Research Article

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Stress-strain characteristics and service life of conventional and asphaltic underlayment track under heavy load Babaranjang trains traffic

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Abstract: A more durable rail track structure is fundamental in the railway industry, allowing the government to operate the train with higher speed and axle load. That means more passengers and better quality of railroads travel, thereby reducing the maintenance costs and ensuring passengers' comfort and safety. The effect of a sub-ballast and asphalt layer thickness and freight train traffic with low operational speed on mechanical behavior and design life of conventional track and asphaltic underlayment track, are presented in this paper. One of the significant findings to emerge from this study is that an AC layer with minimum thickness of 0.20 m is required in the asphalt underlayment track application for Indonesian railway infrastructure to facilitate Babaranjang freight trains with up to 50% more tonnage. The evidence from this study also suggests that the asphalt underlayment track with 0.20 m thick of AC layer that contains grade PG70-28 binder could be beneficial to be applied in Indonesian railway system so that the rail track could be constructed with less volume of works than the regular Indonesia's conventional track with 0.40 m of sub-ballast layer.

Keywords: Asphaltic underlayment track, compressive stress, conventional track, tensile strain, service life, sub-ballast

1 Introduction

Service life means the period of a rail track design used in service. It is known that the ballast structure layer may encounter a decline in mechanical and geometrical performances caused by heavy train loads and environment [1, 2].

Moreover, poor ballast and sub-ballast material conditions can be a benchmark for the needs of maintenance work, the determination of track quality index [3], as well as the application of train speed restrictions [4]. The conventional track may experience further ballast deformations and track misalignments. According to Duong *et al.* [5], the mud pumping has been known to be the worst degradation phenomenon for the railway sub-structure, which is characterized by the fast upward migration of sub-soil fine particles through the ballast voids. Ballast material deficiency always occurs in the transition due to soil subsidence and rainwater erosion.

Adding other materials to the ballast layer can be considered as a solution to improve the quality of rail track structure. Woodward *et al.* [6], Kennedy *et al.* [7], and Woodward *et al.* [8] applied polyurethane polymer to reduce settlement and to increase the stability of rail track. However, due to its lack of availability in the rail industry, its usage should be subject for reconsideration due to its high cost.

Slab track has been widely developed worldwide in recent years due to its superior performance in retaining high speed and heavy loaded trains. Its structure is also more stable and offers a better ride comfort and track performance [9–11]. However, it has some unavoidable problems related to the noise and ground vibration that required to be solved with special countermeasures at the track, such as by using a resilient slab mat and an elastic pad on the fastening [12–17]. The dynamic forces between wheel and rail are considered as a crucial parameter in the slab track analysis and design. They are significantly affected by wheel-rail irregularities, and the temperature loads also attributed to the temperature change [10, 18–21]. Interfacial crack issues in the slab track due to inappropriate manufacture and maintenance are ubiquitous. The propagated deterioration under repeated train load and temperature variations in the slab track also becomes a crucial concern. According to several site investigations and practices, only recently it was found that crack propagation is faster in the wet and inadequate drainage regions compared to the dry areas. It indicates that the coupling effect of train load and moisture may holds a significant role in the process of crack

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propagation within slab track [10, 22]. In other words, the mechanical behaviors of railway superstructures are greatly affected by the environmental loads involving temperature and rainwater due to the poor heat conductivity of the slab track system [16].

The establishment of the slab track is also considered to be more costly compared to the ballasted track. The slab track requires a homogeneity and good-quality subgrade. Moreover, its construction should avoid deep cutting clay soils, embankments on soft peat layers, or in areas with potential earthquakes, since it is fragile to a significant settlement [10, 16, 23, 24]. In addition, slab track systems present environmental impacts higher than the ballasted track which is related to the cement-related carbon footprint [25]. Alternatively, scrap rubber [26–31] and asphalt [32–44] may also be selected for ballast layer treatment and stabilization.

Setiawan and Rosyidi [29], in their research, utilized scrap rubber from worn-out motorcycle tires as additional component for ballast layer. It was divided into two types, a uniformly sized of 3/8" and graded sizes of 1", 1/2", 3/4", and No.4 with the total percentage of scrap rubber in each specimen being 10% of the total aggregate weight. Their study aimed to analyze the characteristics of ballast mixtures with and without scrap rubber and with numbers of manual compactions. They found that in the ballast layer with scrap rubber, an increase in compaction up to 100% was only able to increase the elastic modulus of ballast layers by 6%. However, the compaction works played an essential role in enhancing ballast layer ability to withstand the loads up to 70% and in increasing ballast materials durability up to 38%. The various sized scrap rubber had an effective role in enhancing ballast durability. When the compaction process with manual pounding was carried out, the ballast materials with scrap rubber tended to bounce off each other, causing the sample not to have sufficient and proper density and stiffness.

