ENHANCING RAILWAY TRACK STIFFNESS AND SUSTAINABILITY THROUGH FLOWABLE DREDGED SOIL BACKFILL

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Abstract - This study investigates flowable dredged soil backfill using air-foam technology and simulates a bridge approach structure under high-speed train loads. A comparison between conventional cement-treated soil (CTB) and innovative flowable dredged soil backfill solutions reveals crucial findings: Resilient modulus tests highlight the significant impact of cement and air foam, favoring mixtures with over 210 kg/m^3 cement content and less than 10% air-foam, resulting in a resilient modulus of 354 MPa. Finite Element Method (FEM) simulations show CTB compliance with k_1/k_2 standards for all track options and the effectiveness of lightweight soil, especially Silty Soil (SM), in preventing critical k_1/k_2 increases. The lightweight soil exhibits superior performance through FEM analysis, settling only 3 mm after 800,000 cyclic train loads compared to nearly 5 mm in conventional CTB systems. This confirms the feasibility of lightweight dredged soil backfill in strengthening weak bridge approach foundations, enhancing railway track infrastructure sustainability and performance.

Key words - Flowable dredged soil; bridge approach; backfill; railway; track stiffness.

1. Introduction

The exhausted train loads and the critical environmental impacts contribute to the fast degradation of the railway track substructure [1]. Reports indicate that the railway transitions zone accounted for a large amount of maintenance and rehabilitation costs due to the difference in the track stiffness between the merged sections (bridge and approach zones). Various methods have been introduced to counter the variation in the track support system at this zone [1–3]. From the design stage to the maintenance stage, these researches have partly resolved the issues caused by the sudden drop in the stiffness of railway tracks. However, high construction costs may limit these techniques for large-scale applications [4]. Besides, when constructing the canal system, the excavated soil was usually disposed of due to inhomogeneous particle size and contaminated issues [2]. Recently, there has been a lack of research focus on the application of this material for railway backfill construction.

Hence, this study aims to develop a sustainable railway backfilling material using flowable dredged soil. The consumption of locally dredged soil will not only reduce the disposal of excavated soil to the nearby environment but also mitigate the usage of natural construction sand as filling material [5]. In addition, the newly developed material is incorporated by the air foam technique which broadens the workability in narrow regions and activates the lightweight property of the backfill layer. Mixing proper air foam content into the mixture will also improve the self-leveling behavior and provide insulation benefits [6]. More importantly, the addition of appropriate cement content is expected to enhance the stress-bearing capacity of the bridge approach zone thereby, sustaining the track stiffness of the whole railway system. The stronger backfilling layer is expected to generate a gradual change from the bridge to the approach location, protect the durability of track components, and increase passenger comfort.

The laboratory and numerical analysis will be performed to evaluate the performance of the new backfilling material. The laboratory experiments were conducted to investigate some important properties of the backfilling material. Then, the Finite Element Model process will employ the best mix design to develop a full railway bridge transition section. The reinforcement effectiveness will be compared between the flowable dredged soil backfill and the conventional backfill material by analyzing the elastic displacement and plastic displacement under 800,000 cyclic train loads.

2. Materials and Methods

2.1. Materials

In this study, Type A and Type B soils were obtained through the excavation of a canal system near the bridge approach in Gunsan, South Korea. The collection procedure involved a meticulous approach to sampling and characterizing the excavated soil. First, soil samples were systematically gathered from various points along the canal, aiming to encompass diverse sections with potential soil property variations. Then, these samples were strategically collected across the canal system to ensure a representative distribution, encompassing different depths and lateral positions. Each collected soil sample was meticulously identified and labeled, linking it to its precise location within the canal, including depth and lateral coordinates. Next, these samples underwent comprehensive laboratory analysis to assess their physical and mechanical attributes. Parameters such as water content, specific gravity, liquid limit, plastic limit, and plasticity index were determined through these tests. Finally, following the laboratory analysis, the soil samples were categorized into distinct types based on their properties, enabling a clear differentiation between Type A soil (with high clay content) and Type B soil (with low clay content).

