Kathford Journal of Engineering and Management, *ISSN: 2661-6106.*

https://kathford.edu.np/Journal/

VOL. 2 ISSUE 1 AUGUST 2020, pp. 1-16

Cement Stabilization of soft soil subgrade and Cost Analysis

Harish Paneru*[,1], Mohan Prasad Acharya[2] and Indra Prasad Acharya[3]
[1,3]Department of Civil Engineering, Pulchowk Campus, Institute of Engineering, Tribhuvan University, Kathmandu, Nepal
[2]NEA Engineering Company LTD., Kathmandu, Nepal

*Corresponding author: *paneruh@gmail.com*

ABSTRACT–The soft soil when present in subgrade creates a lot of problem in highways. Due to soft soil subgrade, the rutting is predominant cause of flexible pavement failure all around the world. This kind of soil is either replaced or modified prior to construction of other layers of road to minimize the formation of rut. This study deals with stabilization of soft soil subgrade by cement. The sample was collected from a depth around existing road subgrade. A series of laboratory tests on untreated soil sample was first done to determine the competency of soil as a subgrade layer followed by preparation of sample with varying stabilizer content i.e. 4%, 6% and 8% cement by weight of dry soil, to determine the optimum stabilizer content. Samples with varying cement content were also prepared for California Bearing Ratio (hereafter, CBR) and Unconfined Compressive Strength (hereafter, UCS)with different curing periods i.e. 7 days for CBR and 3, 7, 14 and 28 days for UCS. UCS test on these sample showed a significant improvement over the values of natural soil without stabilizer. CBR showed a similar trend and the resulting modified soil was competent enough to be used as a subgrade for heavy traffic condition. The pavement was modelled using Kenpave for 30 and 50 million standard axle (msa) traffic intensity to determine the ideal pavement section for two types of pavement used in this study. In addition, the cost of construction for replacement method and for cement stabilization are determined using norms of Department of Road and District rate of Kathmandu and are compared. The cement stabilized soil with optimum content is found to be cheaper than conventional method of replacement.

KEYWORDS– Soft soil subgrade, Cement stabilization, Capping layer, Kenpave, Pavement design, Highway economics

1. INTRODUCTION

The population of Kathmandu valley is more than 2.5 million. It is increasing day to day due to internal migration of people (Central Bureau of Statistics, Nepal). With this increase in population, need for well-planned and integrated transportation system is necessary as the previously planned facilities are deemed to be insufficient for the bigger population. To make things worse, the existing facilities are very much affected by the characteristics of soil found in Kathmandu valley. The Kathmandu valley sits on ancient dried up lake. The major soil deposits in valley are lacustrine deposits (kalimati clay) and fluvio deltaic deposits [1]. The fluvio lacustrine deposits in Kathmandu valley is known for its high swell potential, low shear strength and highly compressibility nature. Due to its insufficient bearing capacity, low shear strength and excessive settlements; civil structures such as pavements, walkways, roads, foundations, channel lining etc. possess a high risk of failure. The effects of soft soil as a foundation can be seen as permanent settlement of pavement along the wheel path of vehicle [2]. The major problem associated with soft soil subgrade is that road built over these soil require frequent maintenance and overlay [3].

Presently, the practice of road construction in Kathmandu involves use of capping layer as replacement for soft soil or use of rigid pavement. Despite cement stabilization being one of the most researched topic, it has been hardly used in construction of road in Kathmandu. This study is focused on stabilization of a soft soil found in Kathmandu valley with cement and analyze the pavement constructed on it in terms of structural design and cost with comparison to the road constructed with conventional method of replacement with capping layer. The flexible pavement as shown in figure 1, consists of 4 layers. Out of these subgrade acts as a foundation layer for the whole pavement structure so it has to be strong and stable enough to transfer the traffic load safely without significant deformation. Presence of soft soil in this layers can lead to subgrade rutting. Subgrade rutting occurs when the subgrade exhibits wheel path depressions due to loading. These depression may appear in longitudinal or transverse direction. In this case, the pavement settles into the subgrade ruts causing surface depressions in the wheel path [4].These soils are either replaced or chemical stabilization is done to improve the Insitu properties of soil. This study has been conducted in two parts. First part involved natural soil characterization and cement stabilization of natural soil followed by second part involving modelling of cross section of roads for traffic intensity of 30 million standard axle (hereafter, msa) and 50 msa and determination of construction cost of pavement cross section optimized through models.

