Research Article

Dian M. Setiawan*, Rusdi Sahla Arifan, Syafiq Abdul Ghani, Wilsamilia Nurizki Galihajiningtresna, Anita Rahmawati, Alfian Saleh and Aminudin Syah

Laboratory experimental of ballast–bituminous–latex–roving (Ballbilar) layer for conventional rail track structure

https://doi.org/10.1515/jmbm-2024-0010
received March 02, 2024; accepted June 24, 2024

Abstract: Ballast structures continue to be utilized in Indonesia's railway system. They are essential for conventional railway lines, which experience high levels of stress and are susceptible to damage from train traffic. This study examined the utilization of a pressure test machine and sieve analysis to determine the abrasion value of ballast made of 60/70 penetration asphalt with a binder and stabilizer material consisting of a mixture of latex and roving fiber. The test results revealed that the compressive strength of the ballast structure was positively affected by the addition of asphalt, latex, and roving fiber. However, when comparing the compressive strengths of the two ballast structures, the ballast structure with 2% asphalt and 3% latex generated superior results to that with 4% asphalt and 1% latex. In other words, asphalt, as opposed to latex, was more effective in protecting ballast material from abrasion.

*** Corresponding author: Dian M. Setiawan,** Department of Civil Engineering, Universitas Muhammadiyah Yogyakarta, Bantul, Yogyakarta, 55183, Indonesia, e-mail: diansetiawanm@ft.umy.ac.id
Rusdi Sahla Arifan: Department of Civil Engineering, Universitas Muhammadiyah Yogyakarta, Bantul, Yogyakarta, 55183, Indonesia, e-mail: rusdi.arifan@gmail.com
Syafiq Abdul Ghani: Department of Civil Engineering, Universitas Muhammadiyah Yogyakarta, Bantul, Yogyakarta, 55183, Indonesia, e-mail: syafiqghani619@gmail.com
Wilsamilia Nurizki Galihajiningtresna: Department of Civil Engineering, Universitas Muhammadiyah Yogyakarta, Bantul, Yogyakarta, 55183, Indonesia, e-mail: wilsamilianurizki@gmail.com
Anita Rahmawati: Department of Civil Engineering, Universitas Muhammadiyah Yogyakarta, Bantul, Yogyakarta, 55183, Indonesia, e-mail: anita.rahmawati@umy.ac.id
Alfian Saleh: Department of Civil Engineering, Universitas Lancang Kuning, Jl. Yos Sudarso, Rumbai, Pekanbaru, 28266, Indonesia, e-mail: alfian.saleh@unilak.ac.id
Aminudin Syah: Department of Civil Engineering, Universitas Lampung, Bandar Lampung, Lampung, 35141, Indonesia, e-mail: aminudin.syah@eng.unila.ac.id

Keywords: 60/70 penetration-grade asphalt binder, ballast, compressive strength, latex, roving fiber

1 Introduction

The construction of a reliable, large-capacity, safe railway network is one of the many infrastructure projects prioritized by Indonesia's Ministry of Transportation in an effort to stimulate local economies across the country. High operating speed and large train axle loads are the primary factors that determine the reliability, capacity, and safety of the railway network. The performance of the railway line structure, which is strong and resistant to traffic loads and other environmental factors, greatly influences both of these variables.

The upper and lower structures are the two main components of a typical railway track. Ballast, sub-ballast, and enhanced subgrade make up the structure of the lower part of the railway line. The ballast structure on railway lines is a layer composed of crushed stone aggregate and is located in areas experiencing the greatest concentration of stress due to train traffic. Ballast performance is commonly compromised due to damage, necessitating careful selection of the forming material and intensive maintenance. The sub-ballast layer consists of fine gravel, medium gravel, or coarse sand. This layer functions as a filter layer between the subgrade and the ballast layer. The subgrade layer comprises the soil layer in all its forms, including original, repaired, and artificial. The load is distributed through the ballast or sub-ballast layer, and the subgrade is responsible for carrying it [1–3].

Following the regulations in the Indonesian railway system, the subgrade layer must be solid and have a minimum strength or a California bearing ratio value of 8% [4]. The subgrade layer's resilience and load-bearing capacity are critical to its performance in its function. Its supporting subgrade layer must bear the load of the ballast and sub-ballast layers. Moreover, the stress it undergoes is the result of the force transmitted from the sleeper to those layers, which are, in turn, transmitted and distributed to the subgrade layer by the ballast and sub-ballast [5].

One of the most crucial parts of conventional railway lines – the ones that bear the greatest stress from train traffic – ballast structures continue to be prevalent in Indonesia's railway system. Unfortunately, the ballast in Indonesia is weak and prone to various forms of structural damage, such as deformation and loss of ballast, causing the relatively low speed of passenger and freight trains in the country [2,6]. The maximum permitted operating speed is around 90 km/h, even though some passenger train series in Indonesia can reach a speed of up to 120 km/h. Additionally, the highest permitted operating speed is only about 70 km/h, even though the Babaranjang train in South Sumatra can reach a speed of about 90 km/h [7]. However, conventional railway lines in Indonesia have a maximum axle load capacity of only 18 tonnes [4]. Meanwhile, the maximum train axle load that tracks in many European countries can support has risen to 20 to 23 tonnes [8]. Trains can carry over 30 tonnes of axle load, even in the US [9]. Therefore, it is rather evident that train derailments will become more common in Indonesia if trains keep going faster than the allowed speed and carrying capacities. In a similar vein, the safety of Indonesia's passenger and freight trains heavily depends on the functionality of conventional railway track construction, particularly ballast components.

