was performed to analyze the weight of specimen, vertical deformation, and ballast material abrasion. The most prominent finding to emerge from this research was that the use of 60/70 penetration grade asphalt on ballast surface layer is crucial in retaining the load applied by UTM, in order to produce preferable load distribution to the entire ballast structure. It is found that, the higher the 60/70 penetration grade asphalt proportion and the more layers poured with asphalt, the stronger asphalt in reducing ballast abrasion percentage.

Keywords: 60/70 penetration grade asphalt, ballast abrasion, clean-ballast, fouled-ballast, specimen weight, vertical deformation

1 Introduction

The problems experienced by the Indonesian government in the development of rail transport among others are expensive infrastructure procurement and high maintenance costs, especially of ballast layer. According to In-

draratna *et al.* [1], ballast layer provides structural support to high dynamic pressure transmitted by a moving train. Ballast layer also has a pore structure that supports drainage capabilities of railroad track [2]. Improper maintenance of ballast can lead to potential damage and degradation of railroad structure quality. Ballast layer degradation may occur due to particle rupture and high internal pressure between adjacent aggregate particles [3]. Therefore, ballast layer maintenance must be performed optimally. However, the cost for maintaining conventional railroads is uneconomical. According to D'Angelo *et al.* [4] and Setiawan [5], the alternatives for further technological development for ballast layer must aim to extend its durability and improve its stability, in order to face accelerated operations of and traffic load requirements for rail transport in the future.

It is known that the stiffness of ballast and sub-ballast differs for each layer [6]. Railroad ballast structure layer may experience a decline in mechanical and geometric performance due to continuous exposure to dynamic loads [7]. In order to improve the quality of ballast structure, the addition of other materials to ballast layer can be considered as a solution. Woodward *et al.* [8], through their studies, had applied a unique material named in-situ polyurethane polymer to increase the stability of ballast structure. However, its usage needs to be considered due to its availability in rail industry. Alternatively, scrap rubber [9–13] and asphalt [4, 14–17] may also be opted for ballast layer treatment.

According to Di Mino *et al.* [17], ballast layer with asphalt can reduce the dynamic force and vibration in subgrade and minimize the possibility of structural degradation. This statement was also supported by Asgharzadeh *et al.* [11], which concluded that one of the most effective solutions to increase stability, reduce vibration, and minimize maintenance of ballast layers is by using asphalt mixtures in railroad construction. In a study conducted by D'Angelo *et al.* [7], in order to improve the durability of ballast layer, bitumen stabilized ballast (BSB) can be a new solution. Their results also demonstrated that the addition

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of bitumen emulsion to ballast layer had successfully lowered plastic strain and given better stiffness. The utilization of BSB was also examined in a research conducted by Giunta *et al.* [18] as an innovative solution designed to increase structural endurance and reduce overall maintenance work. Another research by Lee *et al.* [15] observed the mixture of ballast layer with three different types of asphalt, *i.e.* PG64-22, crumb rubber modified (CRM) asphalt, and styrene-butadiene-styrene (SBS) modified asphalt. The results of the study showed that the mixture of asphalt with rubber content (CRM) and SBS modified asphalt showed better performance compared to PG64-22 asphalt.

In their research, D'Angelo *et al.* [7] stated that asphalt is among the potential solutions for reducing damage and improving ballast layer performance. There are several ways to improve ballast performance, one of which is by adding hot mix admixture (HMA) to ballast layer in order to improve ballast bearing capacity and stability. Ballast and sub-ballast layer stabilization can also be sought using polyurethane. Ballast layers undergoing this method are commonly called polyurethane-stabilized ballast (PSB) [19].

The mixture of ballast aggregate with bitumen can enhance the physical endurance of ballast and decrease vertical deformation [5, 7]. The addition of binding material such as asphalt to ballast layer can also minimize the need for maintenance work which in turn reducing maintenance costs [14]. When mixed with aggregate materials, asphalt will improve the binding of the aggregate [20] and reduce the impact of dynamic loads as demonstrated by improved stiffness modulus [17]. Adding asphalt helps minimizing vertical settlement in ballast layer due to the percentage and thickness of the asphalt [21].

