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Sub-grade Service Life and Construction Cost of Ballasted, Asphaltic Underlayment and Combination Rail Track Design

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ABSTRACT

A study that could help a rail track engineer in determining the configuration and thickness design of railway track in accordance with the targeted service life and available budget is absolutely necessary for the benefit of long-term railway development. This paper aims to predict the sub-grade service life of a railway track and to compute its construction cost as well as its service life-cost ratio based on the compressive stresses on the top of the sub-grade. The outputs indicate that the longest sub-grade service life and the highest construction cost come from asphaltic underlayment track, followed by the combination track and the ballasted track. The increase of sub-ballast thickness by 5 cm in an all-granular track can improve the sub-grade service life by only 20% to 50%. However, the increase of asphalt thickness by 5 cm in an asphaltic underlayment track and in a combination track may improve sub-grade service life by 130% to 190% and 63% to 83%, respectively. Addition of sub-ballast thickness by 5 cm will raise all-granular track construction cost only around 80 million rupiahs/km or 5606 USD/km. Nevertheless, the addition of asphalt thickness by 5 cm in asphaltic underlayment and combination tracks may increase construction cost up to 500 million rupiahs/km (35,040 USD/km) or around 7% to 10%.

KEYWORDS: Asphalt underlayment track, Ballasted track, Construction cost, Service life, Sub-ballast, sub-grade.

INTRODUCTION

Heavy trains and environmental loads can cause a decline in mechanical and geometrical performance of ballast structure layer (Zakeri and Mosayebi, 2016). The ballasted (conventional) track may experience track misalignments and higher ballast deformations (Fig. 1a). Ballast material deficiency also occurs due to rainwater erosion and soil subsidence (Fig. 1b). Moreover, mud pumping is characterized by the fast-upward migration of sub-soil fine particles through the ballast void, known as the worst degradation phenomenon for the railway sub-structure (Duong et al., 2013) as can be seen in Fig. 1c. In addition, ballast and sub-ballast material with poor condition can be a benchmark for the application of train speed restrictions (Setiawan, 2016) as well as the determination of track quality index and the need of maintenance work (Setiawan and Rosyidi, 2016).

The railway track instability is one of the primary causes of train derailments. One of the important railway lines in Indonesia, the south Sumatera rail track, is dedicated not only for passenger trains, but also for freight trains, such as Babaranjang train which transports coal. Unfortunately, during the last decade, there were several derailment accidents in the line involving this special train. The accidents have caused not only material loss and damages to the coal, railroad components and carriages, but also delays in other train schedules. Furthermore, the Indonesian railway system is still a conventional one. It is just justifiable therefore that now the Indonesian government is focusing on efforts to improve railway stability to ensure passenger safety and establish a long-lasting rail track structure.

Even though Plooy and Grabe (2017), Woodward et al. (2012), Kennedy et al. (2013) and Woodward et al.

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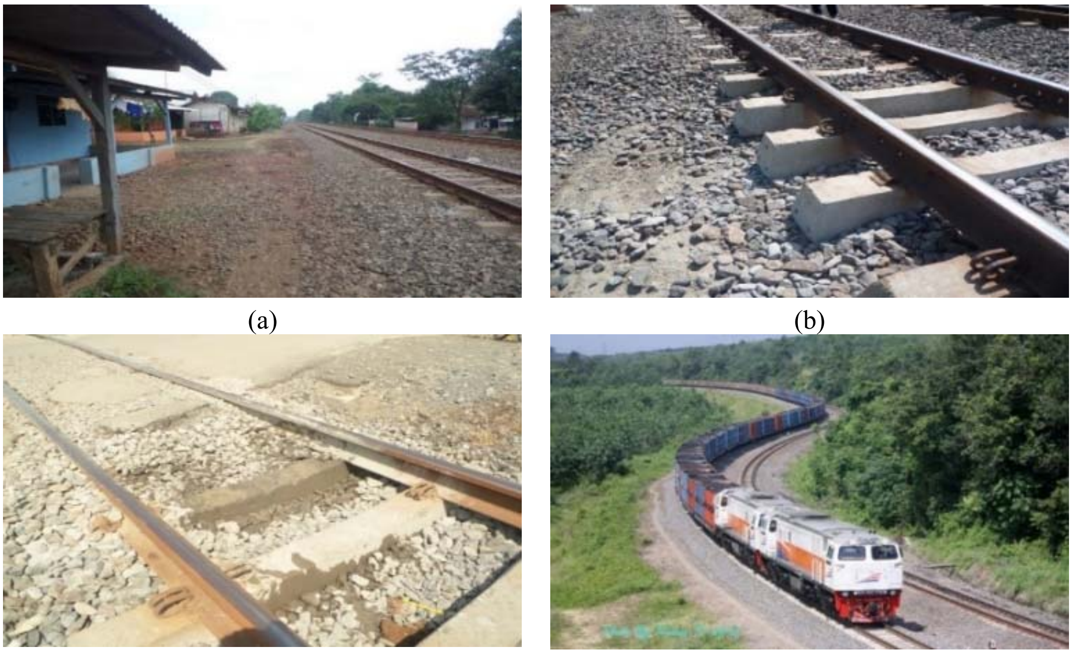
(2014) have been developing a polyurethane polymer to inhibit settlement and improve the stability of railway track, its availability in the railway industry still poses an issue. On the other hand, slab track has been widely developed worldwide in recent years, since it has a higher structural stability and a better ride comfort along with an enhanced track performance (Yang et al., 2015; Zhu and Cai, 2014; Bian et al., 2014).


(a) (b)

(c) (d)

Figure (1): (a) Ballast deformation, (b) Mud pumping, (c) Ballast material deficiency and (d) Babaranjang train (www.kalogistics.co.id) in Indonesian railways

However, as discovered by Auersch (2012), Gautier (2015), Feng et al. (2017), Giannakos (2016), Song et al. (2014) and Galvin et al. (2010), slab track requires resilient slab mat and elastic pad of the fastening as special countermeasures against noise and ground vibration unavoidable problems. Therefore, dynamic forces between wheels and rails are crucial parameters in slab track analysis and design, as they are significantly affected by wheel-rail irregularities (Zhu and Cai, 2014; Sadeghi et al., 2016; Mazilu, 2009; Lei and Noda, 2002; Sun and Dhanasekar, 2002). Due to inappropriate manufacture and maintenance, interfacial crack issue in a slab track is ubiquitous. The propagated deterioration under temperature variations and repeated train load in a concrete slab track is another crucial concern. It was recently found that crack propagation is slower in dry regions with adequate drainage than in wet regions without adequate drainage. This indicates that the coupling effect of moisture and train load may play a significant function in the crack propagation process in a concrete slab track (Cao et al., 2016; Zhu and Cai, 2014). In other words, the mechanical behaviors of railway superstructures are greatly affected by environmental loads involving temperature and rainwater due to the poor heat conductivity of the slab track system (Song et al., 2014).

Ballasted track does not only yield the best performance in terms of construction cost, but also presents a lower environmental impact than the slab track system, since there is an appreciable carbon footprint coming from the cement used in slab track construction. In opposite, by referring to long-term analyses, the slab-based track seems to perform better than the conventional one in regards to its Reliability, Availability, Maintainability and Safety (RAMS) as well as Life Cycle Cost (LCC) (Praticò and Guinta, 2017). However, it requires a homogeny and good-quality sub-grade. This kind of construction should be avoided in deep cutting clay soils, embankments on soft peat layers or in earthquake areas, since it is fragile in a place with significant settlement (Song et al., 2014; Zhu and Cai, 2014; Setiawan et al., 2013; Robertson et al., 2015).

Alternatively, scrap rubber may also be selected for the treatment of ballast layer (Sol-Sánchez et al., 2014; Sol-Sánchez et al., 2015; Signes et al., 2016; Setiawan and Rosyidi, 2018a; Asgharzadeh et al., 2018; Rosyidi et al., 2019) and asphalt (D'Andrea et al., 2012; Di Mino et al., 2012; Lee et al., 2014; D'Angelo et al., 2016; D'Angelo et al., 2017; Setiawan and Rosyidi, 2019; Bressi et al., 2018; Setiawan and Rosyidi, 2018b; Setiawan, 2018; Setiawan et al., 2019). Setiawan and Rosyidi (2018a) in their experiment found out that an increase in compaction up to 100% in the ballast layer with scrap rubber was able to increase the elastic modulus of the layer only by 6%. In addition, various-sized scrap rubber has an effective role in enhancing ballast durability. However, ballast materials with scrap rubber tend to bounce off each other when the compaction process with manual pounding is being exercised, showing that the ballast sample does not have sufficient and proper density and stiffness.

Rosyidi et al. (2019) found that the addition of scrap rubber could decrease ballast layer stiffness as shown by the increase in vertical deformation and the decrease in elastic modulus. However, the use of it for the ballast material could minimize the aggregates' damage significantly, as it can reduce the friction and collision potential between aggregates and as a result, ballast material degradation can be impeded. Furthermore, scrap rubber with uniform size in ballast layer could produce a higher elastic modulus, but a lower ballast durability compared to scrap rubber with continuously graded size.