Rosyidi *et al.* [31] conducted a compression test to several test samples consisting of ballast only, ballast with uniform graded scrap rubber, and ballast with continuous graded scrap rubber, to analyze the mechanical behavior of the ballast layer with scrap rubber mixtures. They concluded that addition of scrap rubber could decrease the ballast layer stiffness, proven by an increase in vertical deformation and a decrease in elastic modulus. However, the use of scrap rubber could significantly minimize the damage to the ballast material. It was because the presence of scrap rubber could reduce the chance of collision and friction between aggregates, causing the possibility of an increase in ballast durability and decrease in material degradation. Furthermore, the addition of uniformly

sized scrap rubber could produce higher elastic modulus, but lower ballast durability compared to the addition of continuous graded scrap rubber in the ballast layer.

According to Setiawan and Rosyidi [37], Setiawan and Rosyidi [39], and Setiawan *et al.* [41], innovations in the field of rail track development need to be advanced, especially in the ballast and sub-ballast structure, which is the essential structure in traditional rail track. Other studies only focused on the use of ballast with scrap rubber or with asphalt. Therefore, these researchers had conducted a study aiming to examine the effect of the application of scrap rubber and asphalt on the characteristics of aggregates abrasion and vertical deformation of the ballast layer. The 60/70 penetration grade asphalt was used in their research since it is commonly used in the construction of highway pavement in Indonesia as well as the absence of special asphalt for railroad construction. The 60/70 penetration grade asphalt was heated in the oven for 5 hours at a temperature of 155°C, with a percentage of 2% [37, 41] and 3% [39, 41] of the total specimen weight. The 10% of scrap rubber was obtained from wornout motorcycle tires cut into two groups of sizes, uniform and continuously graded.

According to Setiawan and Rosyidi [37], degradation of ballast material showed a reduction in line with the use of scrap rubber and asphalt. The use of scrap rubber materials, especially with various sizes between No.4, 3/8", 1/2", 3/4", and 1" combined with 2% asphalt could produce the lowest abrasion value (up to 57%) compared to the sample comprised of ballast and scrap rubber, or the sample comprised of ballast only. It was because the scrap rubber and the asphalt could fill the cavity or pore in the ballast layer. Thus, it could reduce friction between ballast aggregates, decreasing the level of ballast deterioration. Moreover, competent 2% asphalt could minimize vertical deformation and increase the ability to retain loads of up to 28%. At the same time, the elastic modulus could be increased by up to 21%.

Setiawan and Rosyidi [39] discovered that the use of 10% scrap rubber and 3% asphalt could minimize the value of aggregates abrasion in the ballast structure significantly from 47% to 80%. It means that the utilization of both 3% asphalt and 10% scrap rubber had a positive role for ballast durability in rail track structures. Therefore, these materials could be utilized together as a solution to increase service life and reduce maintenance costs for rail tracks. Furthermore, the addition of 3% asphalt in the ballast structure as a binder material could improve the mechanical behavior of the ballast layer up to 14%.

Based on research conducted by Setiawan *et al.* [41], the higher the frequency of compaction occurs, and the more asphalt mixed in the ballast, the higher elastic modulus will be produced. This will lower ballast material abrasion,

and vertical deformation. Hence, the stiffer the ballast layer was, the higher the ballast durability would be. However, in the ballast layer with scrap rubber, the compaction works could not have an optimal impact on the vertical deformation reduction since the ballast materials in the sample with scrap rubber tended to bounce off each other, causing the sample not to have sufficient and proper density and stiffness.

In general, Setiawan and Rosyidi [37], Setiawan and Rosyidi [39], and Setiawan *et al.* [41] concluded that the effect of asphalt emulsion utilization in improving mechanical behavior of ballast structures was more significant or sensitive than that of scrap rubber. Therefore, Setiawan [2] considered addition of asphalt only into the ballast layer as a solution. His research also applied the 60/70 penetration grade asphalt for ballast layer stabilization. By performing a compressing strength test, the study was aimed to evaluate the fouled-ballast and clean-ballast mechanical behavior with 2% and 4% of 60/70 penetration grade asphalt in one (ballast surface layer) and three layers. Fouled ballast was applied to represent the ballast layer in the existing rail track structure in the field. The study revealed that the 60/70 penetration grade asphalt poured on the ballast surface layer was crucial in producing preferable load distribution to the entire ballast structure. Moreover, the more layers glazed with asphalt, and the higher the 60/70 penetration grade asphalt proportion is, the more effective the asphalt would be in minimizing ballast abrasion. The reason was that more ballast aggregate materials could be protected from abrasion during the process of compaction and compressive testing.