Moreover, Priambodo [10] stated that asphalt is a viscoelastic material with various characteristics and properties. To begin with, thixotropy, which is the tendency for asphalt to harden when not subjected to stress, is a crucial factor. In addition, there is the rheologic aspect, which pertains to the asphalt's condition and reveals the time-dependent relationship between stress and strain. Asphalt can retain its elasticity even when subjected to brief loads. Nonetheless, asphalt can undergo plasticity (viscosity) if the loading period is sufficiently prolonged. Finally, there is thermoplastic asphalt, of which the viscosity can vary in response to variations in temperature. As the temperature rises, the viscosity of asphalt decreases, causing it to thin down, and the reverse is also true.

Furthermore, Rianung [11] defined asphalt aging as a factor that determines the durability of the asphalt mixture. As asphalt ages, it hardens and becomes stiffer. It, in turn, makes the asphalt mixture more resistant to permanent deformation and better able to distribute loads. On the flip side, if the asphalt mixture is too brittle, it will crack more readily and be less resistant to repeated loads. Table 1 demonstrates that according to American society for testing and materials standards, asphalt cement can be categorized according to its penetration value at 25°C.

Table 1: Asphalt cement penetration specifications

	Penetration range									
	40–50		60–70		85–100		120–150		200–300	
Penetration at 25°C, 100 grams, 5 s	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
	40	50	60	70	85	100	120	150	200	300

60/70 penetration-grade asphalt binder is a material commonly used in the flexible pavement system in Indonesia. However, asphalt of any type and classification has never been employed as a structural material for railway lines in the Indonesian railway system. It is expected that the use of asphalt can strengthen the ballast structure and be a solution to problems in conventional railway line structures in Indonesia [12–14].

Latex is a liquid milky sap obtained from stripping the bark of rubber trees. Indonesia is one of the largest producers of natural rubber in the world, making it easy to find high-quality latex. There has to be an effort to create and employ latex processing products to raise the commodity prices and utilization of latex. Nevertheless, at the moment, the selling price of latex commodities on the Indonesian market is still inexpensive. The use of natural rubber or latex as a hot mix asphalt (HMA) mixture has been proven to boost quality, extend service life, and reduce flexible pavement maintenance costs [15]. In addition, Setiawan *et al.* [16] also discovered that using tire rubber with varying sizes as a mixture could escalate the durability of the ballast material, as indicated by the smaller percentage of ballast wear after a compression test.

However, roving fiber is a polyester or epoxy fiber typically utilized as a medium for the middle layer of fiberglass plates. Roving fiber, once molded into a fiberglass shape, could be drawn taut enough to resemble a web of interconnected strands. Table 2 displays the fiberglass characteristics. As many researchers asserted, the

Table 2: Fiberglass properties [19]

Fiber type		
E-glass	C-glass	S-glass
Good electrical insulator	Resistant to corrosion	High modulus of elasticity
High strength	Lower strength than E-glass	More resistant to high temperatures
High strength	Higher price than E-glass	Higher price than E-glass

compressive and split tensile strengths of non-sand concrete could be enhanced using roving fiber in place of sand. With the addition of 5% roving fiber concentration, the non-sand concrete obtained a compressive strength of 1.81 MPa and a split tensile strength of 0.29 MPa [17,18].

Hence, this study emphasized the utilization of a binder and stabilizer material mixture of latex and roving fiber in constructing the ballast layer using a 60/70 penetration-grade asphalt binder. The mechanical qualities of chopped strand mat (CSM/M) fiber roving with S-glass material were considered the most appropriate for application to asphalt mixtures. Thus, this type of roving was adopted to support several research parameters.

There are several methods used to determine the compressive strength of materials, including ballast layers. The choice of method depends on the material being tested and the standards or protocols in place for that specific type of material. Uniaxial compressive strength test is the most straightforward and commonly used method for determining the compressive strength of materials, where a cylindrical or cubic sample of the material is prepared and the sample is placed in a universal testing machine (UTM). A compressive load is applied at a constant rate until the sample fails and the maximum load at failure is recorded, and compressive strength is calculated [20–22]. Triaxial compressive strength test is often used for materials such as soils and rocks, where the interaction between different stress components is important [23,24]. Point load test is commonly used for rock and aggregate materials [25,26]. Rebound Hammer test (Schmidt Hammer) is a non-destructive method and is used primarily for concrete [24,27]. Indirect tensile strength test (Brazilian test) determines the compressive strength through tensile failure [28,29]. Flexural strength test measures the tensile strength of concrete beams and provides insights into the compressive strength characteristics [20]. Split cylinder test is used to determine the tensile strength of concrete, which is then correlated with compressive strength [29–31]. Each method has its specific applications and suitability depending on the material and context of the test. Uniaxial compressive strength tests are the most direct and widely used method, particularly for materials such as concrete and rocks. Other methods, such as the rebound Hammer test and the triaxial test, offer additional insights and are useful in different scenarios.

This study has several objectives: (1) analyzing the effect of using latex and roving fiber on the characteristics

