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A Semi-Flexible Composite Trackbed Material for Stiffness Transition in Bridge Approaches and Its Application

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Prepared by:
Shihui Shen, Penn State - Altoona
Shuai Yu, Penn State - University Park

r3utc.psu.edu

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16. Abstract

When railroad tracks extend from a subgrade to a bridge, the abrupt variation of the stiffness or track moduli can lead to transition problems. This is mainly due to a major settlement difference of the foundation and can cause a discontinuity of the track structure. If handled inappropriately, these problems would eventually accelerate the degradation of the railway tracks. Various approaches, focusing on either component modification or structure adjustment, have been tried to mitigate the transition problem. In particular, setting an asphalt track is an effective approach, as it provides enough support to the ballast layer and additional protection to the soil subgrade. However, the limited range of the modulus of the asphalt mixture restricts its application to the railway transition zone. Therefore, a semi-flexible composite mixture (SFCM), which combines the strengths of the asphalt mixture and cement concrete, is proposed in this study as a promising alternative for the asphalt mixture. This research investigated the factors affecting the volumetric and mechanical properties of the SFCM and found that the SFCM is a viscoelastic material and its dynamic modulus could adjust with the air voids of the composite materials and the proportion of the cement slurry. A simulation was then conducted to study the response of the railway track under the dynamic load and evaluate how the SFCM material can be practically used. After different trials of track structures and material, four segments of the transition zones were proposed to make the vertical displacement transition smoothly from the soil subgrade to the cement concrete.

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CHAPTER 1

Introduction

BACKGROUND

When railroad tracks extend from a subgrade to a bridge, the abrupt variation of the stiffness or track moduli can lead to a major settlement difference of the foundation and discontinuity of the track structure, which is often characterized as “transition problems” (shown in Figure 1) [1] [2]. Two leading reasons are related to the transition problems [3]: (1) primary causes, including differences in modulus or stiffness, geotechnical issues, and excessive plastic deformation, etc. ; and (2) secondary causes, such as the magnitude of load and speed, embankment situation and traffic, etc. These problems can lead to uneven paths and poor ride quality and eventually accelerate the degradation of the rail tracks. As shown in Figure 2, under the conditions of a new maintenance surface and impeccable unloaded track profiles, the much larger vertical deflection still occurred in the transition zone when the loads were applied on the track structure [8]. Furthermore, the extension of the settlement gaps can also exacerbate the dynamic responses in the transition zone. 1-mm gaps will lead to 70% more contact force between the ballast and sleeper, and 2-mm gaps can increase 85% of the wheel force [4] [5]. Because of the negative impacts on the trackbed structure, the maintenance costs of the railway tracks are 3-4 times higher than the free tracks in many countries [6].

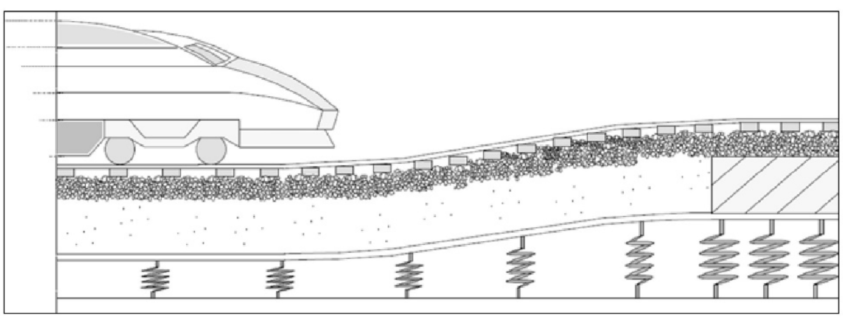


Figure 1. Transition problem in the track structure. *[7]*

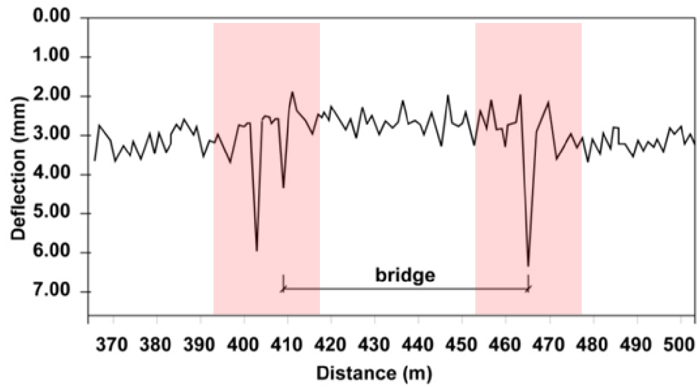
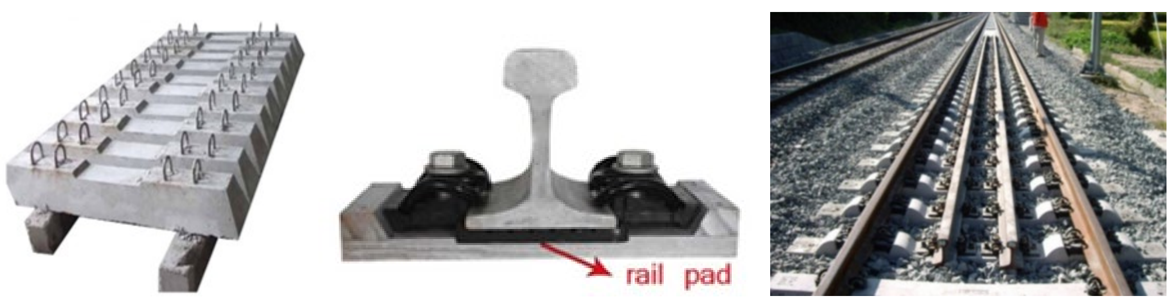


Figure 2. Deflection profile of the track. *[8]*

A "Stiffness Transition Zone" approach has been conceptually proposed to neutralize this sudden stiffness change by gradually changing the stiffness of the track. Nowadays, a couple of methods can mitigate the transition problems from the component modification to the structural adjustment.

1. Varying the size and space of the sleeper in the railroad. Amplifying the size and increasing the space between the sleeper can reduce the vertical displacement by distributing the loads to a broader area (**Figure 3a**) [9] [10].
2. Rubber pads are often used in the railway to reduce vibration and improve the damping of the structure (**Figure 3b**). Rubber pads, however, are a temperature-dependent material whose properties would significantly degrade in high-temperature environments [11].
3. Another component method for the transition problem mitigation is the auxiliary rail (**Figure 3c**) [12] [13]. Total bending stiffness would be dramatically enhanced by placing the extra rail between the main tracks, and it helps decrease the vertical displacement gaps. More contact areas of the rail and ballast layer reduce the stress by distributing the loads to the sleeper.