Setiawan and Rosyidi (2019), Setiawan and Rosyidi (2018b) and Setiawan et al. (2019) have conducted studies to evaluate the effect of scrap rubber and asphalt application on the characteristics of aggregate abrasion and vertical deformation of ballast layer. The 60/70 grade asphalt penetration with a percentage of 2% (Setiawan and Rosyidi, 2019; Setiawan et al., 2019) and 3% (Setiawan and Rosyidi, 2018b; Setiawan et al., 2019) of the total specimen weight was used in their research. It was heated in the oven for 5 hours at a temperature of 155ºC. 10% scrap rubber was obtained from vehicle tires. 2% asphalt combined with scrap rubber in various sizes between No.4, 3/8", 1/2", 3/4" and 1" could produce the lowest abrasion value (up to 57%). Meanwhile, 2% asphalt had the potential to increase the capacity to retain loads up to 28% and minimize vertical deformation, while at the same time increasing elastic modulus up to 21% (Setiawan and Rosyidi, 2019). Setiawan and Rosyidi (2018b) also found out that the application of 3% asphalt and 10% scrap rubber could significantly minimize aggregate abrasion in the ballast structure up to 80%. More compaction times and higher percentages of asphalt will produce a higher elastic modulus, a lower ballast material abrasion and a lower vertical deformation (Setiawan et al., 2019).

In general, Setiawan and Rosyidi (2019), Setiawan and Rosyidi (2018b) and Setiawan et al. (2019) concluded that the effect of asphalt emulsion was more significant or sensitive than that of scrap rubber in improving ballast structural mechanical behavior. Therefore, Setiawan (2019) in his research only applied 60/70 grade penetration asphalt in the ballast layer to evaluate the fouled-ballast and clean-ballast mechanical behavior with 2% and 4% asphalt in one and three ballast surface layers. The study also found out that if there were more layers poured with asphalt and the percentage of penetration grade of asphalt 60/70 was higher, the asphalt would be more effective in minimizing ballast abrasion.

Other than that, the asphalt layer has been studied by several researchers and has been applied in a lot of places. According to Fang et al. (2011), the asphaltic layer substructure would give advantage for long-term stability, since it has the capability to recover the residual vertical deformation of the track structure to a certain extent. Typically, this asphalt-bound impermeable layer is 125 to 200 mm thick and functions to improve track bed performance, protect the rail track bed and support the overlying ballast (Rose et al., 2002; Rose et al., 2010a; Rose, 2013). Rose et al. (2009), Malloy et al. (2014) and Malloy et al. (2015) used the asphaltic track in their research for the cost-effective rehabilitation technique of level crossings.

Atashafrazeh and Shirmohammadi (2016) developed a 2-dimensional model to analyze the displacements, velocities and accelerations of a 100-m train track and investigate the effects of wheel flatness behavior on railway tracks. Several studies have been performed to establish computer models capable of designing and analyzing the railroad track beds structure utilizing the finite element system. Some of those computer models are FEART (Rose et al., 2014; Fateen, 1972), ILLITRACK (Robnett et al., 1975; Rose et al.,

2014) and GEOTRACK (Rose et al., 2014; Chang et al., 1980). However, they can only be used for analyzing all-granular ballast track beds, but cannot function to examine the behavior of asphaltic tracks. For that reason, KENTRACK program which is capable of analyzing the stress-strain distribution for both all-granular and asphaltic tracks was developed (Rose et al., 2014; Huang et al., 1984; Rose et al., 2010b).

This study does not only aim to compute critical compressive stresses and tensile strains within the rail track structure, but also to predict the sub-grade service life and calculate the construction cost of all-granular, asphaltic underlayment and combination railway tracks. Furthermore, the role of sub-ballast and asphalt layer thickness on mechanical behavior, design life and construction cost will be presented in this paper. Lastly, a comparison between sub-grade service life and construction cost of each track type will also be discussed. The outputs of this study will be crucial for the railway industry, since it may help railway track engineers and stakeholders in deciding the most efficient rail track type in terms of service life-cost ratio. If the railway track engineer is able to build a long-lasting rail track structure, train operators will have a good chance to operate trains with a higher speed and a higher axle load. Furthermore, more efficient construction cost and lower life cycle cost will be very beneficial for future long-term development.

RESEARCH METHOD

Heavy-load Train Traffic from Babaranjang (Batubara Rangkaian Panjang)

The main object of this research is the railway track dedicated to Babaranjang train. This track has one of the heaviest traffics in Indonesia (Fig. 1d). Although there are only 20 trains/day and the maximum operation speed is only 70 kph, each train set may have up to 60 cars (Setiawan, 2016).

Rail Track Design

Table 1 presents the combination of asphalt and sub-ballast structure in each rail track design for the KENTRACK analysis. The maximum thickness of asphalt and sub-ballast layer combination is 30 cm. Each combination will be assigned with code "A" for asphalt thickness and "S" for sub-ballast thickness and will be corresponded to the rail track type; i.e., all-granular, asphaltic underlayment and combination. All-granular rail track means that the track bed contains ballast and sub-ballast. Asphaltic underlayment track means that the track bed contains ballast and asphaltic layer, while the combination track means that the track bed consists of ballast, asphaltic and sub-ballast layers. Code A-5&S-20 stands for a rail track with a 5-cm asphalt layer and a 20-cm sub-ballast layer.

Table 1. Combination of asphalt and sub-ballast structure in rail track design

Code	Asphalt (cm) or A	Sub-ballast (cm) or S	Rail Track Type
A-0 & S-0	0	0	Baseline
A-0 & S-5	0	5	All-granular
A-0 & S-10	0	10	All-granular
A-0 & S-15	0	15	All-granular
A-0 & S-20	0	20	All-granular
A-0 & S-25	0	25	All-granular
A-0 & S-30	**0**	**30**	**All-granular**
A-5 & S-0	5	0	Asphaltic Underlayment
A-5 & S-5	5	5	Combination
A-5 & S-10	5	10	Combination
A-5 & S-15	5	15	Combination
A-5 & S-20	5	20	Combination
A-5 & S-25	**5**	**25**	**Combination**
A-10 & S-0	10	0	Asphaltic Underlayment
A-10 & S-5	10	5	Combination

Code	Asphalt (cm) or A	Sub-ballast (cm) or S	Rail Track Type
A-10 & S-10	10	10	Combination
A-10 & S-15	10	15	Combination
A-10 & S-20	**10**	**20**	**Combination**
A-15 & S-0	15	0	Asphaltic Underlayment
A-15 & S-5	15	5	Combination
A-15 & S-10	15	10	Combination
A-15 & S-15	**15**	**15**	**Combination**
A-20 & S-0	20	0	Asphaltic Underlayment
A-20 & S-5	20	5	Combination
A-20 & S-10	**20**	**10**	**Combination**
A-25 & S-0	25	0	Asphaltic Underlayment
A-25 & S-5	25	5	**Combination**
A-30 & S-0	**30**	**0**	**Asphaltic Underlayment**

Tonnage and Repetitions Calculation

Table 2 presents the calculation of Babaranjang Train tonnage and repetitions.

Table 2. Babaranjang train specifications (Sekretariat Negara, 2012)

Parameter	Units (US)	Units (SI)
Axle Load	39,683 lbs	18,000 kg
Static Wheel Load (P_s)	19,842 lbs	9,000 kg
V_{max}	43.5 mph	70 kph
V_r	54.4 mph	$1.25V_{max} = 87.5$ kph
Dynamic Wheel Load (P_d) (Talbot)	29,641 lbs/wheel	13,445 kg/wheel
Total weight for one car, 8 wheels	237,130 lbs/car	107,560 kg/car
Each car equals one repetition	107,560 kg/car/repetition	237,130 lbs/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 cars per year	60 cars/train x20 trains/day x 365 days/year = 438,000 repetitions/year	
Considering that Indonesia has two seasons in terms of climate	219,000 repetitions/season	
The tonnage per year (rail track class 1st)	219,000 repetitions/year x 107,560 kg/repetition 23,555,640 tons/year = 23.6 MGT/year	

Rail Specifications

Table 3 presents the rail specifications.

Table 3. Rail specifications (Sekretariat Negara, 2012)

Parameter	Units (US)	Units (SI)
Rail R54 weight per unit length	3.02 lb/in	54 kg/m
Rail R54 section (head) modulus	17.03 inch^3	279 cm^3
Rail R54 Young modulus	29,869,021 psi	2,100,000 kg/cm^2
Rail R54 moment inertia	56.4 in^4	2346 cm^4
Rail R54 tie spring constant (K)	7,000,000 lb/in	1,250,058 kg/cm

Concrete Sleeper Specifications

Table 4 presents the concrete sleeper specifications.

Table 4. Concrete sleeper (Tie) specifications (Sekretariat Negara, 2012)

Parameter	Units (US)	Units (SI)
Number of transverse points	7	
Tie unit weight	0.033 lb/in^3	900 kg/m^3
Tie thickness	130 mm	5.12 inches
Tie width	220 mm	8.66 inches
Tie moment of inertia	12,155.7 cm^4	292.04 inch^4
Tie Young's modulus	E = 6400 * $f_{cu}^{0.5}$, where f_{cu} = 500 kg/cm^2, E = 143,108 kg/cm^2	2,035,474 psi
Tie spacing	60 cm	23.6 inches
Number of seasons	2 (dry and wet seasons)	
Selected seasons for output	1 and 2	
Location number of rails on tie	4	
Tie length	200 cm	78.74 inches
Rail gauge	1067 mm	42 inches

Properties of the Layers

Ballast

In this research, ballast specifications refer to the standard contained in the Indonesian Railways Track Materials requirements (Table 5).

