IDEA

Innovations Deserving Exploratory Analysis Programs

*High-Speed Rail IDEA Program*

# Rubber-Modified Asphalt Concrete for High-Speed Railway Roadbeds

Final Report for High-Speed Rail IDEA Project 40

Prepared by:
Xiangwu (David) Zeng, Ph.D.
Dept. of Civil Engineering, Case Western Reserve University
Cleveland, Ohio

*March 2005*

TRANSPORTATION RESEARCH BOARD
*OF THE NATIONAL ACADEMIES*

**INNOVATIONS DESERVING EXPLORATORY ANALYSIS (IDEA) PROGRAMS MANAGED BY THE TRANSPORTATION RESEARCH BOARD**

This investigation was performed as part of the High-Speed Rail IDEA program supports innovative methods and technology in support of the Federal Railroad Administration's (FRA) next-generation high-speed rail technology development program.

The High-Speed Rail IDEA program is one of four IDEA programs managed by TRB. The other IDEA programs are listed below.

- NCHRP Highway IDEA focuses on advances in the design, construction, safety, and maintenance of highway systems, is part of the National Cooperative Highway Research Program.
- Transit IDEA focuses on development and testing of innovative concepts and methods for improving transit practice. The Transit IDEA Program is part of the Transit Cooperative Research Program, a cooperative effort of the Federal Transit Administration (FTA), the Transportation Research Board (TRB) and the Transit Development Corporation, a nonprofit educational and research organization of the American Public Transportation Association. The program is funded by the FTA and is managed by TRB.
- Safety IDEA focuses on innovative approaches to improving motor carrier, railroad, and highway safety. The program is supported by the Federal Motor Carrier Safety Administration and the FRA.

Management of the four IDEA programs is integrated to promote the development and testing of nontraditional and innovative concepts, methods, and technologies for surface transportation.

For information on the IDEA programs, contact the IDEA programs office by telephone (202-334-3310); by fax (202-334-3471); or on the Internet at http://www.trb.org/idea

IDEA Programs
Transportation Research Board
500 Fifth Street, NW
Washington, DC 20001

# Rubber-Modified Asphalt Concrete for High-Speed Railway Roadbeds

**IDEA Program Final Report**
**For the Period 01/2003 through 02/2005**

**Contract No: HSR-40**

**Prepared for**
**The IDEA Program**
**Transportation Research Board**
**National Research Council**

**Xiangwu (David) Zeng, Ph.D.**
**Associate Professor**
**Dept. of Civil Engineering, Case Western Reserve University**
**10900 Euclid Avenue, Cleveland, Ohio 44106-7201**

**March, 2005**

## ACKNOWLEDGMENTS

The research work reported here was funded by the IDEA program of the National Research Council. The author would like to thank the program officer, Mr. Charles Taylor, for his continuous support for this research. Technical consultation was provided by the expert panel members: Mr. Bob DeGrace, GDE, Inc., Cleveland, Ohio; Dr. Dingqing Li, TTCI, Pueblo, Colorado; Professor Jerry Rose, University of Kentucky, Lexington, Kentucky; and Mr. Tom Schmidt, CSX Transportation, Jacksonville, Florida.

# ABSTRACT

Interest in high-speed railway as an alternative means of transportation is steadily increasing around the world. However, high-speed trains produce track vibration and induced noise and ground vibration. Excessive track vibration can cause damage to trains and tracks and reduce riding comfort for passengers. The ground vibrations induced by passing trains can also damage and disturb surrounding infrastructure (especially structures housing precision machines or instruments) and residents. This project studies one potential solution toward minimizing these vibrations using rubber-modified asphalt concrete (RMAC) as a material for high-speed railway roadbeds. This report presents the results of a two-dimensional finite-element simulation of a high-speed train foundation, laboratory tests on the influence of temperature and confining pressure on dynamic properties of RMAC, and a three-dimensional simulation of ground vibrations generated by high-speed trains. The simulated roadbeds were subjected to dynamic loading in several test scenarios, with RMAC and other traditional paving materials used as roadbed materials. The ground accelerations at designated points in these simulations were then monitored and compared to one another to determine the relative effectiveness in vibration attenuation. From these parametric studies, RMAC has the potential to be more effective than currently-used paving materials (ballast, concrete, and conventional asphalt concrete) in damping out vibrations from dynamic loading. Implications for field applications are also discussed. The results of laboratory tests show that RMAC has a higher damping ratio and stiffness than conventional AC and can maintain these desired properties for vibration attenuation in a wide variety of environments. The study also shows that some further laboratory tests, numerical simulation, and field tests are needed before the technique is used in the field.

***Key Words**:* Damping, finite-element, ground vibration, high-speed train, numerical simulation, roadbeds, rubber-modified asphalt concrete (RMAC), stiffness, vibration attenuation

## TABLE OF CONTENTS

# EXECUTIVE SUMMARY


The use of high-speed train transportation systems is spreading rapidly throughout countries in eastern Asia and Europe, with interest developing in the United States as well. However, the use of high-speed rail systems comes with mechanical and environmental concerns. Excessive vibration can cause dynamic loading that can damage trains and track structures. It can also reduce the comfort of riding for passengers. The induced ground vibration may also damage local buildings while disturbing occupants and potentially interfering with sensitive equipment. Low frequency vibrations from passing trains can sometimes be felt as far as 100 to 200 meters away from the roadbed. Methods to isolate, absorb, and reduce the effects of passing trains must be developed.

Currently, trackbed typically is made of ballast only or ballast on top of concrete slabs. In recent years, European countries started using a conventional asphalt concrete (AC) underlayment for high-speed railways mainly to provide a stronger support for the track and to reduce maintenance costs. An AC underlayment also has the potential to significantly reduce ground vibration and noise in comparison to traditional track structures.

Some previous laboratory and small-scale tests have shown that rubber modified asphalt concrete (RMAC) has high stiffness and high damping ratios compared with ballast, concrete, and conventional asphalt, ideal properties for a vibration-absorption material. It substantially reduced both the recorded amplitude and duration of vibrations compared with ballast, concrete, and conventional AC underlayment. RMAC also provides extra strength to the foundation. These vibration attenuation characteristics have the potential to reduce track and equipment maintenance costs, and improve the long-term performance of the track structure.

To evaluate the potential of RMAC for reducing the ground vibration generated by high-speed trains, three phases of research were carried out. In phase one, a two-dimensional finite element simulation was conducted to investigate vibrations at the track, and at 20 and 40 meters away from the track, comparing roadbeds composed of either ballast, concrete, AC, or RMAC. These simulations indicated that RMAC compares favorably to typical roadbed materials such as concrete, ballast, and asphalt concrete in terms of vibration attenuation, directly under the track, reducing ground vibrations by up to 37% when compared with traditional ballast underlayment. However, these simulations showed negligible effects in vibration attenuation at 20 and 40 meters away from the track. Several important parameters such as the train weight, train speed, thickness of roadbed, and width of roadbed all were found to have a significant influence on vibration attenuation, usually in a nonlinear pattern. Vibrations tended to increase with train speed up to a point. Further increases in train speed resulted in reduced vibrations, indicating a resonant frequency was approached at around 200 mph.

In the second phase of the project, a series of resonant column tests were carried out on two blends of RMAC under varying temperature and pressure conditions. The blends of RMAC tested were “Type C,” with 20% rubber content, and “Type E,” with 10% rubber content. A sample of conventional asphalt concrete with no rubber was tested as well for comparison. These three samples were tested in a resonant column device for their shear moduli and damping ratios under various temperature and pressure conditions to simulate the range of loading environments expected in typical high-speed railway foundations. From these tests it was evident that as the rubber content of the asphalt blend increases, the shear modulus and damping ratio of the material increases as well. It was also evident that the shear modulus and damping ratio are strongly correlated to changes in temperature. As temperature goes down, the damping ratio drops significantly, which means the capability of vibration attenuation is reduced. However, the stiffness of RMAC increases significantly with lower temperatures. These two effects tend to offset one another. The relationship between the shear modulus and pressure (axle loadings) is related as well. There is a slight decrease in shear modulus as confining pressure increases.

However, the relationship between damping ratio and train weights could not be accurately determined from these tests. To build confidence in the laboratory tests, several tests were repeated and the results showed very good repeatability (with 5% of each other).

In the third phase of the project, three-dimensional finite element simulations of the problem were conducted. They showed that the use of RMAC as an underlayment material had a more significant effect in vibration control at locations away from the track than with the 2-D simulations. This may be due to the addition of the third dimension; the effect of the load traveling in the out-of-plane, lateral direction instead of being confined within one plane, and the ability for energy to dissipate in the out-of-plane direction. This is highly promising in terms of mitigating the negative environmental impacts high-speed railways may pose in densely populated, urban environments. These finite element simulations also indicated that a significant factor for high-speed railway foundations is the weight of the cars passing over the tracks. The variation of the weight of the car had significant effects on the magnitudes of the root-mean-square and peak accelerations, their magnitudes corresponding almost directly with the magnitude of the loading. The RMAC underlayment performed the best of all the materials simulated in most cases in terms of ground vibration control. Conversely, the speed of the train did not appear to have a significant effect on the magnitudes of the acceleration responses, yet it appears to have a significant effect on the relative performance of the underlayment materials in vibration control at the track. Again, this may be attributable to the addition of the third dimension. To test the reliability and consistence of the numerical simulation, the same problem was simulated using different meshes and again, repeatable results were achieved.

In conclusion, this study showed the promising potential of RMAC as a roadbed underlayment material to significantly reduce the ground vibration both at the track and away from the track. It can potentially reduce damage to track structures and reduce maintenance costs. Since airborne noise is also associated with mechanical vibration at the track, this technique is likely to also reduce noise generated by high-speed trains, although noise attenuation was not addressed in this study. In Europe, roadbeds made of conventional asphalt concrete have been introduced in recent years. It has shown superior performance in improving track performance and reducing vibration and noise. The use of RMAC, as shown in this study, could significantly enhance these benefits. The next steps would be to further validate these results through additional laboratory tests to check the repeatability of experimental data, additional numerical simulations to more accurately determine the effect of temperature on vibration attenuation of RMAC, and field tests to demonstrate the effectiveness in reducing both ground vibration and noise.

Based on the results of laboratory tests, RMAC with 20% rubber contents offers the highest stiffness and damping ratio under a wide range of temperature and pressure conditions. In addition, it is still within the range that can be easily manufactured using equipment for conventional AC. The numerical simulation shows that a thickness of 15 cm for a RMAC underlayment can optimize the performance in vibration attenuation. This is the same thickness for AC used in highway construction. Thus, the same equipment can be used. The unit price for rubber-modified asphalt concrete is 20% more than conventional asphalt concrete. However, since the same equipment as used in highway pavement construction could be used and the predominant cost is typically labor, the resulting increase in the overall cost of a project is estimated at less than 5%. In addition, RMAC uses a major industrial waste – discarded tires. This environmental benefit can not be measured in simple dollar values. The overall reductions in maintenance costs, though difficult to estimate, are likely to offset the increase in construction costs. The economic benefits of reduced noise and vibration impacts on adjacent structures and communities can also be significant.

# I BACKGROUND AND OBJECTIVES

In the United States, there is growing interest in high-speed trains as an efficient mode of intercity travel. High-speed trains bring unique challenges to railway roadbeds. To protect mechanical components of trains and track structures, to improve the comfort of riding for passengers, and to reduce ground vibration and noise pollution, the trackbeds of high-speed trains need to be strong while at the same time capable of vibration and noise attenuation. At present, the available techniques such as floating track, rubber mat, trenches, and sound barriers are complex, expensive and in some cases ineffective. Therefore, there is a need to develop a new technology of building high-speed railway roadbeds that is strong, economical, and environmentally friendly.

The research reported here was carried out at Case Western Reserve University, which investigated a new type of roadbed structure using rubber-modified asphalt concrete (RMAC) to assess and compare its stiffness and damping properties. The research included laboratory testing and numerical simulations. Rubber-modified asphalt concrete used in construction of the roadbed is made from commercially available asphalt mixed with crumb rubber produced from discarded tires. Previous studies have shown that roadbeds made with asphalt concrete underneath conventional ballast increases the load capacity of the track and reduces the maintenance cost. Initial laboratory tests have shown that rubber-modified asphalt concrete has high stiffness and much better vibration attenuation capability than conventional asphalt concrete (AC), concrete, or compacted soils. RMAC can be produced by conventional asphalt production plants and installed using conventional paving equipment. Through the research of this project, a new technique to build stronger, more economical, and environmentally friendly railway roadbeds has been evaluated that has the potential to significantly benefit the construction and operation of high-speed railways. It also utilizes one of the major industrial waste materials in the country, discarded rubber tires.

