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Effect of Surface Layer Thickness on the Performance of Lime and Cement Treated Aggregate Surfaced Roads

Ehsan Yaghoubi

M.Sc. of Road and Transportation Engineering,
Iran University of Science and Technology, Tehran, Iran
e-mail: ehsanmnm@yahoo.com

Omid Azadegan

Ph.D. Student of Geotechnical Engineering,
Shahid Bahonar University of Kerman, Iran
e-mail: omid_azadegan@yahoo.com

Jie Li

Senior Lecturer, School of Civil, Environmental and Chemical Engineering, RMIT University, Melbourne, Australia
e-mail: jie.li@rmit.edu.au

ABSTRACT

A gravel layer of adequate thickness, laid over a subgrade, forms the most basic structure of aggregate surfaced roads. Since the pavement system of such roads consists of only a base layer, the thickness of this layer has considerable effects on the performance of the roads. In this study, both laboratory experiments and finite element analysis were conducted to evaluate the performance of lime and cement treated base layers with different thicknesses. To achieve this, five types of lime and cement treated mixtures were defined, three of which were chosen and modelled as base layers with different thicknesses using the finite element software, *PLAXIS*. The *PLAXIS* models were then loaded, analysed and compared by vertical deformation under a specific load as well as the maximum applicable load. Analytical and numerical modelling of the lime and cement treated soils requires a number of soil parameters that are usually obtained from expensive and time-consuming laboratory experiments. An alternative method was proposed in this study, in which the soil parameters required for the finite element analysis were obtained from unconfined compressive strength tests, and estimated using the failure criteria available in existing literature. Results of this study showed that an increase in the base layer thickness leads to a reduction in the vertical deformation of the pavement system under a specific load; however, the increase in the thickness of the base layer does not necessarily result in the increase in bearing capacity of the pavement system.

KEYWORDS: Base layer thickness, stabilization, finite element modelling, deformation, collapse load.

INTRODUCTION

Soil stabilization is the process of blending and mixing materials with a soil to improve soil's physical and chemical properties. It has been used for many years to improve the characteristics of the subgrades with problematic soils. Pavements with stabilized base and subbase layers have also been proven to deliver better performance during their service life [1]. In addition to that, stabilization often results in the reduction of the required pavement thickness; for instance, a research carried out on lime stabilization of an expansive subgrade soil, showed that the application of lime decreased the required thickness of the pavement by about 50-60% compared to the thickness required for a pavement over an untreated subgrade soil [2]. Another research conducted on five construction sites, in Oklahoma, where the subgrade soils were stabilised with cement kiln dust and Class C fly ash, revealed improved resilient modulus values ranging from 7 to 46 times larger than those of the untreated soil, resulting in a reduction in the required pavement thickness over these subgrades [3].

Unpaved roads have stone aggregate layers placed directly above soil subgrades, and that are generally surfaced with sandy gravels for reasonable ride-ability; thus the granular layer serves as a base and a wearing course at the same time [4]. Since these types of roads consist of only one pavement layer, i.e., the base course, the thickness of this layer can have considerable effects on the performance of such roads. Further to this, since stabilization normally improves the strength and bearing capacity of base layers, application of this technique may change the required thickness of pavement in stabilized aggregate surfaced roads.

The main objective of this research is to evaluate the behaviour of lime and cement treated base layers with different thicknesses in unpaved roads. Full scale laboratory simulations seem almost inappropriate for small projects because they are time consuming, labour-intensive and very costly. A combination of laboratory experiments and computer simulations have been considered in recent years to diminish the full scale modelling disadvantages [5, 6], which will also be used in this study. This study consists of two main parts: (1) the laboratory experiments; (2) the numerical simulation of different base courses over the same subgrade using finite element method to evaluate their performance under different loads. The strength parameters of the treated materials, used in the numerical simulation, were estimated by application of estimating functions proposed by Sharma et al. [7].

LITERATURE REVIEW

Unpaved roads, such as gravel surfaced roads, are referred to as low-type surfaces because they usually serve low traffic volumes. The basic structure of gravel roads consists of a gravel layer of adequate quality and thickness, overlying the subgrade. The basic principle in the thickness design of gravel roads is to provide an adequate thickness based on traffic volume and the strength of the subgrade, such that the stress reaching the subgrade does not exceed the in-place strength of the subgrade [8]. In other words, sufficient thickness is needed, so that traffic-induced loads are adequately distributed and stresses on the subgrade can be tolerated [9]. For most conditions, a minimum of 100 to 150 mm of gravel is required; however, the thickness of new aggregate-surfaced roads typically ranges from 150 to 375 mm [8].