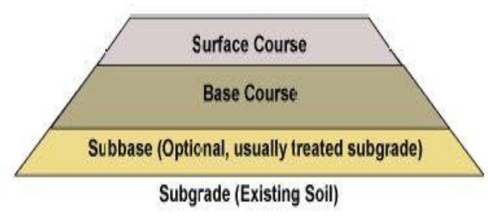


Figure 1. Typical Cross section of Flexible pavement

Chemical stabilization is defined as any treatment or method whereby a chemical is used to either change the soil properties and thereby increase the bearing capacity of the soil layer or increase the strength and stiffness through cementation [5]. Chemical stabilizer can be categorized as Conventional and unconventional stabilizers. Conventional stabilizers are stabilizers such as cement, fly ash, and bituminous products have been intensely researched, and their fundamental stabilization mechanisms have been identified. Unconventional soil stabilization is additives consist of a variety of chemical agents that are diverse in their composition and in the way they interact with the soil. For this study, cement is used as a stabilizer.

1.1 Cement Stabilization

Cement reacts with water to release hydrates of the constituent particles. This reaction is known as the hydration of cement. The hydration of cement is a complex process and modifies the soil through following mechanism [6].

1) **Cation Exchange**: Portland cement, a good calcium-based soil modifier, can provide sufficient calcium ions to replace the monovalent cations on the surfaces. This ion exchange process occurs within hours, shrinking the layer of water between clay particles, and reducing the plasticity of the soil/aggregate [7,8].

2) **Particle restructuring**: The restructuring of modified soil/aggregate particles, known as flocculation and agglomeration, changes the texture of the material from that of a plastic, fine-grained material to one more resembling a friable, granular soil/aggregate. Made possible through cation exchange, flocculation is the process of clay particles altering their arrangement from a flat, parallel structure to a more random edge-to-face orientation.

3) **Cementitious hydration**: Cementitious hydration is a process that is unique to cement, and produces cement hydration products referred to in cement chemistry as calcium-silicate-hydrate (hereafter, CSH) and calcium-aluminum-hydrate (hereafter, CAH)[9]. CSH and CAH act as the "glue" that provides structure in a cement-modified soil/aggregate by stabilizing flocculated clay particles through the formation of clay-cement bonds. This bonding between the hydrating cement and the clay particles improves the gradation of