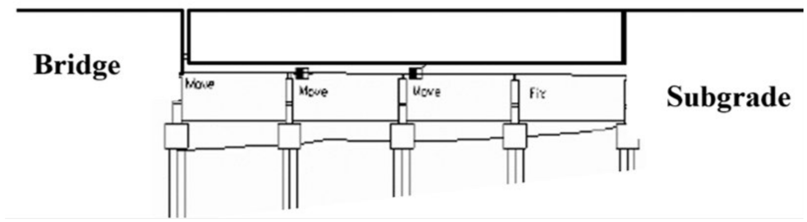


(a) (b) (c)

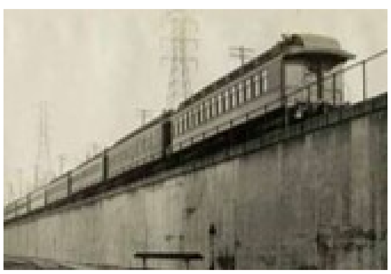
Figure 3. Component mitigations for the transition problem: (a) railway sleeper; (b) rubber pads; (c) auxiliary rail.

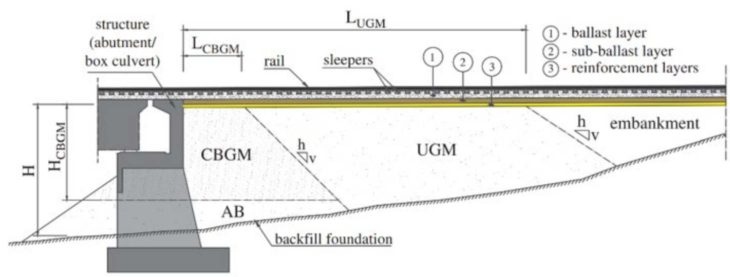
Besides the component modification methods posted previously, some structure adjustments can better address the displacement/stiffness gaps of the transition zone.

1. Steel bars (**Figure 4a**) and concrete confining walls (**Figure 4b**) can mitigate the problem by increasing the lateral confinement and strength of the ballast [14]. Moreover, we can adjust the confinements and strength by varying the length the steel bar extends into the subgrade.
2. A common practice currently used to address the transition problem is to construct wedge-shaped backfills (**Figure 4c**) at approaches to a bridge. By replacing the materials with different compatibility and modulus for the soil subgrade in the approaching area, the dynamic modulus gap between the soil subgrade and concrete bridge can significantly decrease. To realize this objective, the specific geometries and well-compacted selected granular materials need to be considered in the construction to guarantee the gradual transition in the vertical stiffness and modulus. From the construction perspective, unbound granular material (UGM) and cement-bound granular material (CBGM) are frequently applied in the backfill [15].



(a)





(b) (c)

Figure 4. Structure mitigations for the transition problem: (a) steel bar; (b) confining wall; and (c) wedge-shaped backfill. *[15]*

Component methods have a limited effect on the transition problems compared with the structure method. On the contrary, structure methods often require much more work to realize the desired result. Construction of the confining wall and steel bar and backfill replacements are time-consuming and labor-intensive actions. Setting a layer of hot-mix asphalt (HMA) under the ballast is also an effective transition technique to mitigate the transition problem [16] (**Figure 5**). The stiffness of the HMA can be adjusted by varying its gradation and types of materials, and the thickness of the HMA layer can also be modified to guarantee the gradual transition of the vertical displacement. Therefore, the construction of the HMA layer was applied in the research to mitigate the transition problem. However, considering the limited range of the modulus and stiffness of the asphalt mixture, a new engineering design of structural material was proposed and used, which consisted of a large-air-void asphalt mix core and cement slurry, semi-flexible composite mixture (SFCM) to replace the asphalt mixture.

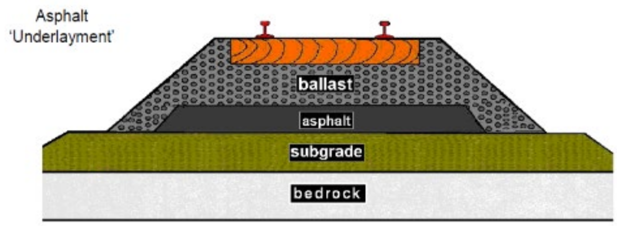


Figure 5. Asphalt underlayment for transition problem.

OBJECTIVES

The objectives of this study were to develop a prototype "stiffness transition" trackbed material, evaluate its engineering properties with laboratory tests, and propose application methods based on computation simulations. A self-compacting SFCM was prepared for easy track modulus adjustment under different stiffness transition scenarios determined from the 3D dynamic track "sandwich model." Controlling the modulus of trackbed with customizable engineering properties can reduce dynamic loading impact to both highway and bridge structures and lead to increased life and improved safety of track components.

In order to realize the above objectives, this study (1) investigated the factors (air voids of the asphalt mix core and the viscosity and fluidity of the cement slurry) affecting the machinal property of the SFCM and (2) simulated the transition zone to enable a smooth vertical displacement transition from the subgrade to the concrete bridge.

CHAPTER 2

Methodology

This report mainly consists of two parts. First, the experimental part presents the procedure to produce various SFCM samples with different mechanical properties. The factors affecting the SFCM mechanical properties (dynamic modulus), such as the air voids or cement content, are also investigated in this part. Second is the simulation part, which includes determining the dynamic responses under different trackbed structures and various types of materials utilizing the finite element model, and proposing a solution to make the vertical displacement (settlements) transition smoothly from the subgrade to the concrete bridge.

Considering the limited modulus range of the asphalt mixture, SFCM was proposed as a new engineering material to replace the asphalt mixture for the mitigation. SFCM is a unique material that uses open-graded asphalt mixture (15%-35% air voids) as the core structure and involves pouring cement mortar into the air voids of the core structure (**Figure 6**). Use of SFCM in the transition zone has many advantages [17]:

1. The SFCM is the combination of the asphalt mixture and cement concrete. It combines the flexibility and durability of asphalt concrete and the stiffness of cement concrete. It exhibits a better rutting resistance compared with asphalt concrete, since the cement concrete in the voids of the core structure offers enough support even in high-temperature environments. SFCM also shows excellent durability compared to rigid materials as the flexible asphalt mixture used in the core structure [18]. It also has excellent resistance to moisture damage because of the impermeable structure [9].
2. SFCM is the open-graded asphalt mixture with the cement slurry poured into the air voids. Its mechanical properties can be adjusted according to the air voids of the core asphalt mixture, the mechanical properties of the cement mortar, and the core structure, which is a critical property for the transition problem mitigation.
3. Moreover, the initial cost of the full depth of SFCM design is 30%-40% less than a comparable portland cement concrete pavement [19]. Considering the construction perspective, the SFCM can also be precast as a slab and transported to the site to save construction time [20].