Several studies have been conducted on the utilization of scrap rubber as a mixture in ballast structure to increase ballast characteristics. Signes *et al.* [10] studied the characteristics of mixing rubber and ballast materials to obtain resilient modulus of ballast layer. Rubber has elastic properties that function as a protector while minimizing direct contact between materials it separates. The mixture of ballast layer and scrap tire rubber successfully minimized the degradation of ballast material while decreasing ballast layer stiffness. Concurrently, the vibration caused by dynamic loads received when a train is operated was also reduced [9, 11, 14]. As stated by Navaratnarajah *et al.* (2017), overlaying rubber at the bottom of the ballast material could reduce ballast structure deformation rate by around 35%-45%. Navaratnarajah *et al.* [22] also concluded that the use of rubber mixture on ballast layers helped minimizing long-term degradation and deformation.

However, rubber is a thermoplastic material which is vulnerable to temperature heating [23]. In addition, excessive utilization of elastic material can reduce density, which may result in immediate reduction in the modulus of elasticity and instability of railroad track. Excessive use of crumb rubber in ballast layer not only decreases ballast layer stiffness but also increases the possibility of ballast layer deformation [9, 10, 16, 24]. Therefore, Sol-Sánchez *et al.* [9] suggested a maximum of 10% rubber content in the ballast layer as the elastic material.

Using scrap rubber without binding material will lead to several drawbacks, particularly ballast stiffness reduction. Setiawan *et al.* [25] combined 10% scrap rubber (used motorcycle tire rubber) with 3% asphalt as ballast layer mixture. They found that applying 10% of used rubber can increase vertical deformation rate, while adding 3% asphalt in the ballast mixture as a binder can increase ballast layer stiffness. Using 10% used rubber, and 3% asphalt can also significantly reduce material abrasion rate in ballast layer by 47% to 80%. Furthermore, Setiawan *et al.* [26] conducted a study using the same rubber material as a mixture in ballast layer and applying variations in rubber size and manual compacting collision frequency in each sample. The results of the study indicated that the variation in the size of used rubber is essential in increasing ballast durability. Further, increasing compaction work by up to 100% (twice the usual) can only increase the modulus of elasticity by 6% in the ballast layer that has been mixed with used rubber. However, the treatment successfully increased ballast aggregate durability by 38% and improved ballast layer ability to withstand loads by up to 70%.

Although some researchers have applied 2%-3% of other particular asphalt types as ballast layer binder, further research is needed to observe the utilization of 60/70 penetration grade asphalt in railroad track structure. The 60/70 penetration grade asphalt is the standard for pavement designs in Indonesia. To that reason, this research will focus on the use of 2% and 4% penetration grade 60/70 asphalt as the binder of ballast structure. The adhesive and cohesive natures of asphalt can bind aggregate and keep them in place so much so that 60/70 penetration grade asphalt is expected to support aggregate to withstand incoming load thus minimizing ballast deformation and increasing ballast structure durability while reducing maintenance costs.

This study aims to evaluate and analyze the mechanical behavior of clean-ballast and fouled-ballast layers with 2% and 4% penetration grade 60/70 asphalt in one (ballast surface layer) and three layers. Compressive strength test was performed along with an analysis of the weight of specimen, vertical deformation, and ballast material abrasion

Table 1: Examination of aggregate physical and mechanical properties

Parameters	Results	Specifications	Standard
Specific Gravity			
•Dry	2.61		
•Bulk	2.68	≥ 2.6	SNI 1969-2008 [29]
•Apparent	2.80		
Water Absorption	2.65	$\leq 3\%$	SNI 1969-2008 [29]
Abrasion – Los Angeles	19.26%	$\leq 25\%$	SNI 2417-2008 [30]
Mud Content	0.21%	$\leq 0.5\%$	SNI 03-4142-1996 [31]