# II IDEA PRODUCT

Through the research effort funded by this IDEA contract, we have evaluated the potential of rubber modified asphalt concrete for high-speed railway roadbeds. We found that RMAC has stiffness and damping characteristics over a wide range of environmental conditions that indicate it should be considered as a serious alternative to more conventional trackbed systems. The numerical simulations showed that it can reduce ground vibration by up to 50% compared with roadbed made from other materials (ballast, AC, or concrete). Thus, when fully developed, we have an environmental friendly product that can enhance the structure performance of the railway and reduce the ground vibration and noise associated with high-speed trains.

The cost-effectiveness of using RMAC is mainly attributed to the reduction of dynamic loading and environmental impact. According to the theory of strength of materials (Gere, 2004), for steel under repeated loading, if the loading intensity is reduced by 5%, the endurance of the material (the number of cycles the material can take) is doubled. If the loading intensity is reduced by 30%, the endurance of the material is increased by 100 times. At the same time, rider comfort can be significantly improved. Therefore, this technique has the potential to significantly increase the life expectance or longevity of track structures and reduce the maintenance costs. In addition, the intensity of airborne noise is closely associated with the intensity of dynamic vibration. Even though we could not evaluate noise reduction in our numerical simulation and laboratory tests, we can predict with some confidence that this technique will reduce noise as well.

One adverse effect of this technique is the increase in construction cost. The unit price for rubber-modified asphalt concrete is 20% more than conventional asphalt concrete. However, since the same equipment as used in highway pavement construction will be used and in most cases, the predominant cost is labor cost, the resulting increase in overall cost of a project is estimated at less than 5%. In addition, RMAC uses a major industrial waste – discarded tires. This environmental benefit can not be measured in simple dollar values. The overall reductions in maintenance costs, though difficult to estimate, are likely to more than offset the increase in construction costs. And, the economic benefits of reduced noise and vibration impacts on adjacent structures and communities also need to be considered.

## III CONCEPT AND INNOVATION

High-speed railways have two basic yet somewhat conflicting demands for the trackbeds. First, the track structure has to be strong and durable so that there is only small deformation under the heavy loads of trains. Secondly, to reduce ground vibration and noise pollution, to reduce impact loading on train and track structures, and to increase the comfort of riding for passengers, the trackbeds need to provide significant vibration attenuation. For most materials, these are conflicting requirements. In general, stiff materials have low damping ratios and hence low capability to absorb energy from vibration, while soft materials are better for vibration attenuation but have larger deformation under external loading. To satisfy these two requirements, complex and expensive techniques are used in today's construction of high-speed railways such as floating track, rubber mast, trenches, sound barriers, etc.

This project investigated the potential of a new material that is strong, durable and has a high damping ratio. Over the past few years, the PI (X. Zeng) and the subcontractor (J.G. Rose) have been working with the Asphalt Institute in Lexington, Kentucky and a rubber company to develop a rubber-modified asphalt concrete that satisfies these two requirements. This research was supported by CSX Transportation Preliminary laboratory tests have shown that we can make rubber-modified asphalt concrete that is stronger than conventional asphalt concrete and has a damping ratio 2 to 4 times higher than conventional asphalt concrete, concrete, or compacted soil. In terms of vibration attenuation, it means lower amplitude of vibration and shorter duration of vibration. According to vibration theory, for a single-degree-of-freedom system, the damping ratio and amplitude of vibration has the following relationship:

$$D = \frac{100\%}{2\pi n} \ln \frac{A_1}{A_{n+1}}$$

where: $D$ = damping ratio

$n$ = cycle numbers between $A_1$ and $A_{n+1}$

$A_1$ = amplitude of vibration for the first cycle

$A_{n+1}$ = amplitude of vibration for the cycle $n+1$

Therefore, when the damping ratio of a material is doubled, the vibration is reduced 8 times. Of course, a railway trackbed is not a simple single-degree-of-freedom system. Therefore, more comprehensive study is necessary to understand the effect of this material on vibration attenuation.

RMAC utilizes one of the major industrial wastes in the country, discarded rubber tires. Also, the twenty years' research experience of the subcontractor (J.G. Rose) showed that trackbeds built with conventional asphalt concrete have better durability, larger loading capacity, and lower maintenance costs. Thus, the possibility of this material to succeed in the field is high.

This technique needs further analysis, development, and field verification before it is applied in the construction of roadbeds for high-speed railways. In the laboratory, we measured the influence of aging, temperature, rubber content, and confining pressure on the dynamic properties of RMAC. Using computer simulations, we investigated the capability of trackbeds made with this the new material to reduce ground vibration. We also carried out optimization of design.

## IV INVESTIGATION

The investigative approach for this project included three parts: initial two-dimensional simulation of the trackbed structure with different types of roadbeds, laboratory testing of RMAC under different temperatures, confining pressures and age, and three-dimensional simulations of RMAC trackbed to estimate vibration reduction.

### 4.1 TWO-DIMENSIONAL SIMULATION OF GROUND VIBRATION WITH DIFFERENT ROADBEDS

For this study, vibration of the high-speed train foundation was simulated using the widely used finite-element program ABAQUS. The simulation represents a cross-section of a typical roadbed as shown in Figure 1. This is a two-dimensional simplification. The roadbed consists of natural soil, a layer of compacted soil, a bed of ballast, a concrete tie, and a trackbed underlayment composed of either ballast, concrete, AC, or RMAC. In this series of parametric studies, the underlayment is placed directly underneath the concrete tie to more clearly observe the effect of varied underlayment materials on vibration attenuation; in reality, a thin layer of ballast would separate the trackbed underlayment from the rail structure. The mechanical properties of the underlayment materials are listed in Table 1. A two-dimensional, plane strain model was used with triangular quadratic elements. Infinite elements were used at the boundaries to simulate vibration dissipation through the surrounding soil. A dynamic, implicit scheme of integration was used with an unsymmetric matrix solver. All the numerical simulations were stable and results were repeatable.

The constitutive equations for RMAC, AC, and concrete are linear elastic with viscous damping ratios of 10%, 4%, and 1%, respectively. The damping ratios of RMAC and AC used here are obtained from experimental results reported by Zeng et al. (2001). For soils (ballast, compacted soil, and natural soil), the constitutive relationship used is linear elastic with Mohr-Coulomb plasticity. Considering the relatively small strain level in the soil, this is a reasonable approach. The small strain damping ratio for soils is 2% (Kramer, 1996). In the finite-element simulation, viscous damping can not be used directly, and Rayleigh damping is commonly used instead. In this study, the method of determining the Rayleigh damping coefficient proposed by Chopra (1995) is used. The mass proportional damping constant alpha is also listed in Table 1.

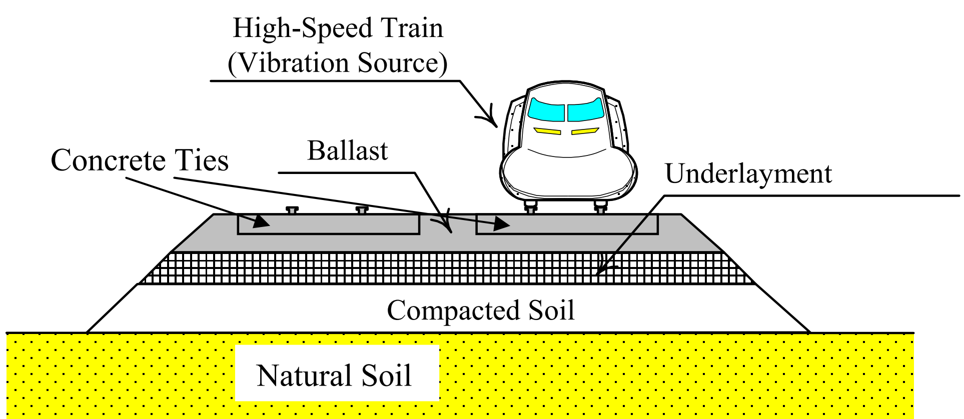


**FIGURE 1 Cross-sectional view of a typical railway roadbed**

A sinusoidal loading was applied to the two points representing the tracks of the railway. The time history of the loading follows the equation of:

$$F(t) = 75 - 75\cos(4\pi t)\ kN \qquad 0 < t \leq 5\ s$$
$$F(t) = 0\ kN \qquad 5 < t \leq 10\ s$$

This is an idealized representation of the dynamic loading applied by a high-speed train followed by the free vibration of the foundation after the train passes. The magnitude of the load represents the axle loading of a passing train while the frequency of the load (2 Hz) represents the typical bogie frequency of loading generated by a high-speed train approaching an urban area in the field. According to field measurements by Degrande (2001), the fundamental bogie passage frequency of a typical high-speed train traveling at 135 km/hr is about 2 Hz; later, the influence of the frequency of the dynamic loading on vibration attenuation will be discussed as well. Three points were monitored for their time histories of displacement, velocity, and acceleration during the simulations: Point A, on the track directly underneath the loading; Point B, 20 meters away from the loading; and Point C, 40 meters away from the loading.

TABLE 1 Underlayment Material Properties used in Numerical Simulations (For AC and RMAC, temperature is 92 degrees F)

| **Material** | **Model Type** | **Density ($kg/m^3$)** | **Elastic Modulus (Pa)** | **Poisson's Ratio** | **Alpha Damping** | **Cohesion (Pa)** | **Friction Angle (degrees)** | **Dilation Angle (degrees)** |
|---|---|---|---|---|---|---|---|---|
| RMAC | Linear Elastic | 2,378 | $2.86 \times 10^9$ | 0.30 | 25.00 | N/A | N/A | N/A |
| AC | Linear Elastic | 2,378 | $2.08 \times 10^9$ | 0.30 | 8.00 | N/A | N/A | N/A |
| Ballast | Linear Elastic with Mohr-Coulomb Plasticity | 2,092 | $2.00 \times 10^7$ | 0.30 | 0.125 | 1,000.00 | 31.00 | 22.5 |
| Compacted Soil | Linear Elastic with Mohr-Coulomb Plasticity | 2,092 | $2.00 \times 10^7$ | 0.30 | 0.125 | 1,000.00 | 30.00 | 21.8 |
| Natural Soil | Linear Elastic with Mohr-Coulomb Plasticity | 1,890 | $1.3 \times 10^7$ | 0.30 | 0.125 | 1,000.00 | 31.00 | 22.5 |
| Concrete | Linear Elastic | 2,480 | $2.67 \times 10^{10}$ | 0.30 | 1.0 | N/A | N/A | N/A |

In this study, five separate sets of simulations were carried out in order to determine the effects of varying materials in the trackbed underlayment, varying load amplitudes, varying load frequencies, varying thicknesses of the underlayment, and varying widths of the underlayment. These sets test the performance of RMAC in comparison to typical paving materials, the effects of different types of trains with different speeds running over the RMAC foundation, and the effects of changing the dimensions of the underlayment. Two parameters recorded at the three selected points were monitored closely for evaluation of vibration attenuation, the peak acceleration and the root-mean-square acceleration. The root-mean-square acceleration, $A_{RMS}$ , is given by

$$A_{RMS} = \sqrt{\frac{1}{T}\int_0^T a^2(t)\,dt}$$

where $a(t)$ = acceleration at time *t*, and $T$ = the duration of vibration. The root-mean-square refers to a common mathematical method of defining the effective magnitude. For a uniform sine wave, the root-mean-square value is 0.707 times the peak value, or 0.354 times the peak-to-peak value**.** For repeated loading situation such as loading generated by high-speed trains, the peak acceleration represents the peak loading amplitude while root-mean-square acceleration represents the average repeated loading amplitude. Both parameters are important in determining the longevity of the track structure and the ground vibration intensity. By comparing the root-mean-square and peak accelerations of monitored points, the capacity of RMAC in vibration attenuation can then be determined.

### 4.1.1 Influence of different trackbed underlayment materials

Four simulations were carried out to determine the effect of different underlayment materials in vibration attenuation. The materials tested were RMAC, AC, concrete, and ballast. The situation with ballast effectively means no underlayment at all. The width of the underlayment is twice that of the track. The underlayment thicknesses of RMAC and AC were 15 cm while the underlayment thickness of concrete was 10 cm; these are the typical thicknesses of asphalt and concrete used in general pavement construction. The two identical dynamic loadings, which represent the loading generated by the train, were applied on the track. Figure 2 shows the acceleration time history at Point A, directly underneath the loading, for the RMAC and the ballast underlayments. The peak acceleration at this location is significantly reduced when RMAC is used. The peak accelerations at the three monitored points with the four different types of materials are shown in Figure 3. At point A, the RMAC underlayment has the lowest level of vibration. Note that at 20 meters and 40 meters (point B and C), there does not appear to be any substantial difference among the four materials. The reduction is most significant at point A which is directly underneath the track.

