

Research Article

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Performance analysis of subgrade in asphaltic rail track design and Indonesia's existing ballasted track

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Abstract: Due to subgrade-related concerns, the performance of Indonesia's ballasted track continues to be significant impediments for the Indonesian railway stakeholders' intention to increase the speed of passenger train operations. This study aims to examine the vertical compressive stress in the subgrade of Indonesia's ballasted track and two asphaltic rail track designs, asphaltic overlayment and asphaltic underlayment, under various cyclic loading conditions based on three different train speeds, 120 (low speed), 240 (medium speed), and 360 kph (high speed). The AC layer thicknesses for each asphaltic rail track design are as follows: 0.1, 0.2, 0.3, and 0.4 m for asphaltic underlayment, and 0.075, 0.15, 0.225, and 0.3 m for asphaltic overlayment. 2D finite element models and simulations were used to capture and predict the subgrade's vertical compressive stress performance. The most obvious finding to emerge from this study is that the asphaltic overlayment track has a greater capacity for transmitting and decreasing stresses from the top structure to subgrade layer than the asphaltic underlayment track and the Indonesia' ballasted track, respectively. This research can shed light on the prospective application of asphaltic rail track to the Indonesian rail network for the faster passenger trains operation.

Keywords: asphaltic rail tracks, ballast, sub-ballast, subgrade, vertical compressive stress

1 Introduction

The increasing global demand for rail travel has resulted in increased line speeds on passenger lines. The performance of the railroad track under these circumstances is dependent on the interaction between the train carriages, the superstructure, and the track support [1]. Track support characteristics have a direct impact on railway track deterioration, which has significant cost and time implications for the rail industry *via* maintenance operations, track replacements, and line speed restrictions [2].

The railway track must serve two primary functions: first, to safely direct the train and second, to carry the train's load and distribute it over an area as large as possible on the subgrade [3]. Subgrade is an essential component of rail track structure, supporting the upper loads of the tracks and trains, and its stability has a direct impact on train safety and passenger comfort [4,5]. Additionally, subgrade provides the ultimate support for the track structure. Therefore, the geotechnical structure of the railway subgrade, which was created by excavation or filling, must be protected by the railway track superstructures, and have

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sufficient engineering stability and very minor permanent deformation to meet track laying and safe operating standards [6].

Ballasted track is the only option for rail track design in Indonesian railway lines due to its low construction costs and high flexibility. Due to subgrade-related concerns, the performance, durability, and maintenance costs of Indonesia's ballasted track system continue to be significant impediments for the government and railway stakeholders' intention to increase the train's speed and axle load. Although the design speed of the track section of Indonesia's ballasted track is 120 kph, passenger trains are not permitted to exceed 90 kph in order to minimize derailment risk [7].

Sadeghi and Askarinejad [8] conducted a sensitivity analysis utilizing several models of track degradation. They discovered that the permitted annual tonnage for a track with a high-quality subgrade is four times that of a track with a subgrade of poor quality. Therefore, low subgrade stiffness can dramatically increase maintenance frequency and decrease overall asset life [9].

Subgrade settlement is the leading source of track damage from a substructure perspective. Differential track settling can lead to defects in the vertical track geometry, which, if left untreated, might result in derailment. Several researchers [10–15] discovered that the subgrade is the primary source of both average and differential long-term settlement in the majority of track designs. The vertical compressive stress at the top of the subgrade shows possible long-term subgrade settlement failure performance and track maintenance costs. The greater the vertical compressive stress at the top of the subgrade layer, the greater the chance of subgrade failure and the higher risk of track-bed settlement.

In certain nations, including the United States [16–18], Japan [19], China [20], France [21,22], Italy [23], and Germany [24], railroad engineers have adopted the asphaltic underlayment track design. This asphaltic rail track design is favored because the asphalt is shielded beneath the ballast layer, minimizing the asphalt's exposure to sunlight and temperature fluctuations. Alternatively, a number of studies investigated another sort of asphaltic rail track design, namely asphaltic overlayment, in which the asphalt concrete (AC) layer is utilized and laid over the sub-ballast or roadbed layer [25,26]. Unfortunately, neither form of asphaltic rail track has ever been installed in Indonesia's rail networks [13].

Ramirez Cardona *et al.* [22] reported that bituminous sub-ballast layers reduced the vertical stress transferred to the soil layer by as much as 30%. Fang *et al.* [27] found that hot mix asphalt is an appropriate material for the

railway substructure in order to increase the resilient performance and stress distribution. Liu [28] and Setiawan [13,15] also analyzed vertical compressive stress using a mechanistic-empirical technique to forecast the subgrade design life of the ballasted and asphaltic underlayment tracks. Setiawan [13] confirmed that the ballasted track has a shorter subgrade service life and greater subgrade vertical compressive stress than the asphaltic underlayment track, despite the fact that the sub-ballast beneath the ballast layer in the ballasted track is one hundred percent thicker than the AC beneath the ballast layer in the asphaltic underlayment track. Due to the decreased compressive stress at the surface of the subgrade layer, Setiawan [15] observed that asphaltic underlayment tracks had a longer subgrade service life than ballasted tracks. Setiawan [26] discovered, using the same mechanistic-empirical technique, that asphaltic overlayment track is superior to ballasted track because it has a greater capacity for transmitting top loads, hence minimizing subgrade compressive stresses.

It is difficult to find research that compares the performance of various asphaltic rail track designs, in this case asphaltic overlayment and asphaltic underlayment track, in terms of the vertical compressive stress attenuation in the subgrade. Additionally, the majority of previous studies continue to rely on the mechanistic-empirical method. Therefore, it is proposed to use a more mechanistic method and finite element simulation, such as ABAQUS Software, to accurately capture and forecast the responses of ballasted track and asphaltic track-bed to varying passenger train operating speeds.

In this study, asphaltic overlayment tracks were those in which the ballast was replaced by AC layer, and asphaltic underlayment tracks were those in which the sub-ballast was replaced by AC layer. The impact of different train speeds on the subgrade behavior of these two asphaltic rail track systems was compared with that of the Indonesian ballasted track. Two-dimensional (2D) finite element models and simulations were applied to characterize and estimate the subgrade's performance in terms of vertical compressive stress.

This study aims to examine the vertical compressive stress curve in the subgrade of Indonesia's ballasted track and two asphaltic rail track designs, namely asphaltic overlayment and asphaltic underlayment, under various cyclic loading conditions based on three different train speeds, 120 (low speed), 240 (medium speed), and 360 kph (high speed). The AC layer thicknesses for each asphaltic rail track design are 0.075, 0.15, 0.225, and 0.3 m for asphaltic overlayment, and 0.1, 0.2, 0.3, and 0.4 m for asphaltic underlayment. This research can shed light on the prospective application of

asphaltic rail track to the Indonesian rail network for the operation of faster passenger trains.

2 Methods

2.1 Indonesia's ballasted rail track

The typical thickness of the sub-ballast layer is 15 cm. In addition, certain railway systems do not use a sub-ballast layer and instead employ a thicker subgrade layer [3]. Nevertheless, according to Regulation No. 60 of 2012 of the Indonesian Minister of Transportation Concerning Railroad Technical Requirements, the design thickness of ballast and sub-ballast for conventional track is fixed regardless of the specific conditions [29]. The thicknesses of the ballast and sub-ballast layers are 0.3 and 0.4 m, respectively. Figure 1 depicts the geometry of Indonesia's ballasted railway and critical location for the examination of vertical compressive stress in the subgrade layer. Its structural design is comprised of 2 m × 0.22 m sleepers, ballast 0.3 m thick, sub-ballast 0.4 m thick, and a subgrade layer 3.3 m thick.

2.2 Asphaltic underlayment track

Figure 2 depicts the geometry of asphaltic underlayment track and critical location for the examination of vertical compressive stress in the subgrade layer. Its structural arrangement consists of 2 m × 0.22 m sleepers, ballast 0.3 m thick, AC layers of varying thickness (0.1, 0.2, 0.3, and 0.4 m), and a subgrade layer 3.3 m thick. In total, four distinct asphaltic underlayment track structural designs are studied in this research.

