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Mechanistic Approach for Predicting Total Permanent Deformation in Conventional and Asphalt-Based Railway Track Systems

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ABSTRACT

The rail track must provide a stable and well-aligned path for trains, with each component performing its function effectively. However, prior studies often focused only on the permanent deformation of a single layer in conventional tracks or on the asphalt layer in asphaltic rail track designs. No study has comprehensively predicted and compared the total permanent deformation of both track types using finite element modeling. This study addresses that gap by employing mechanistic modeling to assess and compare the total permanent deformation in conventional and asphaltic rail tracks. The Generalized Maxwell model represents asphalt behavior, while the Modified Drucker-Prager Cap model captures the response of ballast, sub-ballast, and subgrade layers. Results show that asphaltic tracks outperform conventional tracks in reducing total permanent deformation. Specifically, asphaltic overlayment tracks perform better overall, while asphaltic underlayment tracks more effectively minimize deformation in the asphalt and subgrade layers. The findings highlight the potential benefits of asphaltic designs for long-term track performance. Future studies should incorporate time-dependent creep behavior of unbound granular and soil materials to improve prediction accuracy.

Keywords: Asphaltic Track Structure, Finite Element Modeling, Mechanistic Prediction, Drucker-Prager Cap Constitutive Model, Permanent Track Deformation.

INTRODUCTION

For decades, conventional ballasted tracks have served as the primary railway infrastructure solution in Indonesia because they are cost-effective and relatively easy to construct. The structural integrity of these tracks depends on the combined support of the ballast, sub-ballast, and subgrade layers. Records from 2022 indicate that conventional ballasted tracks accounted for 6,221.70 km of the national railway network. Nevertheless, the operational performance of these track systems has been challenged by progressive permanent deformation, particularly rutting, which has been recognized as a major factor contributing to railway derailments. Recent studies have developed degradation models that tie long-term material property changes of ballast to performance deterioration under repeated loading. Such degradation modelling offers a complementary perspective to constitutive modelling by linking material evolution with permanent deformation behavior in ballast and soil layers (Fathali et al., 2021; Sadiq and Islam, 2023; Vinay et al., 2024; Gao et al., 2025). Numerous investigations have shown that the mechanical response of ballast, sub-ballast, and subgrade materials cannot be realistically represented using a purely linear elastic model. Under repeated wheel loads, these materials exhibit nonlinear and permanent deformation characteristics that require more advanced constitutive descriptions. Consequently, railway track analyses frequently incorporate elastoplastic material models to simulate the inelastic behavior of granular and soil layers. One of the most commonly utilized constitutive frameworks for this purpose is the Mohr–Coulomb model (Jeon, 2024; Punetha and Nimbalkar, 2021; Park and Lim, 2021; Indraratna et al., 2007) and Drucker-Prager (Elastic Perfect-Plastic) Model (Gallego and López Pita, 2009; Gallego et al., 2011; Leshchinsky and Ling, 2013).

In the Mohr–Coulomb constitutive model, cohesion is defined as the portion of material strength that remains effective regardless of frictional resistance between particles. Together with friction angle, this parameter governs the shear and tensile behavior of granular materials. The model describes material behavior as elastic prior to yielding and perfectly plastic after yielding, while accommodating both associated and non-associated plastic flow rules. Geometrically, the corresponding yield locus forms a hexagonal pyramidal shape in three-dimensional principal stress space. However, the sharp corners and edges of this surface often lead to numerical instability because the outward normal direction is not uniquely defined at these locations. Beyond constitutive considerations, the rate at which permanent deformation accumulates is strongly controlled by stress conditions. As reported by Mei et al. (2021), increases in confining pressure and cyclic stress magnitude significantly alter permanent strain development. Moreover, the long-term deformation behavior of ballast, sub-ballast, and subgrade materials subjected to repeated loading can be expressed through a power-law model, with its coefficients accounting for the influence of the applied stress state

The Drucker–Prager constitutive model was developed as an alternative to the Mohr–Coulomb criterion to alleviate numerical challenges associated with the latter's non-smooth yield surface. By employing a continuous conical yield envelope, the D–P model provides a more robust framework for finite element simulations of granular materials. Nevertheless, the original formulation assumes elastic-perfectly plastic behavior, implying that plastic straining does not alter the size or shape of the yield surface and that hardening effects are neglected.

For railway ballast applications, this simplification may lead to inaccurate predictions because ballast behavior is highly sensitive to confining stress. To better represent the response of pressure-dependent frictional materials, researchers have adopted the Modified Drucker–Prager Cap (MDPC) model. In addition to shear failure, the model incorporates a cap surface and isotropic hardening law that enable the simulation of compaction and stress-induced strengthening. As a result, the MDPC model has been shown to outperform both the Mohr–Coulomb and conventional Drucker–Prager models in reproducing the mechanical characteristics of railway aggregate layers and achieving closer agreement with laboratory and field measurements (Shi, 2009; Shih et al., 2019).

The main function of unbound granular layer is to resist lateral, vertical, and longitudinal train loads and spread them out from the sleepers to the subgrade (Setiawan et al., 2023). The numerical results in Teixeira et al. (2025) indicate that ballast and sub-ballast thickness significantly influence the structural behavior conventional tracks. Insufficient ballast thickness increases deflection and stress levels, while excessive thickness leads to higher system stiffness and reduced stress dissipation. The quality of the subgrade is a key factor affecting the structural integrity and operational performance of railway tracks, making it an essential component of track construction systems (Sadeghi et al., 2015). Since each track layer possesses distinct material properties, their susceptibility to permanent deformation differs accordingly. In the ballast and sub-ballast layers, long-term deformation is mainly caused by particle movement, frictional interactions, and aggregate breakage during service loading (Ramos et al., 2020). When subjected to cyclic loads, these granular materials undergo progressive plastic strain accumulation, leading to compaction, a reduction in pore spaces, and an increase in stiffness over time (Ba, 2018). Settlement in the track foundation has been recognized as the leading source of track irregularities (Setiawan, 2025, Grabe et al., 2005]. Conventional tracks are susceptible to settlement owing to repetitive dynamic loads and several geotechnical conditions, such as consolidated settlements and inadequate compaction of soil subgrade (Park and Lim, 2021; Setiawan et al., 2024). In asphaltic rail track structure, the Asphalt Concrete (AC) can be used as waterproofing layer and can be used as substitute of the sub-ballast layer that can prevent water from the surface into the subgrade's body, also it can provide the benefits of anti-cracking properties, vibration reduction, and subgrade deformation coordination (Lee et al., 2018).

Railway tracks are designed to maintain geometric stability and provide a smooth load-transfer mechanism for safe train movement. Achieving these requirements depends on the coordinated performance of all structural layers within the track system. However, the majority of previous investigations have assessed permanent deformation at the material or layer level, focusing separately on ballast, sub-ballast, or subgrade behavior. As a result, there remains a lack of comprehensive understanding regarding the combined contribution of these layers to the total permanent deformation of conventional ballasted railway tracks (Setiawan, 2022; Indraratna et al., 2007; Grossoni et al., 2021; Abadi et al., 2018; Yang et al., 2016; Gomes & Ramos, 2021; Schulz-Poblete et al., 2019). Other studies have investigated the magnitude of permanent deformation in the asphalt concrete (AC) layer (Lee et al., 2018) and subgrade layer of asphaltic railway tracks (Setiawan et al., 2023) or assessed the total permanent deformation of conventional ballasted tracks (Setiawan et al., 2024). Although finite element techniques have been widely employed to investigate railway track behavior, a direct comparison of the overall permanent deformation responses of conventional ballasted tracks and asphaltic track systems has not yet been adequately addressed in the literature (Bose, 2020; Bose et al., 2021; Lee et al., 2019).