Figure 6. Appearance and composition of the SFCM.

In order to obtain the SFCM with various mechanical properties in the experiment part, the factors affecting the mechanical properties of the SFCM were investigated in advance, such as the air voids of the asphalt mix cores and the viscosity of the cement slurry. Some substeps were also included to investigate the relation between the viscosity of the cement slurry and the proportion of the superplasticizer and water-cement ratio. When the SFCM samples were prepared, a dynamic modulus test was conducted to study the relationship between the mechanical properties and the air voids of the composite materials.

In the second part, a 2.5D sandwich model was used in the simulation, which assumed the track property remained uniform along the direction of the train movement, and only a profile of half-space vertical to the course of the load movement was considered [21] [22]. The responses of the trackbed structure under the unit load were simulated in the finite element model to eventually allow a smooth vertical displacement transition from the subgrade to the concrete by changing the material and structure of the railroad.

MATERIAL AND EXPERIMENT

Asphalt mixture core

A single source of the PG 70-22 modified binder, limestone, and fibers was included in the asphalt mixture. In order to get the Φ100×150-mm mixture core for the dynamic modulus test, Φ150×170-mm specimens were compacted in the Superpave gyratory compactor (SGC) following the gradations in **Table 1**. Three air voids were prepared in the experiments, as the air voids of the core structure directly affect the amounts of the slurry in the composite materials. The volumetric parameters of each mixture were also measured and are shown in **Table 1**.

Cement slurry

The viscosity and fluidity of the cement slurry are also critical to the property of the SFCM, which are greatly affected by the water-cement (w/c) ratio and the dosage of the superplasticizer (SP). To investigate the relationship between the viscosity and these two factors, also find their optimum values, two sets of experiments were conducted, (a) fixing the w/c ratio but changing the SP dosages; and (b) fixing the SP dosage but varying the w/c ratio. Regarding the excellent fluidity of the cement slurry and the limited spaces of the core asphalt mixes, sands were absent in the slurry composition, and only water, cement, fly ash, and SP were used. Slurries with various water-cement ratios and the proportion of SP were made in the experiments and presented in **Table 2.** Consistent with previous research studies, a 35% water-cement ratio was used to study the effect of the SP on the viscosity and 3% SP proportion for testing the influence of the water-cement ratio [23]. All of the ingredients were mixed in the concrete mixer for 3 minutes and then the mixture was allowed to stand for 30 seconds. An SNB-1 viscometer (**Figure 7**) was then used to measure the viscosity of the slurries at room temperature (20 ℃). The viscosity results of the different concrete slurries are presented in **Table 2.**

Table 1. Asphalt mixture information.

Sieve Size/mm	Percent Passing/% #1	Percent Passing/% #2	Percent Passing/% #3
19	100	100	100
12.5	96	88	100
9.5	66	68	87
4.75	21	26	20
2.36	8	8	8
1.18	6	6	6
0.6	5	5	5
0.3	4	3	4
0.15	3	2	3
0.075	2	0.9	2.6
Asphalt content	6.0%	5.5%	4.8%
Fiber content	0.4%	0.4%	0.3%
Air voids	17.8%	21.3%	27.9%

Table 2. Proportion of cement slurry.

	No.	W/C Ratio	Cement	Water	Fly Ash	S.P.
w/c=0.35	#1	0.34	50%	25.0%	23.0%	2%
w/c=0.35	#2	0.35	50%	25.0%	22.0%	3%
w/c=0.35	#3	0.35	50%	25.0%	21.0%	4%
SP=3%	#2	0.35	50%	25.0%	22.0%	3%
SP=3%	#4	0.30	50%	22.5%	24.5%	3%
SP=3%	#5	0.26	50%	20.0%	27.0%	3%

Figure 7. SNB-1 viscometer.

Filling the cement slurry into the asphalt mixture is a critical step in preparing the SFCM material. The asphalt specimen was placed in a 6-in (152.4 mm) plastic tube and vibration were used during the filling of the cement slurry to ensure consistency of the filling and good quality control. The entire filling process was quick to avoid segregation. After filling, all SFCM specimens were kept sealed to cure for 7-days before testing for engineering properties.

Mechanical test

Dynamic modulus was used as the mechanical parameter in the research. The dynamic modulus test was conducted using the MTS (materials test service) machine following the AASHTO T 342-11 standard [24]. The sample geometry for the test was Φ100×150 mm, test temperature was 4 °C, 20 °C, and 37 °C, and the testing frequencies were 0.1, 0.5, 1, 5, 10, and 25 Hz. Eventually, the master curve at 20 °C was calculated and plotted for comparison. To obtain the master curve at 20 °C, the data at various temperatures need to shift with respect to time until the curves merge into a single smooth function based on the principle of time-temperature superposition [25]. In general, the master modulus curve can be mathematically modeled by a sigmoidal function described as:

$$\text{Log}\left|E^*\right| = \delta + \frac{\alpha}{1+e^{\beta+\gamma(\log t_r)}}$$

Where,

E* = the dynamic modulus at desired temperature;
t_r = reduced time of loading at reference temperature;
δ = minimum value of E*; $\delta + \alpha$ = maximum value of E*; and
β, γ = parameters describing the shape of the sigmoidal function.

SIMULATION

To implement the concept and develop a practical plan to guide the SFCM application, a computational simulation was first conducted to investigate the responses of the rail track under the dynamic loads. In this part, the depth and the mechanical property (dynamic modulus) would change in the simulation to enable the vertical displacements to transition smoothly from the subgrade to the concrete bridge.