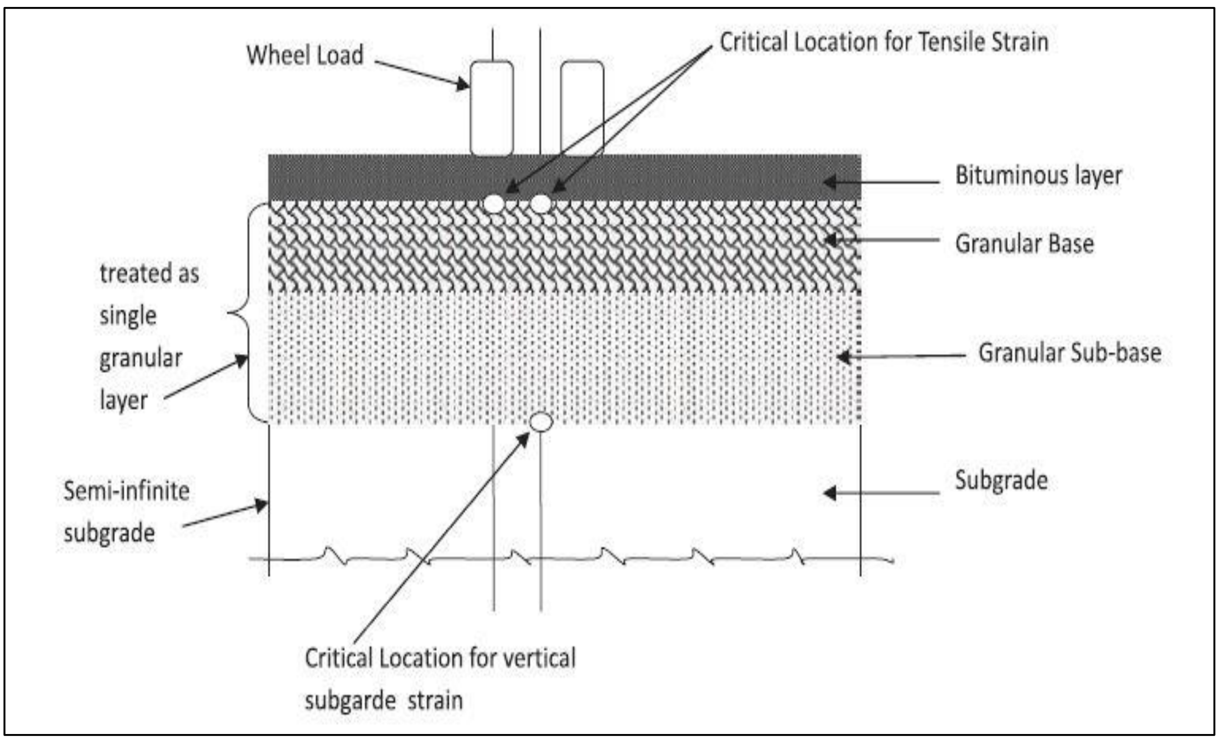


Figure 2. Critical Location of Tensile and Compressive Strains (IRC 37-2012)

the modified clay by forming larger aggregates from fine-grained particles. This process happens between one day and one month after mixing.

4) **Pozzolanic Reaction**: In addition to CSH and CAH, hydrated Portland cement also forms calcium hydroxide, or $Ca(OH)_2$, which enters into a pozzolanic reaction. This secondary soil modification process takes the calcium ions supplied by the incorporation of Portland cement and combines them with the silica and alumina dissolved from the clay structure to form additional CSH and CAH. The strength gain in case of cement is faster which allows for immediate strength gain and reduces the construction time. The strength gain during may be below ultimate strength [10]. However, the cement stabilized soil will continue to gain strength over the course of several days [11].

1.2 Road Design and Cost Determination

Road is designed based on strength of subgrade of subgrade soil and number of standard axle load repetitions which road is going to cater at the end of its service life [12,13]. This study models various cross section of pavement with varying thickness of layers in flexible pavement as shown in figure2. Two types of pavement are considered in study namely:

a) **Type I pavement**: It consist of layer of natural soil stabilized with 6% cement in between the untreated natural soil and sub base layer. Other layer depth are varied as in case of type I pavement. The resulting cross section of road is modeled with Kenpave to determine strain values at critical value

b) **Type II pavement**: It consist of natural soil as subgrade with varying thickness of capping layer above subgrade soil. Capping layer is a layer provided to replace the Insitu material where Insitu material is incompetent to be used as a subgrade layer [12,13]. With variation in depth of capping layer, the sub base, base and surface layer depth are also varied in modelling.

i. **Fatigue Criteria**: The two points shown in figure 2 below bituminous layer are critical location for tensile strain [12,13]. The relationship between fatigue life and critical tensile strain (larger out of these 2 value) is given by Department of Road (hereafter, DOR) flexible pavement guidelines as below:

$$N_f = 2.21 \times 10^{-4} \times \frac{1}{\varepsilon_t^{3.89}} \times \frac{1}{E^{0.854}} \quad (1)$$

Where,

N_f= Number of cumulative standard axles to produce 20 percentage cracked surface area

ε_t = Tensile strain at the bottom of Bituminous layer

E = Elastic modulus of bituminous surfacing

ii. **Rutting Criteria**: The rutting criteria for average rut depth of 20 mm is as below:

$$N_r = 4.1656 \times 10^{-8} \times \frac{1}{\varepsilon_c^{4.5337}} \quad (2)$$

Where,

N_r= number of cumulative standard axles to produce rutting of 20 mm

ε_c= Compressive strain at the top of subgrade

The modelling in Kenpave is done using Burmister multielastic layer theory and requires elastic modulus of layer and Poisson's ratio which are taken as per IRC 37-2012 and DOR Flexible Pavement Guidelines.