There have been researches that investigate the performance of base layers with different thicknesses in pavements. A research was completed in the National Airport Pavement Test Facility (New Jersey), which investigated the effects of variable granular subbase thicknesses on the structural responses of flexible airport pavement test sections subjected to heavy aircraft gear loading. Results of the research showed that test sections with lower subbase thicknesses showed higher Heavy Weight Deflectometer (HWD), maximum surface deflections and higher computed subgrade deviator stress. However, an increase in the subbase thickness did not reduce the deviator stress in the pavement; moreover, test sections with lower subbase thicknesses showed higher levels of early life rut depth development [10]. Another research was carried out to investigate the performance of reinforced recycled materials as base course with different thicknesses, in comparison with unreinforced base course. The experimental results indicated the proposed materials with thicknesses of 0.15, 0.23, and 0.30 m improved the life of pavement section by factors of 6.4, 3.6, and 19.4 respectively at a permanent deformation of 75 mm as compared with the 0.30 m thick unreinforced section at the same permanent deformation [11]. An analysis of load stress in asphalt pavement over lean concrete base revealed that the stress in base course decreased with an increase in base thickness. Furthermore, an increase in the thickness of the base resulted in the decrease in the maximum shear stress [12].

In spite of the fact that thick granular bases are believed to result in higher and uniform structural support, it can also lead to high initial investment; hence, it can make a project uneconomical. The exception is for some environment conditions, such as cold weather with the possibility of freeze and thaw zones, in which case the performance benefits must overcome the extra initial costs of a thick base and results in longer term economic benefits [13]. However, it should be noted that a thicker base layer does not necessarily result in higher bearing capacity of the pavement. Results of a research on bearing capacity of unpaved roads with different thicknesses showed that increases in the base layer thickness do not increase the bearing capacity of the given pavement system [14].

Therefore, it can be concluded from the abovementioned literature that constructing thicker base layers does not necessarily result in better performance of the pavement. As a result, this research has been proposed to investigate the effect of thickness on the performance of the lime and cement treated base layers in unpaved roads.

EXPERIMENT PROGRAM

A laboratory investigation was carried out to obtain the mechanical properties of the stabilized granular soils. A well-graded gravel with maximum particle size of 19 mm, have been stabilized with five different proportion of lime and cement admixtures to form bounded materials with a variety of mechanical characteristics. Three samples were produced for each different design mixes and unconfined compressive tests were conducted on each sample after a curing time of seven weeks.

Materials

Aggregates

Well graded gravel has been selected as the base course in the models. Its particle distribution boundaries proposed by ASTM, make it an ideal gradation. A maximum particle size of 19 mm was selected for gravel. The particle distribution curve of the applied material is illustrated in Figure 1.

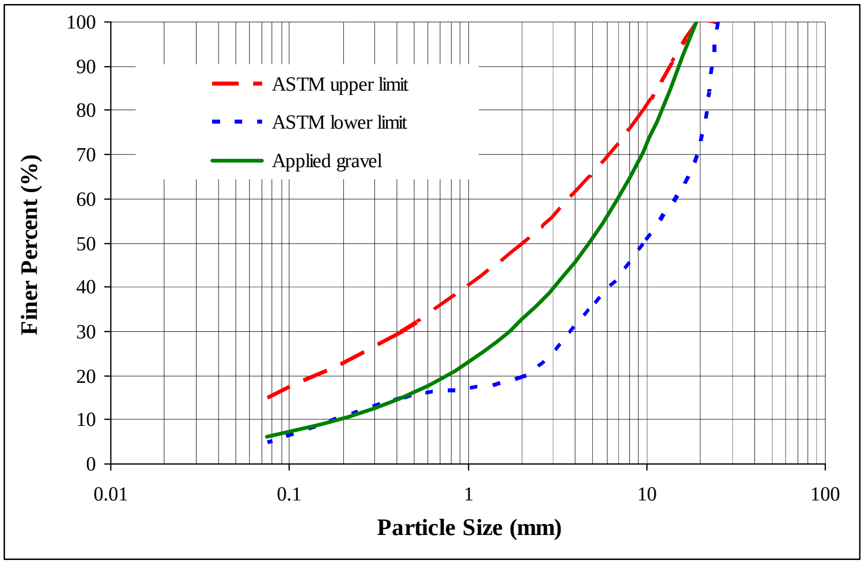

Figure 1: The particles distribution curve of the applied gravel in comparison with provisions of ASTM

Cement

Portland cement type II was used as the basic stabilizing agent to produce the main structural strength. Its resistance against mild acidic attacks has made this type of cement a favourable one, in previous stabilizing projects, and ideal to this research.

