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FINITE ELEMENT ANALYSIS OF CONTROLLED LOW STRENGTH MATERIAL PAVEMENT BASES: FREE VIBRATION ANALYSIS

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This paper presents free vibration analysis of pavement bases constructed using sustainable material, a controlled low-strength material (CLSM), using finite element (FE) method. The CLSM concrete is introduced as pavement bases for its special features of easy compaction, high workability and relatively low cost. Rut-resistant stone matrix asphalt is placed on top of CLSM as wearing surface layer. The Young's moduli of CLSM are obtained from laboratory tests for two different binder mixtures, marked as CLSM-B80/30% and CLSM-B130/30%. Two-dimensional planar strain assumption is employed in the FE formulation of steady-state elasto-dynamic analysis of four-layered flexible pavements in which four kinds of different base materials are considered: graded crushed stone, CLSM-B80/30%, CLSM-B130/30% and AC. Comparison study on computed natural frequencies and mode shapes of the flexible pavement using different bases materials will be conducted. Results show that CLSM pavement bases depict higher natural frequencies as compared with graded crushed stone bases and can be suitable sustainable materials employed for pavement design and construction in highway engineering.

Keywords: CLSM, Finite element method (FEM), Pavement design, Elasto-dynamic analysis, Frequencies, Modes.

1 INTRODUCTION

Recently controlled low-strength material (CLSM) had been widely applied to excavation and backfill problems (Huang *et al*. 2014a, 2014b), bridge abutments (Huang *et al*. 2015a, 2015b), trenched ducts (Huang *et al*. 2016), and especially in the highway engineering (Lin *et al*. 2007). The CLSM is a kind of flowable fill defined as self-compacting cementitious material that has a specified compressive strength of 1200 psi or less at 28 days or is defined as excavatable if the compressive strength is 300 psi or less at 28 days (ACI 2005). However, vehicle loadings are inherently in moving and dynamic types, and thus fully free vibration analysis is required to understand the natural frequencies and mode shapes and further dynamic responses using mode superposition approach.

The paper is aimed at the comparison of frequencies and mode shapes of free vibration analysis of four-layered flexible pavements using different base materials, graded crushed stone, CLSMs of two different binder mixtures (B130/30% and B80/30%), AC, using finite element method.

2 NUMERICAL ANALYSIS OF 4-LAYERED FLEXIBLE PAVEMENTS

2.1 Problem Description

The longitudinal (*xz* plane) and transverse (*yz* plane) cross-sections of a 4-layered flexible pavements with different base materials are shown in Fig. 1(a) and Fig. 1(b), respectively. Different materials in base layer along with all the parameters in all profiles are list in Table 1.

Table 1. Material properties and vertical model dimensions.

Layer #	Materials	Thickness (*mm*)	*E* (*MPa*)	ν	$\rho\,(kg/m^3)$
1 (Surface)	AC	100	2413	0.35	2163
2 (Base)	Graded Crushed Stone CLSM-B80/30% CLSM-B130/30% AC	500	172 270 870 2069	0.40 0.25 0.25 0.35	2003 1695 1800 2163
3 (Sub-grade)	Compacted Soil	300	138	0.45	2003
4(Sub-grade)	Natural Soil	300	55	0.45	1923

The material constants for CLSM-B80/30% and CLSM-B130/30% are obtained from experimental works as explained in Sheen *et al*. (2014).

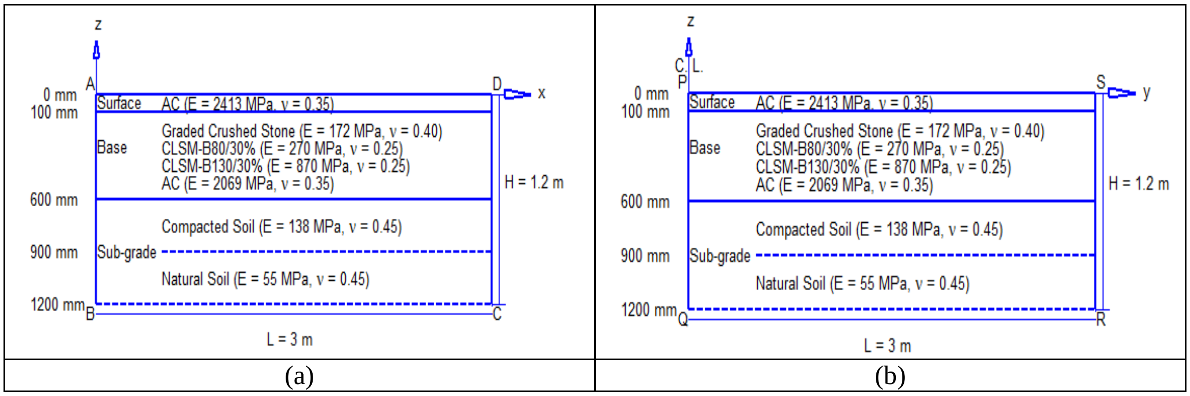

Figure 1. Schematic of cross section of flexible pavements: (a) longitudinal; (b) transverse.