The Failure criteria are taken as per Asphalt Institute Method which is summarized below:

$$N_f = 0.414 \times \frac{1}{\varepsilon_t^{3.291}} \times \frac{1}{E^{0.854}} \qquad (3)$$

$$N_r = 1.365 \times 10^{-9} \times \frac{1}{\varepsilon_c^{4.4777}} \qquad (4)$$

Equation (3) and (4) are the one used in failure criteria evaluation of road section used in f=modelling for 30 msa and 50 msa. The terms in the equation share the same meaning as in the equation (1) and (2). Cost of pavement is determined using present rate as per norms and standard set by Kathmandu Metropolitan and DOR. In addition, reduction in pavement thickness due to cement stabilized soil (hereafter, CSS) over conventional capping layer is also determined for assumed cumulative standard axle at the end of service life of road.

1.3 Study Objectives

1. Determination of optimum cement content for soil under study.
2. Determination and comparison of Atterberg's limits, strength properties and swelling properties with and without cement.
3. Design and modelling of pavement cross section for 30 and 50 msa traffic intensity
4. Cost determination and comparison with conventional method of replacement.

The study mainly focuses on stabilization of soft soil subgrade and determine the thickness of road cross section for conventional method of replacement and for road using stabilized soil as interface layer between subbase and natural subgrade. Finally, the study determines the cost and the determined cost are analyzed and compared. The soil in study is incompatible for subgrade layer. The stability and strength of the soil needs to be modified in order to use it as a foundation layer for road. If used without modification, it leads to subgrade rutting and early deterioration of road surface. For such site condition, the method of construction must be selected. In case of chemical stabilization, optimum stabilizer content must be determined. In this study, the optimum cement content is determined from variation of MDD with cement content. The cement content which gives the maximum MDD for the remoulded sample is used as the optimum content of cement as it will result in minimum void in the compacted specimen. The cement content for study are taken as 4%, 6% and 8% by dry weight of soil. The lower limit of cement for strength test is set to be 4% to ensure proper mixing and upper limit as 8% to prevent shrinkage cracks [8]. For strength test, proper curing is required therefore, for CBR test minimum of 7 days of controlled curing is done to avoid rapid loss of moisture and for UCS test curing days of 3 days, 7 days, 14 days and 28 days inside protective membrane under moist condition is ensured.

For every project, the cost plays an important role therefore the cross section was optimized for sample with optimum cement content. The results from modeling are obtained for a particular soil under study therefore, it might be difficult to replicate the same for other soft soil deposits. The cost are determined for the cross section of road for both cases. The cost determination in this study have some limitation as the cost might vary from place to place.

2 MATERIAL AND METHODOLOGY

The sample is collected from the area which consist of soft soil at shallow depths. The area from where sample was collected is near Sanepa (Balkhu side) of Kathmandu.