Table 2 shows the root-mean-square accelerations and peak accelerations at points A, B, and C for the four materials and the reduction rates of RMAC, AC, and concrete underlayments in comparison to a conventional ballast underlayments. Clearly, RMAC has the best effect in vibration attenuation, reducing the peak acceleration at the track by 35.7% and root-mean-square acceleration by 18.7%, which is 9.2% and 2% better than the next best underlayment material, AC. As discussed earlier, such an improvement in dynamic loading reduction can lead to significant benefits in reduction of maintenance cost and improvement of rider comfort. At point B, which is 20 meters away from the track, RMAC appears to have only a marginal effect. However, at point C, which is 40 meters away from the track, there is no apparent effect, which may be due to the fact that by the time vibrations reach point C, a large amount of soil is vibrating. The damping effect of soil is playing a predominant role, and is not affected much by the underlayment materials.

### 4.1.2 Effect of load magnitude

To study the influence of the weight of the car on the performance of the RMAC underlayment, two additional magnitudes of axle loads were simulated using a 15 cm thick RMAC underlayment. The

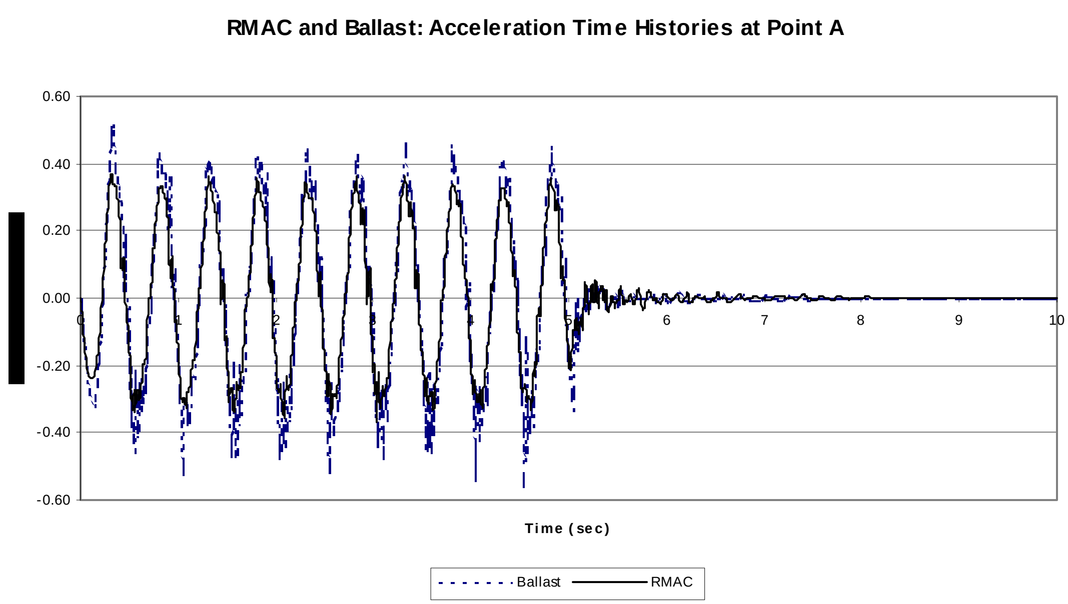


**FIGURE 2 Acceleration time history at point A with RMAC and ballast foundation**

TABLE 2 $A_{RMS}$ and $A_{Peak}$ for Various Trackbed Materials: Ballast, Concrete, AC, and RMAC

| Location | Trackbed | $A_{RMS}$ ($m/s^2$) | Reduction in $A_{RMS}$ (%) | $A_{peak}$ $m/s^2$ | Reduction in $A_{peak}$ (%) |
|---|---|---|---|---|---|
| A | Ballast | 0.198 | -- | 0.565 | -- |
| A | Concrete | 0.168 | 15.1 | 0.416 | 26.4 |
| A | AC | 0.165 | 16.7 | 0.415 | 26.5 |
| A | RMAC | 0.161 | 18.7 | 0.369 | 35.7 |
| B | Ballast | 0.0422 | -- | 0.114 | -- |
| B | Concrete | 0.0369 | 12.5 | 0.122 | -7 |
| B | AC | 0.0363 | 13.9 | 0.110 | 3.5 |
| B | RMAC | 0.0353 | 16.3 | 0.108 | 5.3 |
| C | Ballast | 0.0304 | -- | 0.0917 | -- |
| C | Concrete | 0.0292 | 3.9 | 0.0950 | -3.6 |
| C | AC | 0.0305 | -3.3 | 0.0964 | -5.1 |
| C | RMAC | 0.0299 | 1.6 | 0.0919 | -0.2 |

Note: Positive reduction means decrease in amplitude while negative reduction means increase in amplitude

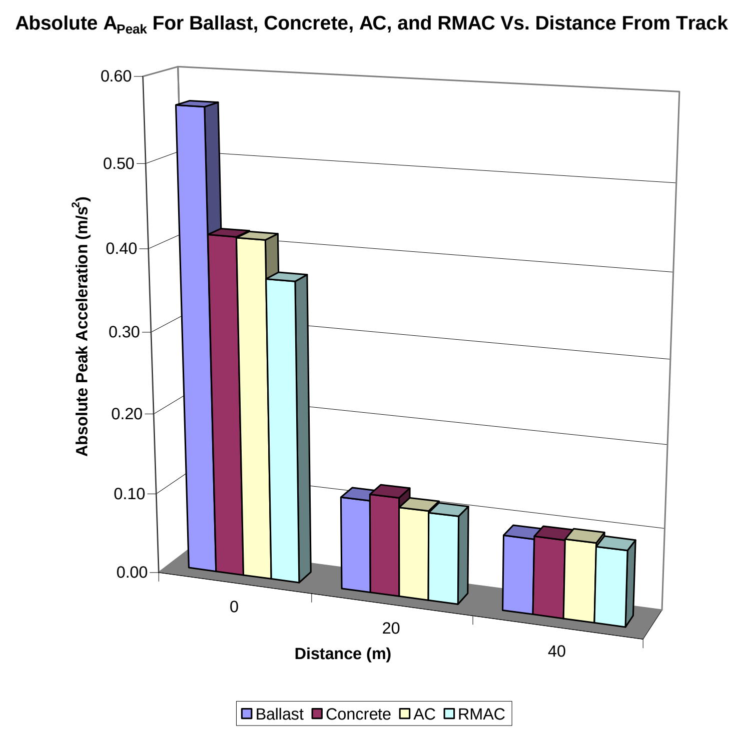


**FIGURE 3 Comparison of peak accelerations with different trackbed materials**

frequency of the loading was held constant at 2 Hz (train speed 135 km/h or 84 mile/hour), while the magnitudes of the loading were changed to 50 kN or 100 kN to represent lighter or heavier cars. Table 3 presents the root-mean-square accelerations and peak accelerations for Points A, B, and C under the varying load magnitudes. It is clear that the dynamic vibration magnitude is strongly nonlinear in relation to the loading magnitude, especially for points B and C which are away from the track. For example, when the load is doubled, the vibration amplitudes at points A, B, and C are increased by 226%, 243%, and 272%, respectively. The further away from the track, the more significant the increase is. This is likely due to the non-linear properties of soil. Therefore, the weight of the cars is an important consideration in vibration attenuation.

#### 4.1.3 Effect of Train Speed

When a high-speed train is running at different speeds, the dynamic loading it generates has a different frequency. Three additional simulations were conducted to determine the effect of lower and higher frequencies (or train speeds) while using the 15 cm thick RMAC underlayment. Frequencies of 1 Hz (train speed 67.4 km/hr or 42 mph), 2 Hz (train speed 135 km/hr or 84 mph), 5 Hz (train speed 337 km/hr or 210 mph), and 10 Hz (train speed 674 km/hr or 420 mph) were tested, while keeping the magnitude of loading at a constant 75 kN. A fundamental train passage frequency of 5 Hz corresponds to a train traveling at a speed of 337 km/hr, or approximately the same speed as some commercial high-speed trains in Europe and Japan. Vibrations at other frequencies are also present in trains traveling at such speeds. The root-mean-square accelerations and peak accelerations for Points A, B, and C under different train speeds (frequencies) are reported in Table 4. Clearly, the frequency of dynamic loading has a significant influence on the ground vibration recorded at the three points. The vibration at the track (point A) increases with the frequency in a non-linear pattern. On the other hand, at points B and C, the vibration seems to be maximized at frequencies around 5 Hz. This may be due to resonance characteristics of the soil at those vibration frequencies.

#### 4.1.4 Influence of the thickness of the trackbed underlayment

One possibility in reducing the vibration generated by a high-speed train is to increase the thickness of the underlayment. In this set of simulations, the thickness of RMAC was varied at 10 cm, 20 cm, and 30 cm. A test with AC at 30 cm was also run, to compare the effectiveness of using RMAC as opposed to increasing the thickness of AC. Table 5 shows the results of the root-mean-square accelerations and the peak accelerations for the three monitored points for different thickness of the RMAC underlayment. The results indicate that increasing the thickness of RMAC underlayment does improve the vibration attenuation in most cases. However, the rate of improvement slows down significantly once the thickness is more than 15 cm. Therefore, for economical considerations, an underlayment thickness of 15 cm seems to be an optimized design. This is also the typical thickness used in highway pavement construction. Therefore, the same equipment used there can also be used for high-speed railways. It is also worth mentioning that a 15 cm RMAC underlayment performs approximately the same as a 30 cm AC underlayment.

#### 4.1.5 Influence of the width of the trackbed underlayment

Another possibility in achieving better vibration attenuation is to increase the width of the underlayment. Typical underlayment width is between 2 to 3 times that of the width of the tracks. In this set of simulations, the width of the underlayment was increased to three times the distance between the center lines of the rail. To increase the underlayment width to three times the width of the rail, the width of the ballast bed had to be increased as well, which may create problems with property ownership along the track. The angle of the ballast shoulder with the ground was kept constant at 20˚. The thickness of the underlayment was kept constant at 15 cm. The root-mean-square accelerations and peak accelerations are listed in Table 6. The increase in the width reduces the vibration at the track by a small margin, but, as the distance from track increases, the effect becomes much more significant. For instance, at point C, the vibration is reduced by more than 50%. Therefore, to reduce the vibration away from the track, increasing the width of RMAC underlayment, where possible, could be effective.

#### 4.1.6 Discussion: 2D Simulation Results

The results from the above tests show the promising potential of RMAC as an effective foundation material for high-speed trains. As shown in Table 2, RMAC performs much better in terms of damping out accelerations directly under the track than typical materials such as asphalt concrete, concrete, and ballast. This is a major consideration for the longevity of tracks and trains. The extended life for the track structure based on root-mean-square acceleration is doubled and based on peak acceleration is 100 time longer. Since RMAC has been proven to be more durable, flexible, and fatigue-resistant over longer periods of time and under a wider range of temperature conditions than asphalt concrete, its use may prove to be more effective and efficient for long-term applications. With regard to damping out accelerations away from the tracks, however, the results of the 2D simulations showed no substantial improvements with RMAC.

These 2D results also illustrate the effects of trains with different weights and speeds on the vibration of rail foundations. The behavior in terms of varying the magnitude of the load is as intuitively expected; when the load is larger and the car is heavier, the ground acceleration is increased, and vice versa. The behavior of the system in terms of varying train speed is less intuitive, however. The loading with 42 mph (1Hz) and 210 mph (5 Hz) train speeds appear to scale with respect to the 84 mph (2 Hz) loading situation; the accelerations at 42 mph are lower than at 84 mph, while the accelerations at 210 mph are higher than at 84 mph. However, the accelerations at Points B and C under 420 mph dynamic loading are significantly lower than the accelerations at 210 mph; the root-mean-square acceleration at Point B for 320 mph is approximately 78% less than for 210 mph. This appears to indicate that a resonant frequency is being approached at 210 mph, and the ground vibrations at Points B and C attenuated by the RMAC underlayment. This issue needs to be studied further so that optimization of design can be achieved.