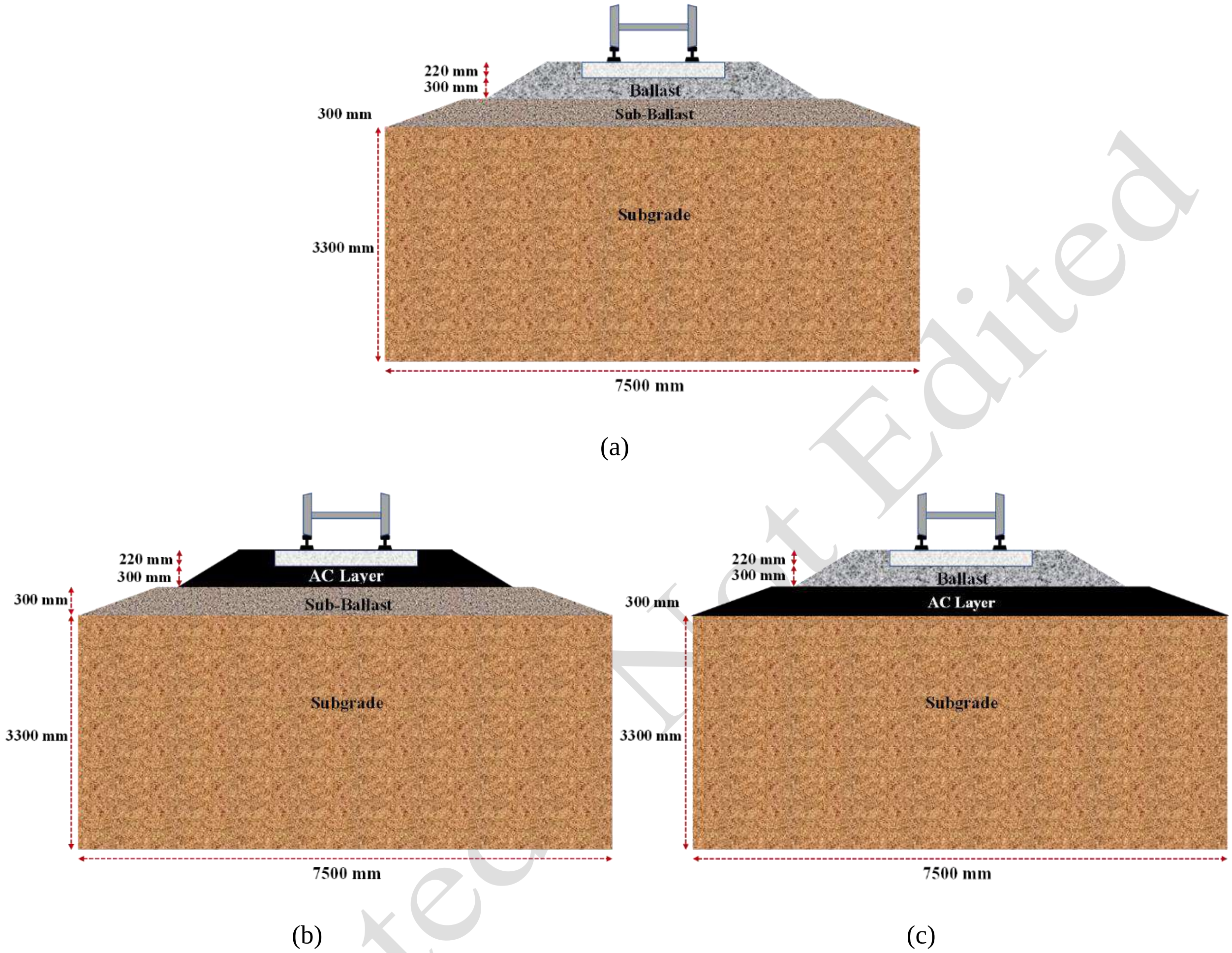


Fig. 1. Geometric and layer thicknesses of rail tracks for numerical modeling: a). conventional; b). asphaltic overlayment; c). asphaltic underlayment

Improving the understanding of total permanent deformation in railway track structures can support the development of more sustainable and economical track systems by minimizing maintenance demands throughout their service life. However, such an understanding cannot be achieved without first examining the deformation behavior of individual structural layers and their respective contributions to the overall track response. Therefore, the permanent deformation characteristics of the asphalt concrete (AC), ballast, sub-ballast, and subgrade layers must be systematically evaluated and compared in both conventional and asphaltic railway tracks. To address this need, the present study develops a mechanistic finite element model in Abaqus to investigate, predict, and directly compare the total permanent deformation of these two track systems. The study also quantifies the contribution of each structural layer to the overall deformation response, thereby providing insights into the mechanisms responsible for long-term track deterioration.

METHODS

Structural Geometry and Dimension

A conventional ballasted railway track structure was modeled with three primary layers, namely a 30 cm ballast layer, a 30 cm sub-ballast layer, and a 330 cm subgrade layer. The structural arrangement is shown in Figure 1a. On the other hand, 2 (two) asphaltic rail tracks design evaluated in this study can be seen in Figure 1b and Figure 1c, in which the 30 cm thick AC layer are laid on top of sub-ballast layer (asphaltic overlayment), and between ballast and subgrade layer (asphaltic underlayment).

Material Properties

Elastic Parameters of Rail Track Materials

The elastic parameters employed in the finite element analysis for the conventional and asphaltic track systems are listed in Table 1. These parameters include material density (ρ), Young's modulus (E), and Poisson's ratio (ν).

Table 1. Elastic Behavior Parameter for Simulation (Park and Lim, 2021, Gallego and López Pita, 2009; Gallego et al., 2011; Lee et al., 2018)

Conventional	**ρ [kg/m^3]**	**E [MPa]**	**ν**
Sleeper	1833.3	30,000	0.20
Ballast	2192.39	150	0.33
Sub-Ballast	1,937.46	120	0.30
Subgrade	2,192.39	20	0.33
Asphaltic Overlayment	**ρ [kg/m^3]**	**E [MPa]**	**ν**
Sleeper	1833.3	30,000	0.20
AC layer	2,345	23,233.7	0.35
Sub-Ballast	1,937.46	120	0.30
Subgrade	2,192.39	20	0.33
Asphaltic Underlayment	**ρ [kg/m^3]**	**E [MPa]**	**ν**
Sleeper	1833.3	30,000	0.20
Ballast	2192.39	150	0.33
AC layer	2,345	23,233.7	0.35
Subgrade	2,192.39	20	0.33

Viscoelastic Parameters of Asphalt

In this study, the behavior of asphalt materials was simulated using the Generalized Maxwel model as illustrated in Figure 2, and the viscoelastic constitutive relationship parameters of the asphalt concrete (AC) were obtained from the dynamic modulus test conducted by Korean Railway Research Institute (Lee et al., 2019), as presented in Table 2.