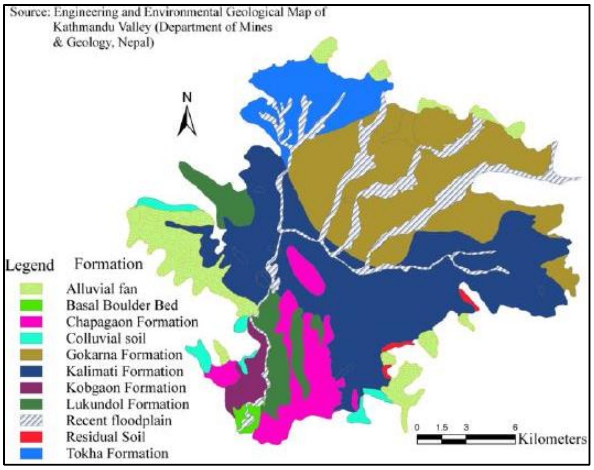
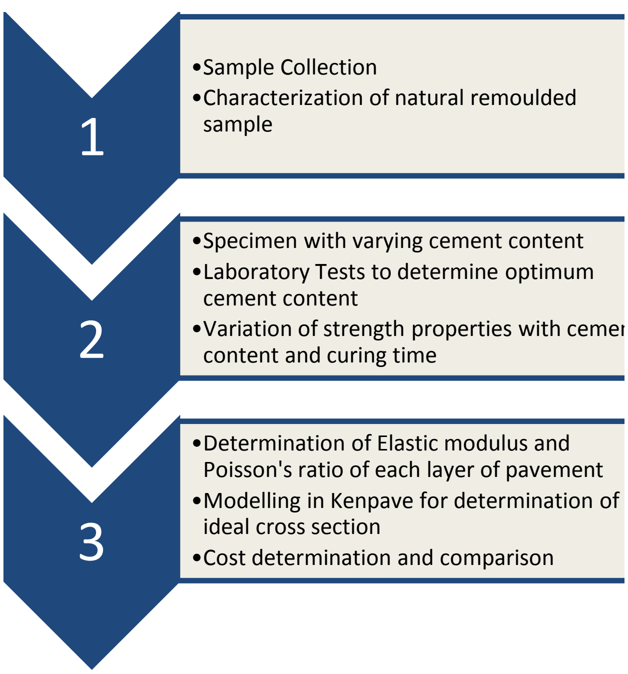


Figure 3. Geological Setting of Kathmandu valley.

As a whole the study follows following flow chart:



The study consists of two parts. In part I of study, the natural soil is collected and tests are done for characterization of soil with and without cement. Following test were done on soil in part I of study.

1) Specific gravity test
2) Determination of Particle size distribution
3) Determination of Atterberg's Limit
4) Determination of Optimum moisture content (hereafter, OMC) and Maximum Dry density (hereafter, MDD)
5) UCS test
6) CBR test with swelling percentage

The laboratory tests on remolded natural soil gave following results:

Table 1. Properties of untreated sample

SN	Property	Value	Remarks
1	Specific Gravity	2.6	
2	Liquid Limit (hereafter, LL)	48.15	
3	Plastic Limit (hereafter, PL)	25.55	
4	Plasticity Index (hereafter, PI)	22.60	
5	Classification of Soil	CL	Unified Soil Classification

6	OMC (%)	29.41	
7	MDD (kg/m^3)	1421.5	
8	Swell (%)	0.72	Should be less than 1% according to DOR norms
9	CBR @ 95% MDD (soaked) (%)	0.9912	Should be greater than 5% according to DOR norms.
10	Unconfined Compressive strength, KPa	136	Remoulded

Table 2. Parameter value used in modelling

	Parameter	**Value**	**Remarks**
1	Weight of Standard Axle	80 KN	Single axle load
2	Contact Pressure	800 KPa	IRC 37-2012
3	Equivalent Standard Axle Load (hereafter, ESAL)	30 and 50 msa	
4	Contact Radius	8.92 cm	IRC 37-2012
5	Elastic Modulus and Poisson's ratioof Surface	1455 MPa and 0.35	Taken for 30 degrees Celsius for 80/100 grade bitumen
6	Elastic modulus and Poisson's ratio of base and sub base course for pavement II		Taken as per clause 7.2 and 7.3 of IRC 37- 2012
7	Elastic modulus and Poisson's ratio of base and sub base course for pavement I		Taken as per ANNEX VIII of IRC 37- 2012
8	Elastic modulus and Poisson's ratio of Capping layer	E= 150 MPa and Poisson's ratio = 0.4	As Per IRC 37- 2012
9	Elastic modulus and Poisson's ratio of CSS	E= 400 MPa and Poisson's Ratio = 0.25	As per ANNEX XII of IRC 37- 2012
10	Elastic modulus and Poisson's ratio of Subgrade		As per clause 5.3 of IRC 37-2012