TABLE 3 $A_{RMS}$ and $A_{Peak}$ for Varied Load Magnitudes: F = 50-50cos(4πt) kN and F=100-100cos(4πt) kN

| **Location** | **Amplitude of loading (kN)** | **$A_{RMS}$ ($m/s^2$)** | **$A_{Peak}$ ($m/s^2$)** |
|---|---|---|---|
| A | 50 | 0.101 | 0.270 |
| A | 75 | 0.161 | 0.369 |
| A | 100 | 0.226 | 0.541 |
| B | 50 | 0.0186 | 0.0608 |
| B | 75 | 0.0353 | 0.108 |
| B | 100 | 0.0452 | 0.142 |
| C | 50 | 0.0130 | 0.0395 |
| C | 75 | 0.0299 | 0.0919 |
| C | 100 | 0.0354 | 0.122 |

TABLE 4 $A_{RMS}$ and $A_{Peak}$ for Varied Train Speed: F = 75-75cos(2πt) kN; F = 75-75cos(10πt) kN; and F = 75-75cos(20πt) kN

| **Location** | **Train Speed km/hr (mph)** | **$A_{RMS}$ ($m/s^2$)** | **$A_{Peak}$ ($m/s^2$)** |
|---|---|---|---|
| A | 67.4 (42) | 0.048 | 0.199 |
| A | 135 (84) | 0.161 | 0.369 |
| A | 337 (210) | 0.488 | 1.232 |
| A | 674 (420) | 0.714 | 1.739 |
| B | 67.4 (42) | 0.00925 | 0.0390 |
| B | 135 (84) | 0.0353 | 0.108 |
| B | 337 (210) | 0.150 | 0.355 |
| B | 674 (420) | 0.0324 | 0.136 |
| C | 67.4 (42) | 0.00586 | 0.0209 |
| C | 135 (84) | 0.0292 | 0.0950 |
| C | 337 (210) | 0.0299 | 0.0919 |
| C | 674 (420) | 0.0258 | 0.0888 |

TABLE 5 $A_{RMS}$ and $A_{Peak}$ for Varied Thicknesses of RMAC and AC Trackbeds: 10 cm, 15cm, 20 cm, and 30 cm.

| Location | Type and Thickness of Trackbed (cm) | $A_{RMS}$ ($m/s^2$) | $A_{Peak}$ ($m/s^2$) |
|---|---|---|---|
| A | RMAC – 10 | 0.164 | 0.405 |
| A | RMAC – 15 | 0.161 | 0.369 |
| A | RMAC – 20 | 0.159 | 0.371 |
| A | RMAC – 30 | 0.153 | 0.345 |
| A | AC – 30 | 0.161 | 0.385 |
| B | RMAC – 10 | 0.0390 | 0.134 |
| B | RMAC – 15 | 0.0353 | 0.108 |
| B | RMAC – 20 | 0.0349 | 0.111 |
| B | RMAC – 30 | 0.0338 | 0.109 |
| B | AC – 30 | 0.0355 | 0.115 |
| C | RMAC – 10 | 0.0289 | 0.0973 |
| C | RMAC – 15 | 0.0299 | 0.0919 |
| C | RMAC – 20 | 0.0288 | 0.0875 |
| C | RMAC – 30 | 0.0274 | 0.0883 |
| C | AC – 30 | 0.0293 | 0.0883 |

TABLE 6 $A_{RMS}$ and $A_{Peak}$ for Varying Widths of RMAC Trackbeds: Triple With of Rail and Double Width of Rail

| Location | Width of Trackbed | $A_{RMS}$ ($m/s^2$) | $A_{peak}$ ($m/s^2$) |
|---|---|---|---|
| A | Triple Width | 0.156 | 0.496 |
| A | Double Width | 0.161 | 0.369 |
| B | Triple Width | 0.0326 | 0.101 |
| B | Double Width | 0.0353 | 0.108 |
| C | Triple Width | 0.0197 | 0.0565 |
| C | Double Width | 0.0299 | 0.0919 |

Changing the dimensions of the trackbed underlayment also has an effect on the vibration of surrounding ground. As the thickness of RMAC is increased, the corresponding accelerations decrease; as the width is increased, the corresponding accelerations appear to decrease as well. At the same time, the performance of a RMAC underlayment at 15cm is as effective as a 30 cm AC underlayment at attenuating the vibrations. This reaffirms the conclusions earlier that RMAC generally performs better than AC in terms of reducing ground vibrations. Increasing the width of the asphalt also brings about a decrease in the accelerations. Since variation of the dimensions of the underlayment appears to have a significant influence upon the attenuation of the ground vibrations, optimizing the size of the underlayment for maximum vibration control needs to be considered as well.

#### 4.1.6 Conclusions: 2D Simulations

From the finite-element simulations presented above, RMAC shows promise as an effective material for the vibration attenuation of high-speed railways. It compares favorably to typical materials such as concrete, ballast, and asphalt concrete in terms of vibration attenuation under and near the track. These results are consistent with the conclusions of previous studies on small-scale model tests. Several important parameters such as the load magnitude, load frequency (train speed), and the dimensions of the trackbed underlayment all have a significant influence on vibration attenuation, usually in a nonlinear pattern.

At the same time, further research needs to be done regarding the actual application of RMAC in high-speed rail. Finite element simulations with load magnitude and frequency data recorded from high-speed trains in the field should be used to determine how RMAC behaves under actual train axle loading conditions. Measured bogie frequencies were used as the driving frequencies in these parametric studies, although measured axle frequencies can be more than ten times as large and should be tested as well. The bogie frequency is the frequency of dynamic loading related to the passage of each carriage of a train while the axle frequency corresponds to the frequency of dynamic loading related to passage of each axle (Krylov, 2001). Finally, the results of numerical simulations need to be compared with data measured in field tests for validation.

## 4.2 LABORATORY TESTING ON RMAC WITH DIFFERENT TEMPERATURES AND CONFINING PRESSURES

Laboratory tests were conducted using a Drnevich-type resonant column machine. The resonant column test is the most commonly used laboratory procedure for measuring low-strain dynamic properties of soils; the specifics of the test procedure and data analysis can be found in ASTM standard D 4015 (ASTM 1992). Materials other than soils such as concrete, asphalt, and rock have been successfully tested with this procedure as well. A resonant column test yields data regarding the shear modulus and the damping ratio of a material. The shear modulus is directly proportional to how stiff the material is in shear, while the damping ratio is an indicator of how effective the material is in vibration attenuation.

For these tests, specimens of Type C RMAC (20% rubber), Type E RMAC (10% rubber), and a conventional asphalt concrete sample were prepared. Cylindrical cores approximately 8.89 cm (3.5 inches) tall with diameters of approximately 6.985 cm (2.75 inches) were cut, massed, and epoxied into resonant column heads. A thin rubber membrane was placed around each sample to protect it from external damage. Depending upon which temperature condition was being tested, the sample was either chilled or heated with hot or cold air until a desired temperature was reached. Once the sample was at its desired temperature level, it was installed into the resonant column device as seen in Figure 4. After the sample was installed, four tests varying the confining pressure within the pressure vessel were performed. These pressures were at 0 kPa, 137.9 kPa, 275.8 kPa, and 551.6 kPa (the range of pressure that can be expected in the underlayment) and were achieved by using an air compressor to increase the air pressure within the vessel.

In performing the tests for each pressure level at each temperature, the magnitude of the voltage input into the sample, the excitation voltage, was increased from approximately 20 mv to 1500 mv. By varying the frequency at which these excitation voltages were applied, the resonant frequency of the asphalt, the lowest frequency which produces the largest output voltage or sample reaction, could be determined. This was achieved via an oscilloscope attached to the resonant column device, as seen on the left in Figure 5. This oscilloscope showed the input voltage on the horizontal axis with the output voltage on the vertical axis; this is known as a Lissajous curve. By varying the frequency and watching the oscilloscope's display, one could determine the resonant frequency at the point at which the oscilloscope displayed an ellipse perpendicular to the horizontal axis. This effectively means that the output reaction is at its highest level from the input excitation, marking it as the resonant frequency of the sample. The resonant frequency and output voltage were then noted, as the two quantities are important in determining the shear modulus and shear strain for the given input excitation.

Damping ratios were also measured at each excitation level for each sample of asphalt at each temperature and pressure condition. This was done by use of an additional oscilloscope connected only to the output response from the resonant column machine; this can be seen in the right foreground of Figure 5. The sample was excited at the input voltage, and the output voltage was measured; the input excitation was then abruptly shut off, and the output response of the asphalt sample was recorded on the oscilloscope to produce an exponentially decaying sine curve as seen in Figure 6. This curve was saved for further analysis.

**FIGURE 4 Typical Asphalt Sample in the Resonant Column Device**

**FIGURE 5 Oscilloscopes and Voltage Generators Attached to the Resonant Column Device**

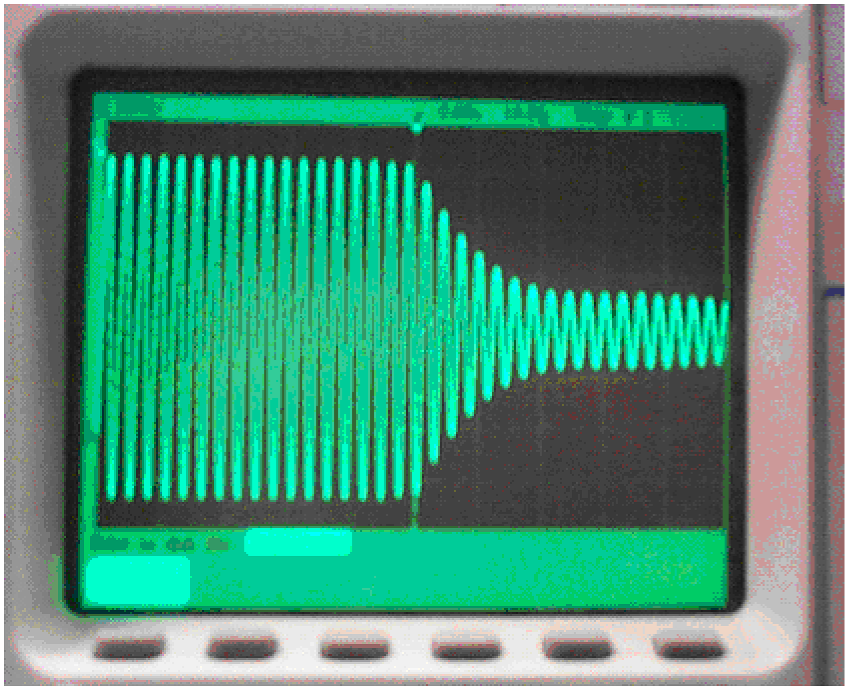

**FIGURE 6 Typical Output Response Curve Used to Determine Damping Ratio**

### 4.2.1 Data Analysis Procedures:

To determine the shear moduli of the samples under the varying temperature and pressure conditions, the formula:

$$G = 3.867\ \rho\ (f_n^2 L^2/\alpha^2)$$

where:
G = shear modulus (kPa)
$\rho$ = mass density (gm-sec$^2$/cm$^4$)
$f_n$ = resonant frequency (Hz)
L = specimen length (cm)
$\alpha$ = obtained from the expression: $\alpha \tan \alpha = J_s/J_m$
where:
$J_s$ = mass polar moment of inertia of asphalt
(gm cm sec$^2$)
$J_m$ = 42.0579 gm cm sec$^2$ was used. To determine the corresponding shear strain percentage for the shear moduli, the formula:

$$\gamma = 0.29507(rV)/(f_n^2 L)$$

where:
$\gamma$ = shear strain (%)
r = asphalt sample radius (cm)
V = output response voltage (mv)
$f_n$ = lowest resonant frequency (Hz)
L = specimen length (cm)
was used.

To determine the percentage damping ratio of each sample under the varied temperature and pressure conditions at each percentage of strain, vibration theory was used while examining the exponentially decaying sine curves:

$$\xi = 100\% * (1/(2\pi n)) * \ln(A_1/A_{n+1})$$

where:
$\xi$ = damping ratio (%)
n = cycle numbers between peaks $A_1$ and $A_{n+1}$
$A_1$ = amplitude of an output response peak after excitation cut off (mv)
$A_{n+1}$ = amplitude of output response peak n cycles after the $A_1$ peak (mv)

### 4.2.2 Results and Discussion

From each of the resonant column tests performed on the various asphalt samples, curves depicting the shear moduli vs. the shear strain and curves depicting the damping ratios vs. the shear strain were generated. The temperature range used in the tests was from -10 degrees C to 37 degrees C. According to Rose (1998), temperature recorded in underlayment is typically a few degrees milder than the extreme temperature recorded in the air. Therefore, the temperature range used in the test covers most possible cases expected in the field. Figure 7 shows the shear modulus vs. shear strain for RMAC sample C which has 20% rubber. It shows clearly that shear modulus decreases as temperature increases. The trend is the same for the sample of RMAC with 10% rubber and for conventional asphalt concrete. For example, the shear modulus at -10 degree C is about 38% higher than the shear modulus of the same material at 37 degrees C. It means that the static deformation under the same loading will be increased by 38% when the temperature is increased from -10 degrees C to 37 degrees C. The damping ratio versus shear strain for the RMAC sample with 10% rubber at different temperature is shown in Figure 8. Again, there is a strong influence of temperature on damping ratio. For example, the damping ratio at 37 degree C is about 3 times that at -10 degree C. It means that as temperature increases, the capability for vibration attenuation of RMAC is also increased. The summary of experimental results at all temperatures for the three samples is listed in Table 7.