Lime

In order to make the stabilized material more resistant to harmful acidic environmental effects and achieving more ductile behaviour, High Calcium Hydrated Lime ($Ca(OH)_2$) was also mixed with the applied cement. This material is a more practical version of lime, due to its fine particle size, which makes the mixture procedure, and the chemical reactions, easier and less time consuming.

Mixture Types

Five mix designs were determined for gravel materials. Table 1 presents the properties of these mixtures. The amounts of optimum water content, w_{opt}, used in preparation of the samples, were obtained from the modified compaction tests according to ASTM D 698-78.

Table 1: Cement, lime and moisture contents of the mixture types

Mixture Type	Cement Ratio (%)	Lime Ratio (%)	Moisture Content (%)
G-1	4.5	6.8	9.4
G-2	4.5	5.6	8.9
G-3	4.5	4.5	8.2
G-4	5.6	6.8	9.6
G-5	5.6	4.5	8.9

Preparing Test Specimens

Three standard cylindrical samples, 10 cm in diameter and 20 cm in height, were produced for unconfined compressive tests for each mix design (Figure 2). Samples were compacted in five layers by the maximum possible compaction energy to reach homogenous samples in elevation [15]. The amount of applied energy for each sample's compaction was about 1124.2 N.m, which was attained by numerous compaction tests [16]. The compacted samples were submerged in water for seven weeks at room temperature before undergoing the unconfined compressive tests.

Figure 2: Specimens' curing at room temperature

Unconfined Compressive Tests

The unconfined compressive tests were carried out on cured samples according to ASTM C39-86. The curing time of seven weeks has been selected so as to drastically reduce any noticeable change in the samples' strength. The unconfined compressive tests were conducted on each sample, from which the ultimate compressive strength, failure strain, and the unconfined elastic modulus (*E*) were extracted and collated in Table 2.

Table 2: Summary of unconfined compressive tests' results

Mixture Type	Average Compressive Strength (kN/m^2)	Average Ultimate Strain (mm/mm)	Average Modulus of Elasticity (kN/m^2)
G-1	4163	0.0107	387485
G-2	4649	0.0135	342694
G-3	5395	0.0102	524628
G-4	5646	0.009	627434
G-5	6822	0.009	756274

THE ESTIMATING RELATIONS

In order to use the results of soil improvement in finite element simulations, the strength parameters of the stabilized soil, cohesion and friction angle must be firstly determined by application of estimating relations. Different failure criteria have been presented for cemented and brittle materials [17-20] which can be used in approximating strength parameters. In a recent research it was concluded that the non-linear failure criterion presented by Sharma et al. has a good compatibility with the treated materials of this research [21]; hence, these relations were used as the estimating relations. The estimating relations of Sharma et al. [7] are described subsequently.

The non-linear failure criterion for weakly cemented sand, Eq. (1), is attained by means of triaxial shear tests:

$$\tau = P_a(0.115\frac{q_u}{P_a}+1.242)(\frac{\sigma+0.035q_u}{P_a})^n \quad (1)$$

where, τ is the shear strength, q_u, P_a and σ are differential axial pressure, atmospheric pressure and confining pressure (in kPa) respectively. n varies from 0.5 to 1.0 and must be calibrated for different soil types.

When the amount of σ is reduced to zero (unconfined compressive test), the amount of τ equals to the amount of real cohesion of materials (C_r):

$$C_r = P_a(0.115\frac{q_u}{P_a}+1.242)(\frac{0.035q_u}{P_a})^n \quad (2)$$

And the tangent friction angel (ϕ_t) at any arbitrary confining pressure of σ is calculated by following relation:

$$\tan(\phi_t) = \frac{(0.115\frac{q_u}{P_a}+1.242)^n}{(\frac{\sigma+0.035q_u}{P_a})^{1-n}} \quad (3)$$

In this research, the cohesion and friction angle of the mixtures are determined by the application of the estimating relations of Sharma et al [7].

FINITE ELEMENT SIMULATION

Model Geometry

Finite element simulations for each mix design were carried out using a commercial finite element analysis (FEA) package, namely, PLAXIS 8.2. In order to generate the models, the properties, like elastic modulus and dry density, were extracted from laboratory tests, and strength parameters such as the cohesion and the internal friction angle were attained by implying the compressive strength in failure criterion presented by Sharma et al., as explained in the previous section. The latter parameters are presented in Table 3.