The tests on natural remoulded sample indicates the soil is very weak and needs modification or replacement. The remoulded sample are prepared with varying cement content. The samples are tested for OMC and MDD. The cement content yielding maximum dry density is chosen as optimum value. The percentage of cement content was taken as 4%, 6% and 8%.The Atterberg's limit were determined at 2%, 4%, 6% and 8% cement content. The UCS samples were prepared with 4%, 6% and 8% cement content and were tested after 3, 7, 14 and 28 days of curing. The CBR sample were also prepared with heavy compaction at 95% MDD with 4%, 6% and 8% cement content and were tested after 7 days of curing followed by 4 days of soaking with net surcharge load of 4.725 kg.

In part II of the study, the pavement is modelled using the soaked CBR value and 7 days UCS value for determination of elastic modulus obtained from laboratory test. Finally, pavement section were designed based on strain value ε_t and ε_c using equation (3) and equation (4) and cost was determined for roads with cement stabilized subgrade and for road with capping layer and were compared. The surface layers consist of two layers namely Dense Bituminous Macadam (hereafter, DBM) as bottom layer and Asphalt Concrete (hereafter, AC) as top layer. The base and sub base layer are taken as granular layer for analysis. The modeling is done using Burmister multilayer elastic theory.

3 RESULT AND DISCUSSION

Part I: Laboratory Testing and Characterizations of Soil:

The test results after addition of cement are summarized below.

1) **Atterberg's Limit**: The LL shows a slight increment up to 4% cement content and then shows a decreasing trend. On the other hand, PL shows an increasing trend while PI is found to be decreasing with increase in cement content. These results (shown by black line in figure 4, 5 and 6) are in agreement with the results obtained by Bell, 1995 (shown by red lines in figures 4, 5 and 6). The increasing trend of LL was also similar to the one studied by Dahal et. al. in Kathmandu clay but for 8% cement content, the curve of this study did not agree with the curve by Dahal et. al. The PL and PI showed similar trend for both the studies conducted on similar soil [14]. The LL, PL and PI are measure of a soil's cohesive properties and is indicative of the amount and nature of clay in the soil/aggregate. Higher PI soil are difficult to work with and lower PI value because of their instability and stickiness. Furthermore, high PI soils also have potential for detrimental volume changes during wetting and drying, which can lead subsequently to pavement roughness.