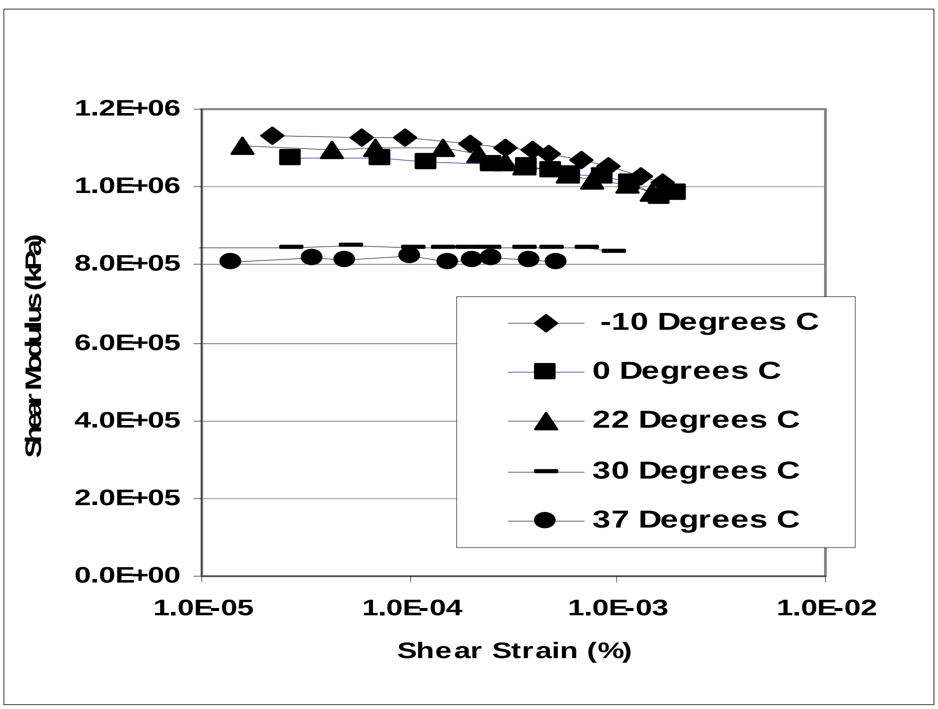


**FIGURE 7 Shear modulus vs. shear strain for RMAC with 20% rubber**

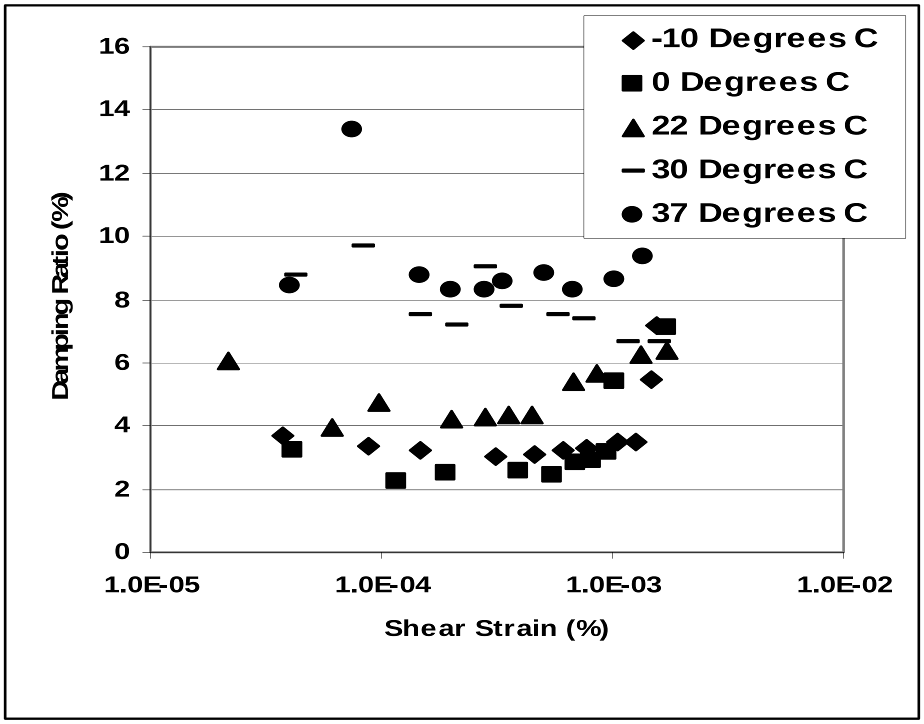


**FIGURE 8 Damping ratio vs. shear strain for RMAC with 10% rubber**

Table 7 Properties of AC and RMAC at different temperatures

| a) Temperature = 98 degree F (37 degree C), confining pressure = 138 kPa, shear strain = 0.0001% | | |
|---|---|---|
| Materials | Shear modulus (kPa) | Damping ratio (%) |
| AC | $5.4 \times 10^5$ | 8.4 |
| 10% rubber RMAC | $5.9 \times 10^5$ | 9.2 |
| 20% rubber RMAC | $8.1 \times 10^5$ | 10.1 |
| b) Temperature = 86 degree F (30 degree C), confining pressure = 138 kPa, shear strain = 0.0001% | | |
| Materials | Shear modulus (kPa) | Damping ratio (%) |
| AC | $6.4 \times 10^5$ | 5 |
| 10% rubber RMAC | $6.4 \times 10^5$ | 7.4 |
| 20% rubber RMAC | $8.2 \times 10^5$ | 8 |
| c) Temperature = 72 degree F (22 degree C), confining pressure = 138 kPa, shear strain = 0.0001% | | |
| Materials | Shear modulus (kPa) | Damping ratio (%) |
| AC | $6.7 \times 10^5$ | 3.8 |
| 10% rubber RMAC | $7.5 \times 10^5$ | 4 |
| 20% rubber RMAC | $1.1 \times 10^6$ | 4.6 |
| d) Temperature = 32 degree F (0 degree C), confining pressure = 138 kPa, shear strain = 0.0001% | | |
| Materials | Shear modulus (kPa) | Damping ratio (%) |
| AC | $6.2 \times 10^5$ | 3.8 |
| 10% rubber RMAC | $7.9 \times 10^5$ | 3.5 |
| 20% rubber RMAC | $1.07 \times 10^6$ | 3.2 |
| e) Temperature = 14 degree F (-10 degree C), confining pressure = 138 kPa, shear strain = 0.0001% | | |
| Materials | Shear modulus (kPa) | Damping ratio (%) |
| AC | $6.8 \times 10^5$ | 2.0 |
| 10% rubber RMAC | $8.1 \times 10^5$ | 2.2 |
| 20% rubber RMAC | $1.15 \times 10^6$ | 2.9 |

From the results of the tests, it is evident that the shear modulus of the 20% rubber RMAC is significantly higher (about 45%) than the shear modulus of asphalt E, the 10% RMAC blend, which in turn is higher (about 5%) than the shear modulus of conventional asphalt concrete. This indicates that the rubber-modified asphalt concrete mixes have higher shear stiffness than conventional asphalt mixes dependent on their rubber content. This is an advantage in terms of reducing the amplitude of vibration. It is also evident that all three of the asphalt samples had a tendency to have higher shear moduli at lower temperatures; the shear modulus of sample C at 37 degrees C is comparable to the shear modulus of sample E at -10 degrees C. In terms of variation of shear modulus vs. strain with respect to temperature, it appears that, at colder temperatures, the shear modulus decreases more noticeably at higher strains, while at warmer temperatures, the shear modulus appears to remain relatively constant for all samples of asphalt. The previous observations are true for all of the pressure conditions tested.

From the results of the tests, it can be seen that the damping ratio increases as the temperature of all of the samples increased. For most temperatures, RMAC with 20% rubber content has the highest damping ratio, though at one temperature, 32 degrees F, the conventional asphalt sample appears to actually outperform the rubber-modified mixtures. This anomaly may be associated with this batch of samples and if a group of samples are tested, one can determine whether this is a true phenomenon associated with RMAC. It can also be noted that, as the shear strain of the sample increases, the damping ratios of all samples at all temperature increase as well.

Based on the experimental data, one concern is as temperature goes down, the damping ratio drops significantly, which means the capability of vibration attenuation is reduced. However, at the same time, the stiffness of RMAC is significantly increased, which would reduce the amplitude of vibration. The combined effect is that one factor tends to cancel the other out, possibly resulting in similar characteristics for all temperatures. For example, if the track is treated as a single-degree-of-freedom system, the dynamic vibration at -10 degree C and 37 degree C have amplitudes within 10% of each other. Of course, the track structure is a system with infinite degrees of freedom and numerical simulations and field tests need to be carried out to study this effect.

### 4.2.3 Conclusions From Laboratory Tests

From these studies, it appears that rubber-modified asphalt concrete has significantly higher shear stiffness under varying temperature and pressure conditions than a traditional asphalt concrete blend. This indicates that rubber-modified asphalt concrete is a stiffer material in shear than traditional asphalt concrete. Having a higher stiffness would be attractive in terms of high-speed rail foundations that are subjected to repetitive dynamic loads, because it reduces the amplitude of vibration. The shear modulus is also dependent upon the temperature of the material. When the material is cooled, it gains stiffness; as it is heated, it loses stiffness. This is of significance in terms of how the material will behave in high-speed rail foundations throughout a regular course of seasonal variations. It is also of concern when studying thermal strains and stresses within the material and determining how those induced stresses cause crack growth and propagation.

It also appears that the damping ratio of all of the asphalt samples is highly dependent upon the temperature of the material. In situations of higher temperature, the damping ratio is significantly increased for all samples. However, the relationship between the damping ratio and various confining pressures is not clearly defined from these tests. It also appears that the damping ratios for all samples of the asphalt concrete are in the same range, even though RMAC with 20% rubber has the highest damping ratio in most cases. The ambiguity of the damping data may possibly be attributed to the method by which damping ratio was calculated. Other methods of determining the damping ratio of the material, such as using a cyclic triaxial test, may have produced a more well behaved trend in the materials' relative behaviors.

These tests indicate that the mechanical properties of the asphalt material are highly dependent upon the environmental conditions to which they are exposed. This suggests that the asphalt is not a material with constant constitutive properties – rather, as seasons and temperatures change, the material will react differently to the same loading situations. How the material changes with seasonal variation is of great importance when utilizing the material in field applications. Further research into the vibration attenuation of different underlayment at different temperature is recommended.

## 4.3 THREE-DIMENSIONAL SIMULATION OF GROUND VIBRATION WITH DIFFERENT ROADBEDS

### 4.3.1 3D Finite Element Simulation

To create the three-dimensional model of the high-speed train trackbed, the finite element program ABAQUS v. 6.4-1 by Hibbitt, Karlsson & Sorensen, Inc. was used. A symmetry model of a 50 m long portion of an idealized high-speed rail structure resting on a block of soil 50 m long, 100 m wide, and 100 m deep was created. The symmetry plane splits the rail structure and the soil foundation in half; points on the symmetry plane may translate in the y (longitudinal) and z (vertical) directions, but not in the x (lateral) direction. The bottom of the foundation is fixed in all translational directions, while the sides of the foundation are fixed in the x and y directions. The soil foundation consists of a bed of natural soil and a layer of compacted soil, while the rail structure consists of a trackbed underlayment, a thin layer of ballast, a concrete tie, and a steel rail. The underlayment was taken to be 15 centimeters thick, a typical thickness for paving materials. Either RMAC, AC, concrete, or ballast was used as the underlayment material; a ballast underlayment effectively meant no underlayment was provided at all. The mechanical properties of the materials used can be seen in Table 8.

The model was meshed using C3D20R elements, which are three-dimensional, 20 node quadratic bricks analyzed with reduced integration. 50 meters of the soil foundation were extended on both ends of the rail to allow for vibration dissipation through the surrounding soil. A static gravity load was applied over the entire system, and then a nonlinear, direct-integration dynamic analysis was performed over a specified amount of simulated time; systems of nonlinear dynamic equilibrium equations were solved at each time increment using Newton's iterative method. Six points were monitored for their acceleration responses; the points and their locations can be seen in Figure 9. Points A and D are directly under the midpoint between the two rails; B and E are approximately 10 meters away from the rail; and C and F are approximately 20 meters away from the rail. Points A, B, and C are located at the middle section of the simulated track portion; points D, E, and F are 2.5 meters away from the middle section.

The constitutive equations for RMAC, AC, concrete, and steel are linear elastic with viscous damping ratios of 10%, 4%, 1%, and 1%, respectively. The damping ratios of RMAC and AC used here are obtained from experimental results reported by Zeng et al. (2001). For the compacted soil and natural soil, the constitutive relationship used is linear elastic with Mohr-Coulomb plasticity. For the ballast, only a linear elastic model is provided. Considering the relatively small strain level in the soil, this is a reasonable approach. The damping ratio for soils is 2% (Kramer, 1996). In the finite-element simulation, viscous damping can not be used directly, and Rayleigh damping is commonly used instead. In this study, the method of determining the Rayleigh damping coefficient proposed by Chopra (1995) was used. The mass proportional damping constant alpha is also listed in Table 8.