Table 2: The 60/70 penetration grade asphalt test results

Parameters	Results	Specifications	Unit	Standard
Penetration	66.7	60-70	0.1 mm	SNI 2456-2011 [32]
Softening Point	53	≥ 48	Celsius	SNI 2434-2011 [33]
Specific Gravity	1.01	≥ 1.0	-	SNI 2441-2011 [34]
Ductility	112	≥ 100	Cm	SNI 2432-2011 [35]
Oil Losses	0.13	≤ 0.8	%	SNI 06-2440-1991 [36]

(from sieve analysis of degraded ballast material after loading process). In this research, clean-ballast was utilized in order to represent and model a new railroad track structure, while fouled-ballast was applied in order to represent and model existing railroad track structure that requires rehabilitation for further use.

2 Research method

2.1 Ballast aggregate

The aggregate materials of this study came from Clereng Sub-District, Kulon Progo Regency, Special Region of Yogyakarta Province with $2\frac{1}{2}$ " (63.5 mm) – $\frac{3}{4}$ " (19 mm) of grain size. The physical and mechanical properties of the aggregate materials were examined among others for the properties of filter analysis, fine material that passes sieve No. 200, specific gravity, and resistance to degradation as specified by Service Regulation No. 10 of 1986 [27], Ministerial Regulation No. 60 of 2012 [28], and the Indonesian National Standard (SNI). After inspection, the aggregate materials were grouped according to predetermined mixtures of test objects, namely clean-ballast and fouled-ballast. Clean-ballast aggregate must first be washed to remove impurities such as sand and mud. The washed aggregate is then oven-dried at 110°C for 24 hours to obtain fixed weight. Fouled-ballast aggregate does not require initial washing and is immediately put into oven to obtain

fixed weight. The examination results of ballast materials for specific gravity, water absorption, sludge content, and aggregate wear can be seen in Table 1.

2.2 The 60/70 penetration grade asphalt

Asphalt is a binding material with solid to semi-solid properties at room temperature ($20\text{--}30^{\circ}\text{C}$) which becomes soft or liquid if heated (thermoplastic). Asphalt can function as a binder and cavity filler between aggregate materials. Asphalt molecules are stable at 25°C , soften at $25\text{--}60^{\circ}\text{C}$, and freeze below 25°C . For this research, the 60/70 penetration grade asphalt was obtained from the asphalt storage at the Transportation Laboratory, Department of Civil Engineering, Universitas Muhammadiyah Yogyakarta. Both the process and the results of asphalt material inspection have followed the specifications shown in Table 2.

The asphalt was tested for its penetration, softening point, specific gravity, ductility, and oil loss properties, in reference to the Indonesian National Standard (SNI). Solid asphalt was put into a teapot and then placed in an oven at 155°C for 4 hours until it melts and is ready as a specimen.

2.3 Vertical deformation

Compressive load is the amount of loads that affect an object based on its cross-sectional area. Vertical deformation

Table 3: Specimen configuration

Specimens	Asphalt Content (%)	Code
Clean-Ballast	-	CB
Fouled-Ballast	-	FB
Clean-Ballast + 2% Asphalt only on Ballast Surface Layer	2%	CB1-2%
Clean-Ballast + 4% Asphalt only on Ballast Surface Layer	4%	CB1-4%
Fouled-Ballast + 2% Asphalt only on Ballast Surface Layer	2%	FB1-2%
Fouled-Ballast + 4% Asphalt only on Ballast Surface Layer	4%	FB1-4%
Clean-Ballast + 2% Asphalt divided into 3 Layers	2%	CB3-2%
Clean-Ballast + 4% Asphalt divided into 3 Layers	4%	CB3-4%
Fouled-Ballast + 2% Asphalt divided into 3 Layers	2%	FB3-2%
Fouled-Ballast + 4% Asphalt divided into 3 Layers	4%	FB3-4%

is a change in the shape of an object due to a force that affects the object vertically. From vertical deformation rate we can obtain the mechanical properties of a material in terms of stiffness.