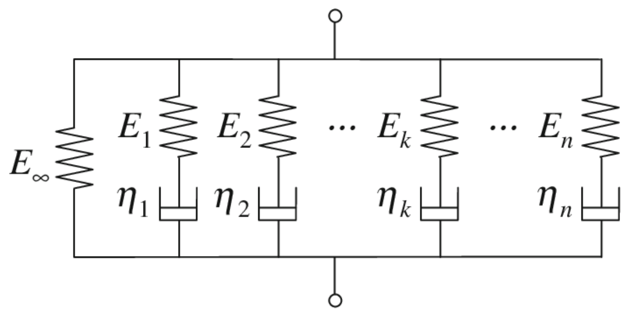


Fig. 2. Viscoelastic behavior parameter of asphalt in Generalized Maxwell Model

Table 2. Prony series for modeling viscoelastic behavior of AC (Lee et al., 2019)

τ_i Prony	g_i Prony	k_i Prony
0.0001	0.283796941	0.283796941
0.001	0.196474805	0.196474805
0.01	0.10915267	0.10915267
0.1	0.150761667	0.150761667
1	0.137056458	0.137056458
10	0.063522488	0.063522488
100	0.04234687	0.04234687
1000	0.015792208	0.015792208
10000	0.000436611	0.000436611

Elasto-Plastic Parameters of Ballast, Sub-Ballast, and Soil Subgrade

To capture the nonlinear and pressure-dependent behavior of granular and soil materials, the Modified Drucker–Prager Cap (MDPC) model was employed in the finite element simulations. The model is capable of representing the yielding and hardening characteristics of geomaterials whose strength and stiffness evolve with increasing stress levels, thereby providing a realistic description of unbound aggregates and subgrade soils.

The constitutive parameters associated with the MDPC model were organized into three principal groups: elastic properties, Drucker–Prager Cap plasticity parameters, and cap hardening parameters. The corresponding values are presented in Tables 1 and 3.

Table 3. Drucker-Prager-Cap Plasticity and Cap Hardening parameters (Park and Lim, 2021, Gallego and López Pita, 2009; Gallego et al., 2011)

Drucker-Prager-Cap Plasticity							**Cap Hardening**	
Materials	**Material Cohesion, d (MPa)**	**Angle of Friction β**	**Cap Eccentricity R**	**Initial Cap Yield Surface Position, Pa (MPa)**	**Transition Surface Radius, α**	**Flow Stress Ratio K**	γ_1	γ_2
Ballast	0.001	45	1.8576	0.5	0	1	0.5	7
Sub-Ballast	0.001	45	2.3201	0.4	0	1	0.4	6
Subgrade	0.012	14.3	5.8405	0.3	0	1	0.3	5

Loading Systems

The magnitude of Babaranjang freight train's dynamic load was computed using Equation 1 (Sunaryo et al., 2020) and Equation 2 (Sunaryo et al., 2020) and transformed into the concentrated force employed to the left and right rail in the form of cyclic load. Figure 3 shows the descriptions of a Babaranjang freight wagon. Each freight wagon has an 18-ton maximum payload capacity. The distance between the two bogies is 10.830 meters. Using Equation 3 (Kennedy et al., 2013), this value was used to calculate the single bogie to single bogie passing frequency in the cyclic loading systems.

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

$$P_d = P_s \times I_p \tag{2}$$

where:

I_p = Conversion Factor

V = Babaranjang Train Speed, (kph)

P_s = Static Wheel Load, (kg)

P_d = Dynamic Wheel Load, (kg)

$$f_p = \frac{V}{d} \tag{3}$$

where:

f_p = Passing Frequencies, (Hz)

V = 40 kph

d = 10.830 m

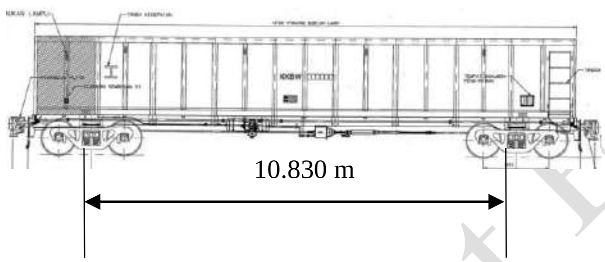
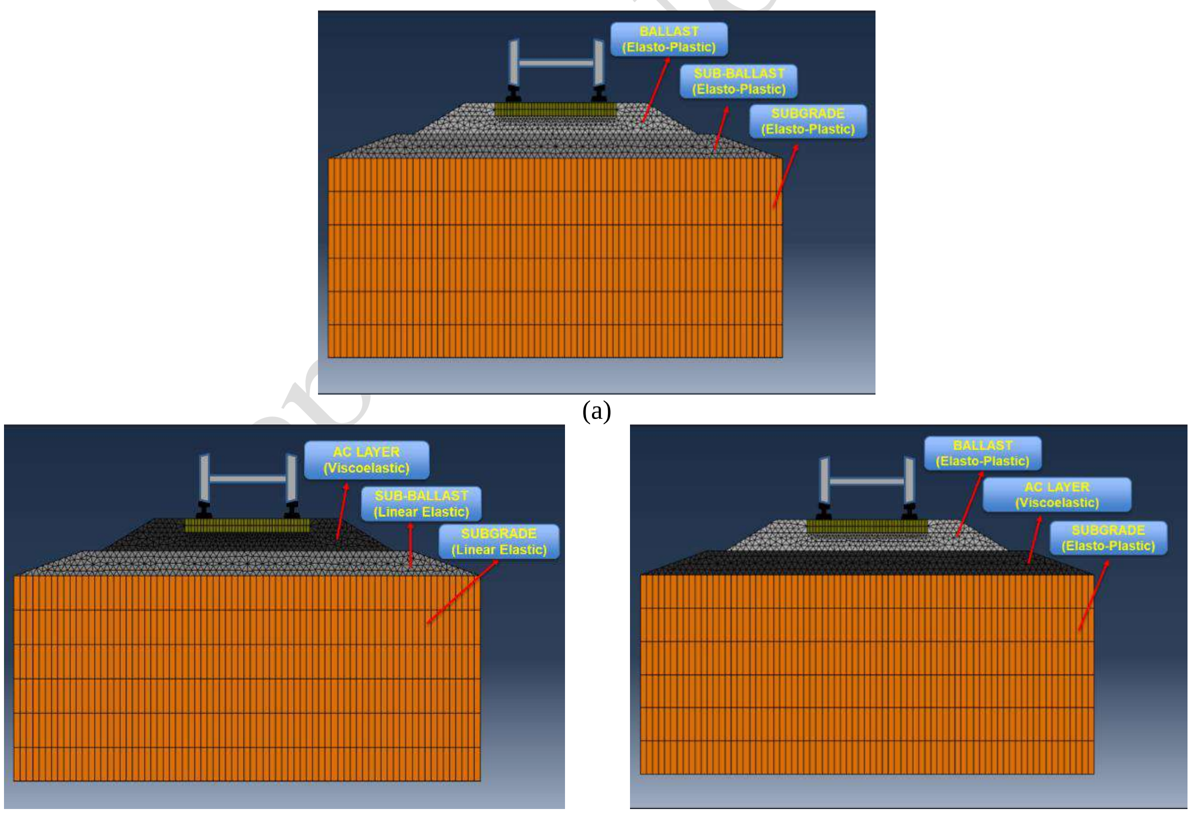


Fig. 3. Dimension of Freight Wagon in Babaranjang Freight Train Set (PT. Kereta Api Indonesia, 2021)



(b) (c)

Fig. 4. 2D Mesh of Simulation Models: a). Conventional Track; b). Asphaltic Overlayment Track; c). Asphaltic Underlayment Track

To examine the long-term deformation behavior of railway infrastructure, conventional and asphaltic track models were subjected to cyclic loading representative of Babaranjang freight train traffic. The loading scenarios incorporated operational train speeds, enabling an assessment of their impact on the total permanent deformation accumulated within the track structure.