Plastic analysis on an axis symmetric soil body comprised of 0.15, 0.20, 0.30, 0.35 and 0.40 m stabilized gravel as base layer laid on a soft clay subgrade material with total dimensions of 5 m (height) by 3 m (diameter), was performed with the special characteristics of each mix design. Figure 3 demonstrates the geometry of the models with a 20 cm thickness of base, together with the applied meshing system. In order to obtain more precise results, the upper 0.60 meters of all models are set to have finer meshes.

In the final stage of the research, a total of 15 finite element models (three mix designs and 5 different thicknesses for each) were generated and analysed, the results of which will be discussed in the "Results and Discussion" section.

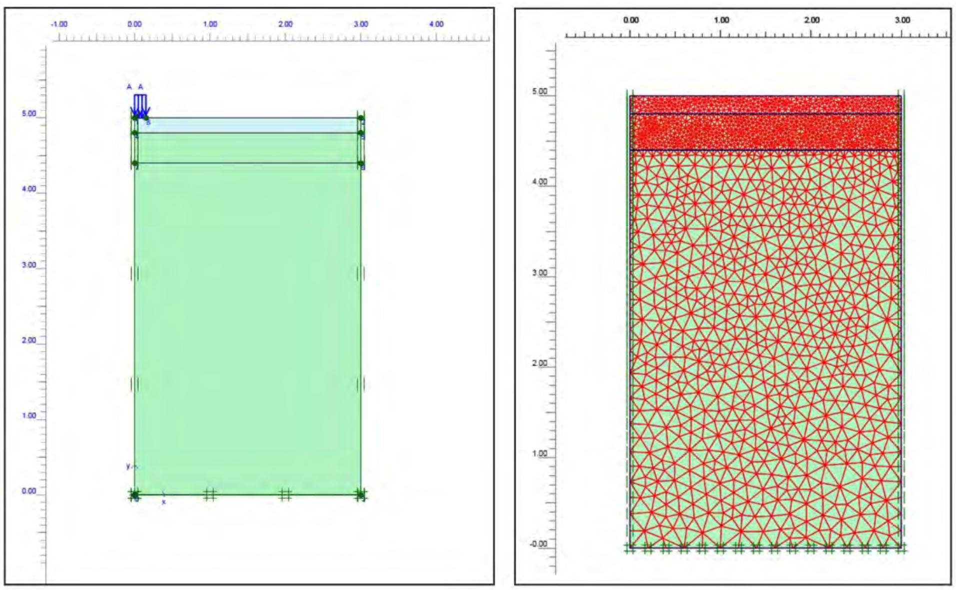

Figure 3: Finite element analysis: model geometry (left), mesh generation (right)

Geotechnical Properties of Subgrade and Base Layer

In a recently published paper by the same authors of this research it was revealed that on a soft clay subgrade, both vertical deformation and collapse load of the mixtures decreased with an increase in their modulus of elasticity [22]. As a result, three of the five defined mixtures were selected to be modelled as the base layer on a soft clay subgrade, namely G-1 (the mixture with the lowest *E*), G-5 (the mixture with the highest *E*) and G-3 (a mixture with an *E* between the lowest and highest amounts of *E*).

The modulus of elasticity (*E*) of the mixture types was obtained by the unconfined compressive tests and has already been presented in Table 2. In order to obtain the cohesions and friction angles of the mixture types, Eq. (1) to Eq. (3) are applied. The calculation process and discussions are available in detail in Azadegan et al [21]. Table 3 presents the estimated amounts of cohesion and friction angles that are assigned to the base materials in the finite element models.

Table 3: Estimated amounts of cohesions and friction angels

Mixture Type	C (kPa)	ϕ (degrees)	*n*
G-1	727.89	44.04	0.5
G-3	1090.23	44.17	0.6
G-5	1531.83	47.33	0.6

In Table 3, "n" denotes the applied power in non-linear failure criterion, which led to more proper simulation results [21].

The properties of the subgrade soil that is used in the finite element models, namely soft clay, are presented in Table 4.

Table 4: Soft clay subgrade soil properties applied in the finite element models [23]

C (kN/m2)	ϕ (degree)	E (kN/m^2)	Poison's Ratio
100	20	32000	0.25

Loading

The contact pressure at the interface of the tyre and the pavement is important for the determination of the structural response of the pavement. For flexible pavement design, commonly a circular contact area with the diameter that equals the tyre width is used [24]. In this research a 12.00R24 tyre type, which is one of the most commonly used tyres for straight trucks, was taken to calculate the contact pressure and the contact area. Normally, these tyres are produced with a width greater than 255 mm. In this research, the width of the tyre, which is also the diameter of the contact circular area, was taken as 300 mm.