2.4 Ballast material abrasion

The abrasion rate of specimens was tested by comparing the distribution of aggregate material gradations before and after the application of compressive strength by Universal Testing Machine. The test was carried out using gradation analysis, which is illustrated by a graph of the aggregate percentage. The damage calculation was based on the weight of the damaged ballast material that was able to pass $\frac{3}{4}$ " sieve.

2.5 Research stages

The first step in this research was to carry out physical and mechanical examination of aggregate materials, followed by material mixing, 50 ballast structure compactions per layer, specimen compressive strength testing, and testing results analysis. 2% and 4% penetration grade 60/70 asphalt were chosen according to typical bitumen-stabilized materials used in pavements. The specimens are displayed in Table 3.

2.6 Sample design and preparation

The ballast aggregate and asphalt in this test were prepared according to Peraturan Dinas (Service Regulation) No. 10 of 1986 [27], the Indonesian National Standard (SNI), and Peraturan Menteri (Indonesian Ministerial Reg-

ulation) No. 60 of 2012 [28]. Once all the materials were ready, a ballast box sized $400 \times 200 \times 300$ mm was set.

2.7 Material compaction and asphalt pouring

Specimen compaction was carried out to each layer (every 10 cm) with 50 compactions per layer. The compaction was carried out using manual compactor and a flat-surfaced rectangular pounder having the same size of the ballast surface layer ($400 \text{ mm} \times 200 \text{ mm}$), weighing 4.5 kg, with 45.7 cm free fall height. The compaction process, asphalt pouring process, specimens without asphalt mixture, and specimens with asphalt mixture can be seen in Figure 1.

The asphalt pouring was performed in four different set-ups. In the first set-up of specimens CB1-2% (clean-ballast with 2% penetration grade 60/70 asphalt only on ballast surface layer) and FB1-2% (fouled-ballast with 2% penetration grade 60/70 asphalt only on ballast surface layer), ballast materials were arranged in the ballast box in three layers, applying compaction to each layer. Each layer was 10 cm-thick, resulting in a total of 30 cm ballast layer thickness. Each of the layers was compacted 50 times using manual compactor. 2% asphalt was poured once the compactions of the three layers complete and were 30 cm thick. Thus, 2% penetration grade 60/70 asphalt was poured only on the ballast surface layer.

In the second set-up of specimens CB1-4% (clean-ballast with 4% penetration grade 60/70 asphalt only on ballast surface layer) and FB1-4% (fouled-ballast with 4% penetration grade 60/70 asphalt only on ballast surface layer), ballast materials were arranged in the ballast box in three layers, applying compaction to each layer. Each layer was 10 cm-thick, resulting in a total of 30 cm ballast layer thickness. Each of the layers was compacted 50 times

Figure 1: (a) Compaction process; (b) asphalt pouring process; (c) specimens without asphalt mixture; (d) specimens with asphalt mixture

using manual compactor. 4% asphalt was poured once the compactions of the three layers complete and were 30 cm thick. Thus, 4% penetration grade 60/70 asphalt was poured only on the ballast surface layer.

In the third set-up of specimens CB3-2% (clean-ballast with 2% penetration grade 60/70 asphalt divided into three layers) and FB3-2% (fouled-ballast with 2% penetration grade 60/70 asphalt divided into three layers), ballast materials were also arranged in the ballast box in three layers, applying compaction to each layer. Each layer was also 10 cm-thick, resulting in a total of 30 cm ballast layer thickness. Each of the layers was compacted 50 times using manual compactor. However, 2% asphalt was poured on top of each layer (10 cm) once the compaction of each layer completes. Therefore each layer was poured with 0.67% of asphalt.