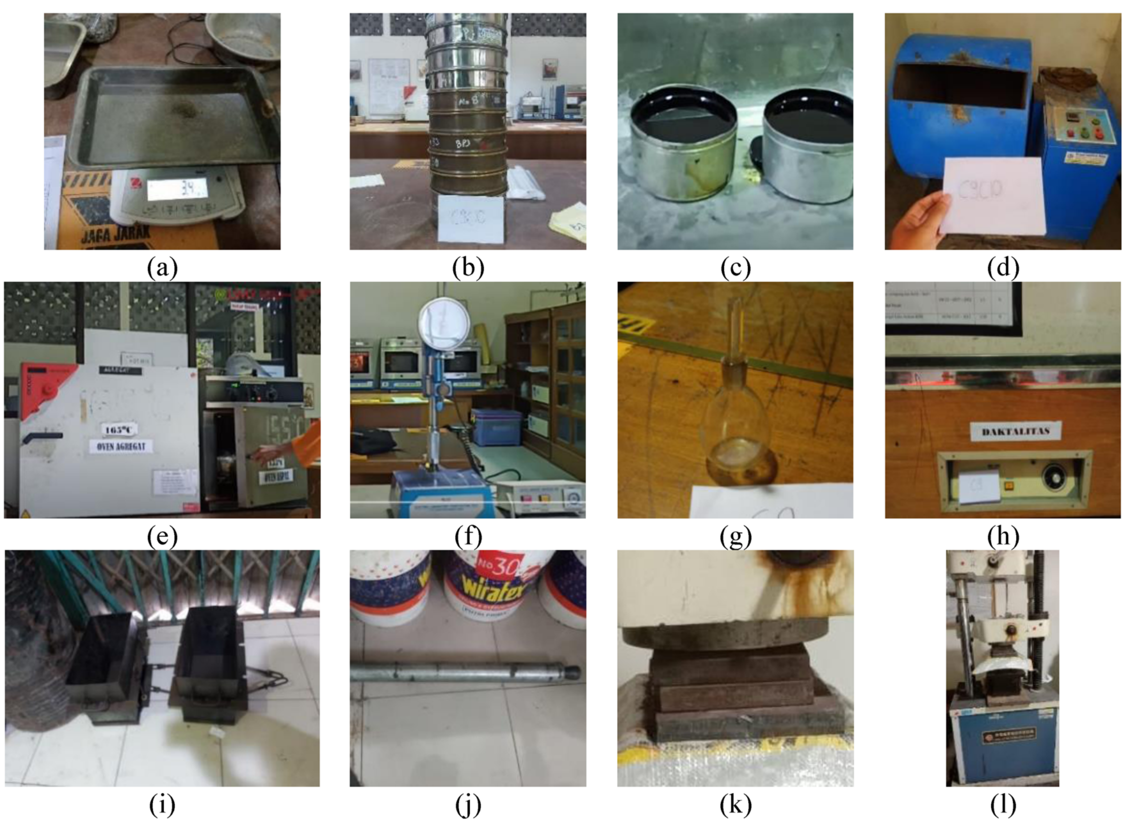


Figure 1: Equipment: (a) scale, (b) sieve, (c) cup, (d) Los Angeles test, (e) oven, (f) penetrometer, (g) pycnometer, (h) ductility test, (i) ballast box, (j) manual compactor, (k) 40 × 20 cm steel plate, and (l) UTM for compressive strength test.

of the HMA mixture consisting of 60/70 penetration asphalt; (2) evaluating the effect of using a mixture of 60/70 penetration asphalt, latex, and roving fiber as binder and stabilizer on the compressive strength and abrasion of ballast layer structures of conventional railway lines; and (3) investigating the performance of rail tracks with conventional ballast layer structures without a mixture, compared with the performance of rail tracks with ballast layer structures mixed with asphalt, latex, and roving fiber. This research has the potential to shed light on how conventional railway lines can be enhanced in terms of quality and durability by combining asphalt, latex, and roving fiber. It could also inform government policy regarding the application of mixtures of asphalt and latex in conventional rail lines in Indonesia, which might have their structural capacity increased by focusing on the ballast layer structure.

2 Research method

2.1 Equipment and materials

Figure 1 exhibits the equipment employed in this research located at the Transportation and Highway Laboratory of the Civil Engineering Department of Universitas Muhammadiyah Yogyakarta, encompassing a scale (Figure 1a), a sieve (Figure 1b), a cup (Figure 1c), a Los Angeles test (Figure 1d), an oven (Figure 1e), a penetrometer (Figure 1f), a pycnometer (Figure 1g), a ductility test (Figure 1h), a ballast box (Figure 1i), a manual compactor (Figure 1j), a 40 × 20 cm steel plate (Figure 1k), and UTM for compressive strength test (Figure 1l). Figure 2 displays four materials tested in this study: ballast aggregates (Figure 2a), 60/70 penetration-grade asphalt binder (Figure 2b), roving fiber (Figure 2c), and latex (Figure 2d). This research began with physically and mechanically examining the ballast aggregates and 60/70 penetration-grade asphalt binder. Subsequently, the materials were mixed, and the specimens were compacted 25 times per layer. Finally, the specimens were tested for compressive strength, and the results were analyzed.

2.2 Ballast aggregate testing

The coarse aggregate materials in this research were the ones utilized for class 1 railway track ballast layers with a nominal size of ¾ to 2 ½ inches [4]. Figure 2a illustrates the results of the physical and mechanical property tests performed on the ballast after its nominal size was selected. These tests included gradation analysis, mud content, specific gravity, and Los Angeles abrasion. Table 3 displays the results of the physical and mechanical characteristic tests.

2.3 60/70 penetration-grade asphalt binder testing

The research utilized asphalt with a penetration value of 60/70, which was sourced from the Transportation and Highway Laboratory of the Civil Engineering Department of Universitas Muhammadiyah Yogyakarta (Figure 2b).