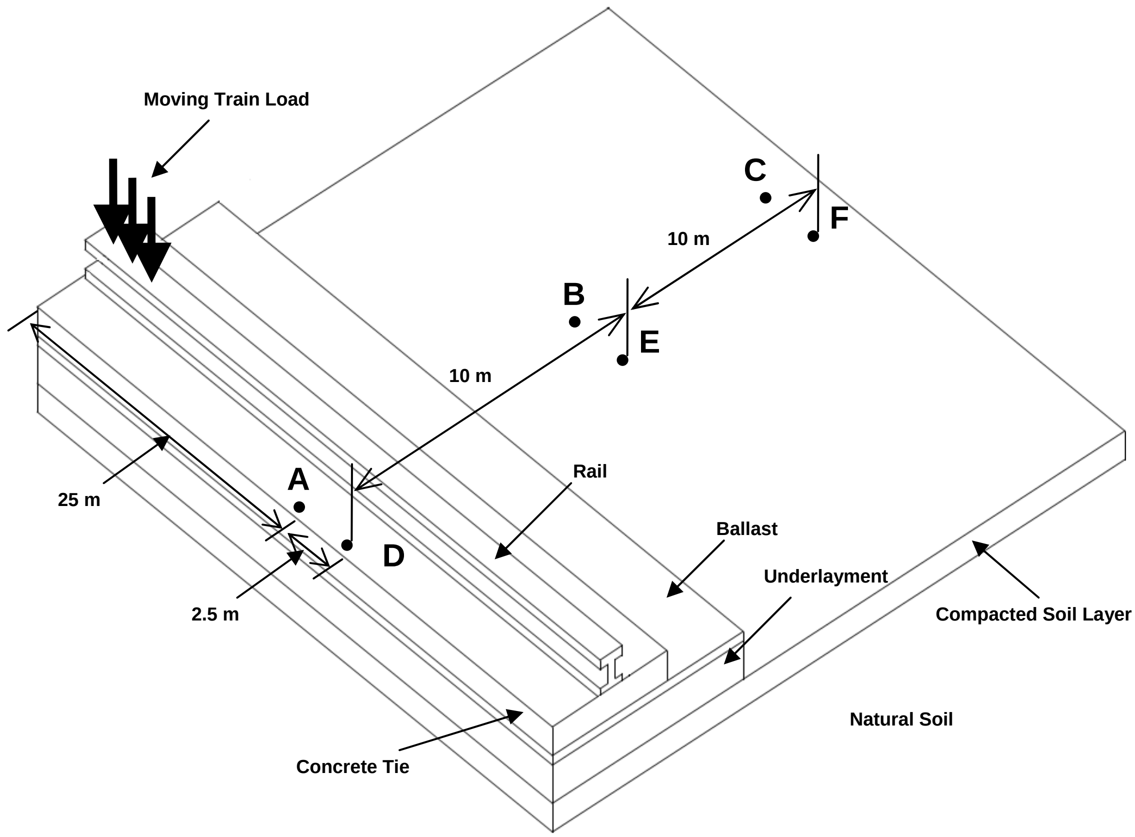


**FIGURE 9 Finite element mesh of high-speed train foundation with monitored locations**

To simulate the loading generated by the passage of a high-speed train, the 50 m long rail was split into ten segments of equal length. Itoh et al. (2003) observed that the sequence of continuous axle loads generated by high-speed trains is similar to dropping a set of weights on the foundation at certain time intervals. Therefore, the passage of a train was modeled as discrete pressure loads moving along each segment of the rail. Each pressure load had a magnitude of 50 kPa; as the pressure was acting over an area 0.75 $m^2$, this corresponds to a force load of 37.5 kN, which corresponds to the weight a 75 kN car would apply to one of its two supporting rails.

The pressure load progressed over the rail, resting on each 5 m long segment of rail for 0.06667 seconds before progressing to the next segment – this corresponds to a velocity of 270 km/hr (168 mph), a typical speed for a contemporary high-speed train. After the dynamic loading, five seconds of no loading were monitored to capture the free vibration response of the system.

In this series of simulations, the four different underlayment materials of RMAC, AC, concrete, and ballast were tested. Four separate runs were made using each material monitoring the six designated points for their acceleration time histories.

To determine the effect of different trains of varying weight traveling over the same track foundation, additional studies were performed by varying the magnitude of the applied pressure load. The 75 kN car applying pressure loads of 50 kPa was taken as an average weight car; a 100 kN car applying pressure loads of 66.667 kPa was simulated to model a heavy car, and a 50 kN car applying pressure loads of 33.333 kPa was simulated to model a light car. The speed of the trains was kept constant, and the same six points were monitored for their acceleration time histories. Two underlayment materials, RMAC and ballast, were simulated to compare their relative vibration attenuating capacities.

Although the typical operating speed of most contemporary high-speed trains is about 270 km/hr (168 mph), high-speed train technology has advanced to the point where trains are able to travel at speeds of 515 km/hr (320 mph). To estimate the effects of trains traveling at higher speeds, a series of simulations was performed varying the time each pressure load spent on each segment of rail. To estimate a train traveling about twice as fast as a typical train (approximately 540 km/hr or 336 mph), simulations were performed using the 50 kPa pressure load magnitude of the 75 kN car resting on each rail segment for 0.03332 seconds before progressing to the next segment. The same six points were monitored for their acceleration time histories, and two different trackbed materials, RMAC and ballast, were used for the trackbed underlayment to compare their relative effectiveness in vibration attenuation.

To gage the effect of increasing the thickness of the trackbed underlayment on vibration attenuation, two more simulations were run. Instead of a 15 cm thick trackbed underlayment, the mesh was modified such that a 30 cm thick underlayment was used. This is twice the thickness used in normal paving applications. Two different materials were used for the modified underlayment, RMAC and ballast. Six points located at approximately the same locations as previously were monitored for their time histories.

### 4.3.2 3D Results and Discussion

*4.3.2.1 Influence of Trackbed Underlayment Materials*

A comparison between acceleration time histories at point A using different underlayment materials can be seen in Figure 10. It can be seen that there are two distinct spikes in all of the acceleration time histories. The first spike at t = 0.267 seconds corresponds to the pressure load impacting the portion of the rail immediately before point A; the second spike at t = 0.4 seconds corresponds to the pressure load leaving the portion of the rail immediately after point A. This is true for all of the acceleration time histories at point A. The forced vibration spans 0.6667 seconds with five seconds of free vibration following.

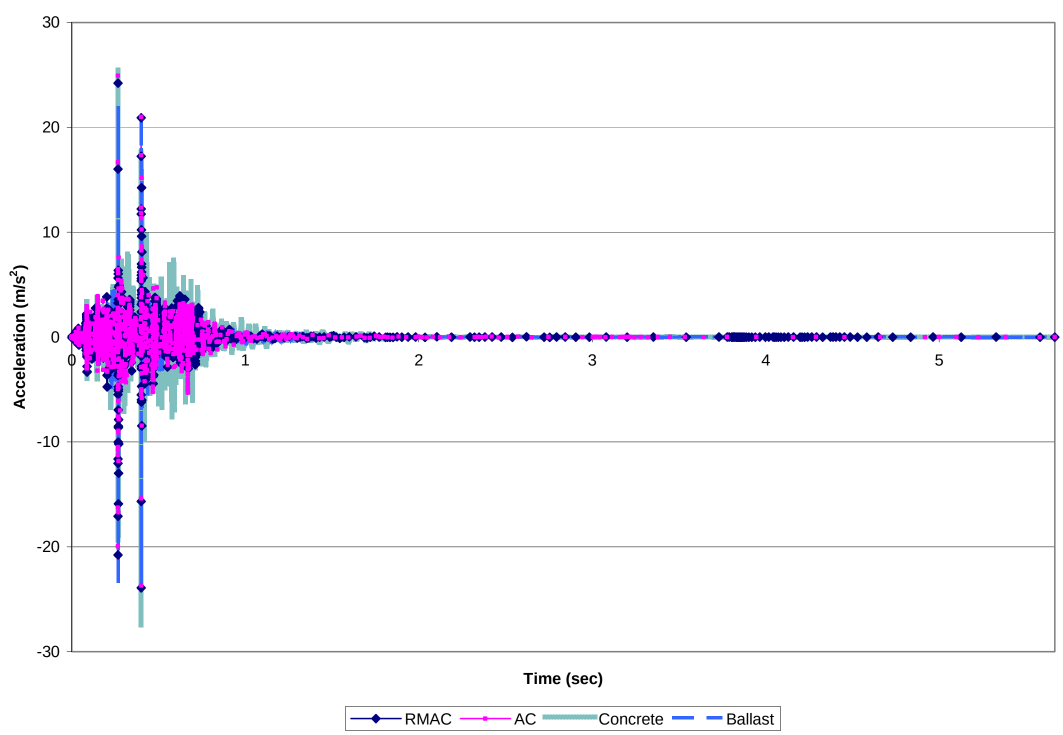


**FIGURE 10 Acceleration time history at point A with various trackbed materials**

TABLE 8 Mechanical properties of materials used in finite element simulations (temperature at 92 degrees F for AC and RMAC)

| Material | Model Type | Density ($kg/m^3$) | Elastic Modulus (Pa) | Poisson's Ratio | Mass Proportional Damping Coefficient α | Cohesion (Pa) | Friction Angle (degrees) | Dilation Angle (degrees) |
|---|---|---|---|---|---|---|---|---|
| RMAC | Linear Elastic | 2378.00 | $2.86 \times 10^{9}$ | 0.30 | 25.00 | N/A | N/A | N/A |
| AC | Linear Elastic | 2378.00 | $2.08 \times 10^{9}$ | 0.30 | 8.00 | N/A | N/A | N/A |
| Concrete | Linear Elastic | 2480.00 | $2.67 \times 10^{10}$ | 0.30 | 1.00 | N/A | N/A | N/A |
| Steel | Linear Elastic | 7850.00 | $2.10 \times 10^{11}$ | 0.30 | 0.125 | N/A | N/A | N/A |
| Ballast | Linear Elastic | 2380.00 | $2.00 \times 10^{7}$ | 0.30 | 0.125 | N/A | N/A | N/A |
| Compacted Soil | Linear Elastic With Mohr-Coulomb Plasticity | 1979.58 | $2.00 \times 10^{7}$ | 0.30 | 0.125 | 1.00 | 41.00 | 20.00 |
| Natural Soil | Linear Elastic With Mohr-Coulomb Plasticity | 1681.28 | $1.30 \times 10^{7}$ | 0.30 | 0.125 | 1.00 | 40.00 | 20.00 |

To gage the relative effectiveness of the different materials for vibration control, the acceleration time histories gathered at each monitored point were analyzed. To quantitatively compare the acceleration responses at each location for the different materials, two measures were chosen: the absolute peak acceleration ($A_{Peak}$) and the root-mean-square acceleration ($A_{RMS}$). The absolute peak acceleration was defined as the largest absolute magnitude of the acceleration time history; the root-mean-square acceleration was defined by:

$$A_{RMS} = \sqrt{\frac{1}{T}\int_0^T a^2(t)\,dt}$$

Where T = Total duration of monitored vibration (sec)
a (t) = The acceleration at time t ($m/s^2$)

Table 9 shows a comparison of the root-mean-square accelerations as well as the peak accelerations at all six points monitored for the four different underlayment materials. We can note that RMAC consistently performs the best of the four materials tested in terms of reducing ground accelerations, especially at locations away from the rail. RMAC consistently reduces the root-mean-square acceleration from the plain ballast case at all locations, reducing it by 47.3% at point F (approximately 20 m away from the track). In contrast, AC and concrete underlayment sometimes worsen the root-mean-square acceleration response from the plain ballast case, resulting in a negative reduction (an increase) in the root-mean-square acceleration; when they do reduce the root-mean-square acceleration, they do not do as well as the RMAC underlayment. Figure 11 graphically represents the root-mean-square accelerations at all locations for all underlayment materials. It can be seen that RMAC consistently results in the lowest root-mean-square accelerations.