In the fourth set-up of specimens CB3-4% (clean-ballast with 4% penetration grade 60/70 asphalt divided into three layers) and FB3-4% (fouled-ballast with 4% penetration grade 60/70 asphalt divided into three layers), ballast materials were also arranged in the ballast box in three layers, applying compaction to each layer. Each layer was also 10 cm-thick, resulting in a total of 30 cm ballast layer thickness. Each of the layers was compacted 50 times us-

ing manual compactor. However, 4% asphalt was poured on top of each layer (10 cm) once the compaction of each layer completes. Therefore each layer was poured with 1.33% of asphalt. The asphalt pouring process is shown in Figure 1(b).

2.8 Compressive strength test

After the specimens were ready, the compressive strength test with Micro-Computer Universal Testing Machine (UTM) with 4000 kg load was carried out twice, the result of which was further analyzed to obtain the vertical deformation rate. The first step was inputting the dimension of the test specimen, the surface area of the loading plate, and the quantity of the load to be tested. Compressive testing was then carried out to the test object, and the loading plate was placed symmetrically.

2.9 Material abrasion

Ballast aggregate abrasion is the aggregate that changes in size (passes $\frac{3}{4}$ " or 19 mm sieve) after compressive strength test was carried out. The aggregate abrasion analysis was

Table 4: Compared means of specimen weights

Treatment	Specimen Weight in Kilogram	t Value	P-value
Ballast			
Clean	36.7460 (0.1060)		
Fouled	37.6940 (0.1060)	−6.33	0.0002*
Penetration Grade Asphalt			
2%	37.1175 (0.2709)		
4%	37.4500 (0.2709)	−0.87	0.4188
Asphalt Pouring Layer			
1	37.3175 (0.2867)		
3	37.2500 (0.2867)	0.17	0.8733

Figure 2: Specimen weight

carried out using filter analysis method. The test was done by weighing the aggregate that passes the $\frac{3}{4}$ " (19 mm) sieve. Abrasion rate is the ratio of damaged ballast material weights to specimen weight. The percentage of ballast material abrasion in each specimen is influenced by several factors, such as ballast material preparation process, ballast material compaction process, and compressive strength test process.

3 Results and discussions

3.1 Sample weight

Table 4 shows compared means of specimen weight for each treatment. From the table, we can conclude that there is a significant difference in specimen weight between "clean" ballast and "fouled" ballast (p -value=0.0002). The estimated difference is −0.9480 Kg with standard error 0.1498 Kg. The specimen weight of clean ballast is signif-

icantly smaller than that of fouled ballast. Statistically, there is no evidence which confirms that the specimen weights of the two levels of penetration grade asphalt differ (p -value=0.4188). Also, there are no differences in the specimen weights of 1 layer and 3 layers of asphalt pouring (p -value=0.8733).

As shown in Figure 2, it can be concluded that the weight of each specimen varies depending on ballast condition (clean or fouled), 60/70 penetration grade asphalt content, and how many layers were poured with asphalt. Fouled-ballast based specimen was relatively heavier compared to clean-ballast based specimen, either with or without the addition of 2% and 4% penetration grade 60/70 asphalt. This is due to sludge residue attached to the fouled-ballast material as opposed to purified clean-ballast materials which were washed and dried. Although statistically the difference in specimen weights between the two levels of penetration grade asphalt was not significant, the specimens with 2% penetration grade 60/70 asphalt produced better output due to its lighter weight when compared to the specimens with 4% penetration grade 60/70 asphalt.

Table 5: Compared means of vertical deformation

Treatment	Vertical Deformation in mm	t Value	P-value
Ballast			
Clean	4.3420 (0.2646)		
Fouled	5.4120 (0.2646)	−2.86	0.0212*
Penetration Grade Asphalt			
2%	5.0100 (0.3086)		
4%	4.3525 (0.3086)	1.51	0.1826
Asphalt Pouring Layer			
1	4.4875 (0.3446)		
3	4.8750 (0.3446)	−0.8	0.4568

Figure 3: Vertical deformation rate after the first loading

Lastly, same ballast condition (clean or fouled) and same asphalt content (2% or 4%) will produce similar specimen weight regardless of how many layers were poured with asphalt.