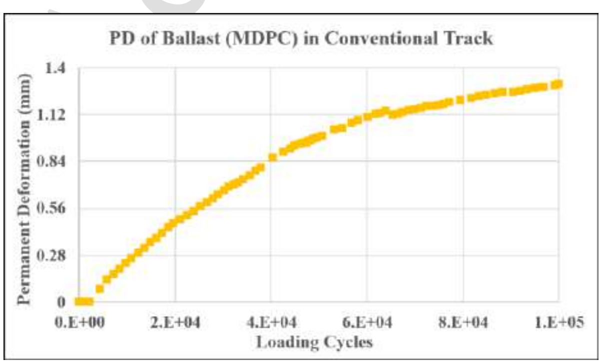
Finite Element Model Simulation

Finite element simulations were conducted using Abaqus/CAE in a two-dimensional framework. The modeling procedure comprised geometric representation of the track structure, mesh generation, assignment of boundary constraints, and application of train loading conditions. Three track systems, consisting of one conventional ballasted track and two asphaltic track alternatives, were analyzed under loading conditions representative of Babaranjang freight train operations. Figure 1 illustrates the model configurations, while Figure 4 presents the mesh employed in the numerical analysis. The reasonableness of the model responses was verified through sensitivity checks on key material parameters and loading conditions to ensure stable and physically consistent behavior.

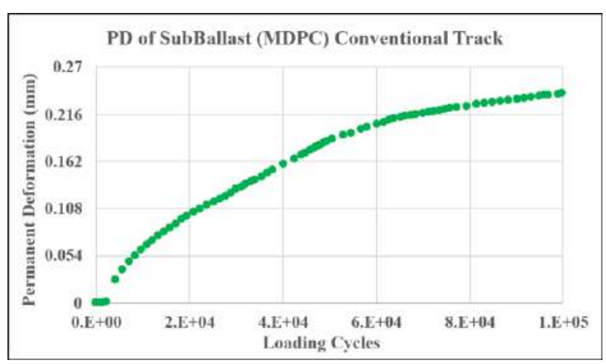
RESULTS

Permanent Deformation of Conventional Track

Figure 5 depicts the permanent deformation responses of the individual layers in the conventional railway track obtained from the MDPC-based finite element analysis. Among the track components, the ballast layer shows the highest deformation accumulation, followed by the subgrade and sub-ballast layers. The observed trend highlights the greater susceptibility of ballast to deformation under repeated train loading compared with the underlying structural layers.



(a)



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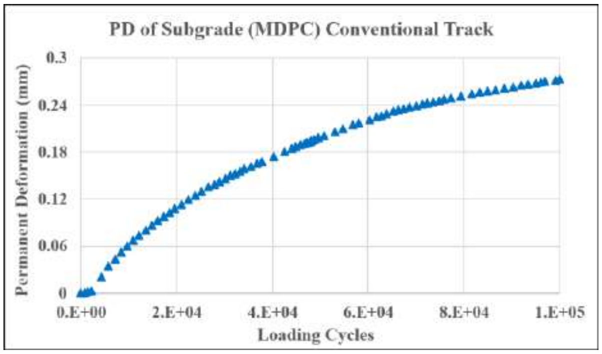

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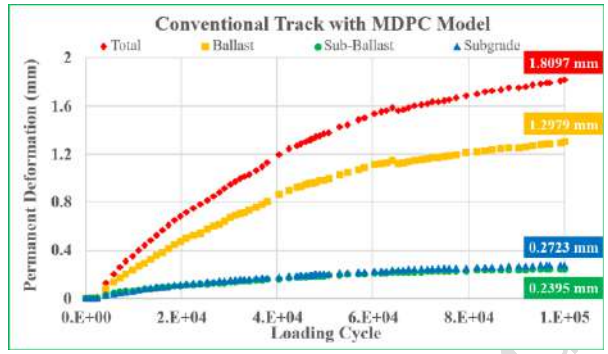
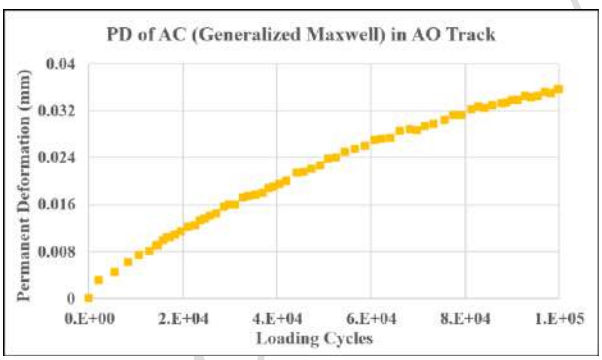


(d)

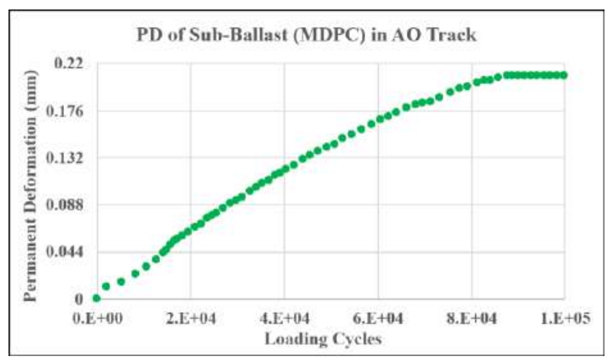
Fig. 5. Permanent deformation of conventional track with MDPC model: a). ballast; b). sub-ballast; c). subgrade; d). combination of all layers

Permanent Deformation of Asphaltic Overlayment Track

Figure 6 presents the permanent deformation response of the individual layers in the asphaltic overlayment (AO) track derived from the finite element simulations. The analysis reveals that deformation is concentrated primarily in the subgrade layer, which records the largest permanent deformation among all structural components. Lower deformation magnitudes are observed in the sub-ballast and AC layers, respectively.



(a)



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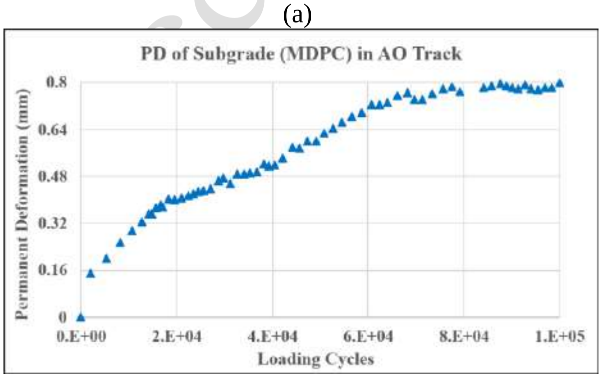

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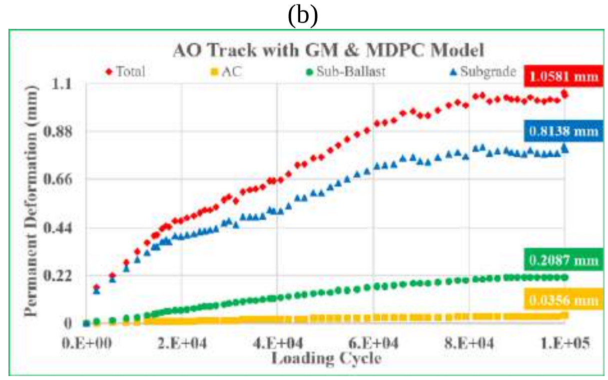


(d)

Fig. 6. Permanent deformation of asphaltic overlayment track with Generalized Maxwell and MDPC model: a). AC; b). sub-ballast; c). subgrade; d). combination of all layers

Permanent Deformation of Asphaltic Underlayment Track

Figure 7 summarizes the permanent deformation responses of the individual layers within the asphaltic underlayment (AU) track. The finite element analysis reveals that the largest deformation occurs in the ballast layer, followed by the subgrade and asphalt concrete (AC) layers. This trend indicates that the ballast layer continues to govern the deformation behavior of the AU track despite the incorporation of an asphalt layer within the track structure.