2.3 Asphaltic overlayment track

The geometrical design and important location for the investigation of vertical compressive stress in the subgrade layer of asphaltic overlayment track can be observed in Figure 3. Its structural configuration consists of 2 m × 0.22 m of sleeper, AC layers of varying thickness (0.07, 0.15, 0.225, and 0.3 m), sub-ballast 0.4 m thick, and subgrade layer 3.3 m thick. In total, four different asphaltic overlayment track structural designs are evaluated in this study.

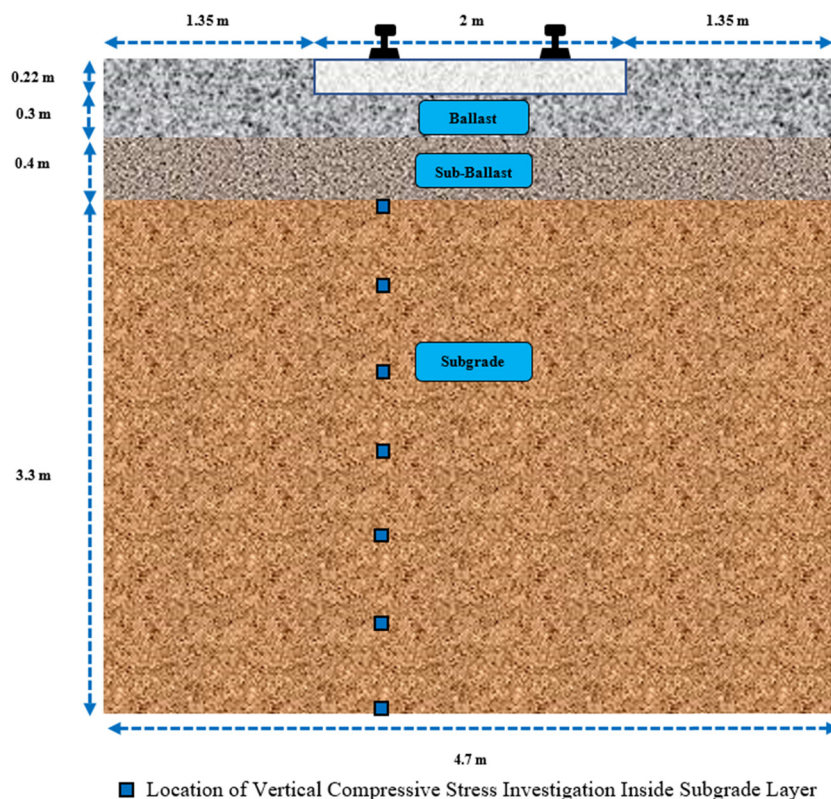


Figure 1: Indonesian's ballasted track geometric for numerical modeling.

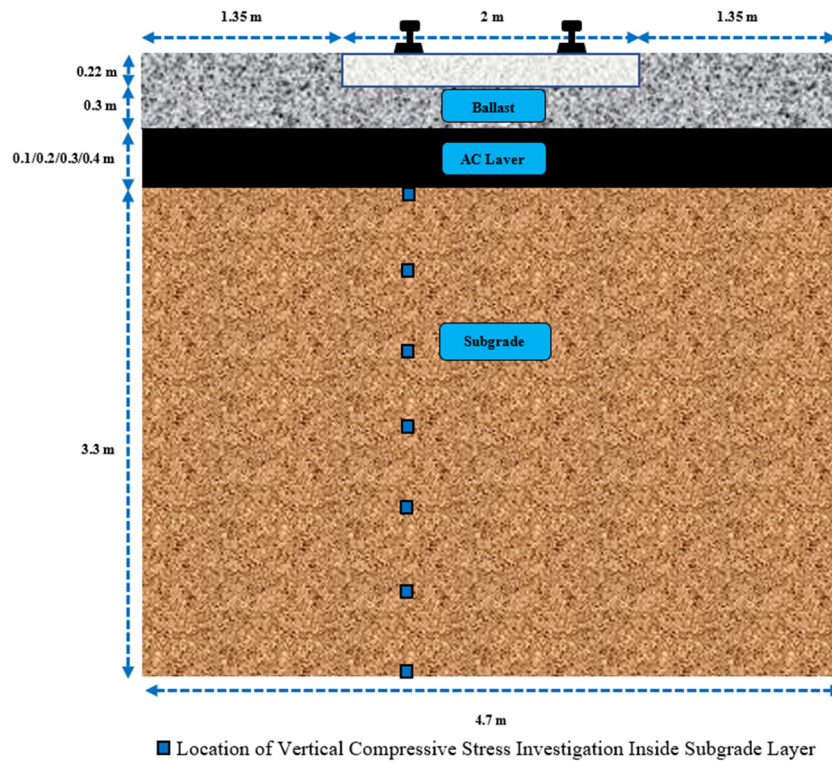


Figure 2: Asphaltic underlayment track geometric for numerical modeling.

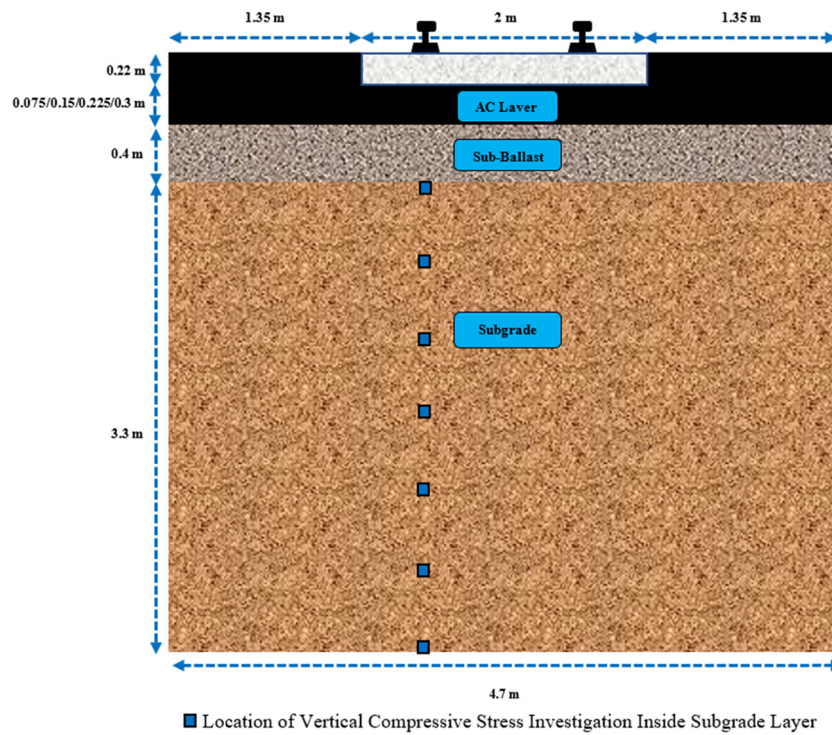


Figure 3: Asphaltic overlayment track geometric for numerical modeling.

Table 1: Material properties of Indonesia's ballasted track

Structural layers in Indonesia's ballasted track	Young's modulus, E (MPa)	Poisson's ratio, ν	Mass density, ρ (kg/m ³)
Sleeper	30,000	0.20	1833.3
Ballast	130	0.20	1,530
Sub-ballast	120	0.30	1,900
Subgrade	60	0.25	2,000

Table 2: Material properties of asphaltic underlayment track

Structural layers in asphaltic underlayment track	Young's modulus, E (MPa)	Poisson's ratio, ν	Mass density, ρ (kg/m ³)
Sleeper	30,000	0.20	1833.3
Ballast	130	0.20	1,530
AC layer	22,904	0.35	2,345
Subgrade	60	0.25	2,000

Table 3: Material properties of asphaltic overlayment track

Structural layers in asphaltic overlayment track	Young's modulus, E (MPa)	Poisson's ratio, ν	Mass density, ρ (kg/m ³)
Sleeper	30,000	0.20	1833.3
AC layer	22,904	0.35	2,345
Sub-ballast	120	0.30	1,900
Subgrade	60	0.25	2,000

2.4 Material properties

Tables 1–3 give the material properties for the simulation of rail tracks in the present work. All three types of rail tracks

are comprised of materials with a linear elastic behavior. The properties of sleeper, ballast, sub-ballast, and subgrade are the typical values based on Indonesian railway regulations.