The dredged soil properties and gradation size are presented in Table 1 and Figure 1, respectively. The Portland cement type II having the 28-day compressive strength of 45 MPa is used in this research to support the strength gain of the mixture. The flowable backfill not only consumes a large volume of dredged soil but also achieves self-leveling behavior for workability purposes. Therefore, air-foam technology is employed in this research. The used air foam is produced from the foaming fluid made by keratin protein. The fresh air foam liquid is mixed with water to a ratio of 1:20, then, the whole mixture is processed through the air foam machine to create a dense foaming [6].

Considering the mix design, the dry components were mixed for approximately 2 mins at a rate of 90 rpm, the water and air foam were then added to the mixing drum, and the whole batch was mixed for additional 5 mins at a rate of 60 rpm. This mixing method will ensure the durability of the preformed foam [6]. The fresh mixture was finally cast into a plastic mold having a diameter of 100 mm and height of 200 mm. The mix design of flowable dredged soil is summarized in Table 2.

Table 1. *Properties of dredged soil*

Properties		Value		Unit
		Type A	Type B	
Watern Content	w	25.86	20.06	%
Specific Gravity	Gs	2.661	2.759	
Liquid Limit	LL	34.1	22.03	%
Plastic Limit	PL	25.2	N.P.	%
Plasticity Index	PI	10.2	N.P.	%

Table 2. *Mix design*

Mix	Cement (kg/m^3)	Type A (CL): Dredged soil with high clay content (kg/m^3)	Type B (SM): Dredged soil with low clay content (kg/m^3)
A10	100	937	1237
A20	100	866	1166
B10	130	901	1202
B20	130	830	1099
C10	160	865	1168
C20	160	794	1064

Air-foam (% volume)	Water/Cement For type A soil	Water/Cement For type B soil
10	0.7	0.45
20	0.65	0.42
10	0.7	0.45
20	0.65	0.42
10	0.7	0.45
20	0.65	0.42

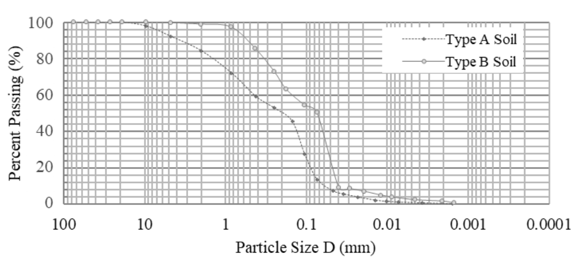

Figure 1. *Percent passing of lightweight soil materials*

2.2. Methodology

2.2.1. Resilient Modulus Test

The resilient modulus test (Figure 2a) is conducted in compliance with standard AASHTO T307 [7]. The resilient modulus (M_r) of the sample is calculated as the ratio of repeated axial deviator stress to the recoverable axial strain, under the confining pressure of 30 kPa. The resilient modulus of flowable dredged soil samples was calculated following Equation 1

$$M_r = \frac{\Delta\sigma_d}{\Delta_{\varepsilon_{axial}}} \quad (1)$$

Where, $\Delta\sigma_d$ deviatoric stress ($=\sigma_1 - \sigma_3$); σ_1, σ_3 major and minor principal stresses, and $\Delta_{\varepsilon_{axial}}$= recoverable axial strain.

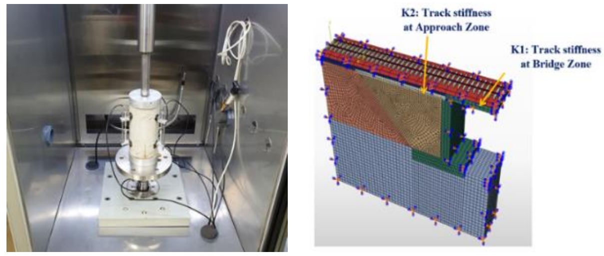

Figure 2. *(a) Resilient modulus test and (b) 3D modeling of the railway approach zone*