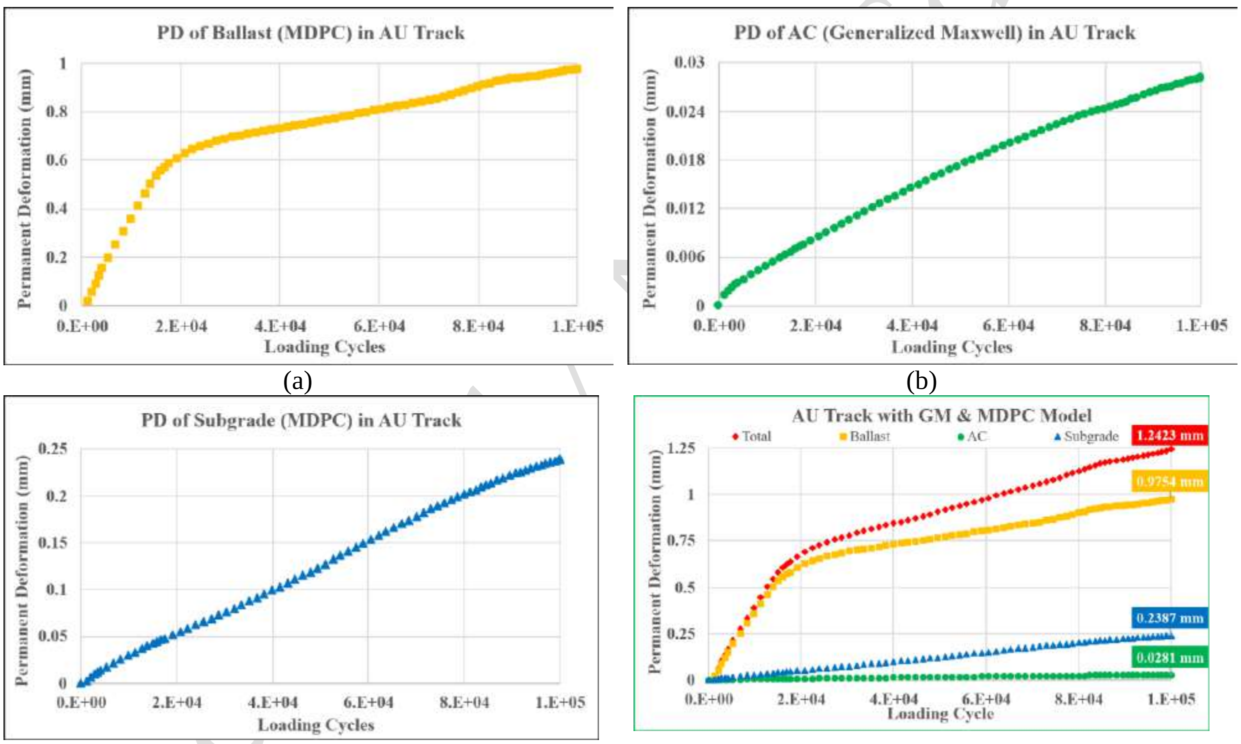
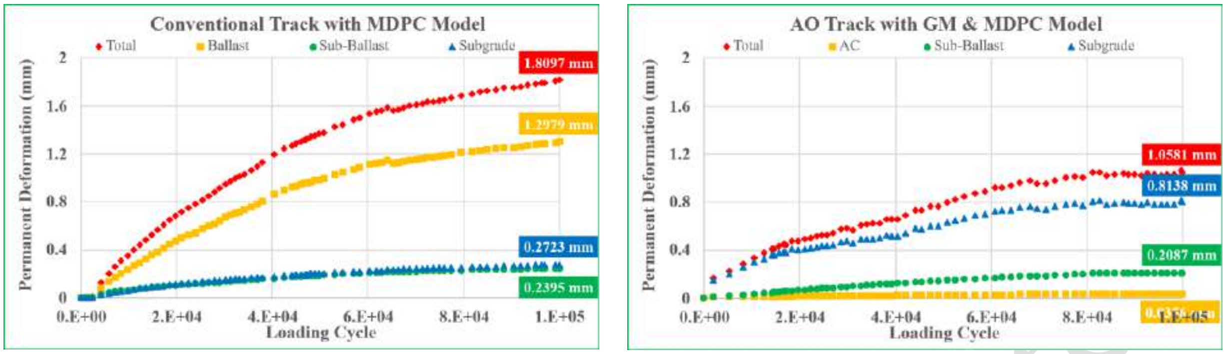


Fig. 7. Permanent deformation of asphaltic underlayment track with Generalized Maxwell and MDPC model: a). Ballast; b). AC; c). subgrade; d). combination of all layers

DISCUSSION

Comparison between Conventional and Asphaltic Overlayment Track

Figure 8 shows the comparison between the permanent deformation of conventional track and AO track. Comparing the two results, it can be concluded that AO track performs better than conventional track. The total permanent deformation of AO track is 41% and 47% lower than conventional track, respectively.

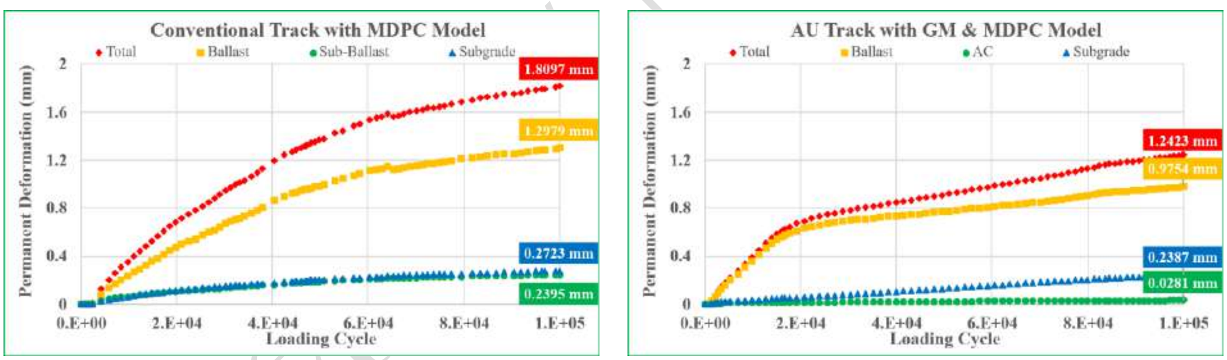


(a) (b)