Moreover, the asphalt layer has been utilized in the rail track structure by several researchers and already applied in the field. Typically, this asphalt-bound impermeable layer is 125 to 200 mm thick and is functioned to improve track-bed performance, protect the rail track-bed, and support the overlying ballast [45–47]. Rose *et al.* [48], Malloy *et al.* [49], and Malloy *et al.* [50] in their research have applied the asphaltic track for the most cost-effective rehabilitation technique for level crossings. According to Fang *et al.* [51], the asphaltic layer substructure would give benefit for the long-term stability of the track structure since it could recover the residual vertical deformation to a certain extent.

Several types of research had been conducted to create computer models that can design and analyze railroad track-beds structure by utilizing the finite element system. ILLITRACK [52, 53], FEART [53, 54], and GEOTRACK [53, 55] are some of the examples. However, they are unable to analyze the behavior of asphalt track-beds and slab track-beds, and they can only be used for the analysis of all-granular

ballast track-beds. Therefore, KENTRACK, a program that can analyze the stress distribution for both asphalt and all-granular track-beds [53, 56, 57], was developed in the United States and it was utilized by Setiawan [58] to evaluate the performance of asphaltic overlayment track.

The objectives of this research are not only to calculate the critical stresses and strains within the rail track structure but also to predict the design service life of the conventional and the asphaltic underlayment rail tracks under the heavy freight train operation. The results of this research are beneficial for the Indonesian railway industry that 100% still rely on the conventional track type in its main line train operation. If the rail track engineer can construct a stronger and more long-lasting rail track structure, the Indonesian government can operate the train with higher speed and axle load (more passengers and goods). At the same time, it will reduce maintenance costs and ensure passenger comfort and safety.

2 Research method

2.1 Freight train traffic from Vatubara Rangkaian Panjang (Babaranjang) trains

In this research, the rail track is dedicated to freight train traffic in Indonesia, namely Babaranjang Train (Figure 1). Although the number of trains traffic is only 20 trains/day, each set of train carries 60 cars and has a maximum operating speed of 70 kph [4].

Figure 1: Babaranjang trains in South Sumatera, Indonesia [59]

Table 1: Babaranjang trains specification [60]

Parameter	Value
Axle Load	18,000 Kg
Static Wheel Load (P_s)	9,000 Kg
$V_{\max}$	70 kph
V_r	$1.25V_{\max} = 87.5$ kph
Dynamic Wheel Load (P_d) Based on TaKgot Equation	13,445 Kg/wheel
The total weight for one car having 8 wheels	107,560 Kg/car
Each car equals one repetition	107,560 Kg/car/repetition
The number of train sets per day	20 train sets/day
The number of cars for each train set	60 cars/train set
The number of the car per year	$60 \text{ car/train} \times 20 \text{ train/day} \times 365 \text{ days/year} = 438,000$ repetition/year
Considering Indonesia has two seasons in terms of climate	219,000 repetition/season
The tonnage per year (Rail Track Class 1 st)	$219,000 \text{ repetition/year} \times 107,560 \text{ Kg/repetition} = 23,555,640 \text{ ton/year} = 23.6 \text{ MGT/year}$

Table 2: Rail specifications [60]

Parameter	Value
Rail type	R54
Rail weight per unit length	54 Kg/m
Rail section (head) modulus	279 cm^3
Rail young modulus	$2,100,000 \text{ Kg/cm}^2$
Rail moment inertia	2346 cm^4
Rail Concrete Sleeper spring constant (K)	$1,250,058 \text{ Kg/cm}$

2.2 Load repetitions

Table 1 shows the data of Babaranjang trains operational specification.

2.3 Material properties and geometry

2.3.1 Rail

Table 2 presents the typical rail specifications used in the South Sumatra rail track line.

2.3.2 Concrete sleeper

Table 3 depicts the concrete sleeper specifications.

Table 3: Sleeper specifications [60]

Parameter	Value
Unit weight	900 Kg/m^3
Thickness	130 mm
Width	220 mm
Length	2000 mm
Moment of inertia	$12,155.7 \text{ cm}^4$
Young's modulus	28,000 MPa
Spacing	60 cm
Number of seasons	2 (dry and wet seasons)
Concrete Sleeper length	200 cm
Rail gauge	1067 mm
Distance between point 1 and 2 in the transverse direction	483 mm

2.3.3 Ballast

According to [60], the ballast layer is a subgrade channel located in an area experiencing the greatest stress concentration due to train traffic on the rail track. Therefore, the ballast material must be selected carefully. Ballast is gravels with specific quality requirements utilized specifically for rail track structure (Table 4).

Table 4: Ballast specifications in Indonesian railway systems

Parameter	Specifications
Size	25-60 mm [60]
Porosity	≤ 3% [60, 61]
Average Compressive Strength	≥ 1000 Kg/cm ² [60, 61]
Mass Density	≥ 1400 [61]
Specific Gravity	≥ 2.6 [60, 61]
Organic and mud content	≤ 0.5% [60, 61]
Oil Content	≤ 0.2% [60]
Abrasion – Los Angeles	≤ 25% [60–63]
Absorption	≤ 3% [60, 64]

2.3.4 Sub-ballast

The sub-ballast layer is a filter layer between the subgrade and the ballast layers that must be able to drain water properly. The minimum thickness of the sub-ballast layer is 15 cm [60]. The sub-ballast layer consisting of fine gravel, medium, or coarse gravel sand meets the following requirements (Table 5).