2.2.2. Modelling For Repeated Load Analysis

Utilizing the ABAQUS software, the simulation procedure is employed to assess the effectiveness of employing flowable dredged soil as a backfill material in railway bridge transitions [5]. Through finite element analysis using a 3D model, an investigation is conducted into the accumulation of settlement in bridge approaches under varying loads of trains, recognizing the hastened settlement patterns observed in 3D models as demonstrated by prior research [5]. To precisely predict settlement values within a reasonable analysis period, a segment of the bridge approach zone is integrated into the 3D model (Figure 2b). The principal objective of this study is to perform a comparative analysis of the performance between conventional backfill material and the newly introduced dredged soil, employing the most suitable mixture determined through resilient modulus tests. The finite element model encompasses the complete railway bridge transition zone and the related railway components (motor car, trailer car), conforming to the guidance outlined in the Korea Railway Design Guideline and Handbook (KR C-14030) [8]. The design of the Finite Element Model for the KTX train is depicted in Figure 3.

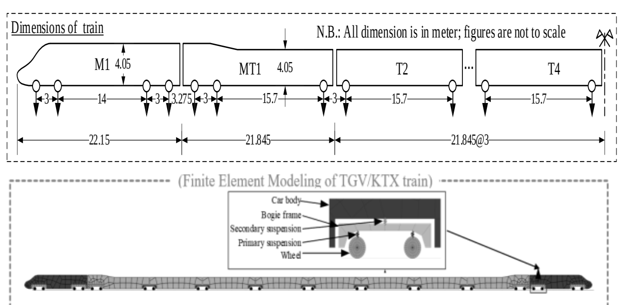

Figure 3. *The design of the full KTX train for the simulation*

2.2.3. Design in the simulation process

In this research, the substructure layer was designed using the Drucker-Prager/Cap model with a friction angle of 45° [5]. The remained materials properties used in the finite element design are summarized in Table 3 which is based on a combination of sources, including relevant literature on soil properties [9, 10], material specifications [11], and Korean engineering standards [12]. In the FEM modeling, the horizontal axis of the model was completely fixed (σ_2=0) while all displacements were constrained at the bottom (σ_1=σ_2=σ_3 =0). Regards to the element property, the 8-node linear brick with reduced integration and hourglass control is the applied model [13]. The interaction between the wheel and rail is frictionless. Meanwhile, the tie contact of the surface is applied to the remained interfaces to streamline the simulation process.

Table 3. *Materials for FEM analysis*

Material	Unit weight (kN/m^3)	Poisson's ratio	Elastic Modulus (MPa)
Rail	78	0.3	210,500
Concrete bridge deck	23.5	0.25	21,000
Optimized lightweight material	13	0.25	325
Conventional cement-treated soil	20	0.2	125
Ballast layer	14	0.28	160
Gravel layer	21	0.25	85
Subgrade layer	18	0.28	70
Weathered rock layer	21	0.2	110
Concrete abutment	25	0.2	24,200
Concrete slab	25	0.21	20,500
Reinforced Roadbed	22	0.21	125
Under sleeper pad (USP)	4.2	0.15	12

2.2.4. Calculation of the train loads

According to the suggestions from prior studies and recommendations from the standard of KRRI [11], the dynamic load of 124 kN and 135 kN is calculated by the passenger train speed of 165 km/h and 300 km/h as shown in the below equation (2). The calculated loads will be applied in the simulation of cyclic train load at the frequency of 10 Hz.

$$P_{dyn} = P_{eff} \times DAF \quad (2)$$

If V≤60 km / h, $DAF = 1 + t \times \emptyset$

If 60 <V≤350 km/h passenger train,

$$DAF = 1 + t \times \emptyset \left(1 + 0.5\frac{V-60}{190}\right)$$

For 60 <V≤160 km/h passenger and cargo trains,

$$DAF = 1 + t \times \emptyset \left(1 + 0.5\frac{V-60}{80}\right)$$

Where: P_{st}: Static wheel load (kN);

P_{eff}: Effective wheel load (P_{st} ×1.2 kN);

P_{dyn}: Dynamic wheel load (kN);

DAF: Dynamic Amplitude Factor;

$\emptyset$ = Coefficient of track (0.2 for good track);

t: standard deviation which depends on the confidence interval of probability (t = 1 for calculation of roadbed).