Fig. 8. Comparison of permanent deformation: a). conventional track with MDPC model; b). asphaltic overlayment (AO) track with Generalized Maxwell and MDPC model

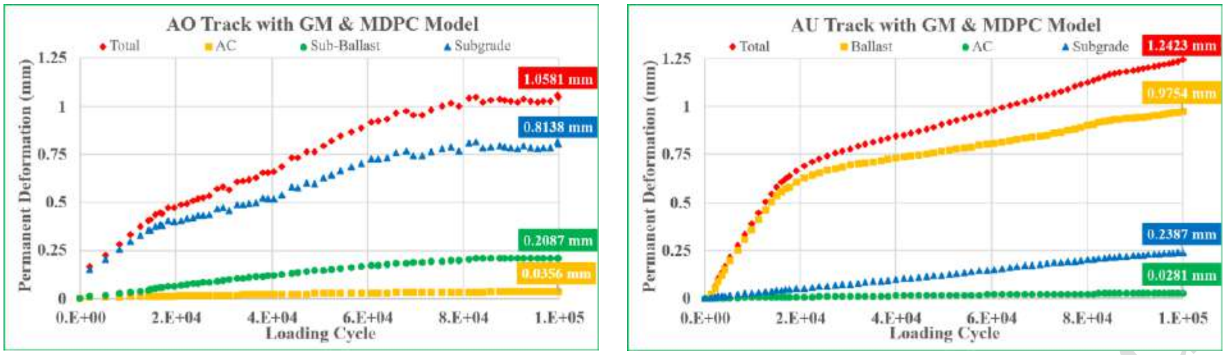
Comparison between Conventional and Asphaltic Underlayment Track

The comparison between the permanent deformation of conventional track and AU track is depicted in Figure 9. The comparison reveals the AU track performs better than conventional track. The total permanent deformation of AU track is 31% lower than conventional track.



(a) (b)

Fig. 9. Comparison of permanent deformation: a). conventional track with MDPC model; b). asphaltic underlayment (AU) track with Generalized Maxwell and MDPC model



(a) (b)

Fig. 10. Comparison of permanent deformation: a). asphaltic overlayment (AO) track; b). asphaltic underlayment (AU) track with Generalized Maxwell and MDPC model

Comparison between Asphaltic Overlayment and Asphaltic Underlayment Track

Figure 10 shows the comparison between the permanent deformation of AO track and AU track. It can be concluded that AO track performs better than AU track. The total permanent deformation of AO track is 15% lower than AU track.

Contribution of the Layers in Rail Tracks to the Total Permanent Deformation

The contribution of individual track layers to the total permanent deformation is quantified in Table 4 for the conventional, AO, and AU configurations. For the conventional track, the ballast layer dominated the deformation response, accounting for 71.72% of the total permanent deformation. Comparatively smaller contributions were observed in the subgrade (15.05%) and sub-ballast (13.23%) layers. A substantially different trend was observed for the AO track, where the subgrade layer became the dominant deformation source, contributing 76.91% of the total permanent deformation. Meanwhile, the sub-ballast and AC layers contributed 19.72% and 3.37%, respectively. These findings indicate that the inclusion of an asphalt layer significantly alters the load-transfer mechanism and redistributes deformation throughout the track structure. Lastly, the contribution of ballast, AC, and subgrade layer in AU track is 78.52%, 2.27%, and 19.21%, respectively.

Table 4. Contribution of the Layers in Rail Tracks to the Total Permanent Deformation

Conventional Track Layer	**Contribution (%)**	**mm**
Ballast	71.72%	1.2979
Sub-Ballast	13.23%	0.2395
Subgrade	15.05%	0.2723
Total	**100%**	**1.8097**
Asphaltic Overlayment Track Layer	**Contribution (%)**	**mm**
AC	3.37%	0.0356
Sub-Ballast	19.72%	0.2087
Subgrade	76.91%	0.8138
Total	**100%**	**1.0581**
Asphaltic Underlayment Track Layer	**Contribution (%)**	**mm**
Ballast	78.52%	0.9754
AC	2.27%	0.0276
Subgrade	19.21%	0.2387
Total	**100%**	**1.2423**

Prediction of Permanent Deformation using Regression and Extrapolation

Due to some conditions and limitations in this study, permanent deformation of the rail tracks was obtained only up to 100,000 loading cycles. Therefore, the regression and extrapolation analysis were performed to obtain the magnitude of the permanent deformation due to higher repetitive loadings, up to 1 million loading cycles. Figure 11 and Table 5 recapitulate the example of regression and extrapolation analysis to predict the permanent deformation of AU track at 1 million cycles of Babaranjang Freight trains loading systems.

Table 5. Comparison of Permanent Deformation of AU Track

Layer	**100,000 Loading Cycles**	**1,000,000 Loading Cycles**
Ballast	0.9754	4.55
AC	0.0275	0.60
Subgrade	0.2387	2.10
Total PD	1.2417	7.25

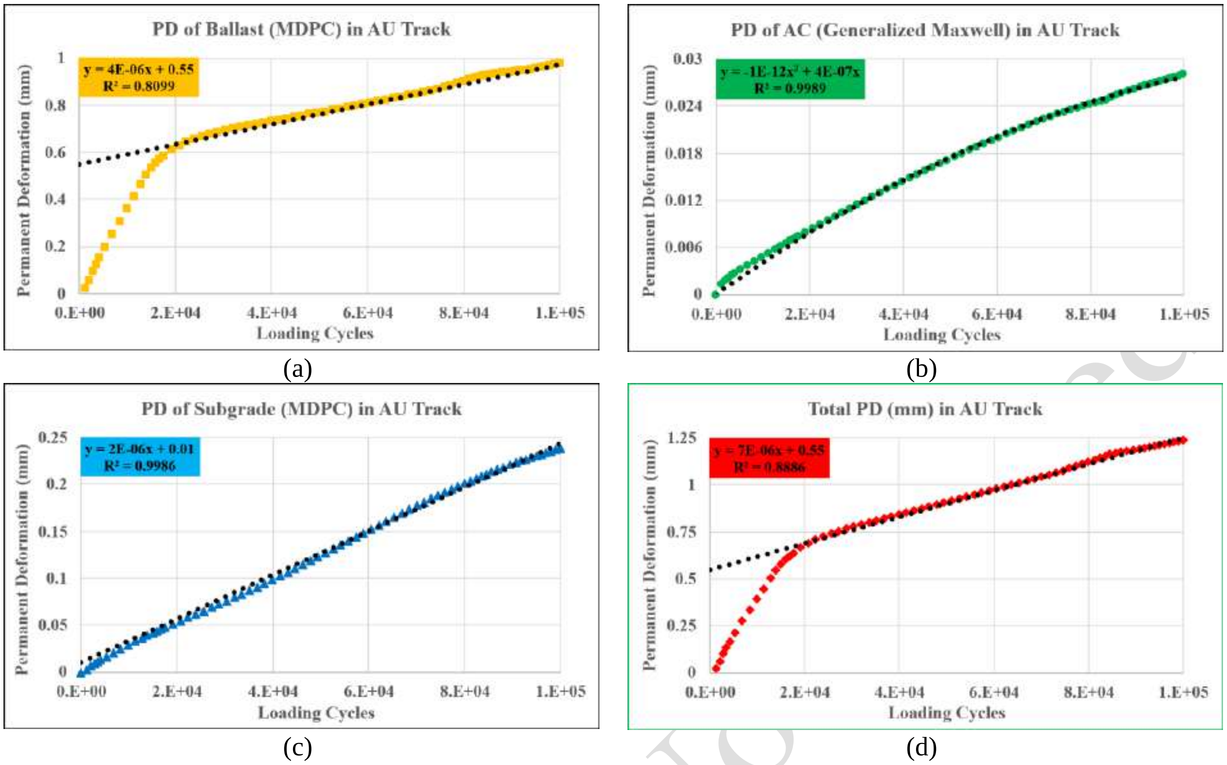


Fig. 11. Example of Permanent Deformation Prediction using Extrapolation for Asphaltic Underlayment (AU) Track: a). Ballast; b). AC; c). Subgrade; d). Total Permanent Deformation

Figures 12–14 illustrate the evolution of permanent deformation in the conventional, AO, and AU track systems under different loading histories. A comparison between the results at 100,000 and 1,000,000 load cycles indicates a marked increase in deformation for all track types. This trend confirms that permanent deformation continues to accumulate as cyclic loading progresses, reflecting the long-term deterioration behavior of railway track structures.