In terms of peak accelerations, all of the materials tested actually performed worse than the plain ballast at point A at the track; however, the RMAC underlayment results in an increase of only 1.4% during just one spike, whereas the other materials result in higher increases. At all other locations, using an RMAC underlayment greatly reduces the peak accelerations; at locations B (approximately 10 meters away from the rail) and F (approximately 20 meters away from the rail) in particular, the reduction in peak accelerations is impressive at 47.3% and 50.3%, respectively. The advantage of RMAC in comparison to AC and concrete is much more significant in the 3D simulations than in previously reported 2D simulations. Since 3D simulations are more realistic in comparison to real field situations, its results may be more relevant. As shown in Table 9, there is considerable difference in the vibration between point A and D, point B and E, and point C and F. This is caused by using the 5m loading section to simulate the moving dynamic load, which is the feasible solution right now because of the limitation of computing power. Point A will be right at the corner of the loading section while point D will be at the middle of the section, resulting in the

Table 9 Comparison of root-mean-square and peak accelerations for different trackbed underlayment materials (Note: a negative reduction indicates an increase)

| **Location** | **Material** | $A_{RMS}$ **(m s$^{-2}$)** | **Reduction in $A_{RMS}$ (%) as opposed to a ballast trackbed** | $A_{peak}$ **(m s$^{-2}$)** | **Reduction in $A_{peak}$ (%) as opposed to a ballast trackbed** |
|---|---|---|---|---|---|
| A | Ballast | 0.6262 | -- | 23.888 | -- |
| A | Concrete | 0.9602 | -53.3 | 27.1053 | -13.5 |
| A | AC | 0.6510 | -4.0 | 24.9174 | -4.3 |
| A | RMAC | 0.5542 | 11.5 | 24.2196 | -1.4 |
| B | Ballast | 0.04619 | -- | 0.3441 | -- |
| B | Concrete | 0.03667 | 20.6 | 0.2576 | 25.1 |
| B | AC | 0.03678 | 20.4 | 0.2764 | 19.7 |
| B | RMAC | 0.02916 | 36.9 | 0.1812 | 47.3 |
| C | Ballast | 0.03971 | -- | 0.1968 | -- |
| C | Concrete | 0.04353 | -9.6 | 0.2484 | -26.2 |
| C | AC | 0.04017 | -1.2 | 0.1899 | 3.5 |
| C | RMAC | 0.03471 | 12.6 | 0.1520 | 22.8 |
| D | Ballast | 0.9458 | -- | 48.7119 | -- |
| D | Concrete | 1.0484 | -10.9 | 45.5386 | 6.5 |
| D | AC | 0.9408 | 0.5 | 47.2294 | 3.0 |
| D | RMAC | 0.9047 | 4.3 | 45.3692 | 6.9 |
| E | Ballast | 0.0941 | -- | 0.6537 | -- |
| E | Concrete | 0.0793 | 15.7 | 0.6802 | -4.1 |
| E | AC | 0.0812 | 13.6 | 0.4578 | 30.0 |
| E | RMAC | 0.0683 | 27.4 | 0.4697 | 28.1 |
| F | Ballast | 0.1069 | -- | 0.6127 | -- |
| F | Concrete | 0.0609 | 43.0 | 0.4072 | 33.5 |
| F | AC | 0.0634 | 40.7 | 0.3634 | 40.7 |
| F | RMAC | 0.0563 | 47.3 | 0.3046 | 50.3 |

differences shown in the table. The 3D dynamic simulation requires considerable computing time and the time increases exponentially with the number of elements used. If a finer finite element mesh is used, the difference between A and D is expected to drop significantly.

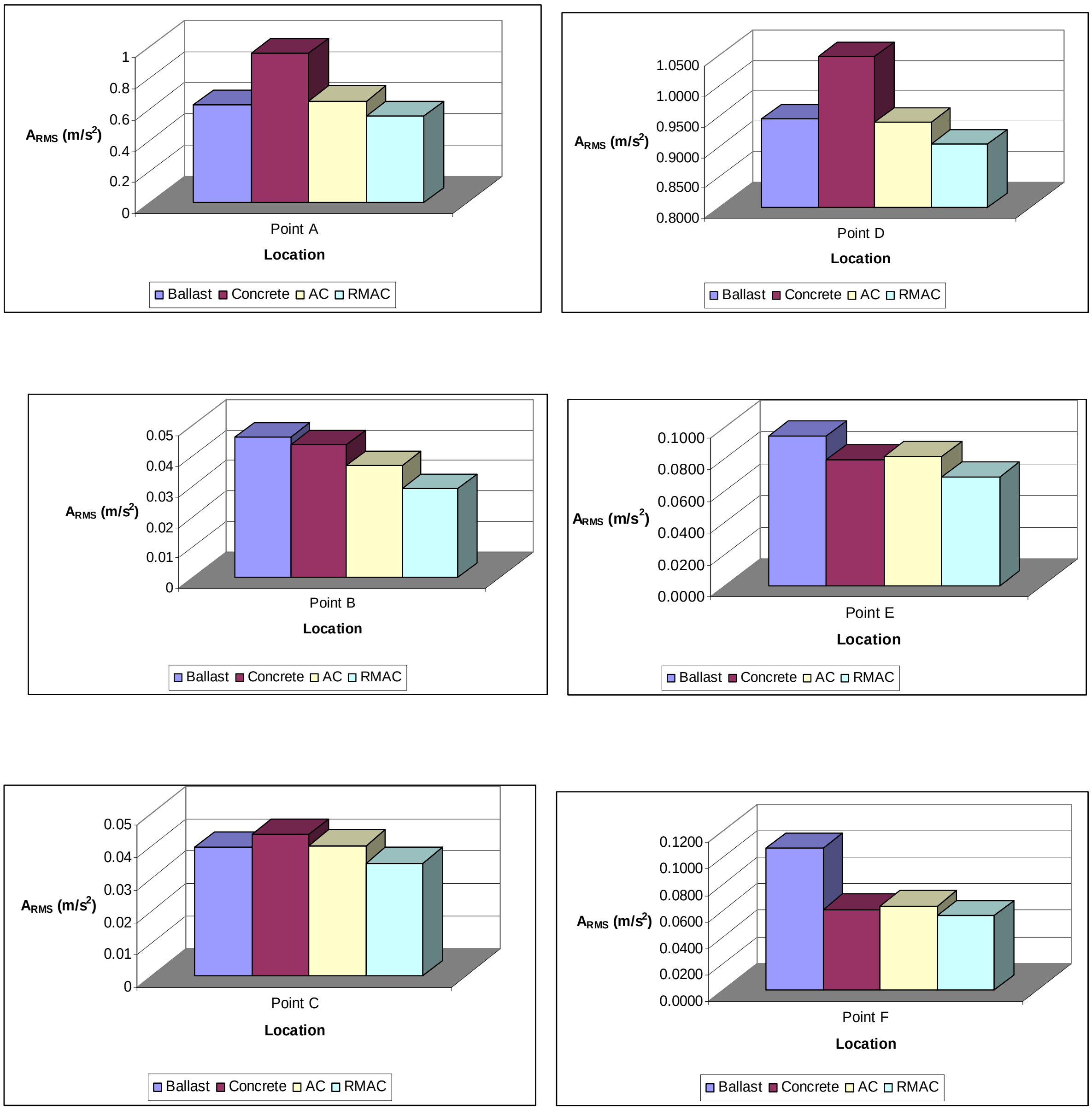


**FIGURE 11 Root-mean-square accelerations at all locations: various underlayment materials**

#### *4.3.2.2 Influence of Load Magnitude*

Table 10 shows a comparison of the root-mean-square and peak accelerations at all locations for RMAC and ballast underlayments under 50 kN cars (light train). Table 11 shows a comparison of the root-mean-square and peak accelerations at all locations for RMAC and ballast underlayments under a 100 kN (heavy) car. It intuitively makes sense that a heavier train would result in a higher acceleration and a lighter train would result in a lower acceleration; this is reflected in the collected data. The accelerations in fact scale almost directly to the magnitude of the loading applied.

It can again be noted that RMAC overall appears to result in a general decrease in the root-mean-square and peak accelerations. The one exception is at location C underneath a 100 kN train loading; there is an increase of 4.9% in root-mean-square acceleration at this point, which may be caused by localization of vibration at that point. However, given its performance at all the other locations in both the 50 kN and 100 kN loading situations, its capacity for vibration reduction is still impressive.

TABLE 10 Comparison of root-mean-square and peak accelerations for RMAC and ballast underlayments underneath a 50 kN loading

| Location | Material | $A_{RMS}$ (m $s^{-2}$) | Reduction in $A_{RMS}$ (%) as opposed to a ballast trackbed | $A_{peak}$ (m $s^{-2}$) | Reduction in $A_{peak}$ (%) as opposed to a ballast trackbed |
|---|---|---|---|---|---|
| A | Ballast | 0.4562 | -- | 16.4531 | -- |
| A | RMAC | 0.3608 | 20.9 | 15.2938 | 7.0 |
| B | Ballast | 0.0344 | -- | 0.2456 | -- |
| B | RMAC | 0.0209 | 39.2 | 0.1133 | 53.9 |
| C | Ballast | 0.0320 | -- | 0.1868 | -- |
| C | RMAC | 0.0256 | 20.0 | 0.1175 | 37.1 |
| D | Ballast | 0.6068 | -- | 31.4368 | -- |
| D | RMAC | 0.5700 | 6.1 | 30.6124 | 2.6 |
| E | Ballast | 0.0763 | -- | 0.5334 | -- |
| E | RMAC | 0.0486 | 36.3 | 0.3219 | 39.7 |
| F | Ballast | 0.0932 | -- | 0.4981 | -- |
| F | RMAC | 0.0387 | 58.5 | 0.2480 | 50.2 |

TABLE 11 Comparison of root-mean-square and peak accelerations for RMAC and ballast underlayments underneath a 100 kN loading

| Location | Material | $A_{RMS}$ (m $s^{-2}$) | Reduction in $A_{RMS}$ (%) as opposed to a ballast trackbed | $A_{peak}$ (m $s^{-2}$) | Reduction in $A_{peak}$ (%) as opposed to a ballast trackbed |
|---|---|---|---|---|---|
| A | Ballast | 0.8376 | -- | 34.6007 | -- |
| A | RMAC | 0.7701 | 8.1 | 33.7450 | 2.5 |
| B | Ballast | 0.0555 | -- | 0.2969 | -- |
| B | RMAC | 0.0390 | 29.7 | 0.2840 | 4.3 |
| C | Ballast | 0.0410 | -- | 0.2592 | -- |
| C | RMAC | 0.0430 | -4.9 | 0.2513 | 3.0 |
| D | Ballast | 1.2340 | -- | 62.1237 | -- |
| D | RMAC | 1.2311 | 0.2 | 62.1044 | 0.0 |
| E | Ballast | 0.1157 | -- | 0.7847 | -- |
| E | RMAC | 0.0887 | 23.3 | 0.6840 | 12.8 |
| F | Ballast | 0.1244 | -- | 0.6671 | -- |
| F | RMAC | 0.0696 | 44.1 | 0.4112 | 38.4 |

*4.3.2.3 Influence of Load (Train) Speed*

Table 12 shows the data for RMAC and ballast underlayments underneath a 75 kN train traveling twice as fast as previously.

In general, the RMAC underlayment outperforms the plain ballast foundation in terms of ground acceleration control away from the rail. Using an RMAC underlayment very effectively reduces the ground accelerations at points C and F, which are approximately 20 meters away from the rail. However, at points A and D, which are located at the rail itself, it can be seen that the root-mean-square accelerations increase with the use of an RMAC underlayment as opposed to a plain ballast underlayment. The effect of the train traveling faster does not appear to drastically affect the magnitudes of the root-mean-square and peak accelerations at the monitored locations, yet it appears to affect the relative performance of the different underlayment materials at the rail itself. At such high-speed (unlikely to occur in the field), the natural frequency of vibration of the track with RMAC underlayment may be approached, resulting in a slight amplification of vibration at the track. This seems to indicate that loading speed is an important design parameter in choosing materials for a very-high-speed rail foundation when considering vibration control directly under the track.

TABLE 12 Comparisons of root-mean-square and peak accelerations for RMAC and ballast underlayments underneath a load traveling at 540 km/hr (336 mph)

| Location | Material | $A_{RMS}$ (m $s^{-2}$) | Reduction in $A_{RMS}$ (%) as opposed to a ballast trackbed | $A_{peak}$ (m $s^{-2}$) | Reduction in $A_{peak}$ (%) as opposed to a ballast trackbed |
|---|---|---|---|---|---|
| A | Ballast | 0.5763 | -- | 24.1729 | -- |
| A | RMAC | 0.6645 | -15.3 | 25.1354 | -4.0 |
| B | Ballast | 0.0472 | -- | 0.2463 | -- |
| B | RMAC | 0.0310 | 34.3 | 0.2871 | -16.6 |
| C | Ballast | 0.0416 | -- | 0.2519 | -- |
| C | RMAC | 0.0271 | 34.9 | 0.1803 | 28.4 |
| D | Ballast | 0.9063 | -- | 45.2412 | -- |
| D | RMAC | 0.9540 | -5.3 | 44.5657 | 1.5 |
| E | Ballast | 0.0822 | -- | 0.6893 | -- |
| E | RMAC | 0.0749 | 8.9 | 0.6833 | 0.9 |
| F | Ballast | 0.0971 | -- | 0.6147 | -- |
| F | RMAC | 0.0646 | 33.5 | 0.4921 | 19.9 |

*4.3.2.4 Influence of Trackbed Underlayment Thickness*

Table 13 shows a comparison between the root-mean-square and peak accelerations when using 30 cm thick ballast and RMAC underlayments.