2.2 Finite Element Formulation

The *Q4* finite elements are employed for the frequency and modal analysis; the formulation for the problem can be expressed in matrix form as Logan (2012). Consistent mass matrices are employed in the dynamic equations. Boundary conditions are: hinge supports along *AB, BC, CD, QR*, *RS*, and roller supports along *PQ*. For the longitudinal and transverse analyses, totally $30 \times 24 = 720$ rectangular elements along with $31 \times 25 = 775$ nodes are employed for numerical calculation using program coded in MATLAB. Convergence tests of the program had been conducted for the application to analysis of problem.

3 NUMERICAL RESULTS AND DISCUSSION

3.1 Analysis of Longitudinal Cross Section

The leading 6 natural frequencies and mode shapes for flexible pavements embedded with four different base materials in longitudinal direction are shown in Table 2 and Figures 2-5. We can observe that the relative amplitudes at upper layers of flexible pavements using CLSM (and AC) bases are smaller than that using graded crushed stone base. Based on principle of mode superposition we can expect that the dynamic responses of flexible pavement using CLSM bases will also be smaller than those using graded crush stones.

Table 2. Natural frequencies of four-layered flexible pavement obtained from FEM $(rad/\sec)$.

Mode #	Mode Type	Base Materials			
		Graded Crushed Stone	CLSM-B80/30%	CLSM-B130/30%	AC
1	1st bending	371.4838	402.0727	440.4339	469.0542
2	1st twisting	413.2871	465.8278	584.1890	676.3153
3	2nd twisting	523.6560	581.9905	711.2108	822.1501
4	2nd bending	596.6207	680.9593	834.2543	889.4923
5	3rd twisting	763.8379	848.3831	955.8566	1076.3497
6	3rd bending	778.6987	865.8819	1025.07529	1107.2753

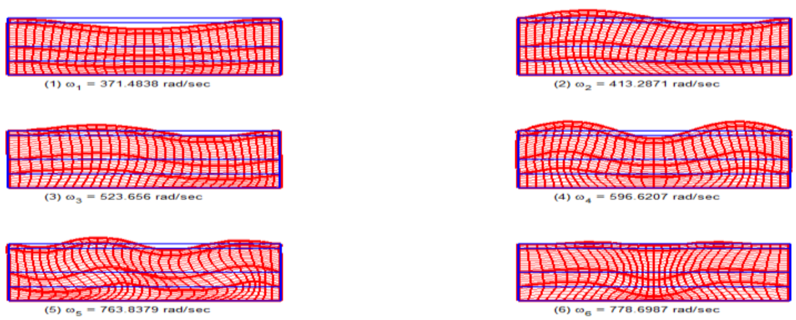

Figure 2. Mode shapes of the first six natural frequencies of four-layered flexible pavement using graded crushed stone base (longitudinal cross section).

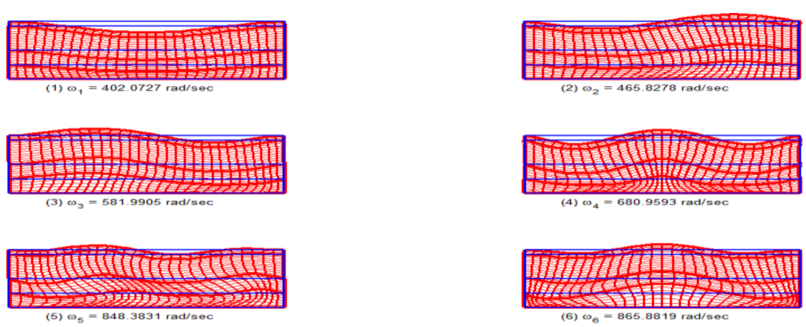

Figure 3. Mode shapes of the first six natural frequencies of four-layered flexible pavement using CLSM-B80/30% base (longitudinal cross section).

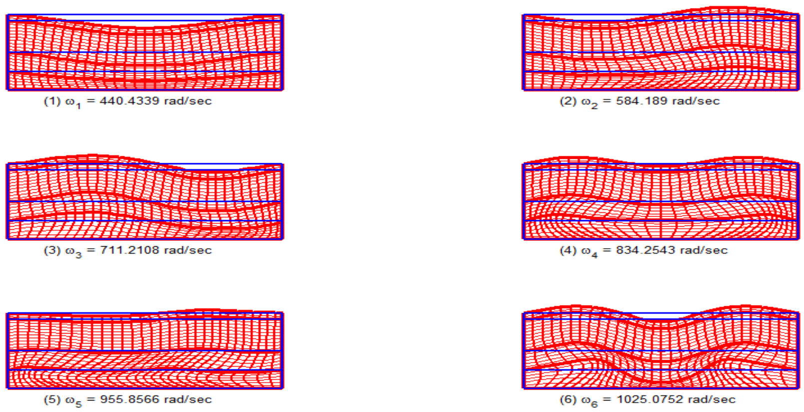

Figure 4. Mode shapes of the first six natural frequencies of four-layered flexible pavement using CLSM-B130/30% base (longitudinal cross section).