Based on a Permanent International Association of Road Congress (PIARC) publication [25], the rear axle maximum allowable load of 3 axle straight trucks ranges between 8 and 28 tonnes in different countries of the world; however, in the majority of the countries, this axle load is 18 tonnes. Taking 18 tones as the axle load and considering the fact that the rear axle of a 3 axle straight truck is a dual tandem axle that consists of 8 tyres (8 circular contact areas), the contact pressure of one tyre is estimated to be approximately 320 kPa.

Aside from the mentioned contact pressure, a number of loads are applied to the PLAXIS models to investigate the behaviour of the pavement systems under different contact pressures, and to determine the collapse load in each model.

RESULTS AND DISCUSSION

This study has been carried out to investigate the effect of the base layer thickness on the performance of lime and cement treated gravel surfaced roads. To this end, 15 finite element models were generated and run in the final stage of the research. Finally, the results of the analysis are discussed from two aspects: vertical deformation under a specific load, and the bearing capacity (maximum applicable load), simply stated as the collapse load.

Vertical Deformation under a Specific Load

In this research, the specific load applied on the models was taken to be 320 kPa, as discussed in the “Loading” section. Figure 4 illustrates the maximum vertical deformation of the 15 models (5 thicknesses for each mixture type) at the centre of the load contact area. Based on this Figure, the following points can be discussed.

Firstly, as it was predicted, a greater modulus of elasticity (according to Table 2) results in lower deformation under the same load. As a result, having the same thickness, G-1 models have the greatest and G-5 models have the lowest vertical deformation. In other words, the G-1 mix design has the lowest stiffness, while the G-5 mix design has the greatest stiffness.

Secondly, in all the mix designs under the same load, an increase in the base layer thickness results in a lower vertical deformation. In this research, all the models consist of a treated gravel layer placed directly on the subgrade, i.e. a two-layer pavement system. Structurally, gravel surfaced roads function as flexible pavements [8]. In such flexible pavement systems, the vertical deformation is a function of E_b/E_s and h/a, where, E_b is the modulus of elasticity of the surface layer (in this case a treated base layer), E_s is the modulus of elasticity of the subgrade, h is the thickness of the surface layer, and a is the radius of the circular contact area [26]. Since for each of the mix designs “E_b”, “E_s”, and “a” are constants, an increase in the thickness (h) results in lower vertical deformation under the same load.

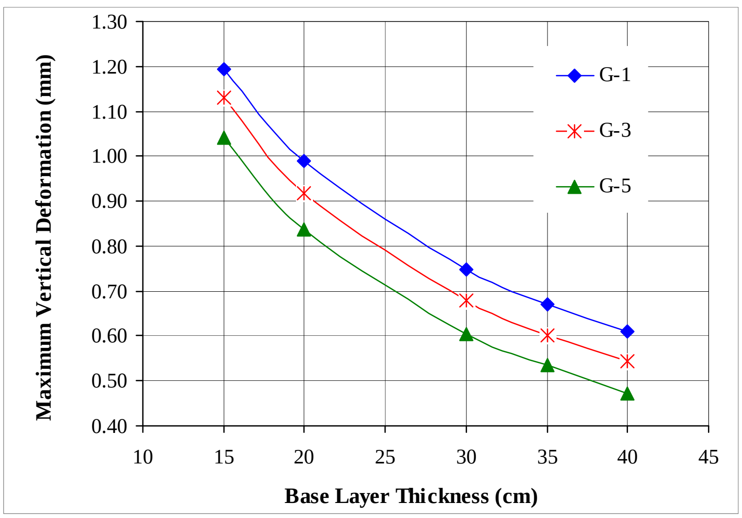

Figure 4: Maximum vertical deformation of the mixture types with different thicknesses under a contact pressure of 320 kPa

The Collapse Load

Figure 5 illustrates the maximum applicable load that can be applied to each model before it collapses, simply mentioned as the collapse load, together with the corresponding modulus of elasticity. The results that are presented in form of a graph in Figure 5 can be discussed from two angles.