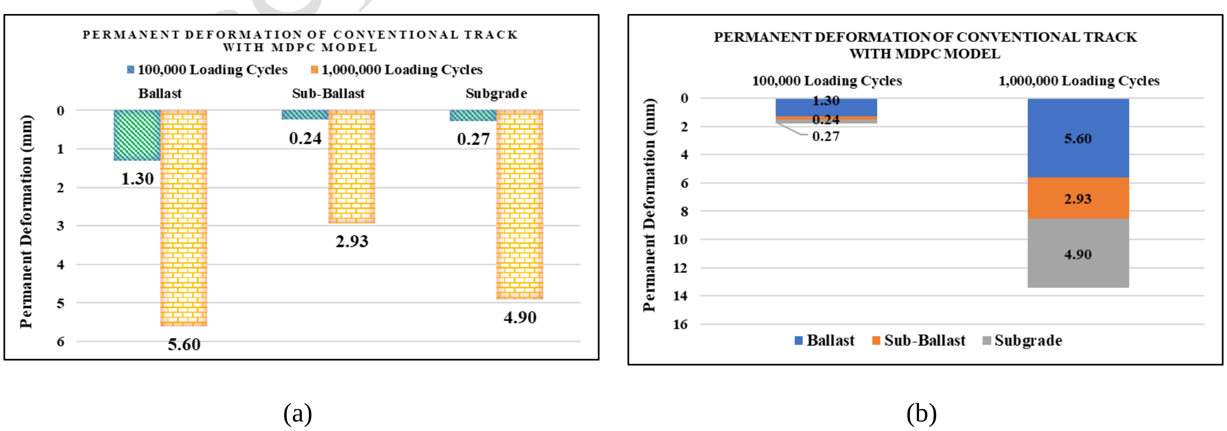
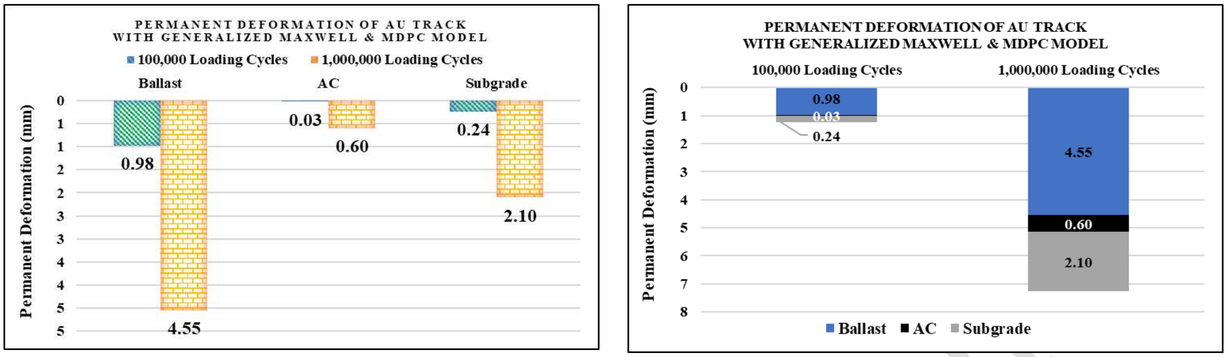
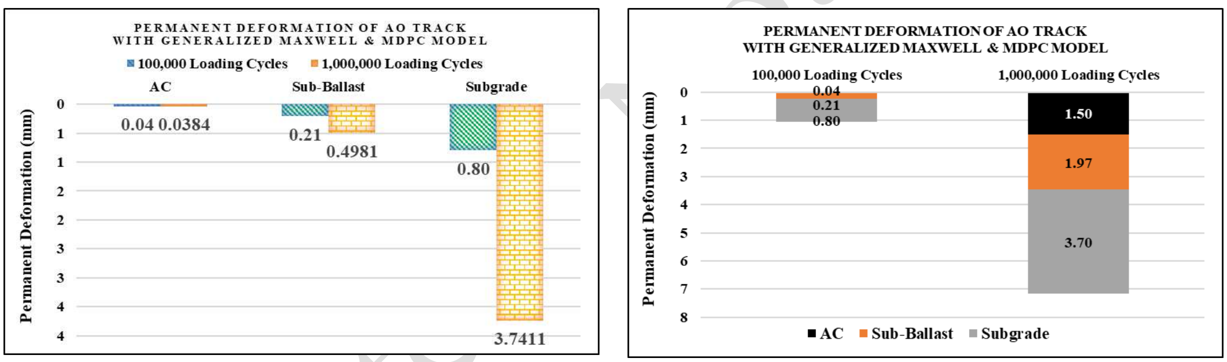


Fig. 12. Permanent Deformation of Conventional Track with MDPC Model at 100,000 and 1,000,000 Loading Cycles: a). Comparison of Each Layers; b). Combination of All Layers



(a) (b)

Fig. 13. Permanent Deformation of Asphaltic Underlayment (AU) Track with Generalized Maxwell and MDPC Model at 100,000 and 1,000,000 Loading Cycles: a). Comparison of Each Layers; b). Combination of All Layers

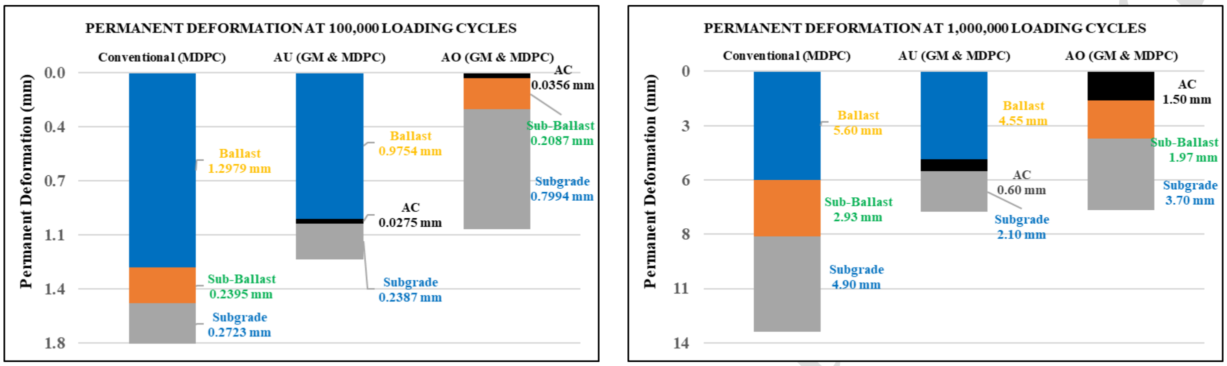


(a) (b)

Fig. 14. Permanent Deformation of Asphaltic Overlayment Track (AO) with Generalized Maxwell and MDPC Model at 100,000 and 1,000,000 Loading Cycles: a). Comparison of Each Layers; b). Combination of All Layers

Figure 15 presents the contribution of each structural layer on the total permanent deformation as well as the comparison of total permanent deformation between conventional (MDPC), AU and AO track (Generalized Maxwell and MDPC). From the figures we can conclude that in conventional and AU track both at 100,000 and 1 million loading cycles, ballast layer contributed to more than 50% of total permanent deformation. This result may be explained by the fact that the effect of pressure-dependent and densification properties of ballast layer in this study plays an important role on the performance of the rail tracks.