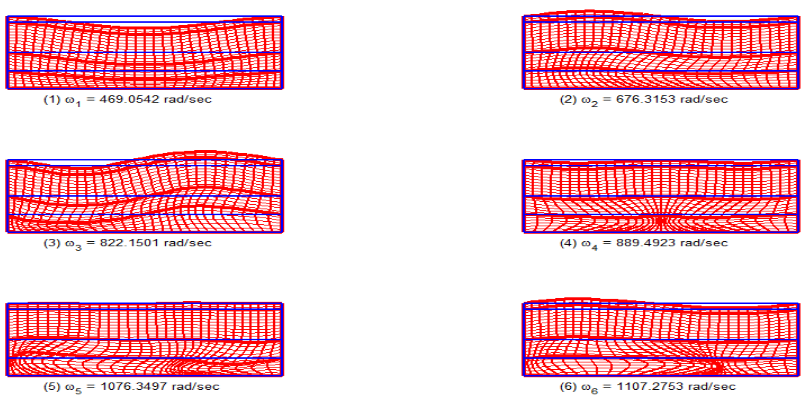

Figure 5. Mode shapes of the first six natural frequencies of four-layered flexible pavement using AC base (longitudinal cross section).

3.2 Analysis of Transverse Cross Section

We then analyze the free vibration for the transverse cross section in order to investigate the characteristics of frequencies and modes using CLSM bases. Table 3 and Figures 6-9 show the leading six natural frequencies, associated mode shapes and kinetic energy contour for the flexible pavements using different base materials. Using CLSM bases seem to reduce the relative amplitudes at the upper layers as compared with that using graded crushed stone base. It is noticed that frequencies of multi-layered flexible pavements are influenced by the combination of density and Young's modulus of each layer. Young's moduli of CLSMs are greater than that of graded crush stone and densities of CLSMs are smaller than that of graded crush stone, both increase the natural frequencies of the flexible pavements.

Table 3. Natural frequencies of four-layered flexible pavement obtained from FEM $(rad/\sec)$.

Mode #	Mode Type	Base Materials			
		Graded Crushed Stone	CLSM-B80/30%	CLSM-B130/30%	AC
1	1st bending	333.9028	357.3373	368.5862	359.5370
2	1st twisting	374.6792	410.5011	470.3886	524.4972
3	2nd twisting	479.1655	533.9787	649.5179	727.5502
4	2nd bending	525.7599	593.5855	743.6153	858.2706
5	3rd twisting	678.3230	777.4126	921.1678	972.3860
6	3rd bending	771.4828	862.6893	956.9743	1078.4588

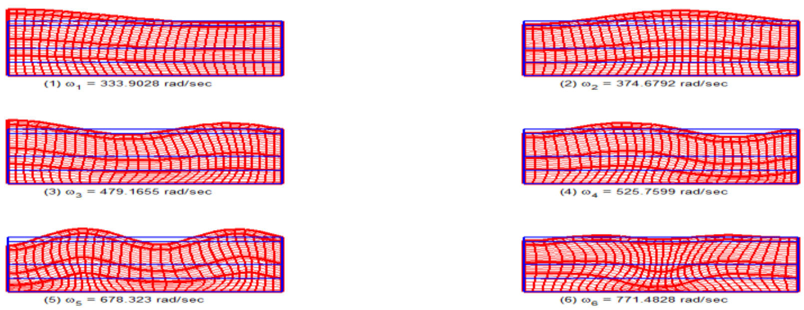

Figure 6. Mode shapes of the first six natural frequencies of four-layered flexible pavement using graded crushed stone base (transverse cross section).

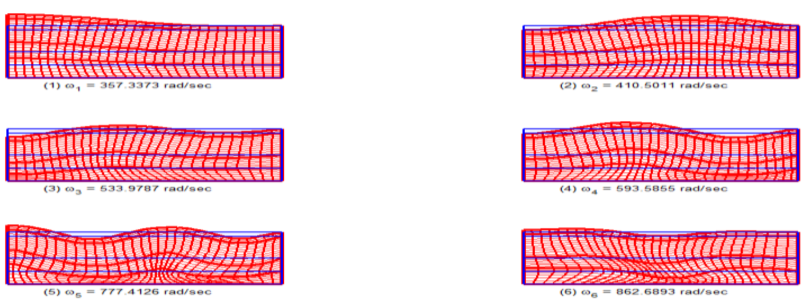

Figure 7. Mode shapes of the first six natural frequencies of four-layered flexible pavement using CLSM-B80/30% base (transverse cross section).