Table 5. Ballast specifications

Parameter	Value
Size	25-60 mm (1-2.5" inches) (Sekretariat Negara, 2012)
Porosity	$\leq$ 3% (Sekretariat Negara, 2012; SNI, 2008a)
Average Compressive Strength	$\leq$ 1000 kg/cm^2 (Sekretariat Negara, 2012)
Specific Gravity	$\geq$ 2.6 (Sekretariat Negara, 2012; SNI, 2008a)
Organic and Mud Content	$\leq$ 0.5% (Sekretariat Negara, 2012; SNI, 1996)
Oil Content	$\leq$ 0.2% (Sekretariat Negara, 2012)
Abrasion – Los Angeles	$\leq$ 25% (Sekretariat Negara, 2012; SNI, 2008b)

Sub-ballast

In this research, sub-ballast gradation refers to the standard contained in the Indonesian Railways Track Materials requirements (Table 6).

Table 6. Sub-ballast specifications (Sekretariat Negara, 2012)

ASTM Sieve Standard	% Passing
2 ½"	100
¾"	55 – 100
No. 4	25 – 95
No. 40	5 – 35
No. 200	0 – 10

60/70 Penetration Grade Asphalt

The most frequently used asphalt types in Indonesia are the ones with 80/100 and 60/70 penetration grades. Table 7 contains the specifications of 60/70 penetration grade asphalt used in this research.

Table 7. 60/70 penetration grade asphalt specifications

Parameter	Method	Specification
Penetration (0.1 mm)	SNI (2011a)	60-70
Viscosity in pascal-second (135°C)	SNI (1991)	385
Softening Point (°C)	SNI (2011b)	$\geq$ 48
Ductility (at 25 °C)	SNI (2011c)	$\geq$ 100
Specific Gravity	SNI (2011d)	$\geq$ 1.0
Oil Losses (%)	SNI (1991)	$\leq$ 0.8

Failure Criteria, Damage Analysis and Sub-grade Service Life

Upon conventional track, KENTRACK can calculate vertical compressive stress (σ_c) that occurs at the top of the sub-grade layer which indicates potential long-term track bed settlement failure. Upon asphalt and sub-ballast combination track bed, this program is not only able to calculate the vertical compressive stress (σ_c) that occurs at the top of the sub-grade layer, but also the tensile strain (ε_t) that occurs at the bottom of the asphalt layer, indicating potential fatigue cracking. Concerning sub-grade damage analysis in conventional and asphaltic tracks, the excessive permanent deformation could control the failure. Deformation is controlled by the vertical compressive stress at the top of the sub-grade. The number of allowable repetitions before failure (N_d) is calculated based on Equation 1 (Asphalt Institute, 1998), where σ_c is the vertical compressive stress (psi) and E_S is the modulus of the sub-grade (psi).

$$N_d = 4.837 \times 10^{-5} \sigma_c^{-3.734} E_s^{3.583} \qquad (1)$$

Regarding asphalt damage analysis in the asphaltic track, at fatigue cracking could control the failure. Fatigue cracking is controlled by the tensile strain at the bottom of the asphalt. The number of allowable repetitions before failure (N_a) is calculated based on Equation 2 (Asphalt Institute, 1998), where ε_t is the horizontal tensile strain and E_a is the asphalt's dynamic modulus (psi).

$$N_a = 0.0795 \varepsilon_t^{-3.291} E_a^{-0.853} \qquad (2)$$

Sub-grade service life is the duration of sub-grade performance until it is considered failed and will strongly affect the structural performance of the railway track, such as causing settlement and track irregularity. When the sub-grade service life almost reaches its end, a huge maintenance and rehabilitation work is fundamentally required to be conducted to prevent train accidents and higher life cycle cost.

Construction Cost

In this research, the construction cost calculation focuses on the material procurement, track work and ballast and sub-ballast work. Table 8 shows an example of construction cost calculation for an all-granular track that has 30 cm sub-ballast layer.

RESULTS AND DISCUSSION

All-granular Rail Track

The cross-sectional view of all-granular track is depicted in Fig. 2. This type of track consists of ballast, sub-ballast, sub-grade and bedrock. The coefficient K2 in Tables 9, 10 and 11 is the regression constant reflecting the ballast and sub-ballast properties.

Table 8. Example of construction cost calculation

No.	Job Description	Volume	Unit	Unit Price (Rupiah, Rp)	Total Price (Rupiah, Rp)
A	**Material Procurement**				
1	Concrete sleeper equipped with elastic rail fastening R54	1,667	Piece	620,000	1,033,333,333
2	Sub-ballast	900	m^3	453,132	407,818,800
3	Ballast	690	m^3	248,243	171,287,670
				Total A	**1,612,439,803**
B	**Track Work**				
1	Rail procurement	1	Kilometer	1,750,000,000	1,750,000,000
2	Carrying and unloading concrete sleeper equipped with elastic rail fastening R54	1,667	Piece	37,794	62,989,700
3	Load, unload / spread R54 rails on location	54	Ton	1,519,693	82,063,395
4	Spread concrete sleeper equipped with elastic rail fastening R54 including loading/unloading and arranging according to the sleeper distance	1,667	Piece	30,980	51,632,566
5	R54 rail welding with aluminothermites including the materials	80	Unit	1,733,634	138,690,745
6	Installing rails R54 into the concrete sleeper equipped with elastic rail fastening	1,000	m	108,053	108,053,220
7	Preparation and installation of kilometer stakes per 100m	10	Unit	574,776	5,747,755
				Total B	**2,199,177,381**
C	**Ballast and Sub-ballast Work**				
1	Transport the ballast by train	690	m^3	96,162	66,351,780
2	Spread the sub-ballast on top of the sub-grade following compaction	900	m^3	32,717	29,445,089.73
3	Working on laying/ inserting ballast into the track including the rail track profile	690	m^3	70,100	48,369,028
4	Lift listring, hand tie tamper up to speed of 20 kph	1,000	m	35,421	35,420,864
5	Lift listring, hand tie tamper up to speed of 40 kph	1,000	m	64,253	64,252,620
6	Lift listring, hand tie tamper up to speed of 60 kph	1,000	m	69,910	69,909,600
7	Lift the listring track with a multi-tie tamper (up to normal train) and PBR machine (3 times)	3,000	m	165,614	496,842,675
Total C					**810,591,656**
Recapitulation					
A. Material Procurement					**1,612,439,803**
B. Track Work					**2,199,177,381**
C. Ballast and Sub-ballast Work					**810,591,656**
Total A+B+C					**4,622,208,840**
Tax 10%					**462,220,884**
Total A+B+C+Tax 10%					**5,084,429,725**

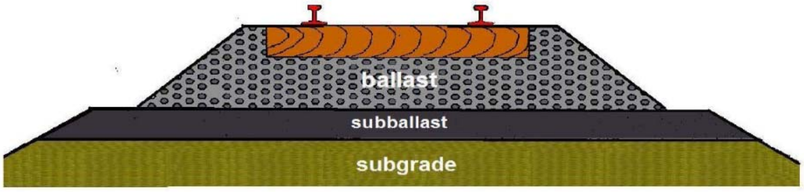


Figure (2): Cross-sectional view of all-granular track (Rose et al., 2009)

The mechanical properties of conventional track materials and layers are presented in Table 9.

Table 9. The mechanical properties of all-granular track layers in dry season and wet season

Layer	Poisson's Ratio	Coefficient K2	Young Modulus in Season 1 and Season 2	Layer Thickness (in)	Unit Weight (lbs/in^3)
Ballast	0.35	0.5	20,000	30 cm (11.81 in)	0.064
Sub-ballast	0.35	0.5	18,000	15 cm (5.91 in)	0.064
Sub-grade	0.4	0	12,000	508 cm (200 in)	0.078
Bedrock	0.5	0	$1*10^{19}$	-	-

Asphaltic Underlayment Rail Track

The cross-sectional view of the asphaltic underlayment track is depicted in Fig. 3. Since the asphalt layer substitutes the sub-ballast layer, the asphaltic underlayment track consists of ballast, asphalt, sub-grade and bedrock (Rose et al., 2014; Anderson and Rose, 2008; Rose and Lees, 2008; Rose and Bryson, 2009).

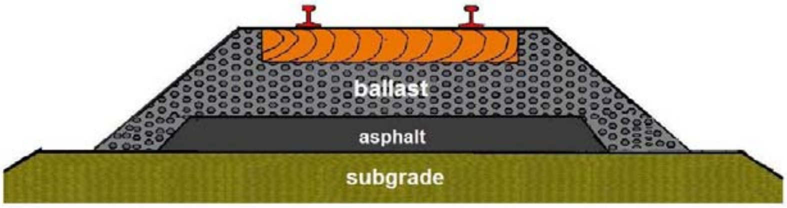


Figure (3): Cross-sectional view of asphaltic underlayment track (Rose et al., 2009)

The mechanical properties of asphaltic track materials and layers are presented in Table 10.