Table 3: Examination of physical and mechanical properties of ballast aggregates

Parameter	Result	Specification	Standard
Specific gravity			SNI 1969-2008 [32]
• Dry	2.62	≥2.6	
• Bulk	2.67		
• Apparent	2.78		
Water absorption	2.55	≤3%	SNI 1969-2008 [32]
Abrasion – Los Angeles	18.62%	≤25%	SNI 2417-2008 [33]
Mud content	0.20 %	≤0.5 %	SNI 03-4141-1996 [34]

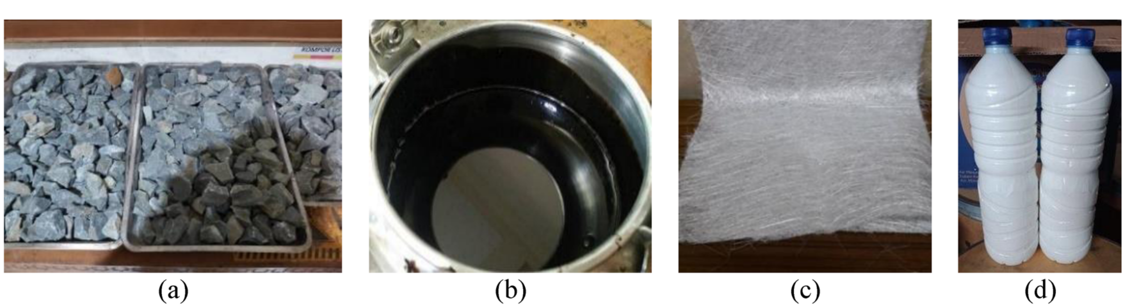


Figure 2: Materials: (a) ballast aggregates, (b) 60/70 penetration-grade asphalt binder, (c) roving fiber, and (d) latex.

Table 4: Test results of the 60/70 penetration-grade asphalt binder

Parameter	Result	Specification	Unit	Standard
Penetration	61.6	60–70	0.1 mm	SNI 2432-2011 [35]
Softening point	53	48 minimum	Celsius	SNI 2434-2011 [36]
Specific gravity	1.05	1.0 minimum	g/cc	SNI 2441-2011 [37]
Ductility	160	≥100	100–200 cm	SNI 06-2432-1991 [38]
Oil losses	0.2	≤0.8	%	SNI 06-2440-1991 [39]

Initially, the solid asphalt was heated for a minimum of 4 h at a temperature of 155°C. Subsequently, the asphalt underwent testing following the Indonesian National Standard (BSN) for penetration, softening point, specific gravity, ductility, and oil losses; the findings are displayed in Table 4. Figure 3 illustrates the specimens. For every 10 cm thickness of the ballast structural layer, 60/70 penetration-grade asphalt binder was poured onto the ballast layer's surface, accounting for 2 and 4% of the ballast's weight, respectively.

2.4 Roving fiber

CSM/M fiber roving with S-glass material was utilized in this research due to its mechanical properties, which have been believed to be most appropriate for application to asphalt to assist in the achievement of multiple research parameters. Figure 2c exhibits the latex appearance. The roving fiber was in sheet form and was applied to the ballast structure in two layers; each layer had a 10 cm thickness, with a total thickness of 30 cm.

2.5 Latex

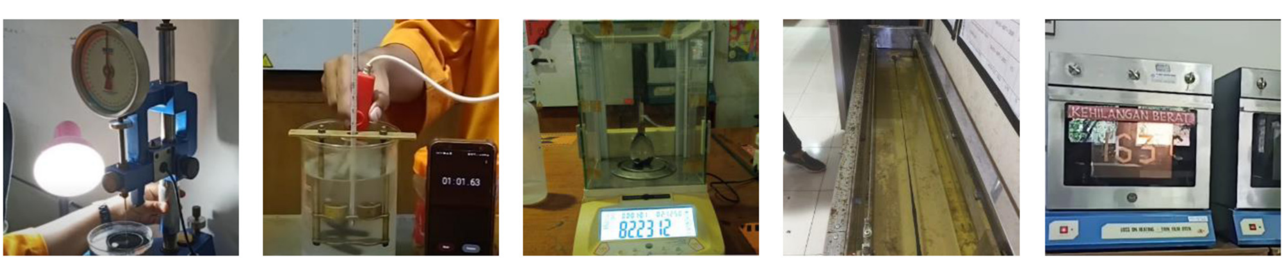
This research employed latex obtained from several producer locations in Gunung Kidul Regency, Special Region of Yogyakarta. Figure 2d portrays the latex appearance. The latex amounted to 1 and 3% of the ballast's weight.

2.6 Design and configuration of the specimens

Table 5 displays the specimens, which were classified into four groups: ballast (B1), ballast with asphalt (B2 and B3), ballast with asphalt and latex (B4, B5, B6, and B7), and ballast with asphalt, latex, and roving fiber (B8, B9, B10, and B11). The ballast aggregate and asphalt preparation was referred to in Service Regulation No. 10 of 1986 [40], Indonesian National Standard (BSN), and Ministerial Regulation No. 60 of 2012 [4]. After preparing all materials, a ballast box with a size of 40 × 20 × 30 cm was set up.

2.7 Material preparation and specimen compaction

This research primarily focused on a ballast-layer structure arranged in a 40 × 20 × 30 cm ballast box. The ballast was arranged in the ballast box until it had a thickness of 30 cm divided into three layers, each with a thickness of 10 cm. A manual compactor with a pounder was employed for compaction; the pounder's rectangular flat surface measured 40 × 20 cm, and the compactor weighed 4.5 kg. Its free-fall height was 45.7 cm. The relationship between stress (σ) and strain (ε) caused by loading from the UTM was determined by conducting a compressive strength test on each specimen once they were prepared.



(a) (b) (c) (d) (e)

Figure 3: 60/70 penetration-grade asphalt binder testing: (a) penetration test using penetrometer, (b) softening point test, (c) specific gravity test, (d) ductility test, and (e) oil losses test using oven.

Figure 4a depicts the compaction of ballast within the ballast box with a thickness of 10 cm for each layer. As demonstrated in Figure 4b, the latex and 60/70 penetration-grade asphalt binder were mixed. Figure 4c illustrates the pouring of the mixture into the ballast structure while putting the roving fiber on top of the ballast and asphalt–latex mixture appears in Figure 4d. Furthermore, Figure 4e exhibits a ballast specimen with a total thickness of 30 cm. Figure 4f displays the final process of pouring the asphalt–latex mixture into the ballast structure.