However, ballast % contribution to the total permanent deformation of conventional and AU tracks become increasing while subgrade % contribution to the total permanent deformation of rail tracks become increasing as the loading cycles reached 1 million loading cycles. It is also interesting to note that the AO track has slightly better performance than AU track at 1 million loading cycles, followed by the conventional track, respectively.



(a) (b)

Fig. 15. Contribution of Each Structural Layer on the Total Permanent Deformation and Comparison of Total Permanent Deformation between Conventional Track (MDPC), Asphaltic Underlayment Track and Asphaltic Overlayment Track (Generalized Maxwell and MDPC): a). 100.000 Loading Cycles; b). 1,000,000 Loading Cycles

Permanent Deformation Prediction and Measurement in Previous Studies

Selected previous investigations on permanent deformation behavior in railway track materials are compiled in Table 6. These studies primarily relied on laboratory-scale and full-scale experimental evaluations to quantify deformation in ballast, sub-ballast, subgrade, and AC layers subjected to repeated loading. Since the reported deformation levels depend on loading history and axle load magnitude, direct comparisons should be interpreted with consideration of the testing conditions employed in each study. Nevertheless, the permanent deformation values predicted by the present finite element model are comparable to those reported in earlier experimental research, indicating that the proposed modeling framework provides a realistic representation of railway track deformation behavior.

Table 6. Various Studies on the Prediction and Measurement of Permanent Deformation of Rail Track Structures

Paper	**Methodology: Field Test or Lab Experiment**	**Tested Materials**	**Measured Permanent Deformation (mm)**	**No. of Loading Cycles (LC)**	**Results from Current Study (1,000,000 LC, 18 Tons Axle Load)**
Grossoni et al., 2021	Southampton Railway Testing Facility (SRTF)	Ballast (Conventional Track)	20 mm	1,000,000 LC of 32 Tons Axle Load	5.60 mm of Ballast Permanent Deformation in Conventional Track (see Figure 15b)
			10 mm	1,000,000 LC of 20 Tons Axle Load	
Zhang and Jiang, 2020	Full-scale model testing	Lime-stabilized weathered red mudstone subgrade with thickness of 2.5 m	5.8 mm	3,000,000 LC of 18 Tons Axle Load	4.90 mm of Subgrade Permanent Deformation in Conventional Track (see Figure 15b)
			7.6 mm	4,000,000 LC of 25 Tons of Axle Load	
Abadi et al., 2018 and Abadi et al., 2016	Southampton Railway Testing Facility (SRTF)	Ballast with 300 mm of thickness	10 mm	3,000,000 LC of a 20 tons axle load	5.60 mm of Ballast Permanent Deformation in Conventional Track (see Figure 15b)
Aingaran, 2014	Laboratory Test	Ballast	12 mm	1,000,000 LC of 25 Tons Axle Load	5.60 mm of Ballast Permanent Deformation in Conventional Track (see Figure 15b)
Brown et al., 2007	The Nottingham railway test facility, a full-scale laboratory test facility for railway trackbeds.	Ballast	7.5 mm	1,000,000 LC. Application of cyclic loads of up to 94-100 kN of Axle Load	5.60 mm of Ballast Permanent Deformation in Conventional Track (see Figure 15b)
Lechner, 2005	Laboratory Scale Test	Asphalt Concrete	1.4 mm	500,000 LC of cyclic rail set loading of 55 kN	0.60 mm of AC Permanent Deformation in Asphaltic Underlayment Track (see Figure 15b)
					1.50 mm of AC Permanent Deformation in Asphaltic Overlayment Track (see Figure 15b)
Lee et al., 2018	Full-Scale Test	Asphalt Concrete	0.95 mm (20 cm AC Layer); 0.98 mm (27 cm AC Layer);	2.000,000 LC Application of cyclic loads of up to 179 kN (18 Tons) of	0.60 mm of AC Permanent Deformation in Asphaltic

Paper	Methodology: Field Test or Lab Experiment	Tested Materials	Measured Permanent Deformation (mm)	No. of Loading Cycles (LC)	Results from Current Study (1,000,000 LC, 18 Tons Axle Load)
			1.14 mm (35 cm AC Layer)	Axle Load	Underlayment Track (see Figure 15b)
					1.50 mm of AC Permanent Deformation in Asphaltic Overlayment Track (see Figure 15b)

Permanent deformation is not the only criterion for selecting the optimal railway pavement design. In this study, permanent deformation was intentionally chosen as the primary performance indicator because it directly governs track geometry deterioration, maintenance frequency, and long-term serviceability. However, the optimal railway track design should be based on a holistic evaluation that also considers allowable stresses in each layer, maintenance and rehabilitation requirements, constructability, and implementation costs. In addition, the asphaltic rail track designs not only reduce permanent deformation but also offer potential benefits in stress redistribution, maintenance reduction, and lifecycle performance. It is suggested that a full multi-criteria optimization, including detailed economic and construction feasibility analyses, is beyond the scope of the present study and is recommended for future research.

CONCLUSIONS

This study developed a two-dimensional finite element model to investigate the permanent deformation behavior of asphaltic railway track systems with different asphalt layer configurations, namely asphaltic overlayment (AO) and asphaltic underlayment (AU). The numerical simulations incorporated the Generalized Maxwell model to represent the viscoelastic behavior of asphalt concrete and the Modified Drucker–Prager Cap (MDPC) constitutive model to characterize the pressure-dependent response of unbound granular and subgrade materials. The deformation responses of individual structural layers, as well as the total permanent deformation of the track systems, were evaluated and compared. The results demonstrated that both asphaltic track configurations outperformed the conventional ballasted track in terms of total permanent deformation resistance. Among the investigated alternatives, the AO configuration exhibited the lowest total permanent deformation, indicating its superior overall structural performance. In contrast, the AU configuration showed improved deformation performance within the asphalt concrete and subgrade layers. These findings highlight the significant influence of asphalt layer placement on load distribution and deformation mechanisms within railway track structures. Consequently, the location of the asphalt layer should be carefully considered during the design and structural evaluation of asphaltic railway tracks. Future research should extend the analysis to higher loading cycles to better assess the long-term performance of conventional and asphaltic track systems. In addition, the incorporation of time-dependent creep and viscoplastic behavior of unbound granular and subgrade materials is recommended to improve the accuracy of permanent deformation predictions and to provide a more comprehensive representation of long-term railway track behavior under repeated train loading.

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