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FINITE ELEMENT ANALYSIS OF CONTROLLED LOW-STRENGTH MATERIAL PAVEMENT BASES: STATIC ANALYSIS

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This paper presents static analysis of pavement bases constructed using sustainable material, a controlled low-strength material (CLSM), using finite element method (FEM). 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 static analysis of the domain with 4-layered flexible pavement with different base materials. Longitudinal and transverse cross sections of pavements are analyzed using 720 rectangular *Q4* elements. Emphasis is put on the settlement at the top surfaces of each layer as well as horizontal and vertical stresses induced by concentrated axle loads or uniform lane loads in longitudinal cross section and concentrated wheel loads in the transverse cross section using different materials for base layers. Numerical results show that the settlement and lateral pressure of CLSM bases are acceptable to assure the applicability of CLSM as a suitable sustainable material employed for pavement bases design and construction.

Keywords: Excavation and backfill, Finite element method (FEM), Pavement design, Sustainable materials.

1 INTRODUCTION

Flexible pavements have been widely employed in highway engineering for a long time and recently an effective rapid pavement construction had been achieved by using the controlled low strength materials (CLSM) (Lin *et al*. 2007, Bassani *et al*. 2015). CLSM is a kind of flowable fill defined as self-compacting cementitious material that is in a flowable state at the initial period of placement and 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). The special features of CLSM include: durable, excavatable, erosion-resistant, self-leveling, rapid curing, flowable around confined spacing, wasting material usage and elimination of compaction labors and equipments, etc. The authors also conducted some preliminary studies on engineering properties of CLSM (Sheen *et al*. 2014, Huang *et al*. 2014a) and the numerical analyses on static and steady state elastodynamic problems of retaining wall with backfilled CLSMs (Huang *et al*. 2014b, 2014c). On the other hands, in the analysis and design of flexible pavements, traditional empirical and mechanics-based approaches were also employed (Huang 1993); recently, 2D and

3D finite elements have been widely applied to pavement analyses (Wang 2001, Kim 2007, Rahman *et al*. 2011).

The paper is aimed at the comparison of static analysis of 4-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

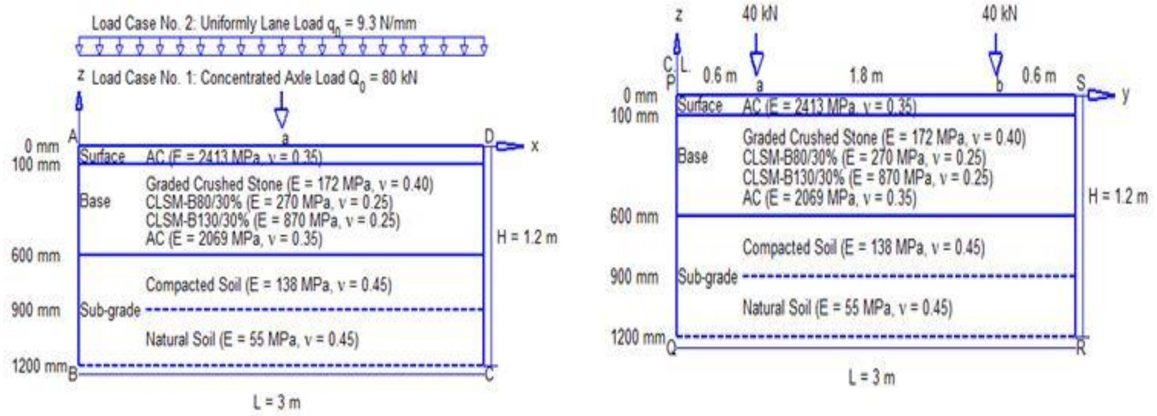
2.1 Problem Description

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

Table 1. Material property and vertical model dimensions.

Layer #	Materials	Thickness (*mm*)	*E* (*MPa*)	ν
1 (Surface)	AC	100	2413	0.35
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
3 (Sub-grade)	Compacted Soil	300	138	0.45
4(Sub-grade)	Natural Soil	300	55	0.45

The material constants for AC, graded crushed stone, compacted soil and natural soil are the same as those employed for typical highway in Taiwan (Chang and Chang 1998). The material constants for CLSM-B80/30% and CLSM-B130/30% are obtained from experimental works as explained in Sheen *et al*. (2014). Selection of materials for the CLSM mixture in this study consisted of fine aggregate, type I Portland cement, stainless steel reducing slag (SSRS), and water. The transient effects such as moving loads and viscoelastic property of asphalt are not included. All the materials are linearly elastic under the assumption of small deformation.