2.5 Loading systems

According to Ghataora *et al.* [30], a frequency between 1 and 3 Hz corresponds well to the primary frequency of train-induced loading in the subgrade. This frequency depends on the train's speed and the distance between the axles, bogies, and coaches. Priest *et al.* [31] found that the pairs of bogies at the ends of adjacent wagons had a loading frequency of 1 Hz on a length of track with an average line speed of 50 kph, whereas individual bogies and axles had loading frequencies of 2 and 6 Hz, respectively.

In this study, the loading frequencies are precisely proportional to the train speed, and they fall within the range of loading frequencies typically experienced by low-, medium-, and high-speed trains. Each rail track design undergoes 5,000 loading cycles at three different frequencies, 2.4, 4.8, and 7.2 Hz, based on three different train speed levels, 120 (low speed), 240 (medium speed), and 360 kph (high speed), and the distance between single bogie to single bogie of the passenger coach is 14 m (Figure 4). Using Eqs. (1) and (2), a 28-ton static bogie load was translated into the dynamic load (Table 4) and then applied as a concentrated force in the left and right rail positions.

$$I_p = 1 + 0.01 \left(\frac{V}{1.609} - 5 \right), \quad (1)$$

$$P_d = P_s \times I_p, \quad (2)$$

where I_p is the conversion factor, V is the design speed (kph), P_s is the static wheel load of a train (kg), and P_d is the dynamic wheel load of a train (kg).

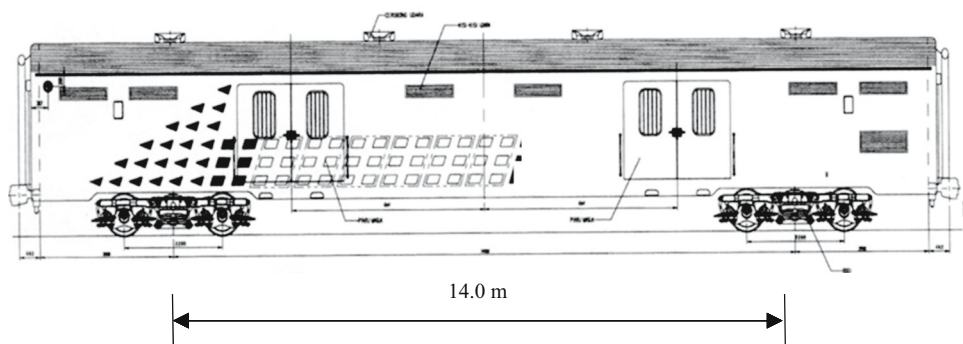
**Figure 4:** Distance between two single bogie in a passenger coach [32].

Table 4: Specification of cyclic loading

Train speed “V” (kph)	Bogie load (kg)	Static load (kg)	Dynamic load (kg)	Dynamic load (N)	Single bogie to single bogie passing frequency (Hz)	Loading cycles
120	28,000	14,000	23,741	232,819	2.4	5,000
240			34,183	335,220	4.8	
360			44,624	437,612	7.2	

2.6 Numerical modeling

Using Abaqus software, a 2D simulation of Indonesia’s ballasted track and two asphaltic rail track design types

was created. Figure 5 illustrates the 2D mesh of the simulation models for the three analyzed tracks. For the ballast, sub-ballast, and subgrade, a mesh size of 50 mm × 50 mm was determined, whereas 55 mm × 50 mm was

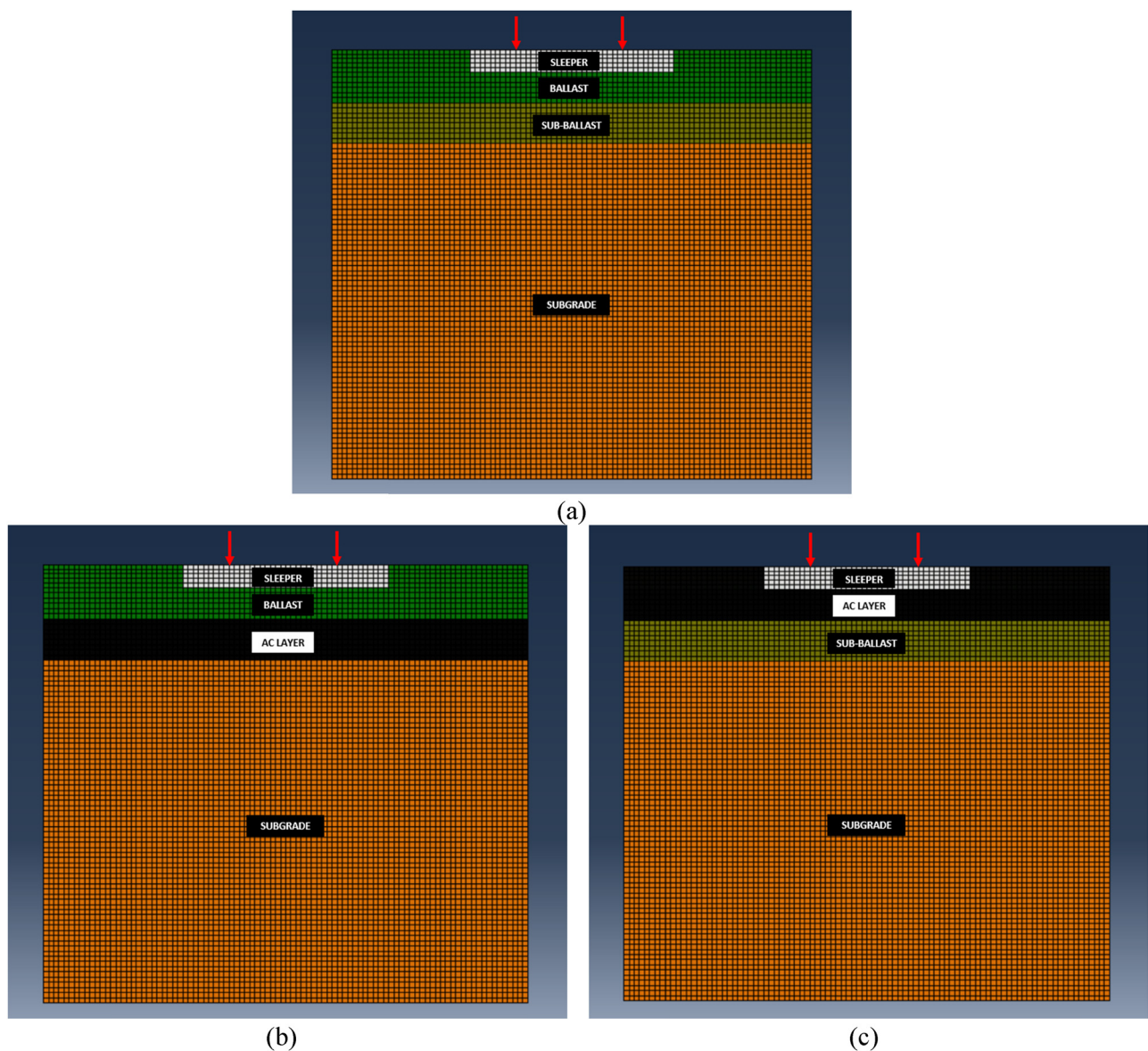


Figure 5: 2D mesh of simulation models: (a) Indonesia’s ballasted track, (b) asphaltic underlayment track, and (c) asphaltic overlayment track.