Table 10. The mechanical properties of asphaltic underlayment track layers in dry season and wet season

Layer	Poisson's Ratio	Coefficient K2	Young Mod. in Season 1 (psi)	Young Mod. in Season 2 (psi)	Layer Thickness (in)	Unit Weight (lbs/in^3)
Ballast	0.35	0.5	20,000	20,000	30 cm or 11.81 inch	0.064
Asphalt	0.35	0	846,838	2,382,408	15 cm or 5.91 inch	0.087
Sub-grade	0.4	0	12,000	12,000	508 cm or 200 inch	0.078
Bedrock	0.5	0	$1*10^{19}$	$1*10^{19}$	-	-

Combination Rail Track

The cross-sectional view of the combination track is depicted in Fig. 4. This type of track consists of ballast, asphalt, sub-ballast, sub-grade and bedrock (Rose et al., 2014; Anderson and Rose, 2008; Rose and Lees, 2008; Rose and Bryson, 2009).

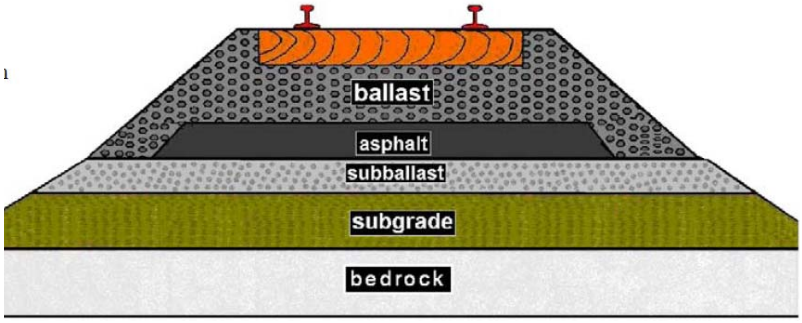


Figure (4): Cross-sectional view of combination rail track (Rose et al., 2009)

The mechanical properties of combination track materials and layers are presented in Table 11.

Table 11. The mechanical properties of combination track layers in dry season and wet season

Layer	Poisson's Ratio	Coefficient K2	Young Mod. in Season 1 (psi)	Young Mod. in Season 2 (psi)	Layer Thickness (in)	Unit Weight (lbs/in^3)
Ballast	0.35	0.5	20,000	20,000	30 cm or 11.81 inch	0.064
Asphalt	0.35	0	846,838	2,382,408	15 cm or 5.91 inch	0.087
Sub-ballast	0.35	0.5	18,000	18,000	15 cm (5.91 in)	0.064
Sub-grade	0.4	0	12,000	12,000	508 cm or 200 inch	0.078
Bedrock	0.5	0	$1*10^{19}$	$1*10^{19}$	-	-

Compressive Stress and Tensile Strain Analysis

The summary of compressive stress-strain and tensile stress-strain analysis for all-granular, asphaltic underlayment and combination tracks with an existing train load of (29,641 lb/wheel) is presented in Table 12. It can be seen that higher compressive stress and tensile strain will result in lower sub-grade and asphalt layer service life. In addition, the highest compressive stress at the top of sub-grade in each sub-ballast thickness of all-granular track type occurs in wet season (season 2) which is rich of rainwater. However, in both asphalt underlayment and combination rail tracks, the highest compressive stress at the top of the sub-grade and the highest tensile strain at the bottom of the asphalt layer occur in season 1 (dry season) that has the highest air temperature.

Table 12. Comparison of sub-grade and asphalt service life for various sub-ballast and asphalt layer thicknesses using KENTRACK program

Track Type	Sub-ballast/Asphalt Layer Thickness	Sub-grade Compressive Stress (psi) and Season	Sub-grade Service Life (years)	Asphalt Tensile Strain (psi) and Season	Asphalt Service Life (years)
Baseline	Without Asphalt and Sub-Ballast	15.05112 (2)	1.83	n/a	n/a
All-granular	5 cm (1.97 inch)	12.75549 (2)	3.40	n/a	n/a
	10 cm (3.94 inch)	11.78010 (2)	4.57	n/a	n/a
	15 cm (5.91 inch)	10.95633 (2)	6.00	n/a	n/a
	20 cm (7.87 inch)	10.17112 (2)	7.96	n/a	n/a
	25 cm (9.84 inch)	9.09297 (2)	12.01	n/a	n/a
	30 cm (11.81 inch)	8.90768 (2)	13.00	n/a	n/a
Asphalt	5 cm (1.97 inch)	11.34771 (1)	5.87	0.00014 (1)	9.71

Track Type	Sub-ballast/Asphalt Layer Thickness	Sub-grade Compressive Stress (psi) and Season	Sub-grade Service Life (years)	Asphalt Tensile Strain (psi) and Season	Asphalt Service Life (years)
Underlayment	10 cm (3.94 inch)	9.72295 (1)	10.84	0.00011 (1)	16.47
	15 cm (5.91 inch)	8.60169 (1)	18.02	0.00010 (1)	22.69
	20 cm (7.87 inch)	7.35151 (1)	31.73	0.00008 (1)	51.64
	25 cm (9.84 inch)	6.69243 (1)	47.15	0.00008 (1)	54.01
	30 cm (11.81 inch)	6.10984 (1)	71.23	0.00008 (1)	51.13
Combination (Asphalt & Sub-ballast)	5 cm & 5 cm	10.81701 (1)	6.81	0.00012 (1)	12.58
	5 cm & 10 cm	10.26768 (1)	8.09	0.00011 (1)	16.36
	5 cm & 15 cm	9.74785 (1)	9.69	0.00011 (1)	19.83
	5 cm & 20 cm	8.50702 (1)	15.98	0.00005 (1)	22.07
	5 cm & 25 cm	8.75104 (1)	14.24	0.00009 (1)	27.45
	10 cm & 5 cm	9.41329 (1)	12.50	0.00011 (1)	21.91
	10 cm & 10 cm	9.10306 (1)	14.31	0.00010 (1)	27.55
	10 cm & 15 cm	8.32859 (1)	18.37	0.00007 (1)	65.57
	10 cm & 20 cm	8.43962 (1)	17.35	0.00010 (1)	22.99
	15 cm & 5 cm	8.10085 (1)	21.68	0.00008 (1)	45.59
	15 cm & 10 cm	7.87136 (1)	23.60	0.00008 (1)	49.60
	15 cm & 15 cm	7.80397 (1)	24.53	0.00009 (1)	30.41
	20 cm & 5 cm	7.24132 (1)	32.66	0.00007 (1)	55.63
	20 cm & 10 cm	7.20940 (1)	34.91	0.00009 (1)	37.09
	25 cm & 5 cm	6.93001 (1)	43.35	0.00009 (1)	39.98

Table 13. Sub-grade service life

Asphalt *vs.* Sub-ballast	0 cm (0 inch)	5 cm (1.97 inch)	10 cm (3.94 inch)	15 cm (5.91 inch)	20 cm (7.87 inch)	25 cm (9.84 inch)	30 cm (11.81 inch)
0 cm (0 inch)	1.83	3.40	4.57	6.00	7.96	12.01	13.00
5 cm (1.97 inch)	5.87	6.81	8.09	9.69	15.98	14.24	X
10 cm (3.94 inch)	10.84	12.50	14.31	18.37	17.35	X	X
15 cm (5.91 inch)	18.02	21.68	23.60	24.53	X	X	X
20 cm (7.87 inch)	31.73	32.66	34.91	X	X	X	X
25 cm (9.84 inch)	47.15	43.35	X	X	X	X	X
30 cm (11.81 inch)	71.23	X	X	X	X	X	X

Fig. 5 and Table 13 show the sub-grade service life corresponding to the configuration and the thickness of sub-ballast and asphaltic layer in all-granular, asphaltic underlayment and combination tracks. In each thickness group; 5 cm, 10 cm, 15 cm, 20 cm, 25 cm and 30 cm; the longest sub-grade service life comes from the asphaltic underlayment track, followed by the combination track and the all-granular track. Moreover, in the same thickness group, a higher asphaltic layer thickness will result in a longer sub-grade service life.

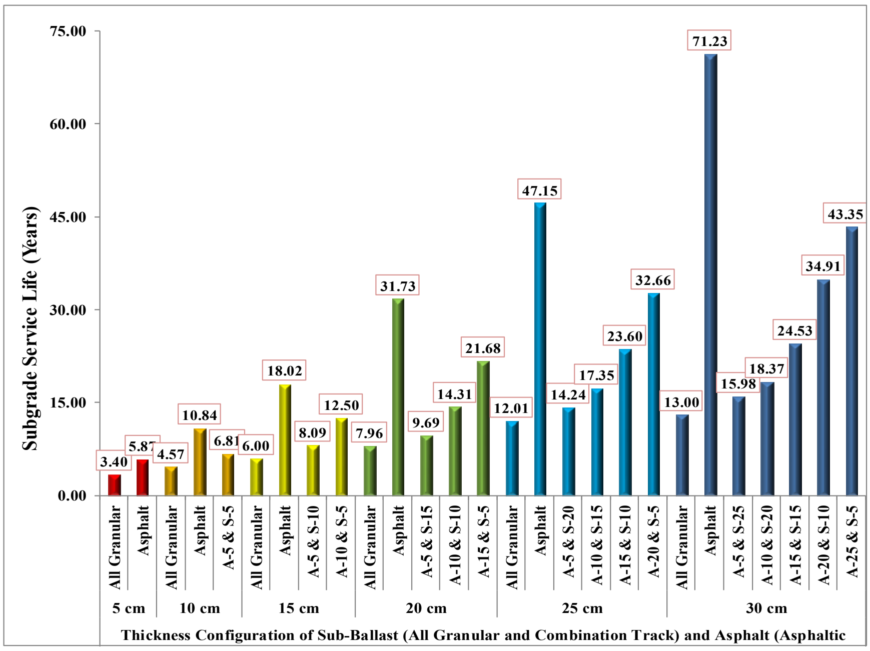


Figure (5): Sub-grade service life corresponding to the sub-ballast and asphalt layer thickness grouping

By looking at Fig. 5, a railway track engineer will be able to choose and determine the layer configuration and thickness design according to the targeted service life. It also can be summarized that higher sub-ballast and asphalt thickness configuration group (sequent from 5 cm to 30 cm) will produce higher significant difference between sub-grade service life in asphaltic underlayment track and sub-grade service life in all-granular track, which are 172% (5.87 years *vs.* 3.40 years), 237% (10.84 years *vs.* 4.57 years), 300% (18.02 years *vs.* 6.00 years), 398% (31.73 years *vs.* 7.96 years), 393% (47.15 years *vs.* 12.01 years) and 548% (71.23 years *vs.* 13.00 years).