Table 5: Sub-ballast specifications [60, 61]

ASTM sieve standard	% Passing
2 1/2"	100
3/4"	55 – 100
No. 4	25 – 95
No. 40	5 – 35
No. 200	0 – 10

Sub-ballast material can be gravel or a mixture of crushed stone and sand. It should not have organic material content for more than 5%. The sub-ballast material, which is a mixture of crushed stone and sand, must contain at least 30% of the crushed stone, 1500 Kg/m³ of mass density, and 2.6 of specific gravity. The thickness of sub-ballast layer in Indonesia's conventional track is 0.40 m [61].

2.3.5 Superpave performance grade of asphalt

This research used the Superpave PG70-28 with aggregate gradation and volumetric design values as provided in Table 6 and the asphalt layer temperature through seasons are shown in Table 7.

Guinta and Pisano [66] proposed the visco-elastoplastic constitutive model for asphalt concretes able to reproduce the non-linear time-dependent behavior of such materials. In this study, the asphalt dynamic complex modulus was computed using the empirical Witczak E^* predictive model (Eq. (1)).

$$\log |E^*| = -1.249937 + 0.02923\rho_{200} - 0.00167(\rho_{200})^2 - 0.002841\rho_4 - 0.058097V_a - 0.802208 \frac{V_{beff}}{V_{beff} + V_a} + \frac{3.971977 - 0.0021\rho_4}{1 + e^{[-0.603313 - 0.31335\log(f) - 0.393532\log(\eta)]}} + \frac{0.003958\rho_{38} - 0.000017(\rho_{38})^2 + 0.00547\rho_{34}}{1 + e^{[-0.603313 - 0.31335\log(f) - 0.393532\log(\eta)]}} \quad (1)$$

Table 7: Asphalt layer Temperature through seasons

Binder grade	Temperature season 1 (°C)	Temperature season 2 (°C)
PG 70-28	15	21

Table 8: Viscosity of binder PG70-28

Binder Grade	Viscosity (η , 10 ⁶ Pa.S) season 1	Viscosity (η , 10 ⁶ Pa.S) season 2
PG 70-28	3.77	0.92

Table 9: Poisson's ratio and Young's modulus throughout seasons

Layer	Poisson's ratio ν	Season 1 (MPa)	Season 2 (MPa)
Asphalt Layer PG70-28	0.45	7646.12	5093.23

Table 6: Aggregate gradation and volumetric design of asphalt layer [65]

Binder grade	% Passing 200, ρ_{200} (0.075 mm)	% Retained No. 4, ρ_4 (4.75 mm)	% Retained No. 3/8, ρ_{38} (9.5 mm)	% Retained No. 3/4, ρ_{34} (19 mm)	% Air Voids, V_a	% Volume of bitumen, V_{beff}
PG 70-28	5	60	37	6	2.55	4.3

With $|E^*|$ is the dynamic modulus (10^5 psi), f is loading frequency (Hz), η is binder viscosity at the age and temperature of interest (10^6 Poise), V_{beff} is effective binder content (% by volume), V_a is volume of air voids (%), ρ_{200} is % passing #200 or 0.075-mm sieve, ρ_4 is cumulative % retained on #4 or 4.76 mm sieve, ρ_{38} is cumulative % retained on 3/8 in or 9.5 mm sieve, and ρ_{34} is cumulative % retained on 3/4 in or 19 mm sieve.

In the predictive equation model, the viscosity is used to specify the shift factors and to describe the temperature effects. From the ASTM viscosity temperature relationship as Eq. (2), the viscosity at the temperature of interest can be determined for un-aged binders.

$$\log \log \eta = A + VTS \log T_R \quad (2)$$

With A and VTS are the parameters of regression, η is viscosity of binder (cP), T_R is temperature (Rankine). Table 8 shows the detail of asphalt binder viscosity (η , 10^6 Pa.S) for different seasons, while Table 9 presents the Poisson's Ratio and Youngs Modulus through seasons based on the empirical Witczak E^* predictive model.

2.3.6 Failure criteria and damage analysis

In conventional tracks, the KENTRACK Program could calculate the vertical compressive stress, (σ_c (psi)), occurring at the top of the subgrade layer, indicating a potential long-term track-bed settlement failure. In asphaltic underlayment track-bed, the KENTRACK Program was not only able to calculate the vertical compressive stress (σ_c) occurring at the top of the subgrade layer, but also the tensile strain

(ϵ_t) occurring at the bottom of the asphalt layer, indicating the potential for fatigue cracking.