The results from these simulations indicate that optimizing the thickness of the trackbed is an important factor in design. The magnitudes of the root-mean-square and peak accelerations are on the same order of magnitude as when using a 15 cm underlayment, yet the relative performance of the two materials in vibration control has changed in an unusual fashion. At locations A and B, down the center of the portion of the rail examined, at the track and approximately 10 meters away from the track, respectively, RMAC still outperforms ballast; this is very noticeable at point B especially, where the decrease in the root-mean-square acceleration is approximately 50%. However, at all other locations monitored, the ballast underlayment actually outperforms the RMAC underlayment; a negative reduction (an increase) in both the root-mean-square and peak accelerations can be seen at points C, D, E, and F.

Comparing these results to the results gathered in Table 9 indicates that there is an optimal thickness of the RMAC underlayment for vibration control. The dimensions of the underlayment clearly play a role in attenuating ground accelerations. At 15 cm thick, using an RMAC underlayment has decided advantages over other traditional paving materials; however, when the underlayment is increased to twice its regular size, the benefits of using an RMAC underlayment become less clear.

Table 13 Comparisons of root-mean-square and peak accelerations for 30 cm thick RMAC and ballast underlayments (train speed = 168 mph, weight of car = 75 kN)

| Location | Material | $A_{RMS}$ (m $s^{-2}$) | Reduction in $A_{RMS}$ (%) as opposed to a ballast trackbed | $A_{peak}$ (m $s^{-2}$) | Reduction in $A_{peak}$ (%) as opposed to a ballast trackbed |
|---|---|---|---|---|---|
| A | Ballast | 0.7589 | -- | 25.9326 | -- |
| A | RMAC | 0.7554 | 0.5 | 25.1354 | 3.1 |
| B | Ballast | 0.0441 | -- | 0.2445 | -- |
| B | RMAC | 0.0220 | 50.1 | 0.1578 | 35.5 |
| C | Ballast | 0.0193 | -- | 0.1292 | -- |
| C | RMAC | 0.0206 | -6.7 | 0.1163 | 10.0 |
| D | Ballast | 1.1808 | -- | 45.2728 | -- |
| D | RMAC | 1.1828 | -0.2 | 50.8190 | -12.3 |
| E | Ballast | 0.0473 | -- | 0.2774 | -- |
| E | RMAC | 0.0514 | -8.6 | 0.3495 | -26.0 |
| F | Ballast | 0.0396 | -- | 0.2018 | -- |
| F | RMAC | 0.0423 | -6.9 | 0.2756 | -36.6 |

### 4.3.3 Conclusions From 3D Simulations

From these parametric studies, it can be seen that the use of RMAC in high-speed train foundations has shown promise for vibration control. In this set of finite element simulations, it can be seen that the usage of RMAC as an underlayment material seems to have its most profound effect in vibration control at locations away from the track. This is opposite to what was previously found in the authors' two-dimensional simulations (Wang and Zeng 2004). This may be attributable to the addition of the third dimension; the effect of the load traveling in the out-of-plane, transverse direction instead of being confined within one plane and the ability for energy to dissipate in the out-of-plane direction appear to have had a significant effect in the response of the system. In these three-dimensional simulations, it can be seen that the RMAC underlayment is very effective at reducing vibrations away from the track, a capability not identified in the previous two-dimensional studies. This is highly promising in terms of mitigating the negative environmental impacts high-speed railways may pose in densely populated, urban environments. RMAC in most cases significantly out-performs other trackbed materials such as concrete and asphalt concrete.

These finite element simulations also indicate that a dominant design factor for high-speed railway foundations is the weight of the car passing over the tracks. The variation of the weight of the car had significant effects on the magnitudes of the root-mean-square and peak accelerations, their magnitudes scaling almost directly with the magnitude of the loading. The RMAC underlayment in most cases performed the best of all the materials tested in terms of ground vibration control under these tests.

Conversely, the speed of the loading did not appear to have a significant effect on the magnitudes of the acceleration responses, yet it appears to have a significant effect on the relative performance of the underlayment materials in vibration control at the track. Even though the load was traveling twice as fast as previously, the ground acceleration magnitudes between the two situations did not fluctuate widely. However, at the points monitored directly under the rail, the root-mean-square accelerations using a RMAC underlayment actually increased from the plain ballast foundation situation. This may be due to the relatively high stiffness of the RMAC as opposed to ballast. However, at the points located away from the rail, RMAC still outperformed the plain ballast situation. This indicates that the speed of the traveling train is a very important factor in terms of choosing a foundation material for effective vibration control at the rail structure.

Additionally, the dimensions of the trackbed underlayment are an important factor in design as well. When a typical thickness of 15 centimeters was used for the underlayment, RMAC did very well in terms of mitigating ground accelerations. However, when the thickness was increased to twice the typical depth, the benefits of using an RMAC underlayment became less clear. Again, this may be due to the higher stiffness of RMAC as opposed to ballast. This indicates that optimization studies determining the optimal thickness for maximum ground acceleration control need to be performed. It appears that this optimal thickness is around 15 centimeters, the typical thickness of paving materials; increasing the thickness seems to actually reduce the positive effects of the underlayment.

These parametric studies have interesting implications for design. It can be seen that, when using a typical thickness for the underlayment, RMAC is quite effective in vibration control. It can also be seen that the variation of the load magnitude upon ground accelerations is as intuitively expected; as the weight of the passing train increases, the ground accelerations increase as well, in almost direct proportion. However, the speed of the passing train and the thickness of the underlayment appear to have significant effects upon the relative performances of the underlayment materials. This suggests that these are two key factors in designing a high-speed rail foundation. Further research would be required to investigate different train speeds and to optimize the dimensions of the underlayment to determine the most effective underlayment for various ranges of train speeds.

## V OVERALL CONCLUSIONS

Based on the results of this study, the following conclusions can be drawn:

1) Rubber modified asphalt in general has consistently higher stiffness and damping ratios under a wide variety of temperature and pressure conditions than conventional asphalt concrete, making it a more suitable material for high-speed railways.

2) Roadbeds made with rubber-modified asphalt can reduce the vibrations generated by high-speed trains more significantly than other conventional trackbed materials. Parameters such as temperature, train speed, weight of the train, and thickness of the material all have some influence on the performance of the roadbeds.

3) The results of both the laboratory tests and 3D numerical simulations show that roadbeds made from rubber-modified asphalt can significantly reduce ground vibration generated by high-speed trains at most locations at or near the track.

4) There are some differences between the results of 2D and 3D simulations. In the 2D simulation, the reduction in the vibration due to RMAC trackbed is most significant at the track but less significant away from the track while for 3D simulation it is the opposite. In addition, the rate of reduction is somewhat different too. This is likely due to the fact that in the 3D simulations, energy is allowed to dissipate in the direction of the track; which is more realistic. However, in each type of numerical simulation, assumptions had to be made to simplify the complex field situation. Eventually, the technique requires to be tested in field tests before we adopt it in the construction of future high-speed railways.

The reduced vibration amplitude at the track when using RMAC underlayment has the potential to substantially increase the longevity of the track structure and hence reduce maintenance costs. It would improve riding comfort for passengers. Although not addressed in this study, it could also substantially reduce the intensity of airborne noise generated by high-speed trains. The reduction of vibrations away from the track can reduce the disturbance to local residents as well as to buildings and the instruments and other vibration-sensitive equipment housed in them. However, many simplifications had to be made due to the scope of this project. Further development of this concept would require additional lab tests and simulations to more precisely define the optimum composition and dimensions of RMAC underlayments. This follow-on work would address such issues at more accurate determinations of the relationship between vibration attenuation and such variables as temperature, axle loads, train speeds, material width and thickness, and material composition. Once these relationships have been more precisely defined, field tests should be performed to compare the performance of RMAC with ballast and AC with respect to both vibration and noise reduction.

## VI PLANS FOR IMPLEMENTATION

Based on the results of this study, it is clear that this technique has promising potential for reducing ground vibrations generated by high-speed trains. In addition, RMAC can significantly improve the performance of the track structure. Therefore, this technique should be considered as an attractive option in the construction of new high-speed railways in the future.

Before this technique could be implemented in the field, additional simulations, lab tests and field tests would be required, as described above. The field tests could be conducted using the test tracks at the TTCI in Pueblo, Colorado. A section of roadbed could be built using rubber-modified asphalt and ground vibration and noise at different distance from the track measured as test trains operate over the test section. For comparison, a section of conventional roadbed should be tested and the same measurements taken. By comparing the results of ground vibration and airborne noise, a comprehensive conclusion about the benefits of this technique could be developed.

**INVESTIGATOR PROFILE**

Prof. Zeng in the Department of Civil Engineering at Case Western Reserve University served as the principal investigator for the project. He obtained his B.S. degree in civil engineering at Tsinghua University in China and Ph.D. degree at Cambridge University. He has been working in the area of geotechnical engineering for the past 18 years. Prof. Zeng's research specialties are vibration of foundations, geotechnical earthquake engineering, centrifuge modeling and numerical simulation, and applications of piezoelectric sensors. His research work has been funded by the National Science Foundation, NASA, National Academy of Sciences, Department of Interior, Department of Labor, and Ohio Department of Transportation. He has over 100 refereed journal publications, conference papers, and research reports. He has given more than 50 seminars, invited lectures, and conference presentations.

Prof. Zeng started working on the research topic of potential of rubber-modified asphalt concrete on vibration reduction of high-speed trains while working at University of Kentucky in collaboration with Prof. Rose. The research was funded by CSX Transportation. In 2002, he collaborated with researchers at Tokyo Institute of Technology in conducting centrifuge simulation of the reduction of vibration generated by high-speed trains using different ground improvement techniques. The research work was funded by the Railway Technical Research Institute of Japan. The results were published in a paper by Itoh et al. (2003). Prof. Zeng directed and guided the research reported in this project.

One graduate student, Miss Judith Wang, carried out most of the research work reported here under the guidance of Prof. Zeng. She finished her M.S. degree in 2004 on numerical simulation of vibration reduction of high-speed trains using rubber-modified asphalt concrete. Currently, she is pursuing her Ph.D. degree on the same topic, conducted laboratory tests and 3D numerical simulation. She is a recipient of the prestigious Research Fellowship of the National Science Foundation. She has won numerous academic awards and wants to become a professor after finishing her Ph.D. degree.

**REFERENCES**

N.K. Chopra. *Dynamics of Structures*. Prentice Hall, New Jersey, 1995.

G. Degrande. Free-field vibrations during the passage of a high-speed train: experimental results and numerical predictions. In *Noise and Vibration from High-Speed Trains*, edited by V.V. Krylov, Thomas Telford, London, pp. 285-314, 2001.

J.M. Gere. Mechanics of Materials. Thomson, Brooks/Cole, Belmont, California, 2004.

K. Itoh, X. Zeng, M. Koda, O. Murata, and O. Kusakabe. Centrifuge Simulation of Wave Propagation due to Vertical Vibration on Shallow Foundations and Vibration Attenuation Countermeasures. *Journal of Vibration and Control*, 2005 (in press).

K. Itoh, X. Zeng, O. Murata & O. Kusakabe. Centrifugal Simulation of Vibration Reduction Generated by High-Speed Trains Using Rubber-Modified Asphalt Foundation and EPS Barrier. *International Journal of Physical Modeling in Geotechnics*, Vol.3, No.2, 1-10, 2003.

V.V. Krylov. Noise and Vibration from High-Speed Trains, Thomas Telford Limited, 2001.

S.L. Kramer. Geotechnical Earthquake Engineering. Prentice Hall, 1996.

J.G. Rose. Long-term Performance, Tests, and Evaluation of Asphalt Trackbeds. *Proceedings of American Railway Engineering and Maintenance-of-Way Association Technical Conference*, Chicago, IL, p.27.

J. Wang, X. Zeng, and R. Mullen. Three-Dimensional Simulation of Ground Vibration Generated by High-Speed Trains and Countermeasures. *Journal of Vibration and Control*, 2005 (in review).

J. Wang and X. Zeng. Influence of Temperature, Pressure, and Long-Term Usage on the Dynamic Properties of Rubber-Modified Asphalt. *ASCE Journal of Materials in Civil Engineering*, 2004 (accepted).

J.Wang and X. Zeng. Numerical Simulation of Vibration Attenuation of a High-Speed Train Foundation with Different Trackbed Materials. *Journal of Vibration and Control,* Vol.10, No.8, pp. 1123-1136, 2004.

X. Zeng, J.G. Rose, and J.S. Rice. Stiffness and Damping Ratio of Rubber-Modified Asphalt Mixes: Potential Vibration Attenuation for High-Speed Railway Trackbeds. *Journal of Vibration and Control,* 7(4), pp. 527-538, 2004.