2.8 Compressive strength test using UTM

Compressive load refers to the amount of load affecting a specimen based on the area of its surface. As displayed in Table 5, compressive strength testing was performed on specimens using a UTM with a maximum load of 6 tonnes. This test aims to obtain several performance parameters of the ballast layer, including stress, strain, compressive strength, and percentage of ballast aggregate abrasion. The initial step was inputting the dimensions of the specimens, the surface

Table 5: Design and configuration of the specimens

Specimen	Asphalt emulsion (%)	Latex (%)	Number of layers of roving fiber	Note
B1	—	—	—	Clean ballast
B2	2	—	—	Ballast + 2% asphalt
B3	4	—	—	Ballast + 4 % asphalt
B4	2	1	—	Ballast + 2% asphalt + 1% latex
B5		3	—	Ballast + 2% asphalt + 3% latex
B6	4	1	—	Ballast + 4% asphalt + 1% latex
B7		3	—	Ballast + 4% asphalt + 3% latex
B8	2	1	2	Ballast + 2% asphalt + 1% latex + roving
B9		3	2	Ballast + 2% asphalt + 3% latex + roving
B10	4	1	2	Ballast + 4% asphalt + 1% latex + roving
B11		3	2	Ballast + 4% asphalt + 3% latex + roving

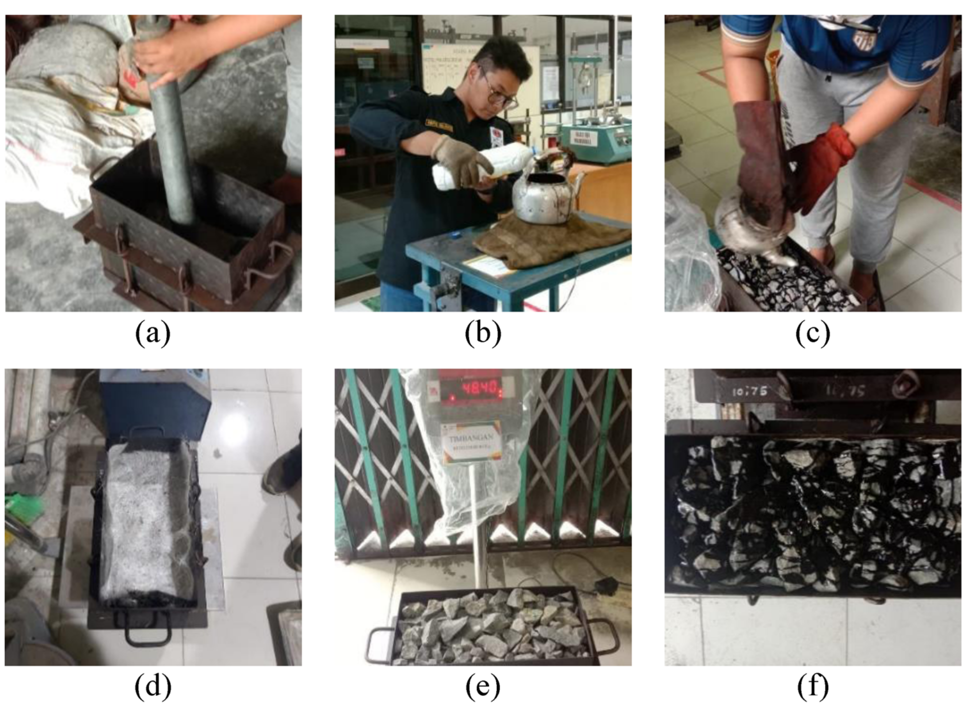


Figure 4: (a) compaction of ballast every 10 cm of layer thickness, (b) mixing of 60/70 penetration-grade asphalt binder and latex, (c) pouring of asphalt–latex mixture into ballast structure, (d) roving fiber placement on top of ballast and asphalt–latex mixture, (e) ballast specimen with total thickness of 30 cm, and (f) the last pouring of asphalt–latex mixture.

Figure 5: A specimen ready for compressive strength test using micro-computer UTM.

area of the loading plate, and the amount of load to be tested. As depicted in Figure 5, a compressive strength test was carried out after the specimens, and the loading plate was placed symmetrically.

3 Results and discussion

3.1 Compressive strength test results

Table 6 exhibits several crucial data obtained from the compressive strength test using the UTM machine. The compressive strength can also be calculated using the theoretical formula:

$$\sigma_c = \frac{P}{A},$$

where σ_c is the compressive strength (MPa), P is the maximum load applied (kg f), and A is the cross-sectional area of the sample = 20 cm × 40 cm = 800 cm^2.

Several previous studies found that the use of a large percentage rubber can increase the instability and reduce the stiffness of the rail track, which is characterized by the high vertical deformation [41–45]. Furthermore, the use of scrap rubber spread on the bottom of ballast material can increase the vertical deformation by about 35–45% [46]. According to the results of the current study, the B11 specimen exhibited the greatest compressive strength of 723 kPa. Following closely behind were B10, B9, B8, B7, B5, B6, B4, B3, B2, and B1 specimens. In conclusion, the compressive strength of the ballast structure was greatly affected by the addition of asphalt, latex, and roving fiber. Comparing the compressive strengths of two different ballast structures, one with 2% asphalt and 3% latex and another with 4% asphalt and 1% latex, the former proved to be superior. The study conducted by D'Angelo *et al.* [47] showed that the bitumen emulsion utilization as stabilization method improved ballast resistance to permanent deformation significantly (higher when the dosage was increased) by enhancing stiffness and damping properties. Based on Setiawan and Rosyidi [12], 2% asphalt (by weight) can improve the stiffness of the ballast layer so it could minimize the vertical deformation and increase the ability to retain the loads up to 28%.