3. Results and discussion

3.1. Resilient Modulus Test

The resilient modulus test of the flowable dredged soil is shown in Figure 4. Overall, almost all mixtures show a compressive strength of higher than 120 MPa except mixtures having 130 kg/m^3 cement and 20% air foam. The analysis of resilient modulus values, supported by the dataset from Figure 4, highlights distinct differences between Type A and Type B soils. In the 210-10 mixture, Type A soil demonstrates a resilient modulus of approximately 354 MPa, while Type B soil exhibits a value of 310 MPa, indicating a difference of around 44 MPa (approximately 14%). As the air foam content increases in the 210-20 mixture, this difference decreases to about 27 MPa (around 8%), with Type A soil having a resilient modulus of 263 MPa and Type B soil at 236 MPa. Similarly, for the 160-10 mixture, Type A soil's resilient modulus of 245 MPa exceeds that of Type B soil (220 MPa) by about 25 MPa (approximately 11%), and this difference decreases to roughly 17 MPa (around 8%) in the 160-20 mixture. Notably, the difference in resilient modulus diminishes further as the air foam content increases. In the 130-10 mixture, the difference is around 15 MPa (approximately 10%), with Type A soil at 147 MPa and Type B soil at 132 MPa. This difference decreases to approximately 8 MPa (around 9%) in the 130-20 mixture, with Type A soil at 95 MPa and Type B soil at 87 MPa. These comparisons underscore the consistent trend of Type A soil exhibiting higher resilient modulus values than Type B soil across various mixtures and demonstrate the influence of air foam content on this relationship.

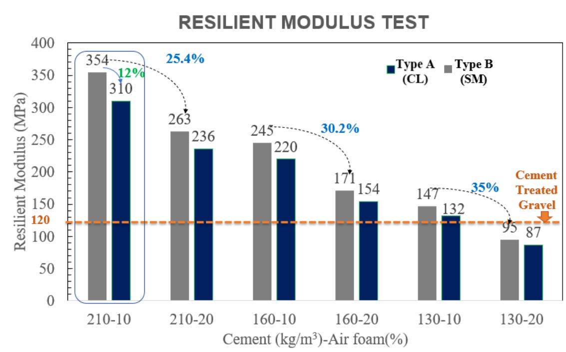

Figure 4. *The design of the full KTX train for the simulation*

Mix 130-20 show poor strength gain due to the deficiency of appropriate hydrated cement products which contribute to the bearing capacity of the structure. The test results indicate a reasonable trend since the dredged soil mixture having high cement content and low air foam volume outperforms the remained mixture. The best mixture has a resilient modulus of 354 MPa which is very adaptable for the replacement of conventional backfill material (120 MPa). Adding 10% air foam by volume will result in a drop in the resilient strength of the mixture, from 354 to 263 MPa. It may be due to the higher air-void system formed in the samples may lead to a weak connection between the solid components. In the proposed research, the foam component is expected to provide the lightweight property for the mixture which will mitigate the pressure to the substructure. Therefore, the slight drop in the strength gain can be compensated by this unique characteristic.