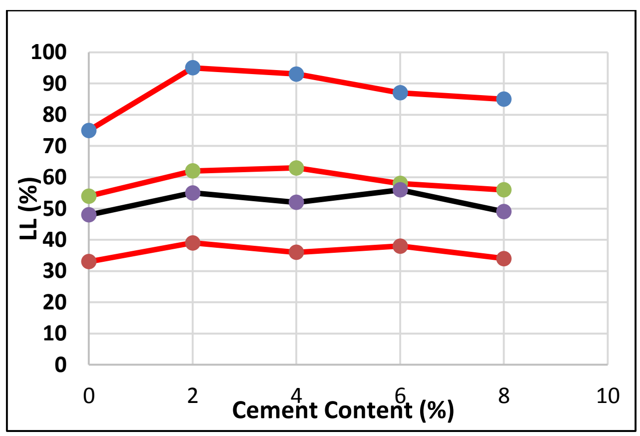


Figure 4. Variation of LL with cement content

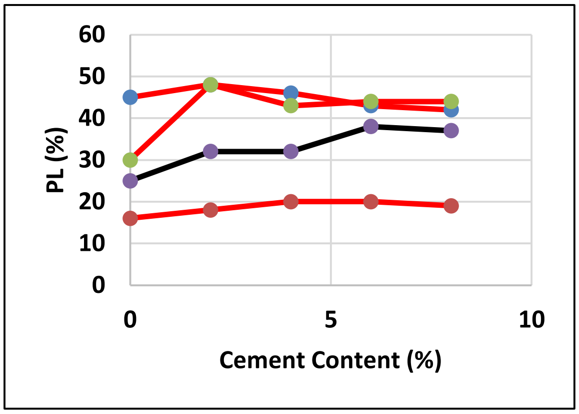


Figure 5. Variation of PL with cement content

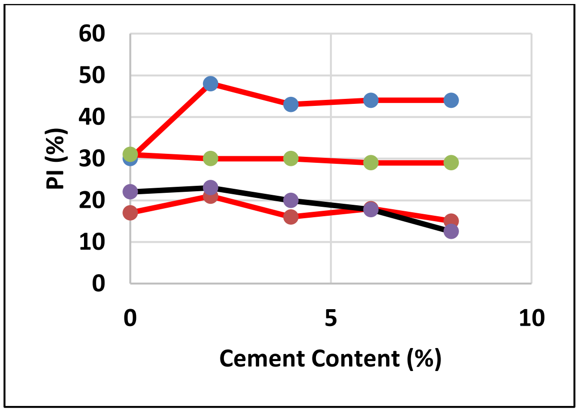


Figure 6. Variation of PI with cement content

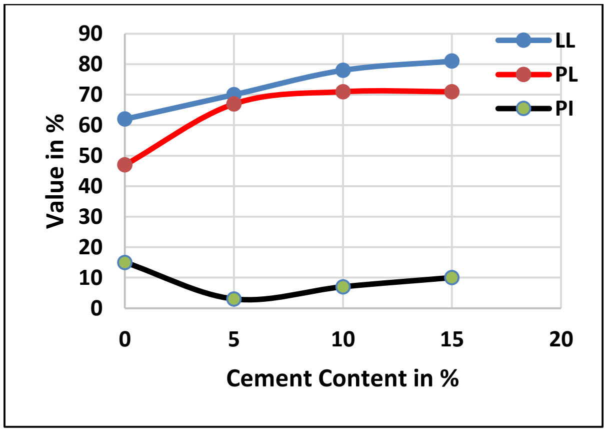


Figure 7. Variation of LL, PL and PI

2) **Moisture Density Relation**: The optimum cement content was found to be 6% as the MDD was maximum for this Cement content. The 6% cement content yielded maximum MDD.

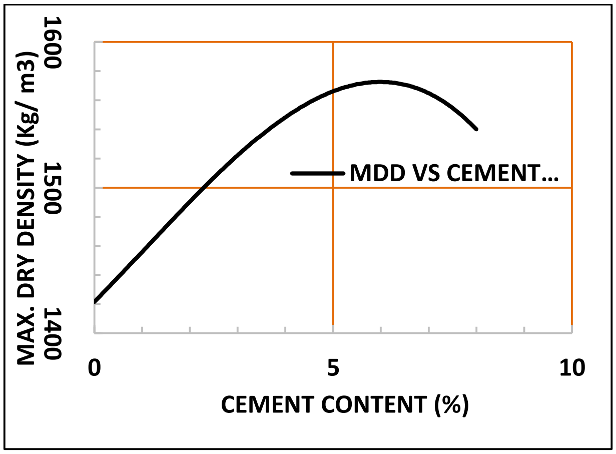


Figure 8. Variation of MDD with Cement Content

1) **CBR test**: The CBR test results showed that the value of CBR was significantly improved. And for the case of optimum cement content, the CBR value showed an increment of 1450% over the value for natural soil. When cement is added to soil, the particles bind together to form larger soil particles and in addition the remaining clay and silt are chemically altered as they become less adhesive [15]. This process results in the increment of CBR value.