Concerning the subgrade damage analysis in conventional and asphaltic tracks, the excessive permanent deformation could act as indicator of possible failure. Deformation was governed by the vertical compressive stress on the top of the subgrade. By considering the modulus of subgrade, E_s (psi), the number of allowable repetitions before failure, N_d , was calculated based on Eq. (3) [56]:

$$N_d = 4.837 \times 10^{-5} \sigma_c^{-3.734} E_s^{3.583} \quad (3)$$

Regarding the asphalt damage analysis in the asphaltic track, the fatigue cracking could act as indicator of possible the failure. Fatigue cracking was governed by the tensile strain at the bottom of the asphalt. By considering the dynamic modulus of asphalt, E_a (psi), The number of allowable repetitions before failure, N_a , was calculated based on Eq. (4) [56]:

$$N_a = 0.0795 \epsilon_t^{-3.291} E_a^{-0.853} \quad (4)$$

Figure 2: Cross-sectional views of conventional track [48]

Table 10: Mechanical properties of conventional track layers

Layer	Poisson's ratio	Coefficient K2	Youngs modulus (MPa)	Layer thickness (m)	Unit weight (Kg/m ³)
Ballast	0.35	0.5	125.00	0.30	1800
Sub-ballast	0.35	0.5	100.00	0.15	1600
Subgrade	0.4	0	80.00	4.00	2150

Table 11: Mechanical properties of asphaltic track layers in season 1 and season 2

Layer	Poisson's ratio	Coefficient K2	Young mod. in season 1 (MPa)	Young mod. in season 2 (MPa)	Layer thickness (m)	Unit weight (Kg/m ³)
Ballast	0.35	0.5	125.00	125.00	0.30	1800
Asphalt	0.45	0	7646.12	5093.23	0.15	2400
Subgrade	0.4	0	80.00	80.00	4.00	2150

3 Results and discussions

3.1 Conventional track

The cross-sectional of the conventional track comprising ballast, sub-ballast, and subgrade is depicted in Figure 2.

The mechanical properties and the layer thickness of conventional track are shown in Table 10.

3.2 Asphaltic underlayment track

The cross-sectional of the asphaltic underlayment track is depicted in Figure 3. Since the asphalt layer substituted the sub-ballast layer, the asphaltic underlayment track consisted of a ballast, AC layer, and subgrade [53, 67–69].

The mechanical properties and the layer thickness of asphaltic underlayment track are shown in Table 11.

Figure 3: Cross-sectional views of asphaltic underlayment track [48]

3.3 Compressive stress and tensile strain analysis

The comparison of subgrade and asphalt service life for various thicknesses of sub-ballast and asphalt layers due to existing train wheel loads (13,445 Kg/wheel) in operations are presented in Table 12. It is apparent from this table that though the sub-ballast layer in conventional tracks is twice thicker than the AC layer with PG70-28 in asphaltic underlayment track, the compressive stress on top of the subgrade in the asphaltic underlayment track is still slightly lower than that of in the conventional track for all thickness variation. As expected, the asphaltic underlayment track has the longer subgrade service life although with 50% less structural thickness compared to the conventional track.

The outputs, as shown in Table 12, also indicate that by increasing the sub-ballast thickness in conventional track 6 times higher than 0.10 m resulted in the subgrade compressive stress reduction and subgrade service life enhancement by around 40.1% and almost 6.8 times respectively. In addition, by increasing the AC layer thickness in asphaltic underlayment track 6 times higher than 0.05 m resulted in the subgrade compressive stress reduction and subgrade service life enhancement by around 41.8% and almost 7.9 times respectively.

Further analysis showed that 0.20 m thickness of AC layer could give around 47.55 years of subgrade service life in the asphaltic underlayment track, which is considered as a long-life track structure if this track design applied in the future of Indonesian rail track systems. This result may be explained by the fact that the AC layer in the asphaltic underlayment track design is applied as a sublayer

Table 12: Subgrade compressive stress and asphalt tensile strain due to 13,445 Kg/wheel

Track type	Sub-ballast/ asphalt layer thickness (m)	Subgrade comp. stress (kPa)	Subgrade service life (years)	Asphalt tensile strain	Asphalt service life (years)
Conventional	0.10	61.02	11.78	n/a	n/a
	0.20	54.47	18.01	n/a	n/a
	0.30	48.17	28.54	n/a	n/a
	0.40	43.35	42.35	n/a	n/a
	0.50	39.67	59.03	n/a	n/a
	0.60	36.53	80.27	n/a	n/a
Asphalt underlayment	0.05	61.53	11.88	9.1786×10^{-5}	38.89
	0.10	53.93	19.69	8.4007×10^{-5}	49.89
	0.15	48.06	30.99	8.2589×10^{-5}	52.78
	0.20	42.81	47.55	7.6541×10^{-5}	67.92
	0.25	39.18	68.02	7.2790×10^{-5}	82.17
	0.30	35.81	93.33	6.8888×10^{-5}	97.59