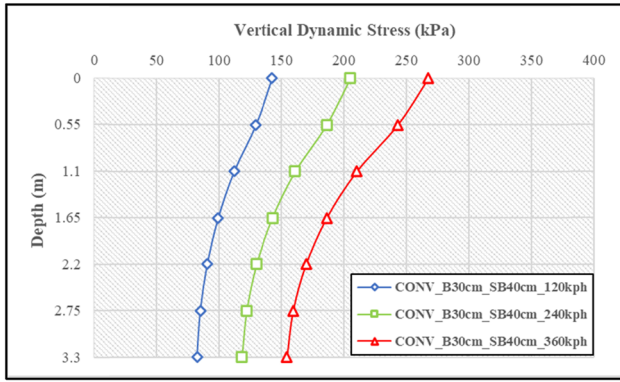


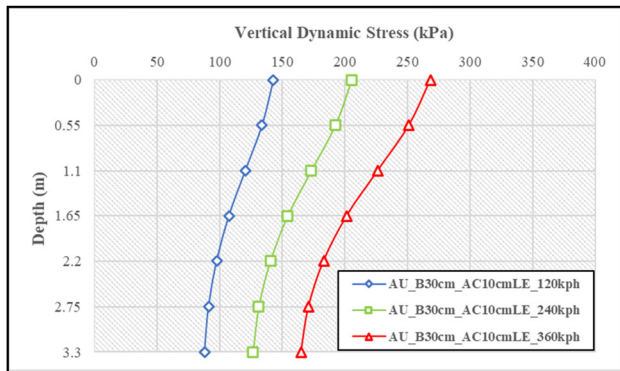
Figure 6: Vertical compressive stress curve in subgrade layer of Indonesia's ballasted track at 120, 240, and 360 kph train speed.

used for the sleeper. As the boundary condition was given as the soil box condition, the vertical displacement at the bottom and the horizontal displacement at the side of the model were fixed. The interactions between the layers were anticipated to be firmly bound, and the sleeper was expected to be a rigid material.

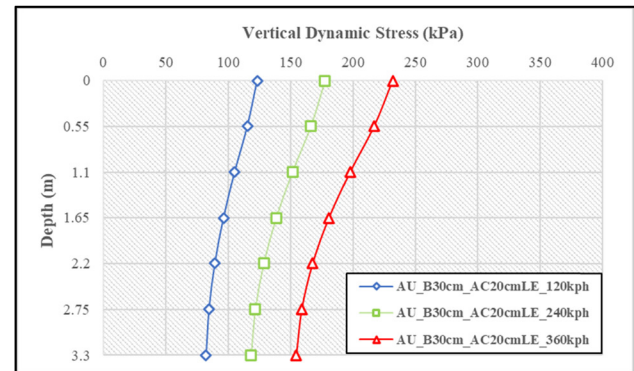
3 Results and discussion

One of the most significant functions of railway track beds is to transfer the load to the formation or subgrade layer beneath the track. The subgrade stresses can be affected by axle load, formation thickness, sleeper spacing, rail bending stiffness, and the existence of any additional layer for load distribution [33]. As the train speed increases, the evaluation and influence of subgrade become ever more crucial to the performance of railroad track structures [4]. According to Uzarski [34], the subgrade permitted stress value for the conventional design is around 137 kPa, although AREMA (The American Railway Engineering and Maintenance-of-Way Association) recommends limiting the stress at the top of the subgrade to 172 kPa.

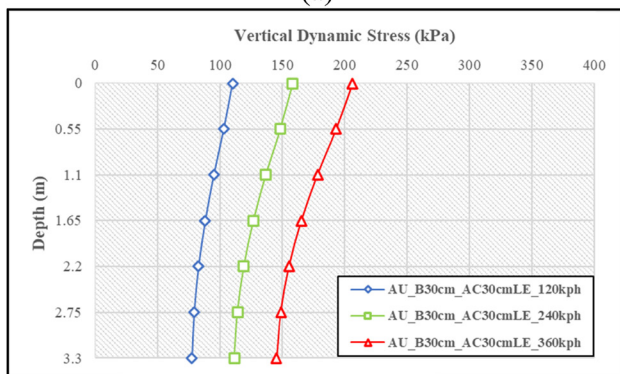
Figure 6 depicts the vertical compressive stress curve in the subgrade of the ballasted track in Indonesia at train speeds of 120, 240, and 360 kph. Under different train speeds, the vertical compressive stress at the top of the subgrade of Indonesia's ballasted track was 142, 204, and 267 kPa, whereas the vertical compressive stress



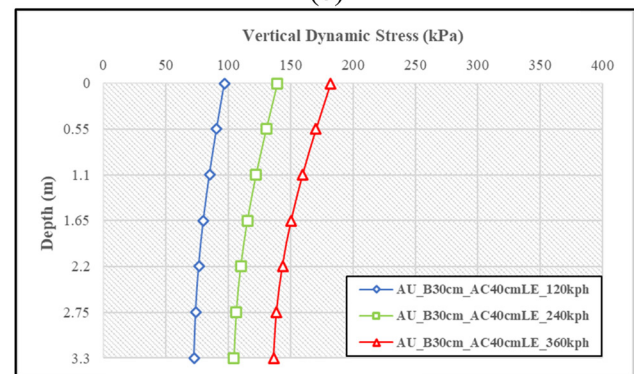
(a)



(b)



(c)



(d)

Figure 7: Vertical compressive stress curve in subgrade layer of asphaltic underlayment track under train speed of 120, 240, and 360 kph: (a) AC layer 10 cm, (b) AC layer 20 cm, (c) AC layer 30 cm, and (d) AC layer 40 cm.

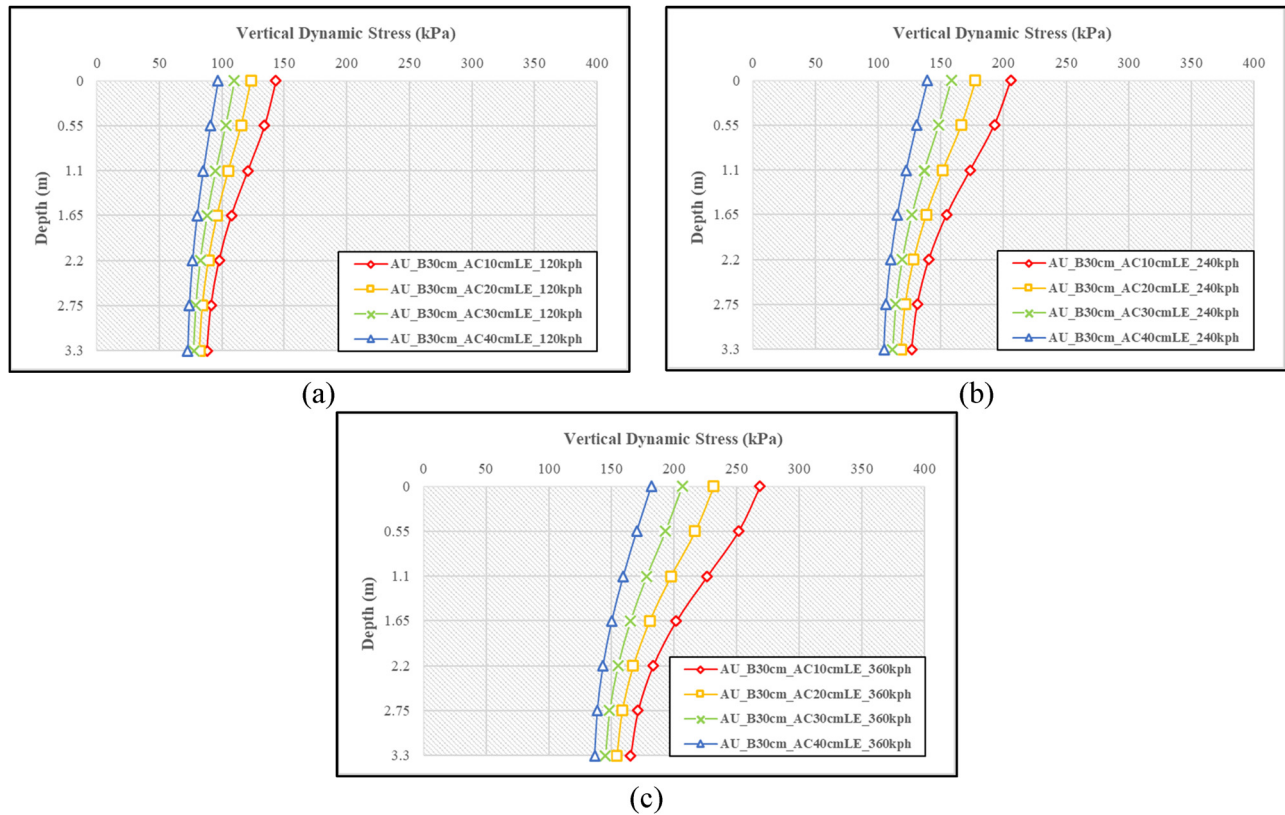


Figure 8: Vertical compressive stress curve in subgrade layer of asphaltic underlayment track with 10, 20, 30, and 40 cm of AC layer: (a) 120 kph, (b) 240 kph, and (c) 360 kph.

at the bottom of the subgrade was 82, 118, and 154 kPa. In accordance with AREMA's advice on the allowed stress at the top of the subgrade, Indonesia's ballasted track can only accommodate the 120 kph low-speed passenger train.