In the fouled-ballast based specimen, the heaviest specimen was FB3-4% (37.92 kg), followed by FB1-4% (37.85 kg), FB3-2% (37.65 kg), FB1-2% (37.56 kg), and FB (37.49 kg). In another side, in the clean-ballast based specimen, the heaviest specimen was CB1-4% (37.11 kg), followed by CB3-4% (36.92 kg), CB1-2% (36.75 kg), CB3-2% (36.51 kg), and CB (36.44 kg).

3.2 Vertical deformation

Table 5 shows the compared means of vertical deformation for each treatment. From the table, we can conclude that there is a significant difference in vertical deformation between “clean” ballast and “fouled” ballast (p-value=0.0212). The estimated difference is -1.07 mm with standard error 0.3742 mm. The vertical deformation of clean ballast is significantly smaller than fouled bal-

last. Statistically, there is no evidence which confirms that the vertical deformations of the two levels of penetration grade asphalt differ (p-value=0.1826). Statistically, there are also no differences in the vertical deformations of 1 layer and 3 layers of asphalt pouring (p-value=0.4568).

Figure 3 presents the vertical deformation rate from first loading. It can be concluded that fouled-ballast based specimen produced higher vertical deformation rate compared to clean-ballast based specimen, with or without the addition of 2% and 4% penetration grade 60/70 asphalt, owing to the fact that fouled-ballast contains mud and dust which can reduce the interlocking ability between ballast materials, as opposed to clean-ballast materials which have undergone washing and drying process. This result is in line with D'Angelo *et al.* [4], D'Angelo *et al.* [7], and D'Angelo *et al.* [37]. Also, at same ballast condition (clean or fouled) and same asphalt content (2% or 4%), specimens with asphalt poured only on ballast surface layer produced lower vertical deformation as compared to specimens with asphalt poured to and divided into three different layers. From the analysis, it also is known that both clean-ballast based specimens (CB1-2%, CB1-4%, CB3-2%,

Figure 4: Vertical deformation of clean-ballast based specimen after the first loading

CB3-4%) and fouled-ballast based specimens (FB1-2%, FB1-4%, FB3-2%, FB3-4%) which were added with 2% and 4% penetration grade 60/70 asphalt have lower vertical deformation as compared to each baseline specimen (CB and FB). This result is in agreement with D'Angelo *et al.* [4] and Setiawan *et al.* [26].

Further, at same ballast condition (clean or fouled) and same number of layers poured with asphalt (either on ballast surface layer only or divided into three layers), the specimens with 4% penetration grade 60/70 asphalt showed lower vertical deformation than the specimens with 2% penetration grade 60/70 asphalt. Lastly, it can be seen that CB3-4% has lower vertical deformation than CB1-2%, while FB3-4% has lower vertical deformation than FB1-2%. Therefore, it can be concluded that although statistically there is no significant difference in the vertical deformations of the two levels of penetration grade asphalt, higher asphalt content in ballast layer gave more significant impact than higher number of layers poured with asphalt in determining ballast layer performance for vertical deformation. In other words, higher percentage of 60/70 penetration grade asphalt was capable to improve clean-ballast and fouled-ballast layer performance since asphalt as the binding material helps enhancing ballast structural stiffness.

According to Figure 4, for clean-ballast based structure, CB1-4% specimen had the lowest vertical deformation (3.74 mm), followed by CB3-4% specimen (4.10 mm), CB1-2% (4.29 mm), and CB3-2% (4.62 mm), or consecutively 24.64%, 17.34%, 13.55%, and 6.85% lower than CB specimen (4.96 mm). According to Figure 5, for fouled-ballast based structure, FB1-4% specimen had the lowest vertical deformation (4.56 mm), followed by FB3-4% specimen (5.10 mm), FB1-2% (5.36 mm), and FB3-2% (5.77 mm), or consecutively 28.30%, 21.23%, 15.72%, and 9.28% lower than FB specimen (6.36 mm).