Table 13: Subgrade compressive stress and asphalt tensile strain for 20,168 Kg/wheel

Track type	Sub-ballast/ asphalt layer thickness (m)	Subgrade comp. stress (kPa)	Subgrade service life (years)	Asphalt tensile strain	Asphalt service life (years)
Conventional	0.10	91.21	2.62	n/a	n/a
	0.20	79.38	4.42	n/a	n/a
	0.30	70.59	6.87	n/a	n/a
	0.40	63.49	10.20	n/a	n/a
	0.50	58.11	14.18	n/a	n/a
	0.60	53.41	19.45	n/a	n/a
Asphalt underlayment	0.05	89.14	2.98	1.3916×10^{-4}	9.92
	0.10	78.11	4.95	1.2757×10^{-4}	12.74
	0.15	69.69	7.71	1.2389×10^{-4}	14.00
	0.20	62.18	11.81	1.1458×10^{-4}	18.14
	0.25	56.90	16.89	1.0851×10^{-4}	22.17
	0.30	51.92	23.40	1.0236×10^{-4}	26.52

Table 14: Subgrade compressive stress and asphalt tensile strain due to 26,890 Kg/wheel

Track Type	Sub-ballast/ asphalt layer thickness (m)	Subgrade comp. stress (kPa)	Subgrade service life (years)	Asphalt tensile strain	Asphalt service life (years)
Conventional	0.10	117.91	1.01	n/a	n/a
	0.20	103.81	1.62	n/a	n/a
	0.30	92.51	2.50	n/a	n/a
	0.40	83.23	3.71	n/a	n/a
	0.50	76.18	5.16	n/a	n/a
	0.60	69.89	7.13	n/a	n/a
Asphalt underlayment	0.05	115.89	1.13	1.8900×10^{-4}	3.66
	0.10	101.45	1.87	1.7158×10^{-4}	4.83
	0.15	90.60	2.90	1.6517×10^{-4}	5.46
	0.20	80.79	4.44	1.5248×10^{-4}	7.11
	0.25	73.96	6.34	1.4397×10^{-4}	8.77
	0.30	67.48	8.83	1.3551×10^{-4}	10.58

Table 15: The change in subgrade service life in conventional track due to three different magnitudes of wheel loads

Sub-ballast thickness (m)	13,445 Kg/Wheel	Subgrade life reduction	20,168 Kg/Wheel	Subgrade life reduction	26,890 Kg/Wheel
0.15	11.78	75%	2.62	63%	1.01
0.30	18.01		4.42		1.62
0.45	28.54		6.87		2.50
0.60	42.35	91%	10.20		3.71
0.75	59.03		14.18		5.16
0.90	80.27		19.45		7.13
Subgrade life reduction if 13,445 Kg/Wheel to 26,890 Kg/Wheel			91%		

Table 16: The change in subgrade service life in asphaltic underlayment track due to three different magnitudes of wheel loads

Asphalt thickness and load weight	13,445 Kg/Wheel	Subgrade life reduction	20,168 Kg/Wheel	Subgrade life reduction	26,890 Kg/Wheel
0.05	11.88	74%	2.98	62%	1.13
0.10	19.69		4.95		1.87
0.15	30.99		7.71		2.90
0.20	47.55		11.81		4.44
0.25	68.02		16.89		6.34
0.30	93.33		23.40		8.83
Subgrade life reduction if 13,445 Kg/Wheel to 26,890 Kg/Wheel			90%		

Table 17: The change in AC layer service life in asphaltic underlayment track due to three different magnitudes of wheel loads

Asphalt thickness and load weight	13,445 Kg/Wheel	Subgrade life reduction	20,168 Kg/Wheel	Subgrade life reduction	26,890 Kg/Wheel
0.05	38.89	73%	9.92	61%	3.66
0.10	49.89		12.74		4.83
0.15	52.78		14.00		5.46
0.20	67.92		18.14		7.11
0.25	82.17		22.17		8.77
0.30	97.59		26.52		10.58
Subgrade life reduction if 13,445 Kg/Wheel to 26,890 Kg/Wheel			89%		

between ballast and subgrade. Therefore, this layer could be maintained in a protected environment because it is buried under the ballast, which provides protection, such as minimizing sunlight exposure and temperature changes.

The comparison of subgrade and asphalt service life for various thicknesses of sub-ballast and asphalt layers from 20,168 Kg/wheel (1.5 times of existing operated train wheel load) are presented in Table 13. The qualitative data presented previously for the subgrade compressive stress and asphalt tensile strain due to the currently operated train wheel loads were applicable in this case as well. The significant difference was the response magnitudes, both subgrade compressive stress and asphalt tensile strain, were much higher than before.