Figure 7 displays the vertical compressive stress curve in the subgrade layer of asphaltic underlayment track at train speeds of 120, 240, and 360 kph for four different AC layer thicknesses, 0.1, 20, 30, and 40 cm, respectively. It has been confirmed that a thicker AC layer in asphaltic underlayment will not only result in lower stresses at the top of the subgrade, but also provide a steeper vertical compressive stress curve. In other words, as the AC layer becomes thicker, the magnitude difference between the vertical compressive stress at the top and bottom of the subgrade would decrease. In addition, the magnitude gap of vertical compressive stress in each measurement location between 120 and 240 kph (Blue Line vs Green Line) is proportional to the magnitude gap of vertical compressive stress in each measurement location between 240 and 360 kph (Green Line vs Red Line).

Figure 8 shows the vertical compressive stress curve in the subgrade layer of asphaltic underlayment track with

different AC layer thicknesses, 10, 20, 30, and 40 cm, under train speeds of 120, 240, and 360 kph, respectively. The greater the train speed, the greater the stress at the top of the subgrade and shallower the vertical compressive stress curve. In other words, when train speed increases, the magnitude difference between the vertical compressive stress at the top and bottom of the subgrade would increase. In addition, the decrease in vertical compressive stress due to the increase in AC layer thickness from 10 to 20 cm (Red Line vs Orange Line) is greater than the decrease in vertical compressive stress owing to the increase in AC layer thickness from 30 to 40 cm (Green Line vs Blue Line).

Figure 9 compares the vertical compressive stress curve in the subgrade layer of Indonesia's ballasted track and asphaltic underlayment track with varying thicknesses of AC layer at train speeds of 120, 240, and 360 kph. Ballasted track in Indonesia continues to outperform asphaltic underlayment track with 10 cm of AC layer. The alternative rail track design is therefore restricted to asphaltic underlayment tracks with 20, 30, and 40 cm of AC layer. In addition, the vertical compressive stress at the top of the subgrade in asphaltic underlayment track with 30 cm of ballast and 40 cm of AC layer at 120, 240, and

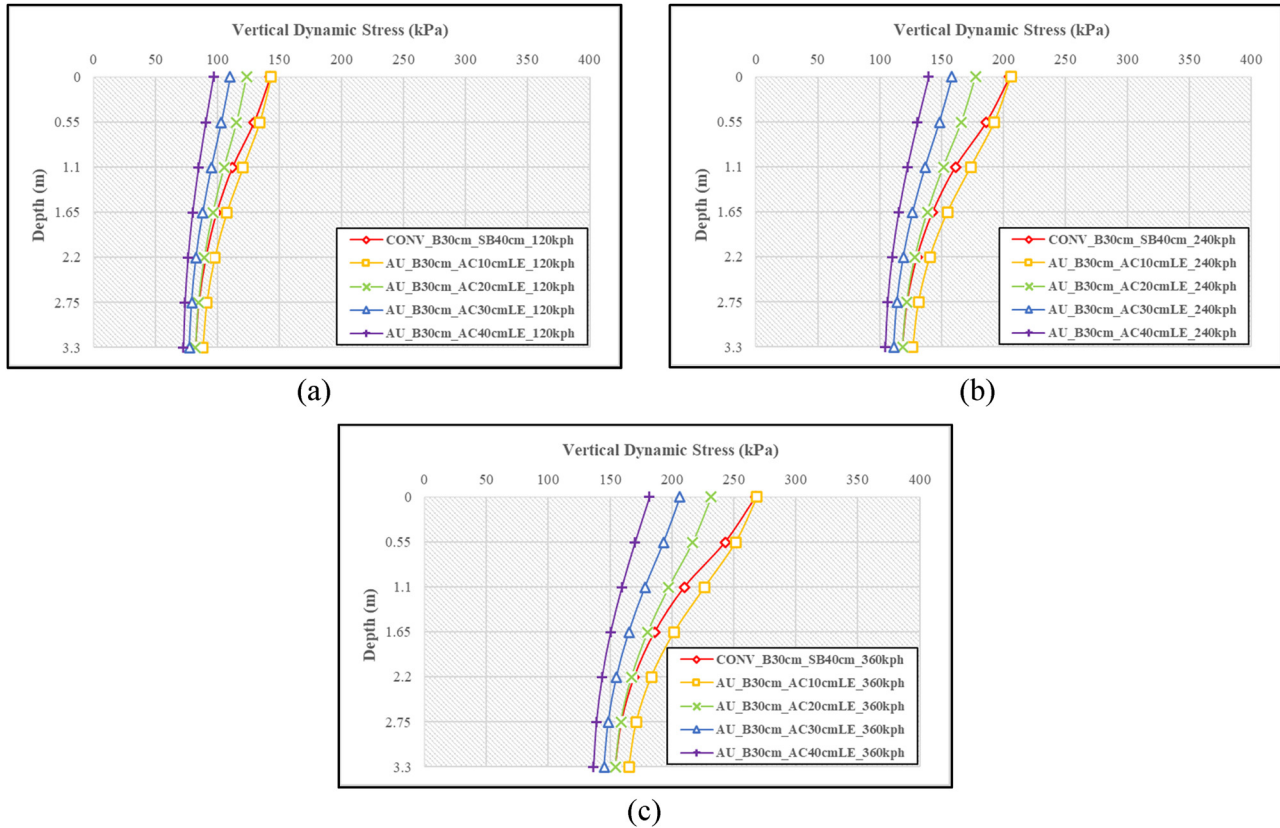


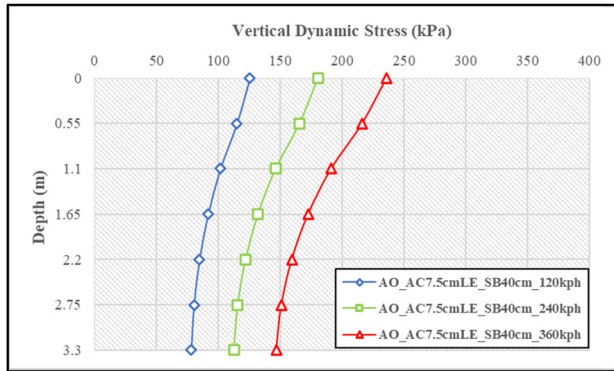
Figure 9: Vertical compressive stress curve in subgrade layer of Indonesia's ballasted track and asphaltic underlayment track with 10, 20, 30, and 40 cm of AC layer: (a) 120 kph, (b) 240 kph, and (c) 360 kph.

360 kph of train speed is 96, 139, and 181 kPa, respectively, which is approximately 47% less than the vertical compressive stress at the top of the subgrade in Indonesia's ballasted track with 30 cm of ballast and 40 cm of sub-ballast layer. In other words, the asphaltic underlayment track is 47% stronger than the Indonesia's ballasted track in terms of vertical compressive stress attenuation in the subgrade, particularly when the AC layer replaces the sub-ballast layer. Several investigations revealed that the dynamic stresses in the subgrade beneath a slab track were four to five times smaller than those under a ballasted track, and that the stresses in the soil rose as train speeds increased [35–39]. In addition, it can be concluded that an asphaltic underlayment track with the same structural thickness as Indonesia's ballasted track can serve not only the low-speed but also the medium-speed passenger train, per AREMA's recommendation regarding the maximum allowable stress at the top of the subgrade.