A standard railroad structure was adopted in this part, which consists of the tie, ballast layer, underlayment layer, and soil subgrade (shown in **Figure 8**). The underlayment would be replaced by the asphalt mixture or SFCM as transition zone material to adjust the modulus of the entire structure. The material properties and the structure geometry are displayed in Figure 5. The 2.5D sandwich model developed by Yang and Hung [26] was used in the analysis (**Figure 9**), which assumes the track property remains uniform along the direction of the train movement, and only a profile of half-space vertical to the direction of the load movement is considered [21] [26]. The ballast was modeled as discrete masses that connect the ties and the ground with springs and dashpots. The rail is modeled as the Euler beam, the rail pad and tie are represented by springs and dashpots. The ballast layer, underlayment, and subgrade layer are modeled by isoparametric quadrilateral elements to condense the 3D issue to a plane strain problem. Generally speaking, the 2.5D model solves the limitation of the 2D model of lacking load consideration in the simulation and also addresses the time-consuming of the 3D weakness. The effect of the train speed on the track performance is also considered in the model because higher speeds may induce a dynamic impact to the rail substructure and cause track and subgrade vibrations. In the simulation, 1kN load was taken as the unit load to investigate the railway displacement under various structures and materials for simplicity. The actual load amplitude will increase the value of displacement but will not alter the relative displacement variation in the transition zone. Inputs of all parameters used for the modeling are presented in **Table 3**.

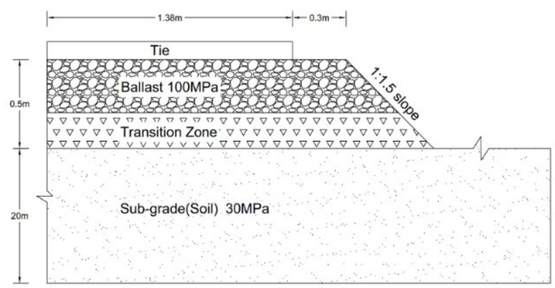


Figure 8. Cross-section of the half standard railroad structure.

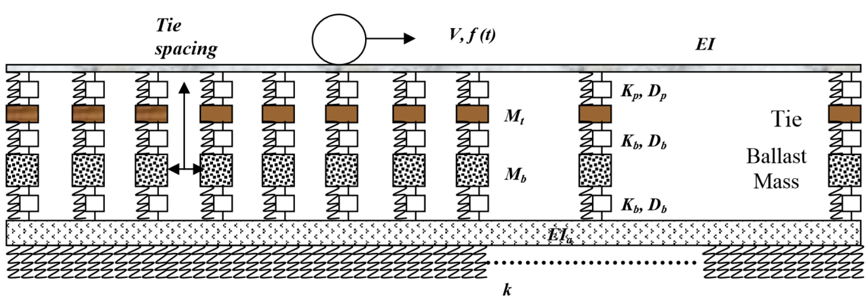


Figure 9. 2.5D sandwich model. *[26]*

Table 3. Parameter inputs for model calculation.

Rail Structure	Parameters	Input Value
Soil subgrade	Shear wave speed	83 m/s
Soil subgrade	Primary wave speed	343 m/s
Soil subgrade	Proportional damping	0.2 N s/m
Track material	Rail bending rigidity	6.3 MN m^2
Track material	Pad stiffness	90 MN/m
Track material	Pad damping	1 MN s/m
Track material	Ballast stiffness	160 MN/m
Track material	Ballast damping	30 MN s/m
Track material	Rail density	60 kg/m^3
Track material	Tie density	240 kg/m^3
Dynamic load	Train speed	75 km/h
Dynamic load	Load magnitude	1 kN

CHAPTER 3

Data Analysis and Discussion

EXPERIMENTAL RESULTS

Viscosity of the cement slurry

The SNB-1 viscometer measured the viscosity of each cement slurry, and the results were plotted in **Figure 10**. It is clear that under the constant proportion of SP, the viscosity of the slurry has a linear relationship with the water-cement ratio, and the lower water-cement ratio of the slurry contributed to the higher slurry viscosity. The similar linear relationship of the proportion of SP and viscosity is shown in **Figure 11**; the lower portion of the SP the slurry has, the higher viscosity the slurry will present. Based on the fluidity and workability of the cement slurry, the #2 slurry was chosen as the target slurry for the SFCM composition. The viscosity of the #2 slurry is 600 CP under room temperature (20 °C), of which the fluidity is between that of sesame oil (900 CP) and motor oil (200 CP) [27].

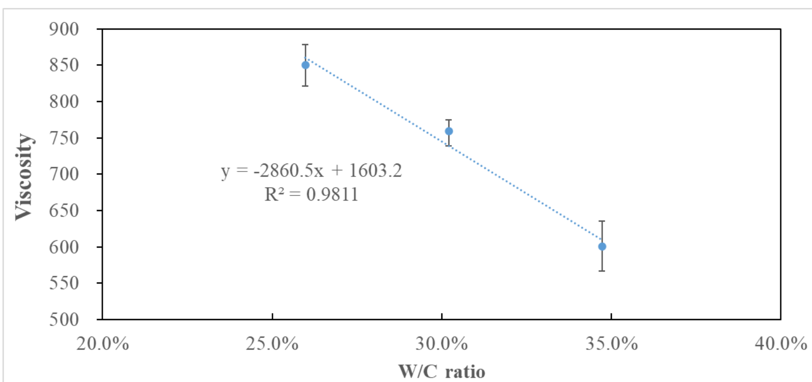


Figure 10. Relation of water-cement ratio and viscosity.

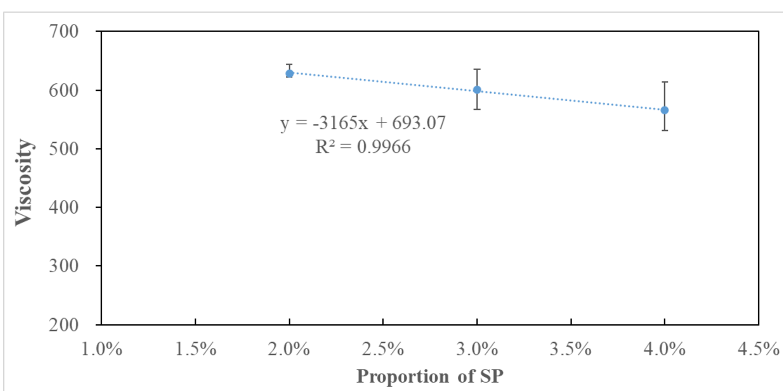


Figure 11. Relation of proportion of SP and viscosity.