Further, Figure 6 shows the total of vertical deformation of the specimens after experiencing compressive

Figure 5: Vertical deformation of fouled-ballast based specimen after the first loading

strength tests twice. The decrease in vertical deformation in the second test in each specimen was due to higher density level applied to the specimens. The first loading contributed to the increase in the sample's stiffness. For clean-ballast based structure, CB1-4% specimen produced the lowest total vertical deformation (5.58 mm), followed by CB3-4% (5.96 mm), CB1-2% (6.48 mm), and CB3-2% (6.71 mm), as compared to CB specimen at 7.30 mm. For fouled-ballast based structure, FB1-4% specimen produced the lowest total vertical deformation (6.67 mm), followed by FB3-4% (7.45 mm), FB1-2% (7.86 mm), and FB3-2% (8.36 mm), as compared to FB specimen at 9.72 mm, which was the highest among the ten specimens.

As shown in Figure 7 above, the three specimens with the highest difference in vertical deformation rate between the first and the second loading were FB3-2% (55.11%), CB3-2% (54.76%), and CB3-4% (54.56%). Meanwhile, specimen FB had the lowest difference in vertical deformation rate between the first and the second loading (47.17%). It can be concluded that penetration grade 60/70 asphalt on ballast surface layer in CB1-2%, CB1-4%, FB1-2%, and FB1-4% is crucial in retaining the load applied by UTM, in order to produce preferable load distribution to the entire ballast structure. Therefore, it was reasonable that these four specimens produced the lowest total vertical deformation (see Figure 6) as compared to other specimens in either ballast based condition (both clean and fouled). According to the vertical deformation parameter, particularly for clean-ballast based condition, it is preferable to apply 4% penetration grade 60/70 asphalt only to a layer (on ballast surface layer) according to the positive test results and the simplicity of application method (CB1-4%). In specimen CB1-4%, the vertical deformation rate was reduced by 50.83% (from 3.74 mm in the first test to 1.84 mm in the second test). In fouled-ballast based condition, it is also preferable to apply 4% penetration grade 60/70 asphalt only to a layer

Figure 6: Total vertical deformation rate

Table 6: Compared means of ballast abrasion

Treatment	Ballast abrasion in percentage	t Value	P-value
Ballast			
Clean	0.6680 (0.1095)		
Fouled	0.8040 (0.1095)	−0.88	0.4053
Penetration Grade Asphalt			
2%	0.7000 (0.08007)		
4%	0.5925 (0.08007)	0.95	0.3791
Asphalt Pouring Layer			
1	0.7700 (0.04764)		
3	0.5225 (0.04764)	3.67	0.0104

Figure 7: Vertical deformation rate change (percentage)

on the ballast surface (FB1-4%). In specimen FB1-4%, the vertical deformation rate was reduced by 53.73% (from 4.56 mm in the first test to 2.11 mm in the second test).

3.3 Ballast abrasion

Table 6 shows the compared means of ballast abrasion for each treatment. From the table, we can conclude that there is no evidence which confirms that the ballast abrasions of “clean” and “fouled” ballast differ (p -value=0.4053). There is no evidence confirming that the ballast abrasions between two levels of penetration grade asphalt differ (p -value=0.3791). Meanwhile, there is a significant difference in the ballast abrasion in 1 layer and 3 layers of asphalt pouring (p -value=0.0104). The estimated ballast abrasion difference is 0.2475% with standard error 0.06738%. 3-layered asphalt pouring has significantly lower ballast abrasion percentage than 1-layered asphalt pouring.

Figure 8: Percentage of ballast material abrasion

Figure 9: Ballast abrasion in clean-ballast based specimen

Figure 10: Ballast abrasion in fouled-ballast based specimen from first loading

According to Figure 8, specimens CB (0.98%) and FB (1.21%) had the highest abrasion rates due to the fact that both contain no additional asphalt materials that help protecting the materials from abrasion during compaction and compressive strength testing.