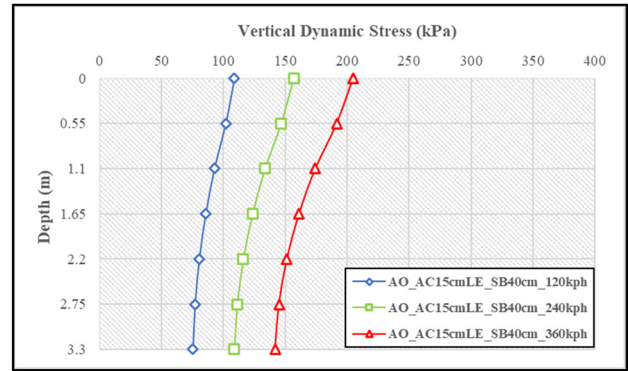
Figure 10 represents the vertical compressive stress curve in the subgrade layer of the asphaltic overlayment track at train speeds of 120, 240, and 360 kph for four different AC layer thicknesses, 7.5, 15, 22.5, and 30 cm, respectively. It has been confirmed that a thicker AC layer

in an asphaltic overlay will not only result in less stress at the top of the subgrade, but also provide a steeper vertical compressive stress curve. In other words, as the AC layer becomes thicker, the magnitude difference between the vertical compressive stress at the top and bottom of the subgrade would decrease. In addition, the magnitude gap of vertical compressive stress in each measurement location between 120 and 240 kph (Blue Line vs Green Line) is proportional to the magnitude gap of vertical compressive stress in each measurement location between 240 and 360 kph (Green Line vs Red Line).

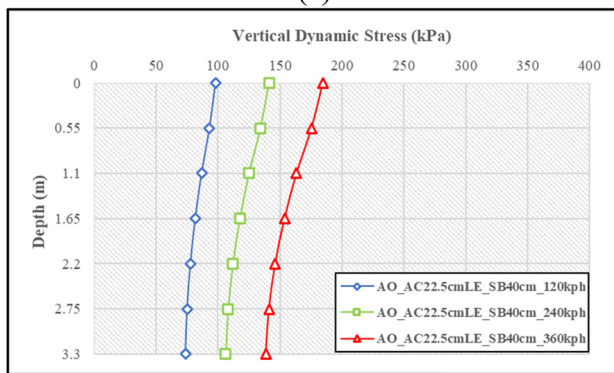
Figure 11 exhibits the vertical compressive stress curve in the subgrade layer of asphaltic overlayment track with varying AC layer thicknesses, 7.5, 15, 22.5, and 30 cm, under train speeds of 120, 240, and 360 kph, respectively. The greater the train speed, the greater the stress at the top of the subgrade and shallower the vertical compressive stress curve. In other words, when the train speed increases, the magnitude difference between the vertical compressive stress at the top and bottom of the subgrade would increase. In addition, the decrease in vertical compressive stress resulting from an increase in AC layer thickness from 7.5 to 15 cm (Red Line vs Orange



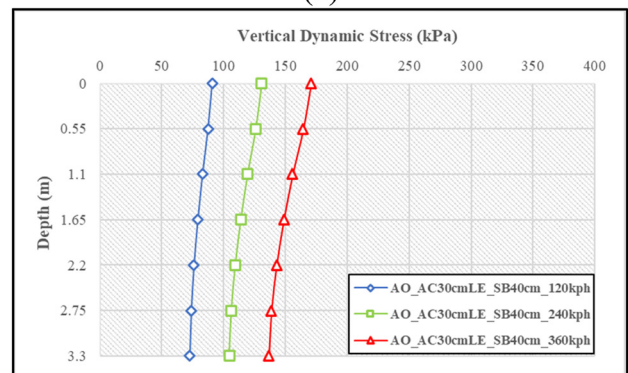
(a)



(b)

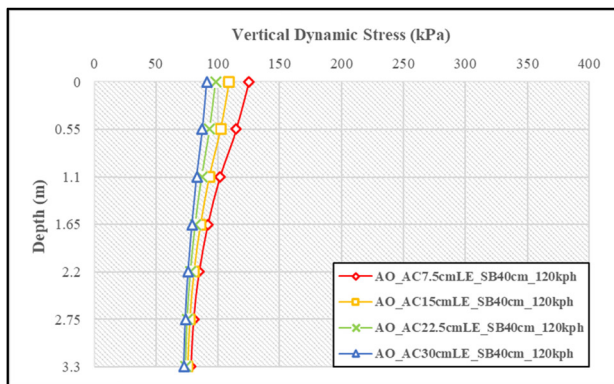


(c)

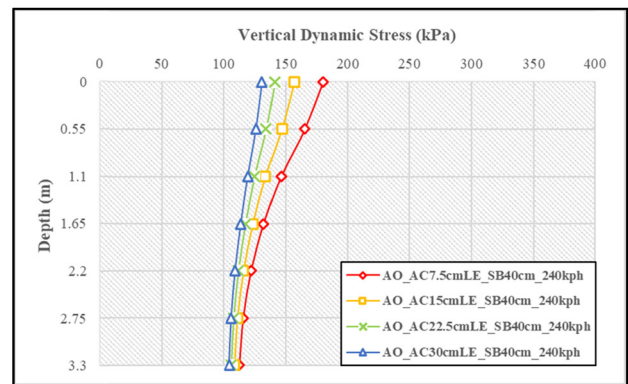


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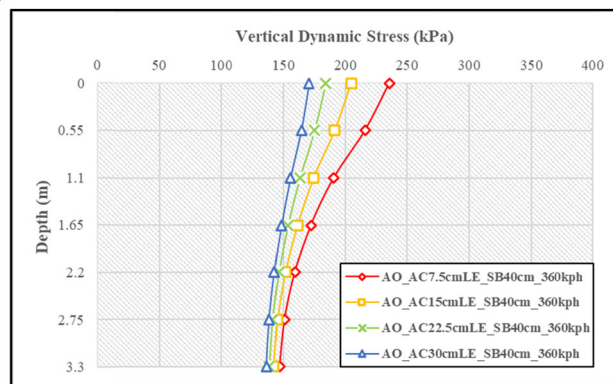
Figure 10: Vertical compressive stress curve in subgrade layer of asphaltic overlayment track under train speed of 120, 240, and 360 kph: (a) AC layer 7.5 cm, (b) AC layer 15 cm, (c) AC layer 22.5 cm, and (d) AC layer 30 cm.



(a)



(b)



(c)

Figure 11: Vertical compressive stress curve in subgrade layer of asphaltic overlayment track with 7.5, 15, 22.5, and 30 cm of AC layer: (a) 120 kph, (b) 240 kph, and (c) 360 kph.