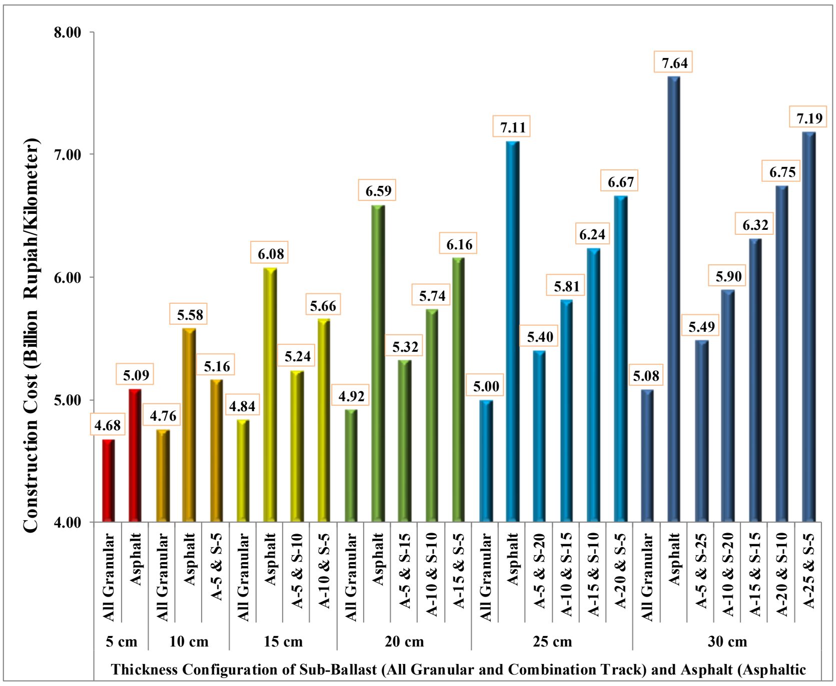


Figure (6): Railway track construction cost corresponding to the sub-ballast and asphalt layer thickness grouping

Fig. 6 shows the rail track construction cost (billion rupiahs/kilometer) in relation to the configuration and the thickness of sub-ballast and asphaltic layer in all-granular, asphaltic underlayment and combination tracks. In each thickness group, whether it is 5 cm, 10 cm, 15 cm, 20 cm, 25 cm or 30 cm, the highest construction cost is generated by the asphaltic underlayment track, followed by the combination track and the all-granular track. Moreover, in the same thickness group, higher asphaltic layer thickness in the combination track will cause higher construction cost. Again, by looking at this graph, a rail track engineer will be able to choose and determine the layer configuration and thickness design of rail track in accordance with the construction budget. It also can be concluded that higher sub-ballast and asphalt thickness configuration group (sequent from 5 cm to 30 cm) will result in bigger construction cost difference between those two types of tracks; i.e. 109% (5.09 billion/km *vs.* 4.68 billion/km), 117% (5.58 billion/km *vs.* 4.76 billion/km), 126% (6.08 billion/km *vs.* 4.84 billion/km), 140% (6.59 billion/km *vs.* 4.92 billion/km), 142% (7.11 billion/km *vs.* 5.00 billion/km) and 150% (7.64 billion/km *vs.* 5.08 billion/km). However, the good news is that this difference is much lower than the difference of sub-grade service life, as explained in the last sentence of the previous paragraph.

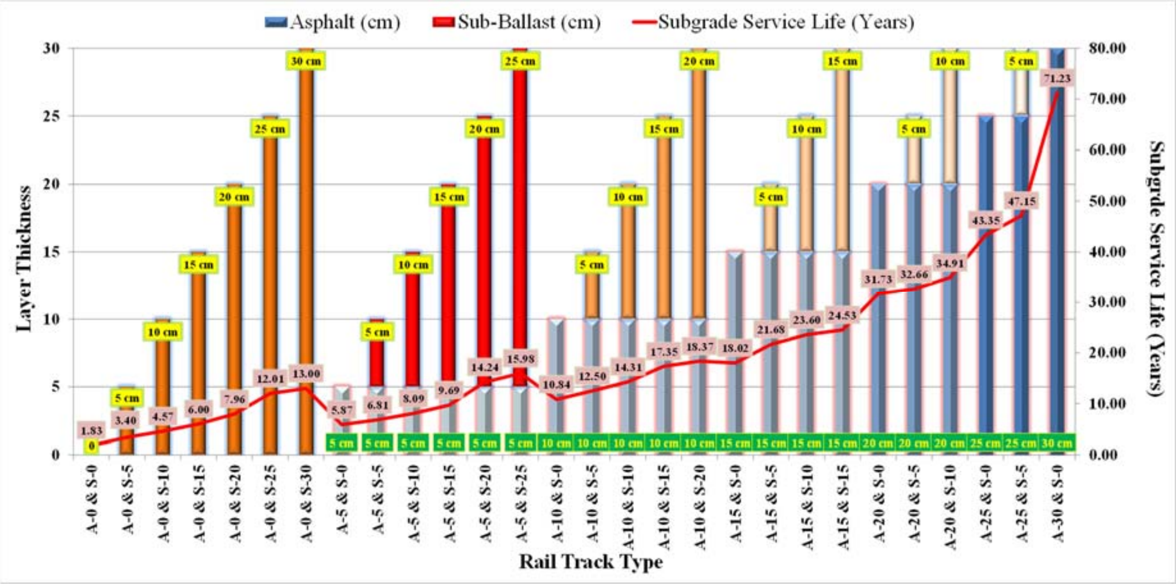


Figure (7): Sub-grade service life corresponding to the configuration and the thickness of sub-ballast and asphaltic layer

As shown in Fig. 7, even though the sub-ballast in an all-granular track has the same thickness as the asphalt layer in an asphaltic underlayment track; i.e., 30 cm, the sub-grade service life of the asphaltic underlayment track A-30&S-0 (71.23 years) is almost 5.5 times higher than that of the all-granular track A-0&S-30 (13 years). Interestingly, although they have different layer configuration and thickness, the all-granular track with 30 cm sub-ballast and the combination track with 10 cm asphalt and 5 cm sub-ballast have a similar sub-grade service life, which is 13 years. The same circumstance also occurs in asphaltic underlayment track with 15 cm asphalt and combination track with 10 cm asphalt and 20 cm sub-ballast that have a sub-grade service life of 18 years. Therefore, it can be inferred that mechanical capability of 10 cm sub-ballast is equal to that of 5 cm asphalt. Furthermore, the increase of sub-ballast thickness by 5 cm in all-granular track is not significant in increasing sub-grade service life (only 20% to 50%). On the other hand, the increase of asphalt thickness by 5 cm in asphaltic underlayment track and in combination track is significant in increasing sub-grade service life by 130% to 190% and by 63% to 83%, respectively.

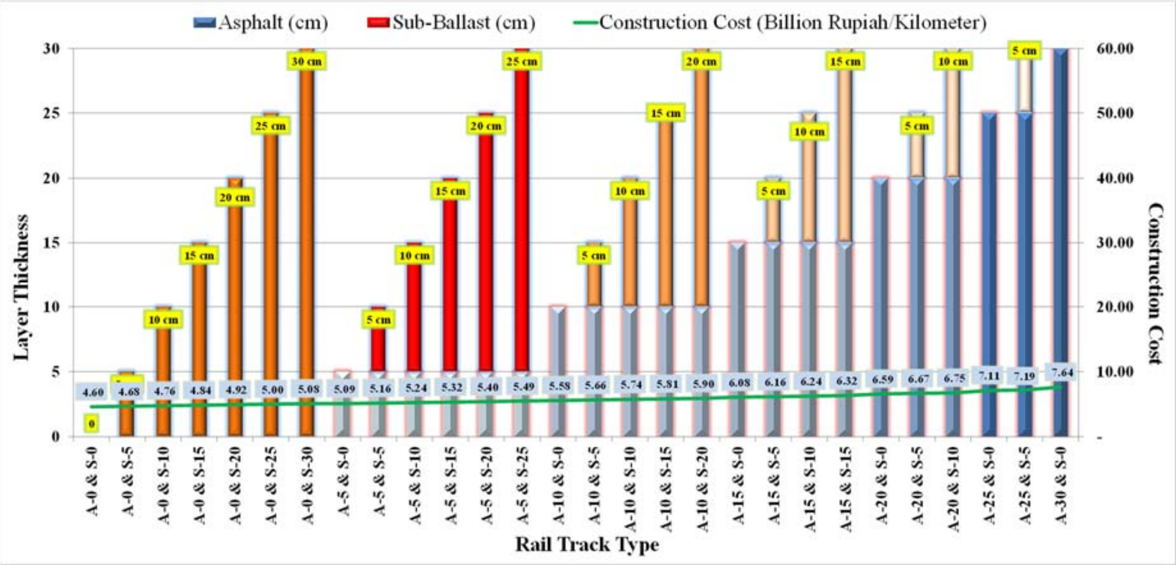


Figure (8): Rail track construction cost corresponding to the configuration and the thickness of sub-ballast and asphaltic layer