Table 6: Compressive strength test results

Specimen	Material	Cross-sectional area of the sample (cm^2)	Max force (kg f)	Compressive strength (kPa)	
				Theoretical	Experimental
B1	Clean ballast	800	3,400	416.7826	417
B2	Ballast + 2% asphalt		3,800	465.8159	466
B3	Ballast + 4% asphalt		3,990	489.1067	489
B4	Ballast + 2% asphalt + 1% latex		4,300	527.1074	527
B5	Ballast + 2% asphalt + 3% latex		4,400	539.3660	539
B6	Ballast + 4% asphalt + 1% latex		4,353	533.6043	534
B7	ballast + 4% asphalt + 3% latex		4,500	551.6241	552
B8	Ballast + 2% asphalt + 1% latex + roving		5,300	649.6906	650
B9	Ballast + 2% asphalt + 3% latex + roving		5,450	668.0780	668
B10	Ballast + 4% asphalt + 1% latex + roving		5,400	661.9489	662
B11	Ballast + 4% asphalt + 3% latex + roving		5,900	723.2404	723


Figure 6: Ballast abrasion test.

3.2 Ballast abrasion

Aggregate abrasion or wear refers to the degradation or breaking of aggregate due to mechanical processes, such as forces during the railway line construction and servicing traffic loads, as well as chemical processes, such as the influence of humidity and temperature changes throughout the day. The aggregate abrasion analysis was performed using filter analysis. The abrasion value indicates the resistance of the coarse aggregate to crushing due to mechanical loads. The abrasion test was run after the compressive strength test by comparing the weight of the material crushed or passed the sieve no. ¾" to the total weight of the specimen, yielding the abrasion percentage of the specimen. Figure 6 exhibits the ballast abrasion test.

Several factors, including material preparation, manufacturing compaction, and compression test, affected the abrasion percentage of the specimens. As stated by Setiawan [14], the new-ballast-based sample with the addition of 4% of the 60/70-grade bitumen had the abrasion value around 0.46–0.50% because ballast materials were protected from abrasion during the process of compaction and compressive testing by the presence of the well-distributed bitumen on three layers.

Figure 7 displays the various abrasion percentages of the specimens. The B1 specimen yielded the greatest abrasion value. In contrast, the specimens with the asphalt, latex, and roving fiber added generated much lower abrasion values. Protecting the ballast from abrasion caused by compaction and compression testing could be accomplished with specimens that employed additives such as asphalt, latex, and roving fiber. On top of that, specimen B3, containing 4% asphalt, depicted a lower abrasion value than specimen B4, containing 2% asphalt and 1% latex. In other words, asphalt was more effective than latex in protecting the ballast material from abrasion. According to several studies, the addition of the elastic materials such as scrap rubber on the ballast layer can reduce the degradation of ballast materials since it can minimize the movement of the ballast particles and reduce the friction between aggregates so that material durability increases and material degradation decreases [42,46–48].

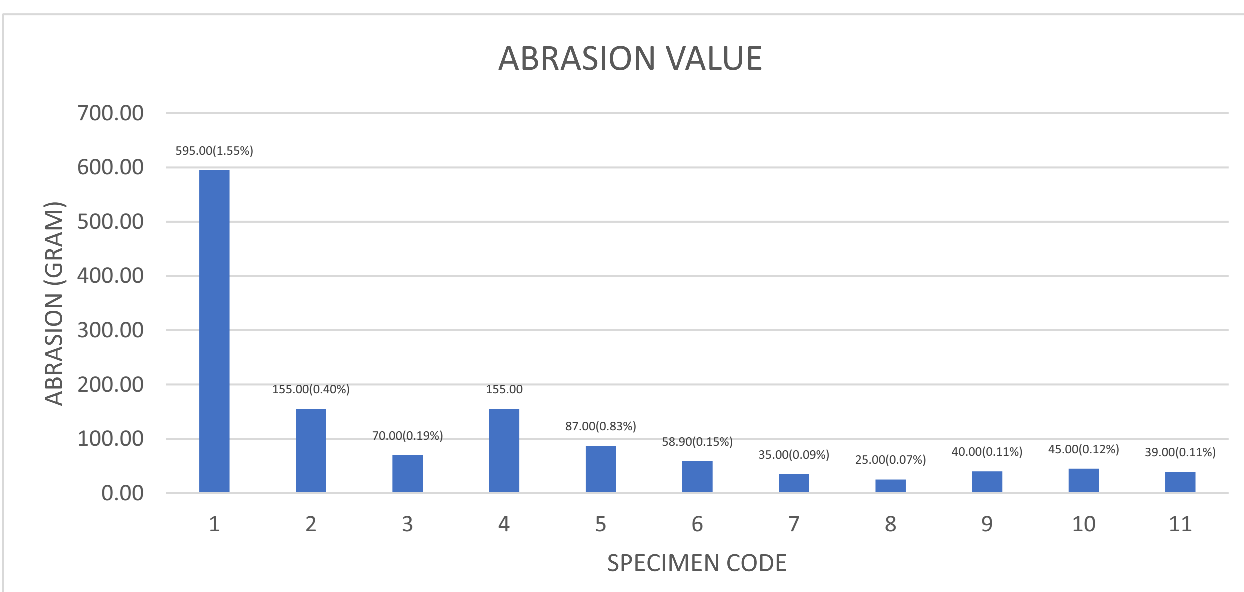


Figure 7: Ballast abrasion.