Air voids of the SFCM

SFCM is made up of the asphalt mix core and cement slurry. However, not all the air voids in the core will be occupied by the cement slurry in the filling process, which leaves the air voids of the composite materials. In this part, the air voids of the SFCM were measured to better understand its relationship with the mechanical properties. Since the cement paste is a water-absorbing material, the traditional method for air void measurement is not applicable. A mathematical method was therefore proposed based on the composition of SFCM. The air voids of the composite materials are illustrated in **Table 4**. **Figure 12** shows the appearance of the SFCMs.

$$Va_{SFCM} = Va_{mix} - V_{cement}$$

$$V_{cement} = (M_a - M_b)/\rho$$

Where,

Va_{SFCM} and Va_{mix} are the air voids of the SFCM and asphalt mix core, respectively;
V_{cement} is the volume of the cement after curing;
M_a and M_b are the masses of the SFCM after and before slurry filling, respectively; and
ρ is the density of the dry cement paste.

The air voids of the SFCM are summarized in **Table 4**, and the appearance of the SFCM core was shown in **Figure 12**. Mixtures 1, 2, and 3 were presented from left side to right, respectively, with specimens 1-1, 1-2, and 3-1 showing more voids at the surface. Although the same filling procedure and curing methods were used in the asphalt core, the SFCM specimen still presented different air voids. The varied internal void distribution and connectivity of each specimen might be an important cause of such a phenomenon.

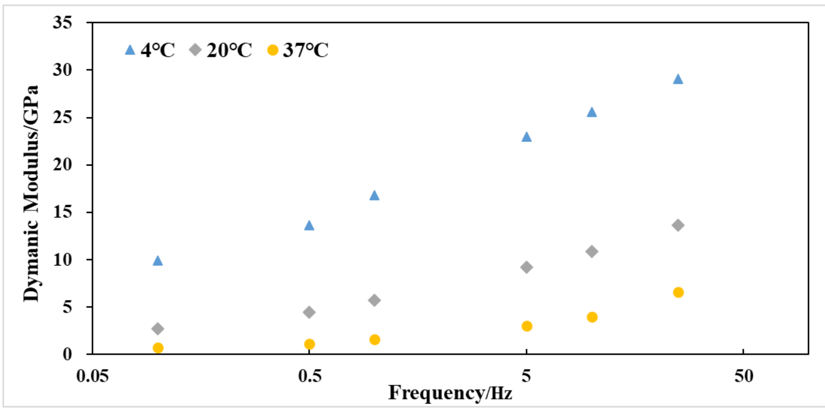
Table 4. Volumetric parameters of the SFCM cores.

	Va_{mix}	V_{cement}	Va_{SFCM}
1-1	17.8%	12.3%	5.4%
1-2	17.8%	12.9%	4.9%
2-1	21.4%	19.7%	1.7%
2-2	21.4%	20.9%	0.5%
3-1	27.9%	16.4%	11.5%
3-2	27.9%	27.7%	0.2%

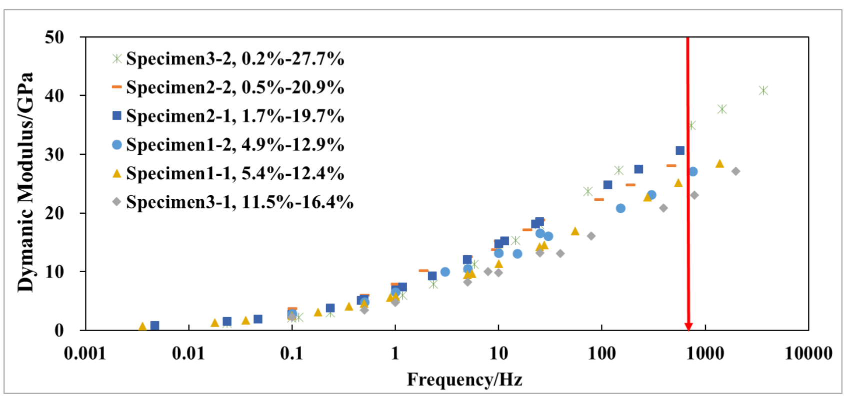
Figure 12. Appearance of the SFCM.

Dynamic modulus

The dynamic modulus test was conducted using the MTS (materials test service) machine following the AASHTO T342-11 specification [24]. Results were used to compare the mechanical properties of different SFCMs. The sample geometry for the dynamic modulus test is Φ100×150mm. 4℃, 20℃, 37℃ test temperature, and 0.1, 0.5, 1, 5, 10, and 25 Hz loading frequency were applied for each sample. **Figure 13 (a)** demonstrates the change of dynamic modulus of specimen1-1 at different temperatures and frequencies, as an example. Other mixtures show a similar relationship. To obtain the dynamic modulus master curve at the specific temperature but on a wide frequency spectrum, the data need to be shifted with respect to time based on the principle of time-temperature superposition. Eventually, the 20℃-master curve of each sample was obtained and presented in **Figure 13(b).**



(a)



(b)

Figure 13. (a) Dynamic modulus of Mix1-1; (b) master curves of the SFCM cores.

As illustrated in **Figure 13(a)**, it is confirmed that the SFCM is a viscoelastic material in nature, and its dynamic modulus will change under different temperatures and loading frequencies. The SFCM would present the lower dynamic modulus under the high temperature and low frequency. In **Figure 13(b)**, the first and second column of the legend refer to the air voids of the composite materials Va_{SFCM} and the volume ratio of the concrete slurry Va_{slurry}, respectively. If a good filling condition is achieved (Va_{SFCM}<6% in our research), the volume ratio of the concrete slurry has a positive correlation with the mechanical properties of the specimen under a certain temperature and frequency. Taking f=800 Hz as an example (red vertical line in the figure), with the increase of the volume ratio of the concrete slurry, the dynamic modulus under the constant frequency increases generally except for the specimen 3-1, of which the air void of the SFCM is larger than 11%. Furthermore, six dynamic modulus points merge when the frequency is less than 1Hz in **Figure 13(b)**, which implies the mechanical property of the SFCM does not present significant differences at low frequency or the warm environment. One possible reason for this phenomenon is that the concrete slurry plays a more dominant role than the asphalt mixture at a higher temperature and lower frequency conditions. In reality, the vibration frequency of the railway track is usually between 30-200 Hz [28], which is in the range where the SFCM presents a clear modulus variation with different air voids and designs. Such property made SFCM an appropriate underlayment material for the transition zone to connect the subgrade and concrete bridge.