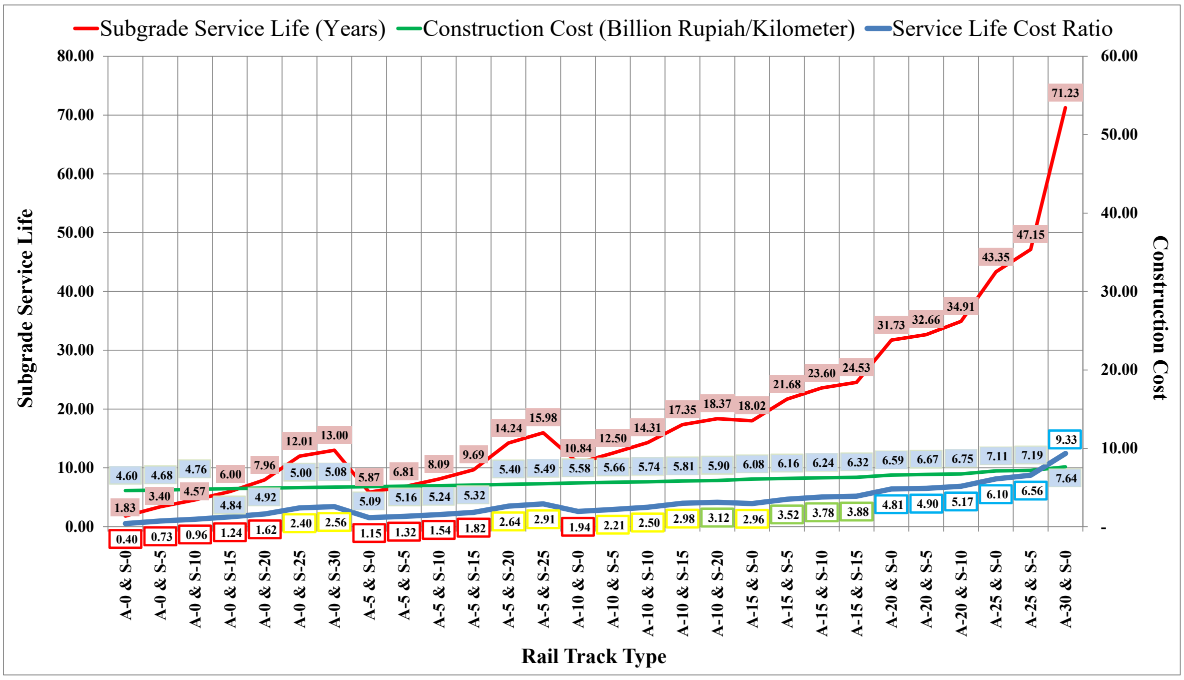


Figure (9): Service life-cost ratio

As presented in Fig. 8, even though the sub-ballast in an all-granular rail track has the same thickness as the asphalt layer in an asphaltic underlayment rail track; i.e., 30 cm, the construction cost of an asphaltic underlayment track (7.64 billion rupiahs/km or 535,413 USD/km) is 1.5 times higher than the construction cost of an all-granular track (5.08 billion rupiahs/km or 356,007 USD/km). Remarkably, having different layer configuration and thickness, all-granular track with 30 cm sub-ballast and asphaltic underlayment track with 5 cm asphalt are not really different in construction cost, which is 5.08 and 5.09 billion rupiahs/km. Also, adding sub-ballast thickness every 5 cm is not significant in increasing all-granular track construction cost (around 80 million rupiah/km or 5606 USD/km), but adding asphalt thickness every 5 cm in asphaltic underlayment and combination tracks is quite significant in increasing construction cost (about 500 million rupiah/km or 35,040 USD/km).

The comparison between sub-grade service life and construction cost in the form of service life-cost ratio (SLC) is given in Fig. 9 and Table 14. There are 10 rail track types considered having the lowest SLC (red; SLC≤2.00), 8 rail track types considered having medium low SLC (yellow; 2.00 < SLC ≤ 3.00), 4 rail track types considered having medium high SLC (green; 3.00 < SLC ≤ 4.00) and 6 rail track types considered having the highest SLC (blue; SLC ≥ 4.00).

Table 14. Summary of the analysis

Rail Track Type	Asphalt (cm)	Sub-ballast (cm)	Sub-grade Service Life (Years)	Construction Cost (Billion Rupiah/km)	Service Life-Cost Ratio
A-0 & S-0	0	0	1.83	4.60	0.40
A-0 & S-5	0	5	3.40	4.68	0.73
A-0 & S-10	0	10	4.57	4.76	0.96
A-0 & S-15	0	15	6.00	4.84	1.24
A-0 & S-20	0	20	7.96	4.92	1.62
A-0 & S-25	0	25	12.01	5.00	2.40
A-0 & S-30	0	30	13.00	5.08	2.56
A-5 & S-0	5	0	5.87	5.09	1.15
A-5 & S-5	5	5	6.81	5.16	1.32
A-5 & S-10	5	10	8.09	5.24	1.54
A-5 & S-15	5	15	9.69	5.32	1.82
A-5 & S-20	5	20	14.24	5.40	2.64
A-5 & S-25	5	25	15.98	5.49	2.91
A-10 & S-0	10	0	10.84	5.58	1.94
A-10 & S-5	10	5	12.50	5.66	2.21
A-10 & S-10	10	10	14.31	5.74	2.50
A-10 & S-15	10	15	17.35	5.81	2.98
A-10 & S-20	10	20	18.37	5.90	3.12
A-15 & S-0	15	0	18.02	6.08	2.96
A-15 & S-5	15	5	21.68	6.16	3.52
A-15 & S-10	15	10	23.60	6.24	3.78
A-15 & S-15	15	15	24.53	6.32	3.88
A-20 & S-0	20	0	31.73	6.59	4.81
A-20 & S-5	20	5	32.66	6.67	4.90
A-20 & S-10	20	10	34.91	6.75	5.17
A-25 & S-0	25	0	43.35	7.11	6.10
A-25 & S-5	25	5	47.15	7.19	6.56
A-30 & S-0	30	0	71.23	7.64	9.33

Setiawan (2021) concluded that the asphaltic overlayment track with a minimum asphalt thickness of 35 cm and a minimum sub-grade modulus of 82 MPa was a better option than all-granular railway track for railway systems with high load repetition per year (>500,000 train cars/year) and high axle load train (> 36 tons). Based on the SLC analysis, it is strongly recommended that railway track engineers and stakeholders choose the types belonging to the blue and green SLC, such as asphaltic underlayment track with 20 cm asphalt layer (the first type in blue SLC group) to replace sub-ballast layer that has 31.73 years of sub-grade service life and 6.59 billion rupiahs/km or 461,829 USD/km of construction cost (SLC 4.81). Constructing railway track with higher service life-cost ratio is believed to result in minimum life cycle cost in the long-term rail track performance.

CONCLUSIONS

Based on the results obtained from this research, the following conclusions are drawn:

- Higher compressive stress and tensile strain may cause lower sub-grade and asphalt layer service life. Mechanical behavior of all-granular track is strongly affected by rainwater (season 2, wet season). Conversely, the mechanical behavior of the asphalt underlayment and combination rail tracks is strongly influenced by air temperature (season 1, dry season).
- The longest sub-grade service life and the highest construction cost are produced by asphaltic underlayment track, followed by combination track and all-granular track. Higher sub-ballast and asphalt thickness configuration group generates wider significant difference between sub-grade service life in asphaltic underlayment track and in all-granular track. Additionally, higher sub-ballast and asphalt thickness configuration group produces more significant difference between construction cost of asphaltic underlayment track and that of all-granular track. However, the difference in construction cost is drastically lower compared to the difference in sub-grade service life.
- The increase of sub-ballast thickness every 5 cm in all-granular track is only able to improve sub-grade service life as much as 20% to 50%, but the increase of asphalt thickness by 5 cm in asphaltic underlayment track and in combination track may improve sub-grade service life as much as 130% to 190% and 63% to 83%, respectively. Also, the addition of sub-ballast thickness by 5 cm could raise all-granular track construction cost around 80 million rupiahs/km or 5606 USD/km, but the addition of asphalt thickness by 5 cm in asphaltic underlayment and combination tracks could enhance construction cost about 500 million rupiahs/km or 35,040 USD/km.
- Rail track engineers and stakeholders are strongly suggested to choose the rail track types included in the group of green and blue SLC with service life-cost ratio higher than 3.00. They are potentially to produce the minimum life cycle cost for the long-term rail track performance.