3.2. Finite element simulation results

3.2.1. Railway track stiffness

The track stiffness strengthening of the newly developed material is shown in Figure 5. It should be mentioned that the ratio of the railway stiffness (k_1/k_2) represents the difference in the railway stiffness measured at the concrete abutment (bridge end) and the approach locations. This value must be controlled as low as possible to reduce the sudden settlement which will impose a negative impact on the passenger experience and the resilience of the railway system. Based on the suggestion from KRRI, the railway stiffness ratio must be designed at smaller than 1.75 to ensure the track integrity. As can be observed from the graph, all dredged soil mixtures containing the lowest binder content of 130 kg/m^3 could not meet the safety requirements. Therefore, the cement content should be controlled at higher than 160 kg/m^3 in consideration of the standard mixture. The simulation results also suggest that the optimum track stiffness ratio can be achieved by increasing the cement volume and reducing the consumption of air foam. For example, when the air-foam content is fixed at 10% by volume, the increase in cement content from 130 to 210 kg/m^3 will diminish the k_1/k_2 ratio from 1.79 to 1.54. Meanwhile, adding more air foam will cause a slightly higher track stiffness ratio. However, the impact of air foam can be considered neglectable in those mixtures having high cement content since the track stiffness ratio of mix SM210-10 and mix SM210-20 is 1.54 and 1.58, respectively.

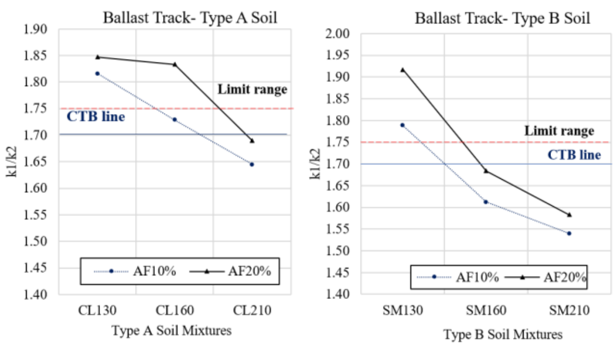

Figure 5. *The track stiffness ratio measured at different backfill options*

Additionally, the primary objective of this study is to address the critical issue of shock reduction at the railway bridge approach, which is closely associated with the k_1/k_2 ratio. Lowering this ratio is crucial to mitigate the abrupt transition between the bridge and approach sections. The results obtained from the analysis indicate that adding cement to 160 kg/m^3 may be effective for Type A (CL) Soil, while Type B (SM) soil shows a favorable decrease in this k_1/k_2 ratio. This trend suggests the potential for stress-bearing capacity improvement and enhanced track stiffness. These findings underscore the significance of tailored mix designs for different soil types, cement contents, and air foam ratios, all of which play a pivotal role in achieving the desired k_1/k_2 ratio and ensuring smoother railway transitions.

3.2.2. Effect of cement and air foam

Figure 6 presents the displacement measured at the bridge transition zone. As can be seen from the graph, the head of the train (motor car) leads to a sharp displacement up to around 6 mm, followed by the trailer car which poses a lower displacement value of around 4 mm. Then, the displacement of the measured point returns to the original value of 0 mm. Under cyclic train loads, the accumulated displacement may gradually build up and result in the track-bed degradation. Regards to the impact of cement content, the simulation results indicate that mixing higher cement will contribute to the displacement resistance of the track structure. For example, the elastic displacement of mix SM210-10 and mix SM130-10 is approximately 6 mm and 5.7 mm, respectively. Meanwhile, the alternation of air-foam content may not significantly affect the reinforcement effectiveness. Therefore, the usage of higher air-foam content should be promoted since this method can reduce the consumption of natural resources and reduce the pressure on the substructure.

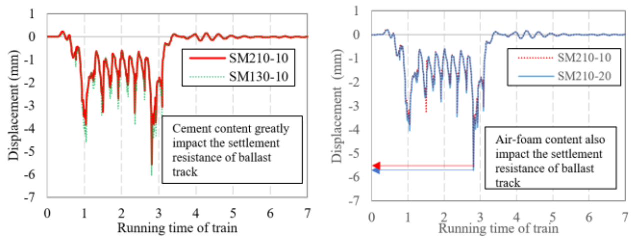

Figure 6. *The track stiffness ratio measured at different backfill options*

3.2.3. Long-term performance

The behavior of the track system under cyclic train loads is displayed in the following Figure 7. Overall, all simulated sections show a sharp displacement value at the first 50,000 cycles. This can be explained by the volume compaction of the substructure which can be easily developed at initial train loads. However, when the track foundation is properly compacted, the displacement value of the track bed will gradually increase under cyclic loads.