SIMULATION RESULTS

In this part, the sandwich model developed by Huang et al. [26] was used for the railroad simulation. This 2.5D sandwich model assumes that the track property remains uniform along the direction of the train movement and only a profile of half-space vertical to the course of the load movement is considered [21][29]. The vertical displacement of the surface was used as the comparison parameter for the transition smoothness. The boundary condition of the project is the vertical displacement of the rail track under the subgrade and concrete bridge. The simulation aims to construct a transition zone to make the vertical displacement transition smoothly from the subgrade to the concrete deck (**Figure 14**). For the convenience of the construction, only the sub-ballast layer was replaced with the SFCM.

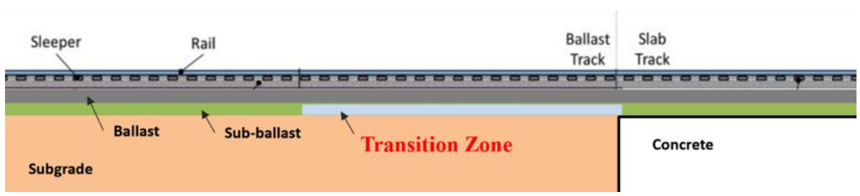


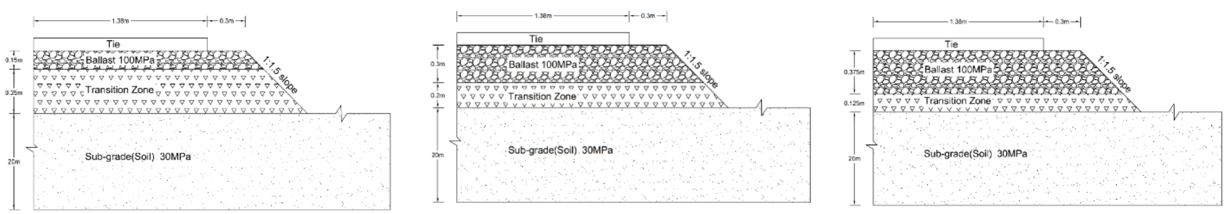
Figure 14. Sub-ballast substitute for the transition problem mitigation.

The ballast layer of the railroad is a significant part of the railway track system. It fulfills several critically important objectives, including the transfer of stress, increasing elasticity, creating a high resistance to longitudinal and lateral displacement of sleepers, increasing the longitudinal and lateral stability of railway tracks, and enabling smooth repair and maintenance of railway tracks. The depth of the ballast layer must follow the specific standard: the minimum thickness of the ballast under the sleepers was 30 cm. For high-speed railways, a ballast layer thickness of at least 45 cm is suggested to provide for proper resistance to lateral displacements.

In our research, the combination of the ballast layer and sub-ballast layer totaled 50 cm under the 20-m soil subgrade, which satisfied the standard specification. Before introducing the transition zone into the railroad structure, the response (vertical displacement) of the surface needs to be known; the elastic modulus of the soil subgrade and concrete bridge is 30 MPa and 30 GPa, respectively. The same 2.5D sandwich model was used to determine the boundary condition in the first place. The vertical displacement of the soil foundation structure and the concrete bridge deck are obtained in advance and presented as follows:

1. Boundary condition I, soil foundation structure (0.5-m, 100-Mpa ballast layer, and 20-m, 30-Mpa soil), of which the vertical displacement is 47.1 µm unit load.
2. Boundary condition II, concrete bridge deck (0.5-m, 100-Mpa ballast layer, and 20-m, 30 Gpa concrete), of which the vertical displacement is 0.2 µm unit load.

Three different structures were built to investigate how the dynamic modulus of the sub-ballast layer change would affect the response of the railway surface. The three structures are presented in **Figure 15**, consiting of: (a) the combination of the 0.15-m ballast layer and 0.35-m transition zone; (b) the combination of the 0.3-m ballast layer and 0.2-m transition zone; and (c) the combination of the 0.375-m ballast layer and 0.125-m transition zone. The dynamic modulus of the transition zone was also adjusted from 1 GPa to 9 GPa, and the relationship of the dynamic modulus and vertical displacement of the surface layer is presented in Figure 14.



(a) (b) (c)

Figure 15. Three railroad structures in the simulation.

Figure 16 illustrates the relationship between the dynamic modulus and vertical displacement. Three scenarios corresponding to the three structures shown in **Figure 15** are presented for comparison. As shown, the vertical displacement has an exponential relationship with the material modulus regardless of the structure type. When the moduli change from 1 GPa to 5 GPa, the vertical displacement of the surface presents a clear drop, and afterward the vertical displacement decreases slowly with the increase of the moduli. It can also be seen that structures (b) and (c) present a similar vertical displacement versus modulus relationship, while structure (a) clearly shows a much lower vertical displacement when compared with structures (b) and (c) at the same modulus level.

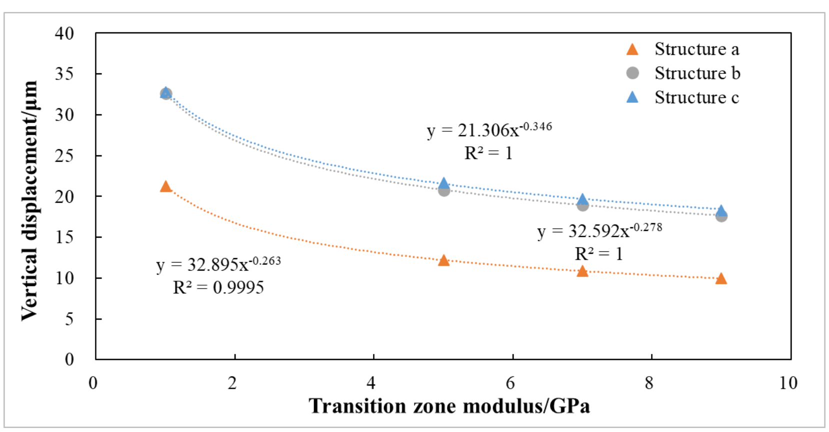


Figure 16. Relationship of dynamic modulus and vertical displacement under three structures.