(a) (b)

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

2.2 Loading Conditions

We consider two loading conditions in the analysis of longitudinal cross section:

a) Load Case No. 1: the vertical concentrated axle load, $Q_0 = 80\ kN$ (18,000 *lbs.* for moment). Load Case No. 1 is equivalent single axle load a common AASHTO (1998) HS20 truck.

b) Load Case No. 2: vertical uniform lane Load: $q_0 = 9.3\ N/mm\ (640\ lbs./ft)$. Load Case No. 2 is used to simulate a series of truck-trailer combinations or trucks with tandem axles.

In the traverse cross section analysis two concentrated wheel loads 40 *kN* are considered.

2.3 Finite Element Formulation

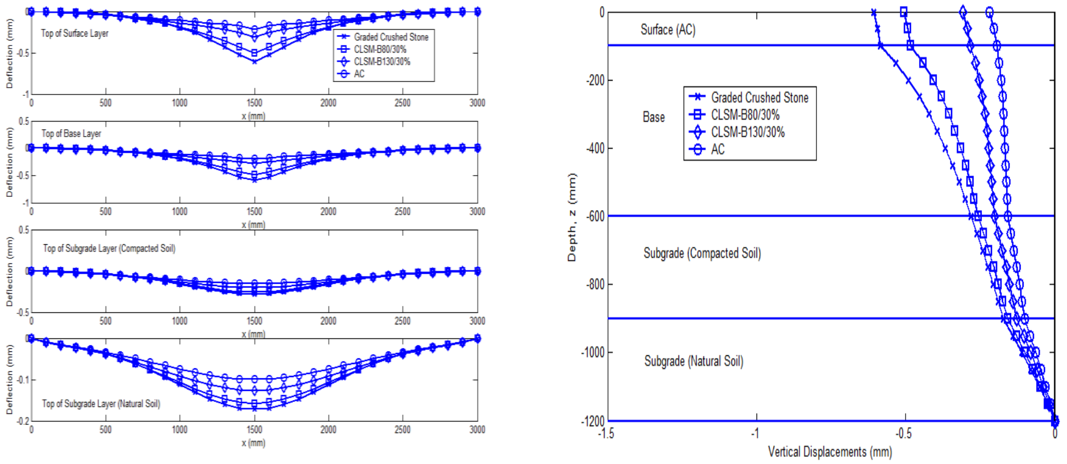
The *Q4* finite elements are selected for the displacement and stress analysis; the FEM formulation can be expressed in matrix form as Logan (2012). Boundary conditions are: hinge supports along *AB*, *BC*, *CD*, *QR*, *RS*, and roller supports along *PQ*. For the longitudinal and transverse analyses, respectively, totally $30 \times 24 = 720$ rectangular elements along with $31 \times 25 = 775$ nodes are employed for numerical calculation using program developed and coded in MATLAB.

3 NUMERICAL RESULTS AND DISCUSSION

3.1 Analysis of Longitudinal Cross Section

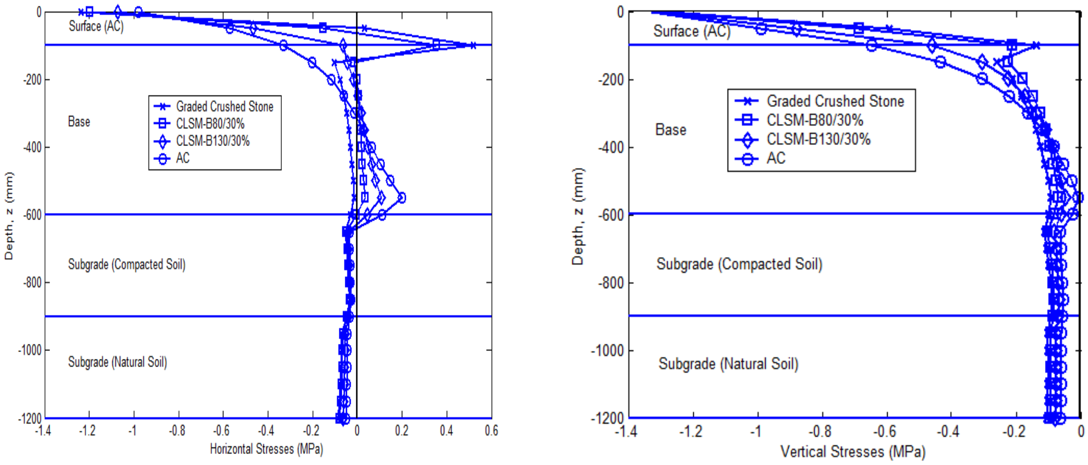
3.1.1 *Load case No. 1 (concentrated axle load)*