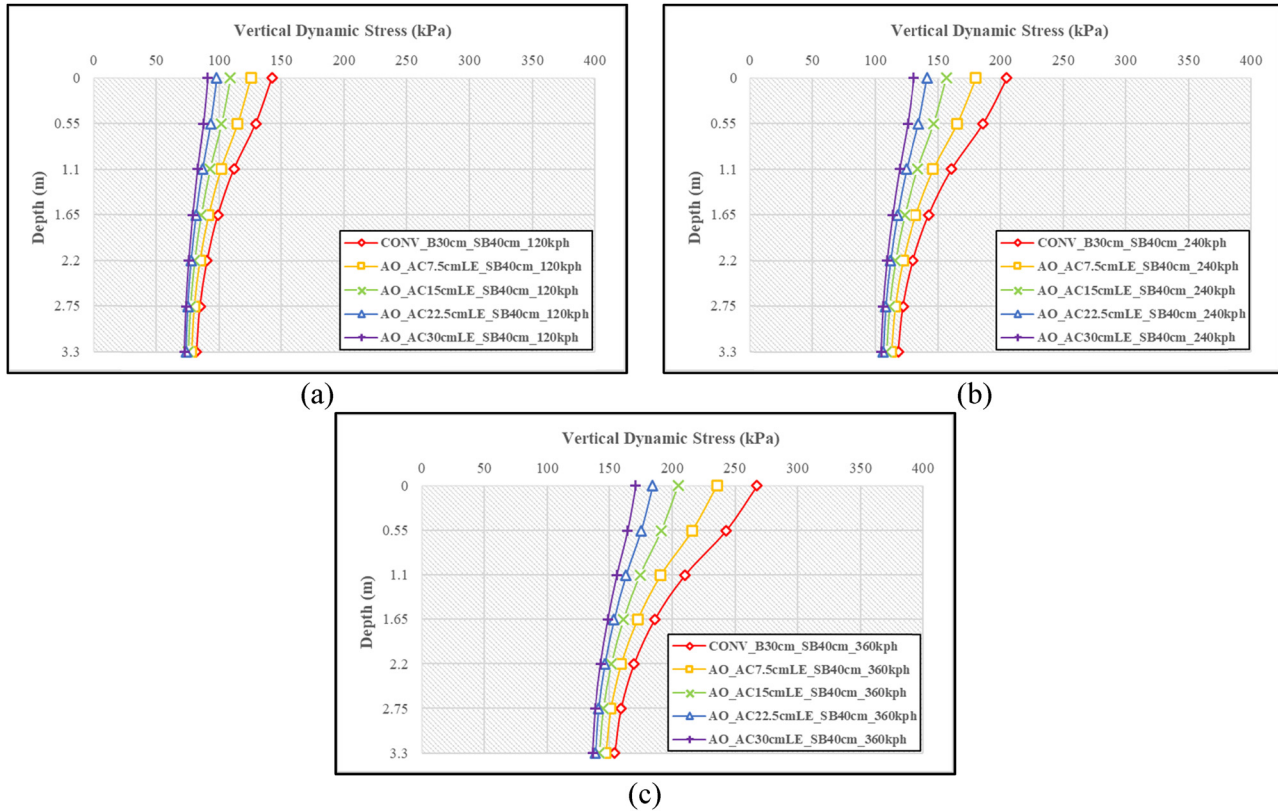


Figure 12: Vertical compressive stress curve in subgrade layer of Indonesia's ballasted track and asphaltic overlayment track with 7.5, 15, 22.5, and 30 cm of AC layer: (a) 120 kph, (b) 240 kph, and (c) 360 kph.

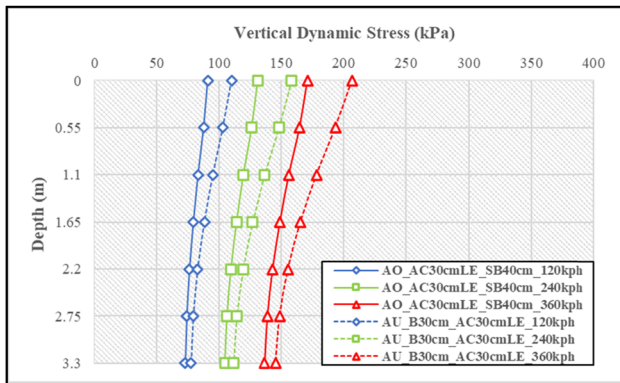


Figure 13: Vertical compressive stress curve in subgrade layer of asphaltic underlayment track and asphaltic overlayment track with 30 cm of AC layer under train speed of 120, 240, and 360 kph.

Line) is more significant than the decrease in vertical compressive stress resulting from an increase in AC layer thickness from 22.5 to 30 cm (Green Line vs Blue Line).

Figure 12 compares the vertical compressive stress curve in the subgrade layer of Indonesia's ballasted track and asphaltic overlayment track with various thicknesses of AC layer at train speeds of 120, 240, and 360 kph. All

asphaltic overlay track variants perform better than the ballasted track in Indonesia. In other words, asphaltic overlayment tracks with 7.5, 15, 22.5, and 30 cm of AC layer can be used as an alternative rail track design due to their significantly lower vertical compressive stress and shallower vertical compressive stress curve in the subgrade. Moreover, the vertical compressive stress at the top of the subgrade in asphaltic overlayment track with 30 cm of AC and 40 cm of sub-ballast layer at 120, 240, and 360 kph of train speed is 90, 130, and 170 kPa, which is 57% less than the vertical compressive stress at the top of the subgrade in Indonesia's ballasted track with 30 cm of ballast and 40 cm of sub-ballast layer. In other words, asphaltic overlayment track with the same structural thicknesses is 57% stronger than Indonesia's ballasted track in terms of vertical compressive stress attenuation in the subgrade, especially when the AC layer replaces the ballast layer. The findings of field measurements of the dynamic stress at the subgrade surface were presented in a number of publications. The dynamic stress in the subgrade surface of a slab track was found to be between 13 and 20 kPa, whereas it was between 50 and 100 kPa for a ballasted track [35–39]. Furthermore, it

can be concluded that asphaltic overlayment track with the same structural thickness as Indonesia's ballasted track can serve all speed levels of passenger train operation, namely 120, 240, and 360 kph, in accordance with AREMA's recommendation regarding the allowable stress at the top of the subgrade.

Figure 13 compares the vertical compressive stress curve in the subgrade layer of asphaltic underlayment track and asphaltic overlayment track with a 30 cm AC layer at train speeds of 120, 240, and 360 kph. In terms of vertical compressive stress attenuation in the subgrade and with the same AC layer thickness, the asphaltic overlayment track design outperforms the asphaltic underlayment track design. Under 120, 240, and 360 kph of train speed, the vertical compressive stress at the top of the subgrade is 109, 158, and 206 kPa, respectively, in asphaltic underlayment track with 30 cm of AC layer. Under 120, 240, and 360 kph of train speed, the vertical compressive stress at the top of the subgrade in asphaltic overlayment track with 30 cm of AC layer is 90, 130, and 170 kPa, respectively. Under a train speed of 350 kph, Lee *et al.* [25] discovered that an asphaltic rail track with AC layer thicknesses of 20, 27, and 35 cm below the sleeper produced vertical compressive stresses of approximately 140, 90, and 50 kPa at the top of the roadbed, respectively.

4 Conclusions

This research analyzed the performance of Indonesia's ballasted track in terms of the distribution of vertical compressive stress in the subgrade, then compared it to the two asphaltic rail track designs. According to the results, the asphaltic overlayment track is superior to the asphaltic underlayment track and the ballasted track in Indonesia in transmitting and decreasing stresses from the top structure to the subgrade layer. Also, the AC layer should be placed right beneath the sleeper, where the majority of the stress is concentrated, to better protect the subgrade.

In addition, it can be concluded that only asphaltic underlayment tracks with 20, 30, and 40 cm of AC layer are viable alternatives for Indonesian railways. In contrast, asphaltic overlayment tracks with all four different AC layer thicknesses can be utilized to replace the ballasted track for higher speed train operations in Indonesia. In accordance with AREMA's advice on the allowed stress at the top of the subgrade, Indonesia's ballasted track can only accommodate the 120 kph low-speed passenger train. On the other hand, asphaltic underlayment track

with the same structural thickness as Indonesia's ballasted track can serve both low-speed and medium-speed passenger trains, whereas asphaltic overlayment track can service all three speed levels of passenger train operation.

This analysis took into account the asphalt material's linear elastic characteristics. Future research should address the linear viscoelastic constitutive behavior of asphalt material to predict the performance of AC layer behavior and the influence of AC layer on the reduction of vertical compressive stress in the subgrade of asphaltic rail tracks.

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References

- [1] Priest JA, Powrie W. Determination of dynamic track modulus from measurement of track velocity during train passage. *J Geotech Geoenviron Eng.* 2009;135(11):1732–40. doi: 10.1061/(ASCE)GT.1943-5606.0000130.
- [2] Kennedy JH, Woodward PK, Banimahd M, Medero GM. Railway track performance study using a new testing facility. *Geotech Eng.* 2012;165(5):309–19. doi: 10.1680/jeng.10.00075.
- [3] Tzanakakis K. The railway track and its long-term behavior. A handbook for a railway track of high quality. Springer tracts on transportation and traffic. Heidelberg, New York, Dordrecht, London: Springer; 2013. doi: 10.1007/978-3-642-36051-0.
- [4] Gomes Correia A, Ramos A. A geomechanics classification for the rating of railroad subgrade performance. *Rail Eng Sci.* 2021;30:323–59. doi: 10.1007/s40534-021-00260-z.
- [5] Tan Q, Li L, Wang S. Measurement and analysis of high-speed railway subgrade settlement in China: a case study. *Sens Transducers.* 2014;170(5):184–91.