Transition zone design

To make the vertical displacement transit smoothly from 47.1 µm (the subgrade structure, boundary condition I) to 0.2 µm (concrete bridge deck, boundary condition II), four transition zones were proposed to make the displacement linearly descend. They were supposed to present the vertical displacement of 37.5 µm,30 µm, 20 µm, and 10 µm, respectively. Based on the regression curve of the three structures in **Figure 16**, four segments of transition zones, as shown in **Figure 17**, were proposed to mitigate the transition problems. They are:

1. Transition zone I (0.375-m, 100-Mpa ballast layer; 0.125-m, 500-Mpa transition zone; and 20-m, 30-Mpa soil), of which the vertical displacement is 37.5 µm unit load. The recommended material for transition zone I is the asphalt mixture.
2. Transition zone II (0.375-m, 100-Mpa ballast layer; 0.125-m, 1.4-Gpa transition zone; and 20-m, 30-Mpa soil), of which the vertical displacement is 30 µm unit load. The recommended material for transition zone II is the asphalt mixture.
3. Transition zone III (0.3-m, 100-Mpa ballast layer; 0.2-m, 5.8-Gpa transition zone; and 20-m, 30-Mpa soil), of which the vertical displacement is 20 µm unit load. The recommended material for transition zone III is SFCM.
4. Transition zone IV (0.15-m, 100-Mpa ballast layer; 0.35-m, 8.9-Gpa transition zone; and 20-m, 30-Mpa soil), of which the vertical displacement is 10 µm unit load. The recommended material for transition zone IV is SFCM.

For practical application, it is recommended that the SFCM be prefabricated into slabs at the factory so that it is more convenient to construct in the field with better quality control.

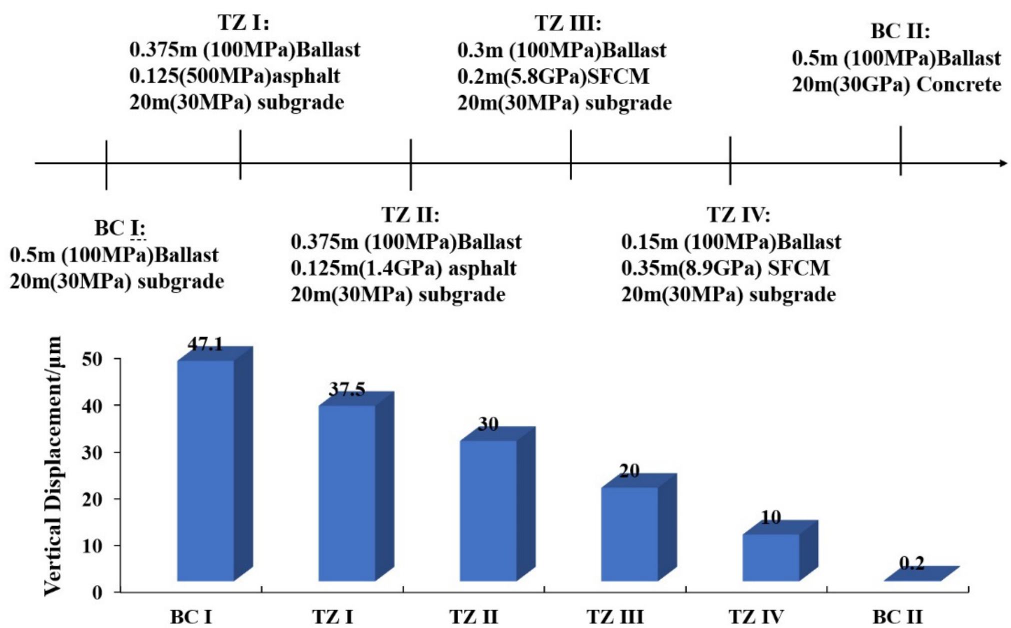


Figure 17. Summary of structure and material selection of the transition zone.
Note: BC means boundary condition; TZ means transition zone.

CHAPTER 4

Conclusions

This report presented the transition problems of the rail track system in the connection area between the soil subgrade and concrete bridge. The experiments and simulations were jointly carried out to investigate the solution for the transition problem. The following findings and conclusions were obtained.

1. SFCM is a promising and appropriate material for transition problem mitigation, since it combines the advantages of the asphalt mixture and cement concrete. The mechanical properties of the SFCM can be adjusted to address the vertical displacement gaps. The air voids of the composite materials have more powerful effects on the mechanical properties of the SFCM than the asphalt mixture core structure.
2. There is a linear relationship between the water-cement ratio and the cement slurry viscosity, and a similar linear relationship between the proportion of the SP and the cement slurry viscosity.
3. SFCM is a viscoelastic material, and its dynamic modulus would change with the variation of the temperature and loading frequency. The master curve also shows that the SFCM samples presented significant differences under the train loading frequency.
4. The smoothness of the vertical displacement governs the implementation of the transition zone design. A four-segment transition zone design was proposed in this study, which would allow railway track to experience a smooth transition at the bridge approach.

Simulations were conducted later to make the vertical displacement transition smoothly from the soil subgrade to the concrete bridge by changing the railroad structure and material of the sub-ballast layers. A 2.5D sandwich model was adopted in the simulation because it is highly efficient and can take into account the load effects. The structure of the railroad and material types of the transition zone were eventually determined and can be summarized as follows:

1. Boundary condition I (0.5-m, 100-Mpa ballast layer and 20-m, 30-Mpa soil), of which the vertical displacement was 47.1 µm unit load.
2. Transition zone I (0.375-m, 100-Mpa ballast layer, 0.125-m, 500-Mpa transition zone, and 20-m, 30-Mpa soil), of which the vertical displacement was 37.5 µm unit load. The material used in the transition zone was the asphalt mixture.
3. Transition zone II (0.375-m, 100-Mpa ballast layer, 0.125-m, 1.4-Gpa transition zone, and 20-m, 30-Mpa soil), of which the vertical displacement was 30 µm unit load. The material used in the transition zone was the asphalt mixture.
4. Transition zone III (0.3-m, 100-Mpa ballast layer, 0.2-m, 5.8-Gpa transition zone, and 20-m, 30-Mpa soil), of which the vertical displacement was 20 µm unit load. The material used in the transition zone was SFCM.
5. Transition zone IV (0.15-m, 100-Mpa ballast layer, 0.35-m, 8.9-Gpa transition zone, and 20-m,

30-Mpa soil), of which the vertical displacement was 10 μm unit load. The material used in the transition zone was SFCM.

6. Boundary condition II (0.5-m, 100-Mpa ballast layer and 20-m, 30-Gpa concrete), of which the vertical displacement was 0.2 μm unit load.

It is worth noting that the purpose of the report is to provide a design concept and an implementation method to mitigate the transition problem at the bridge approach. The specific four-segment design, as proposed, is based on a special case of transition, which by no means will fit all field conditions. Actual design analysis must be performed to determine the geometry and the mix design of the SFCM materials for an individual project. Also, for the practical application, we recommend that the SFCM be prefabricated into slabs at the factory so that it is more convenient to construct in the field with better quality control. Large-scale experiments and field verification are recommended as future work to implement the proposed concept.