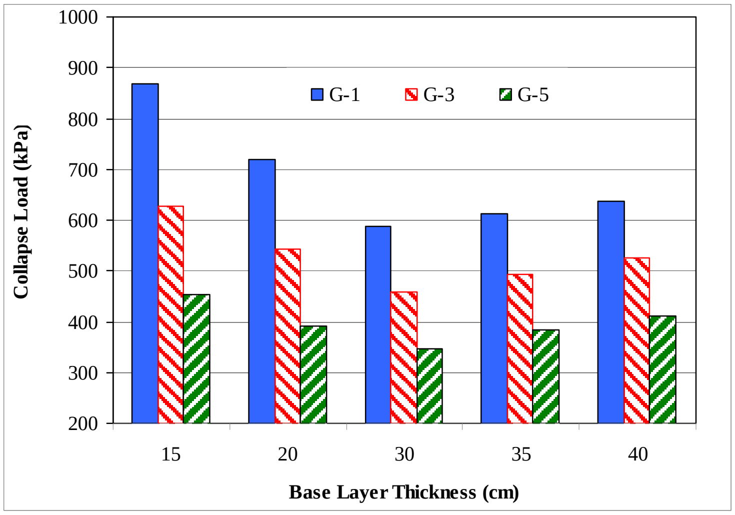

Figure 5: Collapse loads of the mixtures with different thicknesses.

Firstly, it is revealed that for the same thickness, models with the G-5 mixture (the mix design with the greatest stiffness) presented the lowest collapse load, while models with G-1 (the mix design with the lowest stiffness) showed the greatest bearing capacity. A detailed reasoning and discussion regarding the previous statement is available in a recently published paper by the same authors of this research [22]. In the same mentioned paper, it was finally concluded that, the stress distribution through the depth of the subgrade is highly dependent on the difference between the stiffness of the base layer and the subgrade. If the stiffness ratio of base/subgrade is high, a great proportion of the energy will be absorbed by the base layer, and the contact pressure will be concentrated in a limited zone under the tyre and base layer interface instead of being distributed into its depth. This limited stress zone of a stiff pavement layer can lead to a premature destruction due to fatigue stress. As a result, in spite of the fact that G-5 has the lowest deformation under the load of 320 kN/m^2 and possesses the greatest E among the other mixtures, it presented the lowest bearing capacity. However, it should be noted that a reduction in the stiffness leads to greater static deformations that appear in long time, such as the rutting distress.

Figure 5 also shows that the maximum applicable load (collapse load) decreases at first by increasing the thickness of the base layer, and increases again by increasing the thickness from 0.30 m to 0.4 m. As a result, the increase in the thickness of the base layer does not necessarily result in the increase in the collapse load. This is discussed in the following paragraphs.

As an example, the development of the plastic points at the collapse loads of the G-5 models with the thicknesses of 0.15, 0.30 and 0.40 m are extracted from PLAXIS outputs and presented in Figure 6. The plastic points are the stress points in a plastic state. Normally, two types of plastic points are defined: tension cut-off point and Mohr-Coulomb point. Tension cut-off point indicates that the tension cut-off criterion was applied to the integration point [27]. In PLAXIS, white plastic points indicate that the tension cut-off criterion was applied. Figure 6 shows that with a thickness of 0.15 m, the plastic points are distributed uniformly in the cross section of the base layer; hence, no stress concentration occurs. In addition to that, the subgrade contributes properly in resistance to the loads. Consequently, this model presents the greatest collapse load among other models. In contrast, with a thickness of 30 cm, the plastic points are not distributed uniformly; hence, stress concentration occurs, and the subgrade has a limited contribution to the load bearing. Consequently, the lowest collapse load belongs to this model. With the thickness of 0.4 m, the uniformity of the distribution of the plastic loads increases again, and in spite of the subgrade possessing limited contribution in resistance to loads, the base layer is thick enough to present a higher bearing capacity compared to the 0.3 m models.