Figure 2(a) and 2(b) shows the numerical prediction of settlements at top surface of each layer and vertical displacements at the centerline of concentrated loading, respectively. Pavements using two kinds of CLSM bases depict settlements smaller than graded crushed stone base as expected. In Figure 3(a) and 3(b) we can observe the predicted horizontal and vertical stress distributions at the centerline of loading using different base materials. The stress levels are nearly the same order of magnitude.



(a) (b)

Figure 2. Predicted vertical deflections (a) at top surface of each layer; (b) at the centerline of loading.

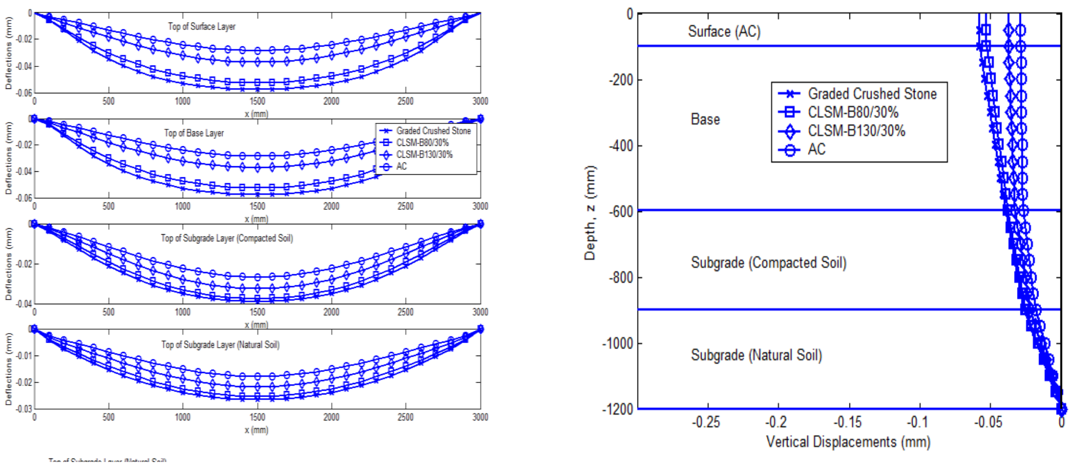


(a) (b)

Figure 3. Predicted distributions at the centerline of loading: (a) horizontal stresses (b) vertical stresses.

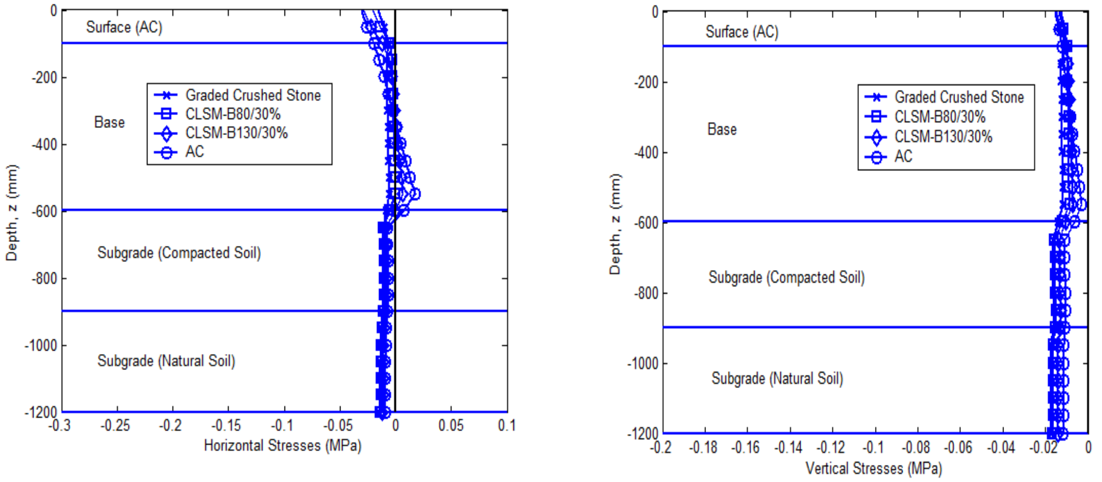
3.1.2 *Load case No. 2 (uniform lane load)*