This paper is expected to help rail track engineers and stakeholders to choose and determine the most appropriate layer configuration and thickness design of railway tracks according to the targeted service life and available budget. Further research on comprehensive life cycle cost including maintenance and rehabilitation cost should be conducted in order to provide better understanding on the service life-cost ratio of the rail track.

REFERENCES

Anderson, J., and Rose, J. (2008). "*In-situ* test measurement techniques within railway track structures." Proceedings of the 2008 ASME/IEEE/ ASCE Joint Rail Conference.

Asgharzadeh, S.M., Sadeghi, J., Peivast, P., and Pedram, M. (2018). "Fatigue properties of crumb rubber asphalt mixtures used in railways." Construction and Building Materials, 184, 248-257. DOI: https://doi.org/10.1016/j.conbuildmat.2018.06.189

Asphalt Institute. (1998). "HMA trackbeds: Hot mix asphalt for quality railroad and transit trackbeds". Information Series 137, 10 pages.

Atashafrazeh, M., and Shirmohammadi, H. (2016). "2D modeling and analysis of railway track under subjected loads." Jordan Journal of Civil Engineering, 10 (3), 290-296.

Auersch, L. (2012). "Dynamic behavior of slab tracks on homogeneous and layered soils and the reduction of ground vibration by floating slab tracks." Journal of Engineering Mechanics, 138(8), 923-933. DOI: https://doi.org/10.1061/(ASCE)EM.1943-7889.0000407

Bian, X., Jiang, H., Cheng, C., Chen, Y., Chen, R., and Jiang, J. (2014). "Full-scale model testing on a ballastless high-speed railway under simulated train moving loads." Soil Dynamics and Earthquake Engineering, 66, 368-384. DOI: http://dx.doi.org/10.1016/j.soildyn.2014.08.003

Bressi, S., Santos, J., Giunta, M., Pistonesi, L., and Lo Presti, D. (2018). "A comparative life-cycle assessment of asphalt mixture for railway sub-ballast containing alternative materials." Resources, Conservation & Recycling, 137, 76-88. DOI: https://doi.org/10.1016/j.resconrec.2018.05.028

Cao, S., Yang, R., Su, C., Dai, F., Liu, X., and Jiang, X. (2016). "Damage mechanism of slab track under the coupling effects of train load and water." Engineering Fracture Mechanics, 163, 160-175. DOI: http://dx.doi.org/10.1016/j.engfracmech.2016.07.005

Chang, C. S., Adegoke, C. W., and Selig, E. T. (1980). "GEOTRACK model for railroad track performance." Journal of the Geotechnical Engineering Division, ASCE, 106, No. GT 11, 1201-1218.

D'Angelo, G., Lo Presti, D., and Thom N. (2017). "Optimisation of bitumen emulsion properties for ballast stabilization." Materiales de Construcción, 67 (327), 124-e124. DOI: https://doi.org/10.3989/mc.2017.04416

D'Angelo, G., Thom, N., and Lo Presti, D. (2016). "Bitumen-stabilized ballast: A potential solution for railway track bed." Construction dan Building Materials, 124, 118-126. DOI: https://doi.org/10.1016/j.conbuildmat.2016.07.067

D'Andrea, A., Loprencipe, G., and Xhixha, E. (2012). "Vibration induced by rail traffic: Evaluation of attenuation properties in a bituminous sub-ballast layer." Procedia - Social and Behavioral Sciences, 53, 245-255. DOI: https://doi.org/10.1016/j.sbspro.2012.09.877

Di Mino, G., Di Liberto, M., Maggiore, C., and Noto, S. (2012). "A dynamic model of ballasted rail track with bituminous sub-ballast layer." Procedia - Social and Behavioral Sciences, 53, 366-378. DOI: https://doi.org/10.1016/j.sbspro.2012.09.888

Duong, T. V., Cui, Y. J, Tang, A. M., Dupla, J. C., Canoua, J., Calon, N., and Robinet, A. (2013). "Investigating the mud pumping and interlayer creation phenomena in railway sub-structure." Engineering Geology, 171, 45-58. DOI: http://dx.doi.org/10.1016/j.enggeo.2013.12.016

Du Plooy, R., and Grabe, H. (2017). "Characterisation of rigid polyurethane foam-reinforced ballast through cyclic loading box tests." Journal of the South African Institution of Civil Engineering, 59 (2), 2-10. DOI: http://dx.doi.org/10.17159/2309-8775/2017/v59n2a1

Fang, M., Qiu, Y., Rose, J.G., West, R.C., and Ai, C. (2011). "Comparative analysis on dynamic behavior of two HMA railway substructures." Journal of Modern Transportation, 19 (1), 26-34. DOI: https://doi.org/10.3969/j.issn.2095-087X.2011.01.005

Fateen, S. (1972). "A finite element analysis of full-depth asphalt railway track." Master Thesis, Department of Civil Engineering, University of Maryland.

Feng, S.J., Zhang, X.L., Wang, L., Zheng, Q.T., Du, F.L., and Wang, Z.L. (2017). "*In situ* experimental study on high-speed train-induced ground vibrations with ballastless track." Soil Dynamics and Earthquake Engineering, 102, 195-214. DOI: http://dx.doi.org/10.1016/j.soildyn.2017.09.001

Galvin, P., Romero, A., and Domınguez, J. (2010). "Vibrations induced by HST passage on ballast and non-ballast tracks." Soil Dynamics and Earthquake Engineering, 30, 862-873. DOI: https://doi.org/10.1016/j.soildyn.2010.02.004

Gautier, P.E. (2015). "Slab track: Review of existing systems and optimization potentials including very high speed." Construction and Building Materials, 92, 9-15. DOI: http://dx.doi.org/10.1016/j.conbuildmat.2015.03.102

Giannakos, K. (2016). "Deflection of a railway reinforced concrete slab track: Comparing the theoretical results with experimental measurements." Engineering Structures, 122, 296-309. DOI: http://dx.doi.org/10.1016/j.engstruct.2016.04.058

Huang, Y.H., Lin, C., Deng, X.J., and Rose, J. (1984). "KENTRACK: A computer program for hot-mix asphalt and conventional ballast railway trackbeds". Asphalt Institute (Publication RR-84-1) and National Asphalt Pavement Association (Publication QIP-105).

Kennedy, J., Woodward, P. K., Medero, G., and Banimahd, M. (2013). "Reducing railway track settlement using three-dimensional polyurethane polymer reinforcement of the ballast." Construction and Building Materials, 44, 615-625. DOI: http://dx.doi.org/10.1016/j.conbuildmat.2013.03.002

Lee, S. H., Lee, J. W., Park, D. W., and Vo, H. V. (2014). "Evaluation of asphalt concrete mixture for railway track." Construction and Building Materials, 73, 13-18. DOI: https://doi.org/10.1016/j.conbuildmat.2014.09.053

Lei, X., and Noda, N. A. (2002). “Analyses of dynamic response of vehicle and track coupling system with random irregularity of track vertical profile.” Journal of Sound and Vibration, 258 (1), 147-165.

Malloy, B. R., Rose, J. G., and Souleyrette, R. (2014). “Rehabilitation, assessment and management practices to ensure long-life, high-performance highway-railway at-grade crossings.” Conference: 2014 Joint Rail Conference. DOI: https://doi.org/10.1115/JRC2014-3761

Malloy, B. R., Rose, J. G., and Souleyrette, R. (2015). “Rehabilitation of railway-highway at-grade crossings: Recommendations and guides.” Transportation Research Record Journal of the Transportation Research Board, 2545, 100-114. DOI: https://doi.org/10.3141/2545-11

Mazilu, T. (2009). “Analysis of infinite structure response due to moving wheel in the presence of irregularities *via* Green's functions method.” Proceedings of the Romanian Academy Series A, 10(2), 139-150.

Praticò, F.G., and Giunta, M. (2017). “An integrative approach RAMS-LCC to support decision on design and maintenance of rail track.” Proceedings of the Environmental Engineering 10th International Conference, Vilnius Gediminas Technical University, 1-8.

Robertson, I., Masson, C., Sedran, T., Barresi, F., Caillau, J., Keseljevic, C., and Vanzenberg, J. M. (2015). “Advantages of a new ballastless trackform.” Construction and Building Materials, 92, 16-22. DOI: http://dx.doi.org/10.1016/j.conbuildmat.2014.06.099

Robnett, Q.L., Thompson, M.R., Knutson, R.M., and Tayabji, S.D. (1975). “Development of a structural model and materials valuation procedures”. Ballast and Foundation Materials Research Program, University of Illinois, report to FRA of US/DOT, Report No. DOT-FR-30038.

Rose, J. G. (2013). “Selected in-track applications and performance of hot-mix asphalt track beds.” Proceedings of the 2013 Joint Rail Conference, V001T01A017. DOI: https://doi.org/10.1115/JRC 2013-2525

Rose, J. G., Agarwal, N., Brown, J. D., and Ilavala, N. (2010b). “KENTRACK: A performance-based layered elastic railway trackbed structural design and analysis procedure: A tutorial.” Proceedings of the 2010 Joint Rail Conference. DOI: https://doi.org/10.1115/JRC2010-36067

Rose, J. G., Li, D., and Walker, L. A. (2002). “Tests and evaluations of in-service asphalt trackbeds.” Annual Conference & Exposition at the American Railway Engineering and Maintenance-of-Way Association (AREMA) 2002.