4 Conclusion

Ballast material, commonly used in railway tracks, resists abrasion through several factors related to its physical properties and the quality of the materials used, such as material hardness, shape and size, durability, testing and standards, regular maintenance, and environmental factors. The following conclusions were derived from the results of the analysis.

a. Adding asphalt, latex, and roving fiber could enhance the compressive strength of the ballast structure.
b. Comparing the compressive strength of two ballast structures, one with 2% asphalt and 3% latex and the other with 4% asphalt and 1% latex, the former achieved a greater outcome.
c. Asphalt, latex, and roving fiber could be utilized to prevent the ballast from being abrasive during compression and compaction tests.
d. Asphalt was more effective than latex in protecting ballast from abrasion.

Funding information: The author would like to express gratitude to the Institute of Research, Publications & Community Service of Universitas Muhammadiyah Yogyakarta (LPPM UMY) for the Funding of Domestic Partnership Scheme 2023 (No: 16/R-LRI/I/2023).

Author contributions: The authors confirm contribution to this article as follows: study conception and design: Dian M. Setiawan; data collection: Anita Rahmawati, Rusdi Sahla Arifan, Wilsamilia Nurizki Galihajiningtresna, Syafiq Abdul Ghani; analysis and interpretation of results: Dian M. Setiawan, Alfian Saleh, Aminudin Syah; draft manuscript preparation: Dian M. Setiawan. All authors have accepted responsibility for the entire content of this manuscript and consented to its submission to the journal, reviewed all the results and approved the final version of the manuscript.

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

References

[1] Setiawan DM. Sub-grade service life and construction cost of ballasted, asphaltic underlayment and combination rail track design. Jordan J Civ Eng. 2022;16(1):173–92.
[2] Setiawan DM. Conventional and asphaltic underlayment track performance subjected to Argo Jati passenger trains. Civ Environ Eng. 2022;18(2):389–401. doi: 10.2478/cee-2022-0036.
[3] Setiawan DM, Rosyidi SAP, Imron NA, Aprilia NA, Drajat B, Arifan RS, Galihajiningtresna WN, Ghani SA. Performance analysis of subgrade in asphaltic rail track design and Indonesia's existing ballasted track. J Mech Behav Mater. 2023;32(1):1–14. doi: 10.1515/jmbm-2022-0270.
[4] Sekretariat N. Peraturan menteri perhubungan nomor 60 tahun 2012 tentang persyaratan teknis jalur KA. Jakarta, Indonesia: 2012.
[5] Utomo SHT. Jalan Rel. Yogyakarta: Beta Offset; 2013.
[6] Setiawan DM. Structural response and sensitivity analysis of granular and asphaltic overlayment track considering linear viscoelastic behavior of asphalt. J Mech Behav Mater. 2021;30(1):66–86. doi: 10.1515/jmbm-2021-0008.
[7] Setiawan DM. Pembatasan kecepatan maksimum dan kaitannya terhadap kapasitas lintas jalur KA Muara Enim – Lahat Sumatera Selatan. Prosiding Seminar Nasional Teknik Sipil 2016, Fakultas Teknik Universitas Muhammadiyah Surakarta; 2016. p. 36–46. ISSN: 2459–9727.
[8] Rajamanickam V. Why is Europe so absurdly backward compared to the U.S. in rail freight transport; 2019. https://www.freightwaves.com/news/why-is-europe-so-absurdly-backward-compared-to-the-u-s-in-rail-freight-transport. Accessed 1 January 2022.
[9] Kala S, LoPresti J, Davis D. Development of enabling technologies for heavy axle load operations in North America. challenge c: increasing freight capacity and services. 9th World Congress on Railway Research; May 22-26, 2011.
[10] Priambodo A. Kajian laboratorium pengaruh penggunaan pasir besi sebagai agregat halus campuran aspal panas HRA terhadap sifat marshall dan durabilitas. Thesis. Magister UNDIP Semarang; 2003.
[11] Rianung S. Kajian laboratorium pengaruh bahan tambah gondorukem pada asphalt concrete-binder course (AC-BC) terhadap nilai propertis marshall dan durabilitas. Jurnal Ilmiah Teknosains. Vol. 2, No. 1, 2016.
[12] Setiawan DM, Rosyidi SAP. Scrap rubber and asphalt for ballast layer improvement. Int J Integr Eng. 2019;11(8):247–58. doi: 10.30880/ijie.2019.11.08.025.
[13] Setiawan DM. Utilization of 60/70 penetration grade asphalt on ballast structures with the variation of percentage and the number of pouring layers. J Mech Behav Mater. 2020;28(1):107–18. doi: 10.1515/jmbm-2019-0013.
[14] Setiawan DM. Application of 60/70 grade bitumen with layer variations on ballast structures. Int J Adv Sci Eng Inf Technol. 2021;11(2):698–702. doi: 10.18517/ijaseit.11.2.9898.
[15] Amal AS. Pemanfaatan getah karet pada aspal ac 60/70 terhadap stabilitas marshall pada asphalt treated base (ATB). Media Teknik Sipil. 2012;9(1):8–16.
[16] Setiawan DM, Rosyidi SAP, Budiyantoro C. The role of scrap rubber, asphalt and manual compaction against the quality of ballast layer. Jordan J Civ Eng. 2019;13(4):594–608.
[17] Widodo A, Basith MA. Analisis kuat tekan beton dengan penambahan serat roving pada beton non pasir. J Teknik Sipil Perenc. 2017;19(2):115–20. doi: 10.15294/jtsp.v19i2.12138.
[18] Wijasari AR. Pengaruh penambahan serat roving sebesar 0%, 2,5%, 5%, 7,5%, dan 10% dengan perbandingan agregat 1:9 dan fas 0,5 terhadap kuat tekan dan kuat tarik belah beton non pasir. Skripsi. Jurusan Teknik Sipil, Fakultas Teknik, Universitas Negeri Semarang, Semarang; 2017.
[19] Nayiroh N. Teknologi material komposit. Universitas Islam Negeri Maulana Malik Ibrahim, Malang; 2016.
[20] Mindess S, Young JF, Darwin D. Concrete. Upper Saddle River. NJ: Prentice Hall; 2003.