References

1. Chen, C. (2013). *Discrete element modeling of geogrid-reinforced railway ballast and track transition zones.* Doctoral Thesis, University of Nottingham.
2. Chen, C., and G.R. McDowell (2014). An investigation of the dynamic behaviour of track transition zones using discrete element modelling. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, **230**(1):117-128.
3. Wang, H.-Y., and V.L. Markine (2018). Corrective countermeasure for track transition zones in railways: Adjustable fastener. *Engineering Structures*, **169**:1-14.
4. Wang, H., V.L. Markine, I.Y. Shevtsov, and R. Dollevoet (2015). Analysis of the Dynamic Behaviour of a Railway Track in Transition Zones with Differential Settlement. In *Proceedings of the 2015 Joint Rail Conference, March 23-26, 2015, San Jose, CA*. DOI: 10.1115/JRC2015-5735
5. Lundqvist, A., and T. Dahlberg (2005). Load impact on railway track due to unsupported sleepers. *Proceedings of the Institution of Mechanical Engineers Part F Journal of Rail & Rapid Transit*, **219**(2):67-77.
6. Varandas, J.N., P. Hölscher, and M.A.G. Silva (2011). Dynamic behaviour of railway tracks on transitions zones. *Computers & Structures*, **89**(13-14):1468-1479.
7. Basirat, R., R. Hassani, and N. Mahmoodian (2017). 2D Numerical Modeling of Differential Settlement in Transition Zone Induced by Train Load. Presented at 5th International Conference on Recent Advances in Railway Engineering (ICRARE 2017), May 2017, Tehran, Iran.
8. Coelho, B., P. Hölscher, J. Priest, W. Powrie, and F. Barends (2011). An Assessment of Transition Zone Performance. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, **225**(2):129-139.
9. Martin, A.E., E. Arambula, F. Yin, and L.G. Cucalon, A. Chowdhury, R.L. Lytton, J. Epps, C. Estakhri and E.S. Park (2014). *Evaluation of the Moisture Susceptibility of WMA Technologies*, NCHRP Report 763, Washington, D.C.: The National Academies Press.
10. Sasaoka, C., and D. Davis (2005). Implementing Track Transition Solutions for Heavy Axle Load Service. 2005.
11. Esmaeili, M., J.A. Zakeri, and M. Babaei (2017). Laboratory and field investigation of the effect of geogrid-reinforced ballast on railway track lateral resistance. *Geotextiles & Geomembranes*, **45**(2):23-33.
12. Esmaeili, M., J.A. Zakeri, and M. Babaei (2017). Laboratory and field investigation of the effect of geogrid-reinforced ballast on railway track lateral resistance. *Geotextiles and Geomembranes*, **45**(2):23-33.
13. Shahraki, M., C. Warnakulasooriya, and K.J. Witt (2015). Numerical study of transition zone between ballasted and ballastless railway track. *Transportation Geotechnics*, **3**:58-67.
14. Read, D. (2006). Design of Track Transitions. *Transit Cooperative Research Program (TCRP) Research Results Digest* **79**, Washington, D.C.: Transportation Research Board.
15. Paixão, A., E. Fortunato, and R. Calçada (2013). Design and construction of backfills for railway track transition zones. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, **229**(1):58-70.
16. Rose, J.G., E.R. Brown, and M.L. Osborne (2000). Asphalt Trackbed Technology Development: The First 20 Years. *Transportation Research Record*, **1713**(1):1-9.
17. Huang, C., J. P. Liu, J. X. Hong, and Z. F. Liu (2012). Improvement on the Crack Resistance Property of Semi-Flexible Pavement by Cement-Emulsified Asphalt Mortar. *Key Engineering Materials*, **509**:26-32.

18. Zhang, W., S. Shen, R.D. Goodwin, D. Wang, and J. Zhong (2020). Performance Characterization of Semi-Flexible Composite Mixture. *Materials* (Basel), **13**(2):342.
19. Hassan, K., A. Setyawan, and S. Zoorob (2017). Effect of cementitious grouts on the properties of semi-flexible bituminous pavements. *Proceedings of the Fourth European Symposium on Performance of Bituminous and Hydraulic Materials in Pavements, Bitmat,* **4**:113-120.
20. Anderton, G. (2000). Engineering Properties of Resin Modified Pavement (RMP) for Mechanistic Design, 209.
21. Gao, Y., H. Huang, C.L. Ho, and A. Judge (2016). Field validation of a three-dimensional dynamic track-subgrade interaction model. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, **232**(1):130-143.
22. Yang, Y.B., and H.H. Hung (2001). A 2.5D finite/infinite element approach for modelling visco-elastic bodies subjected to moving loads. *International Journal for Numerical Methods in Engineering*, **51**:1317-1336.
23. Zhang, M.-H., K. Sisomphon, T.S. Ng, and D.J. Sun (2010). Effect of superplasticizers on workability retention and initial setting time of cement pastes. *Construction and Building Materials*, **24**(9):1700-1707.
24. AASHTO (2011). *Standard Method of Test for Determining Dynamic Modulus of Hot-Mix Asphalt Concrete Mixtures.* AASHTO T 342, American Association of State Highway and Transportation Officials.
25. Pellinen, T., M. Witczak, and R. Bonaquist (2003). Asphalt Mix Master Curve Construction Using Sigmoidal Fitting Function with Non-Linear Least Squares Optimization. *Proceedings of 15th Engineering Mechanics Division Conference, Geotechnical Special Publication*, 83-101. DOI: 10.1061/40709(257)6
26. Huang, H., S. Shen, and E. Tutumluer (2009). Sandwich Model to Evaluate Railroad Asphalt Trackbed Performance Under Moving Loads. *Transportation Research Record*, **2117**:57-65.
27. Wikipedia (2020). Viscosity. https://en.wikipedia.org/w/index.php?title=Viscosity&oldid=967864186, accessed July 22, 2020.
28. Kouroussis, G., D.P. Connolly, and O. Verlinden (2014). Railway-induced ground vibrations – a review of vehicle effects. *International Journal of Rail Transportation*, **2**(2):69-110.
29. Bian, X., Y. Chen, and T. Hu (2008). Numerical simulation of high-speed train induced ground vibrations using 2.5D finite element approach. *Science in China Series G Physics Mechanics and Astronomy*, **51**:632-650.