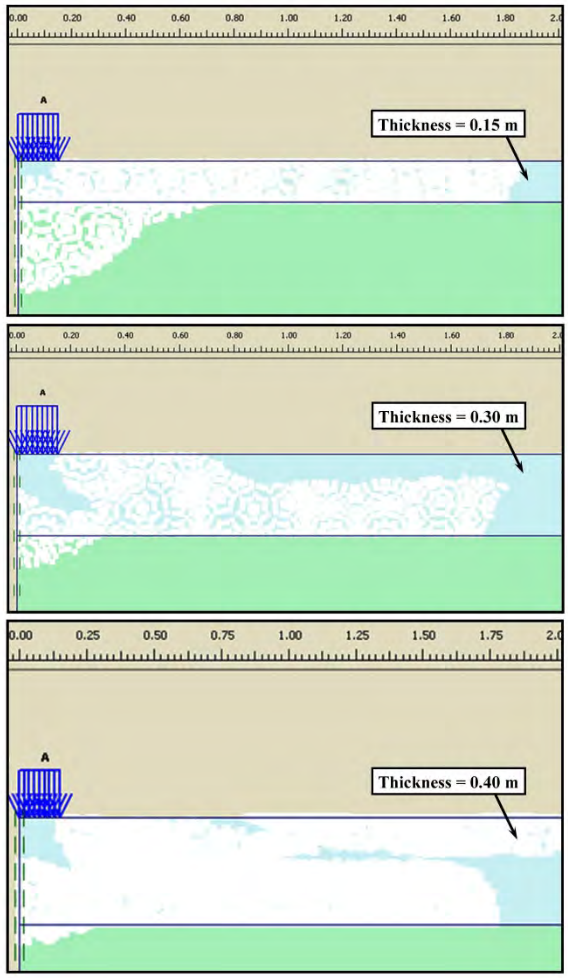

Figure 6: Distribution of the plastic points in the G-5 models with different thicknesses.

CONCLUSIONS

In this research, the performance of three types of gravel surfaced pavement systems with different thicknesses over a soft clay subgrade soils was investigated. To this end, five mixture types were defined to produce compressive test specimens, three of which were selected for the final finite element simulation. Since performing comprehensive laboratory experiments on stabilized soils to obtain all parameters required for finite element simulations are very time consuming and expensive, hence almost impossible for small projects, the required characteristics of stabilized soils were estimated by performing unconfined compressive tests and applying the non-linear failure criterion proposed by Sharma et al. The estimated material properties were then assigned in the PLAXIS 8.2 models to compare the vertical deformations of the 15 pavement models under a specific load, and to determine the maximum bearing capacity of each. Based on the obtained results, the following points are derived:

• For the same material, the increase in the base layer, results in the reduction of the vertical deformation of the pavement system under a specific load.

• The correspondence of the base and the subgrade should be noted, since a great difference in stiffness of the two layers can cause a great reduction in the bearing capacity of the pavement system.

• The increase in the thickness of the base layer does not necessarily result in the increase in the bearing capacity of the pavement system, since it may result in stress concentration in the base layer and reduce the contribution of the subgrade in resistance to the loads.

Finally, based on the findings of this research, a finite element simulation is recommended to evaluate the designed thickness of the base layer, in order to avoid the construction of a pavement with a thickness that results in the lowest bearing capacity.

REFERENCES

[1] O'Flaherty C.A., 2002, "Highways-The Location, Design, Construction and Maintenance of Pavements - Chapter 6", 4th Edition, Butterworth and Heinemann, p 163.

[2] Adam, A.A.M., Ibrahim, I.A., Alhardllo, A.J., Hadi, A.M., and Ibrahim, M.Y., 2012, "Effect of Hydrated Lime on Behavior of Expansive Soil as Subgrade of Flexible Pavement Structural System", Proceeding of Second International Conference on Sustainable Construction Materials: Design, Performance, and Application, Wuhan, China.

[3] Pinilla J. D., Miller, G. A., Cerato, A. B., Snethen, D. S., 2011, "Influence of Curing Time on the Resilient Modulus of Chemically Stabilized Soils", Geotechnical Testing Journal (ASTM), Vol. 34 (4), ISSN 0149-6115, pp. 364-372.

[4] Shukla, S. K. and Yin, J. H., 2006, "Fundamentals of Geosynthetic Engineering - Chapter 4", 5th Edition, Taylor & Francis Group, LLC, London, UK, ISBN10 0–415–39444–9, p 117.

[5] Gueddouda, M.K., I. Goual, M. Lamara, A. Smaida and B. Mekarta, 2011, "Chemical Stabilization of Expansive Clays from Algeria", Global Journal of researches in engineering (J: General Engineering), Vol. 11(5), pp. 1-8.

[6] Arroyo, M., Ciantia, M., Castellanza, R., Gens, A., and Nova, R., (2012), "Simulation of Cement-Improved Clay Structures With a Bonded Elasto-Plastic Model: A Practical Approach", Computers and Geotechnics, 45, 140–150.

[7] Ravi Sharma, M.S., Baxter, C.D.P., Huffman, W., Moran, K. And Vaziri, H., (2011), "Characterization of Weakly Cemented Sands Using Nonlinear Failure Envelopes", International Journal of Rock Mechanics and Mining Science, 48(1), pp 146-151.

[8] Beckemeyer, C. A. and McPeak, T. J., 1995, “Rural Road Design, Maintenance, and Rehabilitation Guide”, South Dakota Department of Transportation, Report No. SD95-16-G2, p 11 and 22.