[21] ASTM International. Standard test method for compressive strength of cylindrical concrete specimens (ASTM C39/C39M-18). West Conshohocken, PA: ASTM International; 2018a.
[22] Trong DN, Long VC, Talu S. The influence of shape and matrix size on the mechanical properties of the 2D epoxy thin film by Monte Carlo simulation method. AIP Adv. 2023;13:015209. doi: 10.1063/5.0138329.
[23] Das BM. Advanced soil mechanics. Boca Raton, FL: CRC Press; 2013.
[24] ASTM International. Standard test method for triaxial compressive strength of undrained rock core specimens without pore pressure measurements (ASTM D7012-14). West Conshohocken, PA: ASTM International; 2016.
[25] ISRM Commission on Testing Methods. Suggested method for determining point load strength. International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts. Vol. 22, No. 2, 1985. p. 51–60.
[26] ASTM International. Standard test method for determination of the point load strength index of rock and application to rock strength classifications (ASTM D5731-16). West Conshohocken, PA: ASTM International; 2018b.
[27] Malhotra VM, Carino NJ. Handbook on nondestructive testing of concrete. Boca Raton, FL: CRC Press; 2004.
[28] ISRM Commission on Testing Methods. Suggested methods for determining tensile strength of rock materials. Int J Rock Mech Min Sci Geomech Abstr. 1978;15(3):99–103.
[29] ASTM International. Standard test method for splitting tensile strength of cylindrical concrete specimens (ASTM C496/C496M-17). West Conshohocken, PA: ASTM International; 2017.
[30] Neville AM. Properties of concrete. Harlow, England: Pearson Education Limited; 2011.
[31] ASTM International. Standard Test Method for Rebound Number of Hardened Concrete (ASTM C805/C805M-13a). West Conshohocken, PA: ASTM International; 2015.
[32] BSN (Indonesian National Standard). SNI 1969-2008: Test methods of density and absorption of coarse aggregates (cara uji berat jenis dan penyerapan agregat kasar). Jakarta: 2008a.
[33] BSN (Indonesian National Standard). SNI 2417:2008: Test method of aggregate wear with the Los Angeles abrasion machine (cara keausan agregat dengan mesin abrasi los angeles). Jakarta: 2008b.
[34] BSN (Indonesian National Standard). SNI 03-4141-1996: Test methods of clay clumps and easily broken items in aggregate (metode pengujian gumpalan lempung dan butir-butir mudah pecah dalam agregat). Jakarta: 1996.
[35] BSN (Indonesian National Standard). SNI 2432-2011: Test method for asphalt penetration (cara uji penetrasi aspal). Jakarta: 2011a.
[36] BSN (Indonesian National Standard). SNI 2434-2011: Test methods for asphalt softening point with ring and ball tools (cara uji titik lembek aspal dengan alat cincin dan bola). Jakarta: 2011b.
[37] BSN (Indonesian National Standard). SNI 2441-2011: Test method for asphalt-specific weight (cara uji berat jenis aspal keras). Jakarta: 2011c.
[38] BSN (Indonesian National Standard). SNI 06-2432-1991. Metode pengujian daktilitas bahan-bahan aspal. Jakarta
[39] BSN (Indonesian National Standard). 1991b. SNI 06-2440-1991: Test methods of asphalt and oil weight losses (metode pengujian kehilangan berat minyak dan aspal). Jakarta1991a
[40] PJKA. Peraturan Dinas No. 10 the Year 1986 Tentang peraturan perencanaan konstruksi jalur KA. Perusahaan Jawatan KA, Balai Besar, Bandung, Indonesia; 1986.
[41] Farhan AH, Dawson AR, Thom NH, Adam S, Smith MJ. Flexural Characteristics of rubberized cement-stabilized crushed aggregate for pavement structure. Mater Des. 2015;88:897–905.
[42] D'Angelo G, Thom NH, Presti DL. Optimisation of bitumen emulsion properties for ballast stabilization. Mater De Constr. 2017;67(327):124–33.
[43] Abadi T, Pen LL, Zervous A, Powrie W. A review and evaluation of ballast settlement models using result from the Southampton railway testing facility (SRTF). Procedia Eng. 2016;143:999–1006.
[44] Bressi S, Santos J, Giunta M, Pistonesi L, Presti DL. A comparative life-cycle assessment of asphalt mixture for railway sub-ballast containing alternative materials. Resour Conserv Recycl. 2018;137:76–88.
[45] Signes CH, Hernandez PM, Roca JG, del la Torre MEG, Franco RI. An evaluation of the resilient modulus and permanent deformation of unbound mixtures of granular materials and rubber particles from scrap tyres to be used in subballast layers. Transp Res Procedia. 2016;18:384–91.
[46] Setiawan DM, Rosyidi SAP. Vertical deformation and ballast abrasion characteristics of asphalt-scrap rubber track bed. Int J Adv Sci Eng Inf Technol. 2018;8(6):2479–84.
[47] D'Angelo G, Thom NH, Presti DL. Bitumen stabilized ballast: a potential solution for railway track bed. Constr Build Mater. 2016;124:118–26.
[48] Indraratna B, Ngo NT, Rujikiatkamjorn C Improved performance of ballasted rail tracks using plastics and rubber inclusions. Proceeding in Transportation Geotechnics and Geoecology, Saint Petersburg, Rusia, 2017; p. 207–14.