- [6] Chen SX, Song J, Zhou QN. Theory and practice for high-speed railway settlement deformation observation assessment. Beijing, China: China Railway Press; 2010.
- [7] Setiawan DM. Evaluation of Indonesia's ballasted track performance based on mechanistic approach. *Int J Sustain Constr Eng Technol*. 2022;13(1):185–201. doi: 10.30880/ijscet.2022.13.01.017.
- [8] Sadeghi J, Askarinejad H. Influences of track structure, geometry and traffic parameters on railway deterioration. *Int J Eng Trans B Appl*. 2007;20(3):292–300.
- [9] Brough MJ, Ghataora GS, Stirling AB, Madelin KB, Rogers CDF, Chapman DN. Investigation of railway track subgrade. 1: In-situ assessment. *Proc Inst Civ Eng Transp*. 2003;156(3):145–54. doi: 10.1680/TRAN.2003.156.3.145.
- [10] Setiawan DM. Ballasted track and asphaltic underlayment track mechanical behavior under Indonesia's Babaranjang freight trains loading. *Eng Appl Sci Res*. 2022;49(5):657–68. doi: 10.14456/easr.2022.64.
- [11] Setiawan DM. Investigation of ballasted and asphaltic underlayment track behaviors subjected to freight train load: mechanistic approach. *J Appl Eng Sci*. 2022;20(3):673–87. doi: 10.5937/jaes0-35499.
- [12] Martinez Soto F, Di Mino G. Procedure for a temperature-traffic model on rubberized asphalt layers for roads and railways. *J Traffic Transp Eng*. 2017;5:171–202. doi: 10.17265/2328-2142/2017.04.001.
- [13] Setiawan DM. Stress–strain characteristics and service life of ballasted and asphaltic underlayment track under heavy load Babaranjang trains traffic. *J Mech Behav Mater*. 2022;31(1):22–36. doi: 10.1515/jmbm-2022-0003.
- [14] Selig ET, Waters JM. Track geotechnology and substructure management. London, UK: Thomas Telford; 1994.
- [15] 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.
- [16] Zeng X. Rubber-modified asphalt concrete for high-speed railway roadbeds. Final Report for High-Speed Rail IDEA Project 40. Washington DC, USA: Transport Research Board; 2005.
- [17] Rose JG, Bryson LS. Hot mix asphalt railway trackbeds: trackbed materials, performance evaluations, and significant implications. The International Conference on Perpetual Pavements; 2009 Sep 30–Oct 2; Columbus (OH), USA. Columbus: Ohio Research Institute for Transportation and Environment, 2009. p. 1–19.
- [18] Rose JG, Agarwal NK, Brown JD, Ilavala N. KENTRACK, a performance-based layered elastic railway track-bed structural design and analysis procedure: a tutorial. Proceedings of the 2010 Joint Rail Conference: 2010 Apr 27–29; Urbana (IL), USA. New York: The American Society of Mechanical Engineers, 2010. p. 73–110.
- [19] Teixeira PF, López-Pita A, Casas C, Bachiller A, Robuste F. Improvements in high-speed ballasted track design: benefits of bituminous subballast layers. *Transp Res Rec J Transp Res Board*. 2006;1943(1):43–9. doi: 10.1177/0361198106194300106.
- [20] Fang M, Cerdas SF, Qiu Y. Numerical determination for optimal location of sub-track asphalt layer in high-speed rails. *J Mod Transp*. 2013;21(2):103–10. doi: 10.1007/s40534-013-0012-0.
- [21] Ramirez Cardona D, Di Benedetto H, Sauzeat C, Calon N, Saussine G. Use of a bituminous mixture layer in high-speed line trackbeds. *Constr Build Mater*. 2016;125:398–407. doi: 10.1016/j.conbuildmat.2016.07.118.
- [22] Ramirez Cardona D, Benkahla J, Costa D'Aguiar S, Calon N, Robinet A, Di Benedetto H et al. High-speed ballasted track behavior with sub-ballast bituminous layer. GEORAIL 2014. Second International Symposium Railway Geotechnical Engineering; 2014 Nov 6–7; Marne-laVallée, France. IFSTTAR, 2014. p. 1–11.
- [23] Rose JG, Brown ER, Osborne ML. Asphalt trackbed technology development: the first 20 years. *Transp Res Rec J Transp Res Board*. 2000;1713(1):1–9. doi: 10.3141/1713-01.
- [24] Lechner B. Developments in road pavement construction and railway track technology for a sustainable surface transportation infrastructure. Proceedings of the Eighth International Conference of Chinese Logistics and Transportation Professionals; 2008 Oct 8–10. Chengdu, China. ASCE, 2008. p. 2656–65.
- [25] Lee SH, Vo HV, Park DW. Investigation of asphalt track behavior under cyclic loading: full-scale testing and numerical simulation. *J Test Eval*. 2018;46(3):934–42. doi: 10.1520/JTE20160554.
- [26] 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.
- [27] Fang M, Qiu Y, Rose JG, West RC, Ai C. Comparative analysis on dynamic behavior of two HMA railway substructures. *J Mod Transp*. 2011;19(1):26–34. doi: 10.1007/BF03325737.
- [28] Liu S. KENTRACK 4.0: a railway track-bed structural design program. Theses and Dissertations. USA: Department of Civil Engineering, University of Kentucky; 2013.
- [29] Sekretariat Negara. Minister of Transportation Regulation No. 60 of 2012 concerning Railroad Technical Requirements (Peraturan Menteri Perhubungan No. 60 Tahun 2012 tentang Persyaratan Teknis Jalur Kereta Api). Jakarta; 2012.
- [30] Ghataora G, Burrow M, Matson N. A laboratory investigation into the effectiveness of a geocomposite as sand blanket replacement. Proceedings of the International Seminar on Geotechnics in Pavement and Railway Design and Construction; 2004 Dec 16–17; Athens, Greece. ISSMGE, 2004. p. 201–8.
- [31] Priest JA, Powrie W, Yang L, Grabe PJ, Clayton CRI. Measurements of transient ground movements below a ballasted railway line. *Geotechnique*. 2010;60(9):667–77. doi: 10.1680/geot.7.00172.
- [32] Sarana Gerbong (Title in English: Rolling Stock). PT. Kereta Api Indonesia. <https://cargo.kai.id/produk/sarana>. [Accessed December 31, 2021].
- [33] Esen AF, Woodward PK, Laghrouche O, Connolly DP. Stress distribution in reinforced railway structures. *Transp Geotech*. 2022;32:100699. doi: 10.1016/j.trgeo.2021.100699.
- [34] Uzarski D. Introduction to railroad track structural design. BCR2A'09 Railroad Track Design Including Asphalt Trackbeds Pre-Conference Workshop; 2009 29 Jun–2 Jul; Urbana (IL), USA.
- [35] Xiaohong L, Guolin Y, Liangliang W. Dynamic response testing and analysis on red-clay cutting bed under ballastless

- track of high-speed railway. *Geotech Invest Surv.* 2011;39(8):12–8.
- [36] Hu YF, Li NF. *Theory of ballastless track-subgrade for high-speed railway.* Beijing: China Railway Published House; 2010.
- [37] Dong L, Zhao C, Cai DZQ, Ye Y. Experimental validation of a numerical model for prediction of the dynamic response of ballastless subgrade of high-speed railways. *China Civ Eng J.* 2008;41(10):81–96.
- [38] Nie Z, Ruan B, Li L. Testing and analysis on dynamic performance of subgrade of Qinshen railway. *J Vib Shock.* 2005;24(2):30–42.
- [39] Lamas-Lopez F, Cui YJ, Calon N, Costa D’Aguir S, Peixoto DOM, Zhang TW. Track-bed mechanical behaviour under the impact of train at different speeds. *Soils Found.* 2016;56(4):627–39. doi: 10.1016/j.sandf.2016.07.004.