As seen in Figure 9 and 10, at same ballast condition (clean or fouled) and same quantity of 60/70 penetration grade asphalt, the more layers of asphalt poured, the lower ballast abrasion percentage. Although statistically there is no significant difference in the ballast abrasions of the two levels of penetration grade asphalt, at same ballast condition (clean or fouled) and same number of layers of asphalt poured, the use of 4% penetration grade 60/70 asphalt had lower ballast abrasion percentage than that of 2% penetration grade 60/70 asphalt. This result is in agreement with D'Angelo *et al.* [4], D'Angelo *et al.* [7], Setiawan *et al.* [26], and D'Angelo *et al.* [37] statements in their research regarding asphalt materials as track-bed structural stabilizer that can improve ballast ability to dissipate energy.

Based on the ballast abrasion parameter, especially in clean-ballast based condition, it is preferable to pour and divide 4% penetration grade 60/70 asphalt to three layers (CB3-4%). In specimen CB3-4%, the ballast abrasion per-

centage was 53.06% lower than baseline specimen CB. In fouled-ballast based condition, it is also preferable to pour and divide 4% penetration grade 60/70 asphalt to three layers (FB3-4%). In specimen FB3-4%, the ballast abrasion percentage was 59.50% lower than the baseline specimen FB.

In specimens CB1-2%, CB1-4%, FB1-2%, and FB1-4%, although adding asphalt can reduce the abrasion percentage as compared to specimens CB and FB, distributing 4% penetration grade 60/70 asphalt only to one layer (on ballast surface layer) could merely protect some materials at the top layer of the ballast structure. In specimens CB3-2%, CB3-4%, FB3-2%, and FB3-4% where asphalt was properly distributed to three different layers, more materials were protected from abrasion during the process of compaction and compressive testing.

Therefore, it can be concluded that the more layers poured with asphalt, the better it reduces the ballast abrasion percentage. This means that 60/70 penetration grade asphalt poured to and divided into three different layers could improve the performance of clean-ballast and fouled-ballast layers since asphalt as the binding mate-

rial helps increasing the stiffness of ballast structure. This owes to the adhesive and cohesive attributes of asphalt which bind aggregate and hold them in position. As a comparison, in ballast without the addition of binding material in its mixture, aggregate move more freely than when a load is applied, a friction between aggregate materials occurs. Such a friction is more serious as compared to frictions in ballast with binder. Additionally, specimens with clean-ballast have lower abrasion percentage than specimens with fouled-ballast, as clay and sand grains contained in the aggregate materials of the fouled-ballast are more susceptible to wear and prone to abrasion. In specimens with asphalt mixture, specimens with 3 layers of asphalt mixture have lower abrasion percentage than specimens with 1 layer of asphalt mixture, since specimens with 3 layers of asphalt mixture distribute asphalt more evenly, whereas specimens with 1 layer of asphalt have asphalt accumulation only on the surface of the layer. When asphalt fails to reach the bottom part of the ballast layer, the unreachable part will be more susceptible to abrasion.

4 Conclusions

On the basis of the results obtained in this study, the following conclusions can be drawn:

- (a) Fouled-ballast based specimens were relatively heavier in weight and produced higher vertical deformation rate and ballast abrasion percentage compared to clean-ballast based specimens, either with or without the addition of 2% and 4% penetration grade 60/70 asphalt.
- (b) Based on the vertical deformation parameter, it is preferable to apply 4% penetration grade 60/70 asphalt only to 1 layer (on ballast surface layer) according to the positive test results and the simplicity of application method. The 60/70 penetration grade asphalt poured on ballast surface layer is crucial in retaining the load applied by UTM, in order to produce more preferable load distribution to the entire ballast structure and lower vertical deformation rate compared to specimens with asphalt poured to and divided into three different layers.
- (c) Based on the ballast abrasion parameter, it is preferable to apply 4% penetration grade 60/70 asphalt poured to and divided into three layers since asphalt will be properly distributed to the specimens, and therefore more ballast aggregate materials can be protected from abrasion during the process of compaction and compressive testing.

Conflict of Interests: The corresponding author states that there is no conflict of interest.

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