The FEM results reveal that a train operated at a higher speed will impose greater dynamic pressure to the substructure and thereby, leading to higher plastic displacement to the track. The increase in train speed leads to a higher dynamic pressure exerted on the track substructure due to the greater kinetic energy and impact forces associated with higher velocities. As a result, the substructure experiences more significant cyclic loading, causing increased plastic deformation over time [14]. The higher dynamic pressure induces greater stress on the materials within the substructure, contributing to the accumulation of plastic displacement in the track. This effect is particularly pronounced at higher speeds, where the increased energy transfer between the train and track exacerbates the cyclic loading and deformation process.

In addition, the application of the flowable dredged soil shows remarkable reinforcement effectiveness at higher train speeds since the plastic displacement reduction measured at a train speed of 300 km/h is 0.4 mm while this value of a train speed of 165 km/h is 0.15 mm. Besides, the simulation results indicate that the plastic displacement resistance of the proposed dredged soil mixture is more prominent in the long-term service life. For example, after the first 100,000 cyclic train loads, the plastic displacement gap is 0.2 mm between the newly developed section while this value measured after 800,000 cycles is up to 0.4 mm. Therefore, the findings confirm the improvement in the displacement resistance when the proposed dredged soil is used as backfilling material.

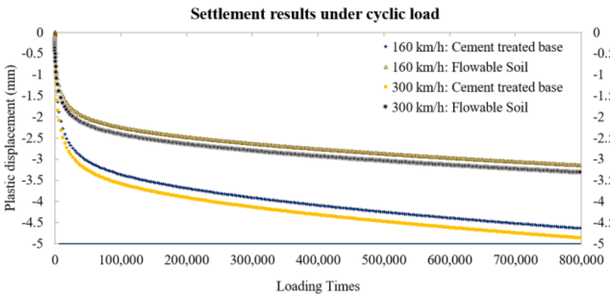

Figure 7. *The plastic displacement under cyclic train loads*

4. Conclusion

After investigating the resilient modulus of the lightweight soil using the air-foam technique, the proposed research aims to simulate the whole bridge approach structure and analyze the performance of dredged soil backfill under high-speed train loads. The performance of the whole bridge approach structure having conventional cement-treated soil and flowable dredged soil backfill solutions were compared, respectively. The following remarks were generated from the study:

• From the resilient modulus data presented in the laboratory test, it is observed that the trend suggests an optimized mixture with cement content exceeding 210 kg/m^3 and air-foam levels below 10%. While this range showcases improved performance, it is important to note that our study did not explicitly explore mixtures with cement content higher than 210 kg/m^3 or air-foam content lower than 10%. Consequently, it is recommended that further investigations be conducted to validate the applicability of these trends beyond the studied range.

• Resilient modulus test highlights that most mixtures exhibit strengths exceeding 120 MPa, revealing a trend except for cases with 130 kg/m^3 cement and 20% air foam, underscoring the influence of hydration on strength gain and bearing capacity. The optimal mixture attains an impressive resilient modulus of 354 MPa, favoring its potential replacement of conventional backfill material (120 MPa), while 10% air foam induces a drop to 263 MPa, potentially attributed to air-void formation and compensated by foam's lightweight property to alleviate substructure pressure.

• The FEM simulation results suggest that the conventional cement-treated base (CTB) meets the k_1/k_2 standard in all track options. However, in the ballast track under the highspeed train, it should be noted that the k_1/k_2 of the CTB structure is very close to the maximum allowable ratio. Under service life, the deterioration of the track system at the bridge approach may lead to the increase of this value to the critical range, therefore, the application of new lightweight soil is suggested to prevent this issue, especially Silty Soil (SM).

• The air-foam and cement content greatly impact the stress-bearing ability of the backfill layer. The desired k_1/k_2 ratio can be obtained from a mixture having 10 % air-foam and cement content higher than 210 kg/m^3. The test results indicate that a mixture having 130 kg/m^3 should be avoided in the construction of a high-speed train system due to the very high k_1/k_2 ratio.