The results, as presented in Table 13, denote that by rising the sub-ballast thickness in conventional track 6 times higher than 0.10 m led to the subgrade compressive stress reduction and subgrade service life improvement by around 41.4% and around 7.4 times respectively. In addition, by enhancing the AC layer thickness in the asphaltic underlayment track 6 times higher than 0.05 m led to the

subgrade compressive stress reduction by around 41.8% and subgrade service life enhancement by 7.9 times.

Further investigation revealed that 0.20 m thickness of AC layer in asphaltic underlayment track for 20,168 Kg/wheel load could deliver only about 11.81 years of asphalt service life, which is lower than the expected result to be considered as long-life track structure if this track design applied in the future of Indonesian rail track systems. As can be seen in Table 13, asphaltic underlayment track with 0.30 m of AC layer could functions well to serve the train operation with 1.5 times higher wheel loads up to 23 years.

The comparison of subgrade and asphalt service life for various thicknesses of sub-ballast and asphalt layers for 26,890 Kg/wheel (2 times of currently operated train wheel load) are presented in Table 14. As Table 14 presents, the compressive stress on top of the subgrade in the conventional track is slightly higher than that of in the asphaltic underlayment track for all thickness variation although the AC layer in the asphaltic underlayment track is twice thinner than the sub-ballast layer in the conventional track. As expected, the conventional track has the shorter sub-

Figure 4: Relationship between predicted subgrade compressive stress and service life with sub-ballast thickness and wheel loads magnitude in conventional track

Figure 5: Relationship between predicted subgrade compressive stress and service life with asphalt thickness and wheel loads magnitude in asphaltic underlayment track

Figure 6: Relationship between predicted asphalt tensile strain and service life with asphalt thickness and wheel loads magnitude in asphaltic underlayment track

Table 18: Predicted subgrade service life in conventional track based on three different magnitudes of wheel loads and six different sub-ballast thicknesses

Wheel load	Sub-ballast thickness (variable X, in meter)	Regression formula	Predicted subgrade service life (variable Y, in years)
13,445 Kg/Wheel	0.10	$y = 0.0006x^3 + 1.7727x^2 + 1.2592x + 8.6567$ $R^2 = 0.9999$	11.78
	0.20		18.01
	0.30		28.54
	0.40		42.35
	0.50		59.03
	0.60		80.27
20,168 Kg/Wheel	0.10	$y = 0.0232x^3 + 0.1751x^2 + 1.139x + 1.2733$ $R^2 = 0.9999$	2.62
	0.20		4.42
	0.30		6.87
	0.40		10.20
	0.50		14.18
	0.60		19.45
26,890 Kg/Wheel	0.10	$y = 0.0091x^3 + 0.0669x^2 + 0.3649x + 0.5633$ $R^2 = 0.9999$	1.01
	0.20		1.62
	0.30		2.50
	0.40		3.71
	0.50		5.16
	0.60		7.13

Table 19: Predicted subgrade service life in asphaltic underlayment track based on three different magnitudes of wheel loads and six different sub-ballast thicknesses

Wheel load	Sub-ballast thickness (variable X, in meter)	Regression formula	Predicted subgrade service life (variable Y, in years)
13,445 Kg/Wheel	0.10	$y = 0.025x^3 + 1.955x^2 + 1.5214x + 8.43$ $R^2 = 1$	11.88
	0.20		19.69
	0.30		30.99
	0.40		47.55
	0.50		68.02
	0.60		93.33
20,168 Kg/Wheel	0.10	$y = 0.0196x^3 + 0.365x^2 + 0.6825x + 1.9233$ $R^2 = 1$	2.98
	0.20		4.95
	0.30		7.71
	0.40		11.81
	0.50		16.89
	0.60		23.40
26,890 Kg/Wheel	0.10	$y = 0.0097x^3 + 0.1163x^2 + 0.3066x + 0.7$ $R^2 = 0.9999$	1.13
	0.20		1.87
	0.30		2.90
	0.40		4.44
	0.50		6.34
	0.60		8.83

Table 20: Predicted AC layer service life in asphaltic underlayment track based on three different magnitude of wheel loads and six different sub-ballast thicknesses

Wheel load	AC layer thickness (variable X, in meter)	Regression formula	Predicted AC layer service life (variable Y, in years)
13,445 Kg/Wheel	0.10	$y = 0.0646x^3 + 0.5275x^2 + 5.1914x + 33.953$ $R^2 = 0.9912$	38.89
	0.20		49.89
	0.30		52.78
	0.40		67.92
	0.50		82.17
	0.60		97.59
20,168 Kg/Wheel	0.10	$y = 0.004x^3 + 0.2927x^2 + 1.083x + 8.7267$ $R^2 = 0.9947$	9.92
	0.20		12.74
	0.30		14.00
	0.40		18.14
	0.50		22.17
	0.60		26.52
26,890 Kg/Wheel	0.10	$y = 0.0039x^3 + 0.0899x^2 + 0.5817x + 3.05$ $R^2 = 0.9962$	3.66
	0.20		4.83
	0.30		5.46
	0.40		7.11
	0.50		8.77
	0.60		10.58

grade service life even though with 2 times higher structural thickness compared to the asphaltic underlayment track.