Rose, J. G., Shushu Liu., and Souleyrette, R. (2014). “KENTRACK 4.0: A railway trackbed structural design program.” Proceedings of the 2014 Joint Rail Conference. DOI: https://doi.org/10.1115/JRC2014-3752

Rose, J.G., Swiderski, M.G., Anderson, J.S., and Walker, L.A. (2009). “Highway-railway st-grade crossings: Long-term settlement measurements and assessments”. Research Report: KTC-09-06/FR 136-04-3F.

Rose, J.G., Teixeira, P.F., and Ridgway, N.E. (2010a). “Utilization of asphalt/bituminous layers and coatings in railway track-beds: A compendium of international applications.” Proceedings of the 2010 Joint Rail Conference. Urbana, Illinois, USA. April 2010. DOI: https://doi.org/10.1115/JRC2010-36146

Rose, J., and Bryson, L. (2009). “Hot-mix asphalt railway trackbeds: Trackbed materials, performance evaluations and significant implications.” 2009 International Conference on Perpetual Pavements, Ohio Research Institute for Transportation and Environment.

Rose, J., and Lees, H. (2008). “Long-term assessment of asphalt trackbed component material properties and performance.” Proceedings of the 2008 AREMA Conference.

Rosyidi, S. A. P., Setiawan, D. M., Budiyantoro, C., and Bintari, L.N. (2019). “The role of scrap rubber size against the characteristics of ballast layer.” IOP Conf. Series: Materials Science and Engineering, 650, 1-10. DOI: https://doi.org/10.1088/1757-899X/650/1/012052

Sadeghi, J., Khajehdezfuly, A., Esmaeili, M., and Poorveis, D. (2016). “Investigation of rail irregularity effects on wheel/ rail dynamic force in slab track: Comparison of two -and three-dimensional models.” Journal of Sound and Vibration, 374, 228-244. DOI: http://dx.doi.org/10.1016/j.jsv.2016.03.033

Sekretariat Negara. (2012). "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.

Setiawan, D.M. (2016). "Pembatasan Kecepatan maksimum dan kaitannya terhadap kapasitas lintas jalur kereta api Muara Enim–Lahat Sumatera Selatan." Prosiding Seminar Nasional Teknik Sipil ke-VI 2016, Surakarta, pp. 36-46.

Setiawan, D.M. (2018). "Worldwide hot-mix asphalt layer application and scrap rubber and bitumen emulsion studies on railway track bed." Semesta Teknika, 21 (2), 166-177, DOI: https://doi.org/10.18196/st.212223

Setiawan, D.M. (2019). "Utilization of 60/70 penetration grade asphalt on ballast structures with the variation of percentage and the number of pouring layers." Journal of the Mechanical Behavior of Materials, 28, 107-118. DOI: https://doi.org/10.1515/jmbm-2019-0013

Setiawan, D.M. (2021). "Structural response and sensitivity analysis of granular and asphaltic overlayment track considering linear viscoelastic behavior of asphalt." Journal of the Mechanical Behavior of Materials, 30 (1), 66-86. DOI: https://doi.org/10.1515/jmbm-2021-0008

Setiawan, D.M., and Rosyidi S. A. P. (2018a). "The role of compaction and scrap rubber size against the performance of ballast layer." International Journal of Civil Engineering and Technology (IJCIET), 9(13), 1275-1286.

Setiawan, D. M., and Rosyidi, S. A. P. (2016). "Track quality index as track quality assessment indicator." Proceedings of the 19th International Symposium of Indonesian Inter-University Transportation Studies Forum (FSTPT), Universitas Islam Indonesia, Indonesia, Ch. 2, pp. 197-207.

Setiawan, D. M., and Rosyidi, S. A. P. (2018b). "Vertical deformation and ballast abrasion characteristics of asphalt-scrap rubber track bed." International Journal on Advanced Science, Engineering and Information Technology, 8(6), 2479-2484. DOI: https://doi.org/10.18517/ijaseit.8.6.7411

Setiawan, D. M., and Rosyidi, S. A. P. (2019). "Scrap rubber and asphalt for ballast layer improvement." International Journal of Integrated Engineering, 11(8), 247-258. DOI: https://doi.org/10.30880/ijie.2019.11.08.025

Setiawan, D. M., Muthohar, I., and Ghataora, G. (2013). "Conventional and unconventional railway for rail ways on soft ground in Indonesia (case study: Rantau Prapat-duri railways development)." Proceedings of the 16th FSTPT International Symposium, Universitas Muhammadiyah Surakarta, 610-620.

Setiawan, D. M., Rosyidi, S. A. P., and Budiyantoro, C. (2019). "The role of scrap rubber, asphalt and manual compaction against the quality of ballast layer." Jordan Journal of Civil Engineering, 13(4), 594-608.

Signes, C. H., Fernandez, P. M., Garzon-Roca, J., de la Torre, M. E. G., and Franco, R. I. (2016). "An evaluation of the resilient modulus and permanent deformation of unbound mixture of granular materials and rubber particles from scrap tyres to be used in sub-balast layers." Transportation Research Procedia, 18, 384-391. DOI: https://doi.org/10.1016/j.trpro.2016.12.0500

SNI. (1991). "SNI (Indonesian National Standard) 06-2440-1991: Oil and asphalt weight-loss testing method by method A." (Metode pengujian kehilangan berat minyak dan aspal dengan cara A). Badan Standardisasi Nasional. Jakarta.

SNI. (1996). "SNI (Indonesian National Standard) 03-4142-1996: The test methods of clay clumps and easily broken items in aggregate." (Metode pengujian gumpalan lempung dan butir-butir mudah pecah dalam agregat). Badan Standardisasi Nasional. Jakarta.

SNI. (2008a). "SNI (Indonesian National Standard) 1969-2008: The test method of density and absorption of coarse aggregates." (Cara uji berat jenis dan penyerapan agregat kasar). Badan Standardisasi Nasional. Jakarta.

SNI. (2008b). "SNI (Indonesian National Standard) 2417:2008: The test method of aggregate wear with the Los Angeles abrasion machine." (Cara uji keausan agregat dengan mesin Los Angeles). Badan Standardisasi Nasional. Jakarta.

SNI. (2011a). "SNI (Indonesian National Standard) 2456-2011: The method for asphalt penetration test." (Cara uji penetrasi aspal). Badan Standardisasi Nasional. Jakarta.

SNI. (2011b). "SNI (Indonesian National Standard) 2434-2011: Test method for asphalt softening point with ring and ball tools." (Cara uji titik lembek aspal dengan alat cincin dan bola). Badan Standardisasi Nasional. Jakarta.

SNI. (2011c). "SNI (Indonesian National Standard) 2432-2011: The test method for asphalt ductility." (Cara uji daktilitas aspal). Badan Standardisasi Nasional. Jakarta.

SNI. (2011d). "SNI (Indonesian National Standard) 2441-2011: The method for asphalt specific weight test." (Cara uji berat jenis aspal keras). Badan Standardisasi Nasional. Jakarta.

Sol-Sánchez, M., Moreno-Navarro, F., and Rubio-Gámez, M. C. (2014). "The use of deconstructed tires as elastic elements in railway tracks." Materials, 7(8), 5903-5919. DOI: https://doi.org/10.3390/ma7085903

Sol-Sánchez, M., Thom, N. H., Moreno-Navarro, F., Rubio-Gamez, M. C., and Airey G.D. (2015). "A study into the use of crumb rubber in railway ballast." Construction and Building Materials, 75, 19-24. DOI: https://doi.org/10.1016/j.conbuildmat.2014.10.045

Song, X., Zhao, C. F., and Zhu, X. J. (2014). "Temperature-induced deformation of CRTS II slab track and its effect on track dynamical properties." Science China Technological Sciences, 57(10), 1917-1924. DOI: https://doi.org/10.1007/s11431-014-5634-x

Sun, Y.Q., and Dhanasekar, M. (2002). "A dynamic model for the vertical interaction of the rail track and wagon system." International Journal of Solids and Structures, 39, 1337-1359.

Woodward, P. K., El Kacimi, A., Laghrouche, O., Medero, G., and Banimahd, M. (2012). "Application of polyurethane geocomposites to help maintain track geometry for high-speed ballasted railway tracks." Journal of Zhejiang University Science, 13 (11), 836-849.

Woodward, P. K., Kennedy, J., Laghrouche, O., Connolly, D. P., and Medero, G. (2014). "Study of railway track stiffness modification by polyurethane reinforcement of the ballast." Transportation Geotechnics, 1, 214-224. DOI: http://dx.doi.org/10.1016/j.trgeo.2014.06.005

www.kalogistics.co.id

Yang, X., Gu, S., Zhou, S., Yang, J., Zhou, Yu., and Lian, S. (2015). "Effect of track irregularity on the dynamic response of a slab track under a high-speed train based on the composite track element method." Applied Acoustics, 99, 72-84. DOI: http://dx.doi.org/10.1016/j.apacoust.2015.05.009

Zakeri, J.A., and Mosayebi, S. A. (2016). "Study of ballast layer stiffness in railway tracks." Gradevinar, 68 (4), 311-318.

Zhu, S., and Cai, C. (2014). "Interface damage and its effect on vibrations of slab track under temperature and vehicle dynamic loads." International Journal of Non-linear Mechanics, 58, 222-232. DOI: http://dx.doi.org/10.1016/j.ijnonlinmec.2013.10.004