[9] Mishra, D., Tutumluer, E., and Heckel, G., 2012, “Performance Evaluation of Uncrushed Aggregates in Unsurfaced Road Applications through Accelerated Pavement Testing”, Transportation Research Record: Journal of the Transportation Research Board, Vol. 2282/2012, ISSN 0361-1981, pp 67-78.

[10] Gopalakrishnan, K., and Thompson, M. R., 2008, “Effect of Granular Subbase Thickness on Airfield Pavement Structural Response”, Journal of Materials in Civil Engineering, Vol. 20 (5), ISSN 0899-1561, pp 331-342.

[11] Thakura, J. K., Hana, J., Pokharel, S. K., Parsons, R., L., 2012, “Performance of geocell-reinforced recycled asphalt pavement (RAP) bases over weak subgrade under cyclic plate loading”, Geotextiles & Geomembranes (Elsevier), Vol. 35, ISSN 0899-1561, pp 14-24.

[12] Lijun, S., and Xinwu, W., 2012, “Analysis of Load Stress for Asphalt Pavement of Lean Concrete Base”, Physics Procedia (Elsevier), Vol. 24 (A), pp 404-411.

[13] Beck, R., Yu, B., and Green, R., 2010, “The Performance and Economic Benefits of Thick Granular Base for Flexible Pavement Design in Frost Susceptible Regions”, Proceedings of GeoShanghai International Conference 2010, Shanghai, China.

[14] Oloo, S.Y., Fredlund, D.G., and Gan, J.K.M., 1997, “Bearing Capacity of Unpaved Roads”, Canadian Geotechnical Journal, Vol. 34 (3), pp 398-407.

[15] Ladd, R. S., 1978, “Preparing Test Specimens Using Undercompaction”, Geotechnical Testing Journal, GTJODJ, Vol. 1, No. 1, March 1978, pp 16–23.

[16] Azadegan, O. Jafari, S.H., and Li, J., 2012, “Compaction Characteristics and Mechnical Properties of Lime/Cement Treated Granular Soils”, Electronic Journal of Geotechnical Engineering (EJGE), Vol 17(P), pp 2275-2284.

[17] Hegermier, G.A., and Read, H.E., 1985, “On Deformation and Failure of Brittle Solids: Some Outstanding Issues”, Mechanics of Materials 4 (1985), pp. 215-259.

[18] Boswell, L. F., and Chen, Z., 1987, “A General Failure Criterion for Plain Concrete”, International Journal of Solid Structures, Vol. 23 (5), pp 621-630.

[19] Chiu, C.F., W. Zhu and C.L. Zhang, 2008, “Yielding and shear behaviour of cement-treated dredged materials”, Engineering Geology, Vol. 103, pp 1-12.

[20] Jan, G.M., van Mier, 2008, “Framework for a generalized four-stage fracture model of cement-based materials”, Engineering Fracture Mechanics, Vol. 75, pp 5072–5086.

[21] Azadegan, O., Li, J., and Jaffari, S.H., 2013, “Estimation of Strength Parameters and Finite Element simulation of Lime and Cement Stabilized Granular Soils”, Advanced Materials Research, Vol. 681, pp 276-280.

[22] Azadegan, O., Yaghoubi, E., and Li, J., 2012, “Evaluation of the Performance of Lime and Cement Treated Base Layers in Unpaved Roads”, Electronic Journal of Geotechnical Engineering (EJGE), Vol 18(D), pp 647-660.

[23] Bowles, J. E., 1982, Foundation analysis and design, fifth edition, The McGraw-Hill companies, pp 15-112.

[24] Mallik, R. B., and El-Korchi T., 2009, "Pavement Engineering: Principles and Practice - Chapter 5", Taylor & Francis Group, Boca Raton, USA, ISBN987–1–4200–6029–4, p 65.

[25] Technical Committee 19 Freight Transport, 2004, "Vehicle Size and Weight Limits - Experiences and Trends", Permanent International Association of Road Congresses (PIARC), ISBN 2-84060-170-2.

[26] Huang. Y. H., 2004, "Pavement Analysis and Design – Chapter 2", Pearson Prentice Hall, NJ, USA, ISBN 0-13-142473- 4, pp 57-60.

[27] CNA Consulting Engineers, 2009, "NCHRP Report 647-Appendix A: 3-D Numerical Analysis of Live Load Distribution: Soil Constitutive Models, Load Factoring and Comparison with Field Measurements", Transportation Research Board, Washington, D.C., pp 97-98.
(Available @ http://www.trb.org/main/blurbs/163515.aspx)