• After 800,000 cyclic train loads, the conventional CTB system showed a very high accumulated settlement of nearly 5 mm, meanwhiles, this value of the proposed lightweight soil accounts for a smaller value of 3 mm. The equivalent trend was found for both train speed options which confirms the potential effectiveness of lightweight dredged soil backfill technique for the reinforcement of weak bridge approach foundation.

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REFERENCES

[1] E. Berggren, *Railway Track Stiffness – Dynamic Measurements and Evaluation for Efficient Maintenance*, Stockholm Royal Institute of Technology, 2009.

[2] A. Paixão, E. Fortunato, and R. Calçada, "A numerical study on the influence of backfill settlements in the train/track interaction at transition zones to railway bridges", *Proc. Inst. Mech. Eng. Part F J. Rail Rapid Transit*, vol. 230, no. 3, pp. 866–878, 2016. https://doi.org/10.1177/09544097155732

[3] G. Ognibene, W. Powrie, L. Le Pen, and J. Harkness, "Analysis of a bridge approach: long-term behavior from short-term response", *In 15th Railway Engineering Conference, Edinburgh, U.K*, 2019. pp. 1-15.

[4] C. Gallage, B. Dareeju, and M. Dhanasekar, State-of-the-art: track degradation at bridge transitions, *Proc. 4th Int. Conf. Struct. Engineering Constr. Manag*. 2013, pp. 40–52.

[5] T. H. M. Le, D. W. Park, T. W. Lee, and J. W. Seo, "Feasibility study of locally excavated soil in foamed cement mixture as backfill material for abutments of railway bridges", *Journal of Testing and Evaluation*, vol. 50, no. 6, pp. 21, 2021, DOI:10.1520/JTE20210169.

[6] T. H. M. Le, D.-W. Park, and J.-W. Seo, "Evaluation of Ponded Ash as a Sustainable Backfill Material", *J. Mater. Civ. Eng.*, vol. 30, no. 8, 04018158, 2018. DOI:10.1061/(ASCE)MT.1943-5533.0002359.

[7] AASHTO: T 307-99, "Standard Method of Test for Determining the Resilient Modulus of Soils and Aggregate Materials Standard Method of Test for of Soils and Aggregate Materials", *Resilient Modul. Test. Pavement Components*, vol. 99, pp. 0–42, 2012.

[8] KR C-14030 2018 *Korea Railway Design Guidelines and Handbook – Ballasted Track Structure*, Korea Rail Netw. Auth, 2018.

[9] D.-W. Park, H. V. Vo, and Y. Lim, "Recycling of Dredged Soil Waste Using Air-foam Stabilization Method as Highway Construction Material", *Innovative and Sustainable Use of Geomaterials and Geosystems*, 2014, pp. 41–48. https://doi.org/10.1061/9780784478455.006

[10] T. Q. Tran, Y. S. Kim, G. O. Kang, B. H. Dinh, and T. M. Do, "Feasibility of Reusing Marine Dredged Clay Stabilized by a Combination of By-Products in Coastal Road Construction", *Transp. Res. Rec.*, vol. 2673, no. 12, pp. 519–528, 2019.

[11] S. H. Lee, D. W. Park, H. V. Vo, and M. Fang, "Analysis of asphalt concrete track based on service line test results", *Constr. Build. Mater.* vol. 203, no. 10, pp. 558–566, 2019.

[12] MOLIT (Ministry of Land, Infrastructure & Transport), *Stat. Syst*, Korea National Standard, 2017.

[13] M. M. Biabani, B. Indraratna, and N. T. Ngo, "Modelling of geocell-reinforced subballast subjected to cyclic loading", *Geotext. Geomembranes*, vol. 44, no. 4, pp. 489–503, 2016.

[14] M. A. Sayeed and M. A. Shahin, "Investigation into Impact of Train Speed for Behavior of Ballasted Railway Track Foundations", *Procedia Eng.*, vol. 143, pp. 1152–1159, 2016.