Figure 4(a) and 4(b) shows the numerical prediction of settlements at top surface of each layer and vertical displacements at the centerline of uniform lane loading, respectively, considering different materials used in the base layer. Pavements using CLSM bases depict settlements smaller than graded crushed stone base and keep the same order of magnitude of predicted horizontal and vertical stress distributions at the centerline of loading as shown in Figure 5(a) and 5(b).



(a) (b)

Figure 4. (a) Predicted vertical deflections at top surface of each layer; (b) Predicted vertical displacement distributions at the centerline of loading.

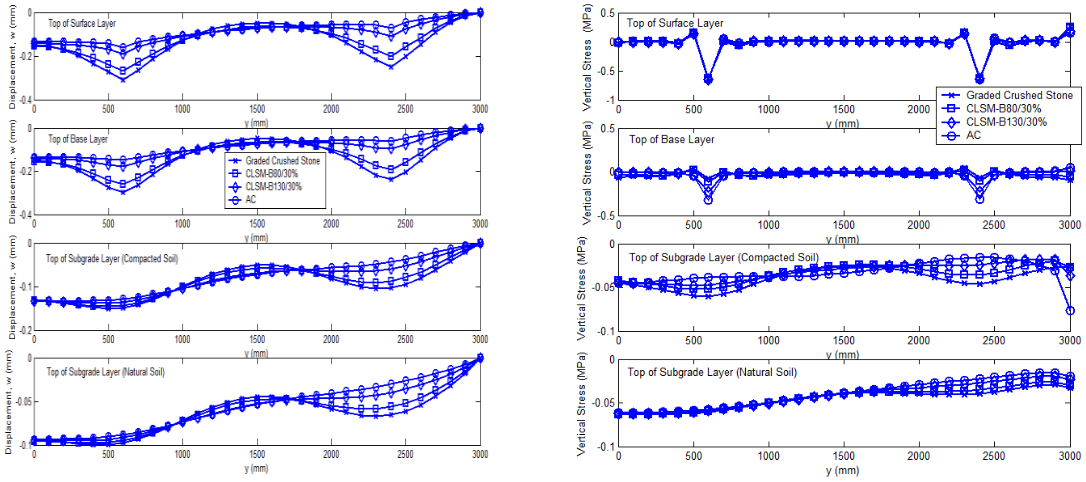


(a) (b)

Figure 5. Predicted distributions at the centerline of loading: (a) horizontal stresses (b) vertical stresses

3.2 Analysis of Transverse Cross Section

We then analyze the displacement and stress fields for the transverse cross section in order to investigate the characteristics of rutting reduction using CLSM bases. Figure 6(a) and 6(b) shows the predicted settlements and vertical stresses at top surface of each layer. Using CLSM bases seem to reduce the potential of rutting occurs at the surface layer as compared with that using graded crushed stone base.



(a) (b)

Figure 6. (a) Predicted vertical deflections at top surface of each layer; (b) Predicted horizontal stress distributions along wall.

4 CONCLUDING REMARKS

Numerical results of 4-layered flexible pavements using four different base materials analyzed using FEM show that maximal displacements at top surface of each layer using CLSMs are smaller than those using graded crushed stone base while keeping within the same level of horizontal and vertical stresses. Consideration of displacements and stresses in finite element analyses of both longitudinal and transverse cross section of 4-layered flexible pavements using different base materials, subjected to concentrated axle/uniform lane and concentrated wheel loads, CLSM-B130/30% and CLSM-B80/30% show to be good materials employed as base substitutes for graded crushed stone in flexible pavement design.

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