It can be seen from the data in Table 14 that by enhancing the AC layer thickness in the asphaltic underlayment track 6 times higher than 0.05 m could cause the subgrade compressive stress reduction by 41.8% and subgrade service life enhancement by approximately 7.8 times. In addition, by rising the sub-ballast thickness in conventional track 6 times higher than 0.10 m, the subgrade compressive stress gets lower by 40.7% and subgrade service life improved by 7.1 times.

Further findings discovered that 0.20 m thickness of AC layer in asphaltic underlayment track for 26,890 Kg/wheel of train load could last no more than 5 years of asphalt service life, which is unacceptable to be applied in the future of Indonesian rail track systems. As presented by Table 14, asphaltic underlayment track with 0.30 m of AC layer only able to serve the train operation with wheel load weighted 2 times as much less than 9 years.

Tables 15, 16, and 17 illustrate the change in subgrade service life in conventional track as well as subgrade service life and AC layer service life in asphaltic underlayment track, respectively, due to 3 different magnitude of wheel loads. What interesting in these data is that those three layers have similar percentage of service life reduction when the train wheel loads increased by 50% (either

from 13,445 Kg/wheel to 20,168 Kg/wheel) and 100% (from 13,445 Kg/wheel to 26,890 Kg/wheel).

Figure 4 presents the relationship between predicted subgrade compressive stress and service life with sub-ballast thickness and wheel loads magnitude in conventional track. Figure 5 shows the relationship between predicted subgrade compressive stress and service life with asphalt thickness and wheel loads magnitude in asphaltic underlayment track. Figure 6 illustrates the relationship between predicted asphalt tensile strain and service life with asphalt thickness and wheel loads magnitude in asphaltic underlayment track. The bar charts in those pictures indicate that the linear improvement of sub-ballast by 0.10 m and AC layer thickness by 0.05 m resulted in the non-linear reduction of subgrade compressive stress and asphalt tensile strain as well as led to the non-linear enhancement of subgrade and AC layer service layer.

Moreover, Tables 18 and 19 provide the non-linear formulas that can be utilized to estimate the subgrade layer service life (Y) in conventional track and asphaltic underlayment track, respectively, based on the sub-ballast layer design thickness (X). In addition, Table 20 provides the non-linear formulas that can be utilized to predict the AC layer service life (Y) in asphaltic underlayment track based on the AC layer design thickness (X).

It is apparent from those figures that all formulas have a high R^2 -Value as an indication of a better fit for the regression model to predict subgrade and AC layer service life.

4 Conclusions

This study evaluated the effect of a sub-ballast and asphalt layer thickness and freight train traffic with low operational speed on mechanical behavior of conventional track and asphaltic underlayment track. Mechanistic-empirical design concept was utilized in this research to predict the design life of subgrade and AC layer. The evidence from this study shown that for all wheel loads variations, the subgrade service life in the asphaltic underlayment track that consists of 0.20 m AC layer exceeds the subgrade service life in Indonesia's conventional track that consists of 0.40 m sub-ballast layer. The findings of this study also suggest that the asphalt underlayment track with 0.20 m thick of AC layer that contains grade PG70-28 binder could be beneficial to be applied in Indonesian railway system so that the heavy freight train operation could be run with more tonnage and the rail track could be constructed with less volume of works.

Additional investigation should be organized to analyze the mechanical behavior and service life of the same properties and thickness of AC layer that constructed in the asphaltic overlayment track type where the AC layer laid directly below the rail structure or on top of the unbound granular structure. Since this study still consider the mechanistic-empirical method, therefore, in the next research, it is suggested to perform full-mechanistic approach and finite element simulation using ABAQUS Software to accurately capture and predict Indonesia's conventional track and asphaltic track-bed responses subjected to different operating speed and various axle loads of Babaranjang freight train.

Further studies should be conducted to determine the suitable Superpave binder grade for Indonesian railway track and Indonesian climate. Even though the Babaranjang trains operated with a low speed of only 70 kph, however, their load weight of 60 cars/train set significantly affect the mechanical behavior and design life of both conventional and asphaltic underlayment rail tracks. Next examination on the 3D finite element modelling in ABAQUS software could be beneficial in understanding the effect of moving freight train and its wheelset configuration on the mechanical behavior of either asphaltic underlayment or asphaltic overlayment track.

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