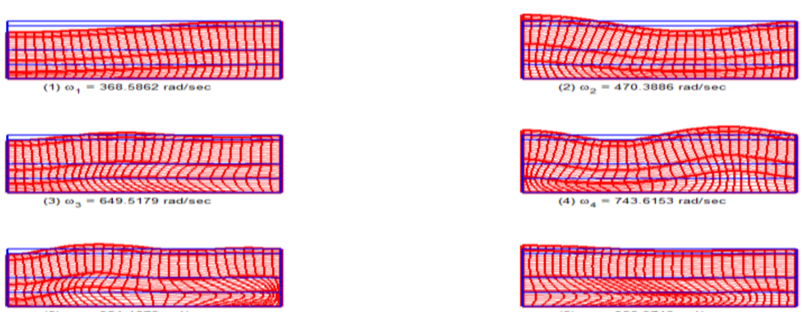

Figure 8. Mode shapes of the first six natural frequencies of four-layered flexible pavement using CLSM-B130/30% base (transverse cross section).

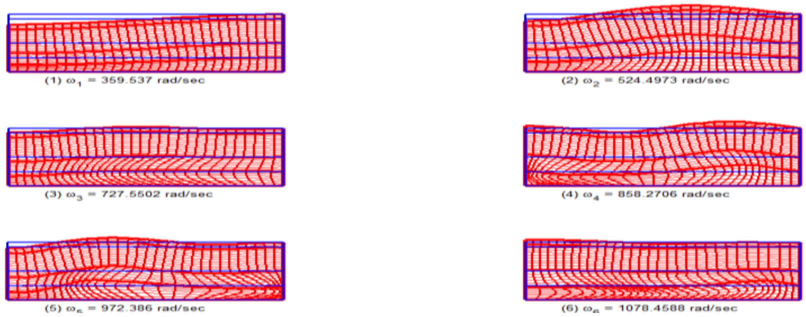

Figure 9. Mode shapes of the first six natural frequencies of four-layered flexible pavement using AC base (transverse cross section).

4 CONCLUDING REMARKS

Natural frequencies and mode shapes of free vibration of 4-layered flexible pavements designed with four different base materials have been fully analyzed using finite element methods. The flexible pavements using CLSM bases made of binder mixture B130/30% as well as B80/30% show to have higher natural frequencies as compared to flexible pavement using graded crushed stone base.

References

ACI-229R, Controlled Low-Strength Materials (Reproved 2005), Farmington Hills (MI) 2005.

Huang L. J., Sheen Y. N., Hsiao D. H. and Le D. H., Numerical Analysis of Excavation Backfilled with Soil-based Controlled Low-Strength Materials: Part I- Static Analysis, *IJETAE*, 4(12), 132-139, December, 2014a.

Huang L. J., Sheen Y. N., Hsiao D. H. and Le D. H., Numerical Analysis of Excavation Backfilled with Soil-based Controlled Low-Strength Materials: Part II- Steady State Elastodynamic Analysis, *IJETAE*, 4(12), 140-148, December, 2014b.

Huang, L. J, Sheen, Y. N., and Le, D. H., Numerical Analysis of Controlled Low Strength Material Bridge Abutments: Part-I: Static Analysis, *The Eighth Structural Engineering and Construction Conference (ISEC-8)*, Sydney, Australia, November 23-28, 2015a.

Huang, L. J., Sheen, Y. N., and Le, D. H., Numerical Analysis of Controlled Low Strength Material Bridge Abutments: Part-II: Steady-state Elasodynamic Analysis, *The Eighth Structural Engineering and Construction Conference (ISEC-8)*, Sydney, Australia, November 23-28, 2015b.

Huang, L. J., Wang H. Y., Sheen Y. N., and Le D. H., Earth Pressure and Settlement Analysis of Trench Ducts Backfilled with Controlled Low Strength Materials, *Procedia Engineering*, 142, 173-180, 2016.

Lin, D. F., Luo, H. L., Wang, H. Y. and Hung, M. J., Successful Application of CLSM on a Weak Pavement Base/Subgrade for Heavy Truck Traffic, *J. Performance of Constructed Facilities*, 70-77, 2007.

Logan, D. L., *A First Course in the Finite Element Method*, Cengage Learning, United States, 2012.

Sheen, Y. N., Huang, L. J. and Le, D. H., Engineering Properties of Controlled Low-Strength Material Made with Residual Soil and Class F Fly Ash, *3rd International Conference for Advanced Materials Design and Mechanics and Workshop on Android Robotics,* Singapore, May 23-24, 2014.