Table 3. Variation of CBR with Varying content of Cement

Cement Content	CBR value	Swelling (%)	Increment of CBR by % of the initial value
4%	13.47	0.38	1250
6%	15.32	0.12	1450
8%	17.97	0.04	1713

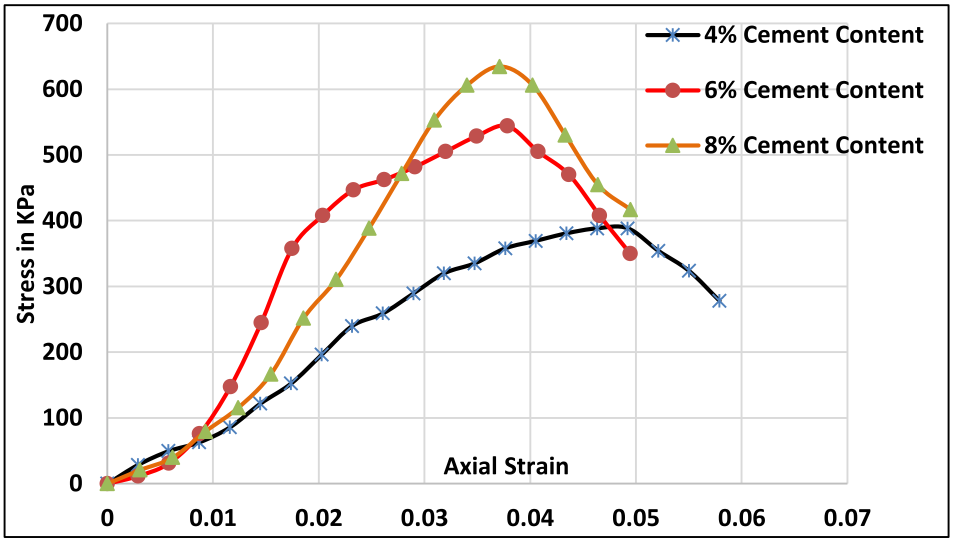


Figure 9. UCS at 3 days

2) UCS test: The UCS of soil sample showed signification increment with the increment of cement content and curing time. The trend showed a rapid increment in the initial days. With the hydration of cement, a kind of gel is formed which binds particle together to form a more stiff mass. In addition to this, the hydration of cement gives byproducts like calcium hydroxide, which undergoes pozzolanic reaction to form CSH and CAH which further add to the strength of cement.

This is shown by strength gain by time of curing. The strength gain in initial days is high as rapid hydration of cement occurs in initial days. As the days of curing are increased the pozzolanic reaction starts to contribute to the strength gain. The increase in strength with cement content can be explained by amount of CSH and CAH increment with more amount of cement [8,9,15,16]. The increment in UCS value are summarized in the table below.

Table 4. UCS With varying Cement Content and Curing period

Cement Content (%)	3 days UCS (KPa)	7 days UCS (KPa)	14 days UCS (KPa)	28 days UCS (KPa)
4	388	522	764	868
6	544	776	946	1254
8	634	940	1160	1407

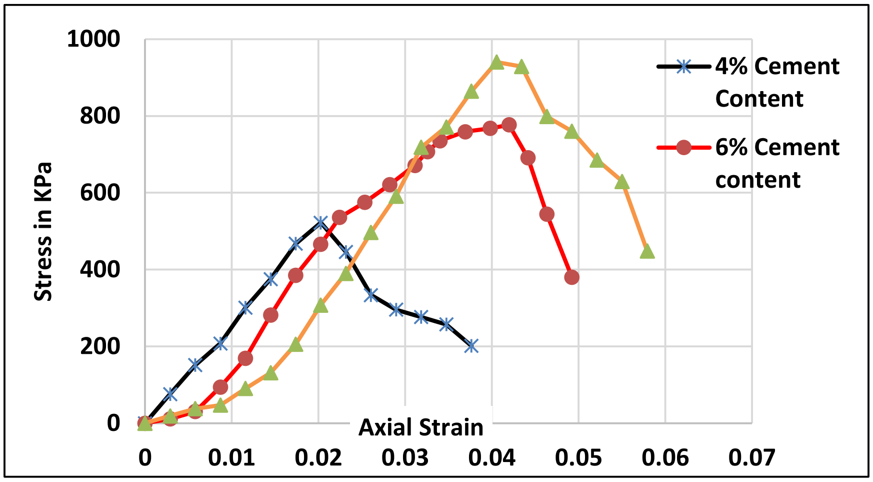


Figure 10. UCS after7 days curing time

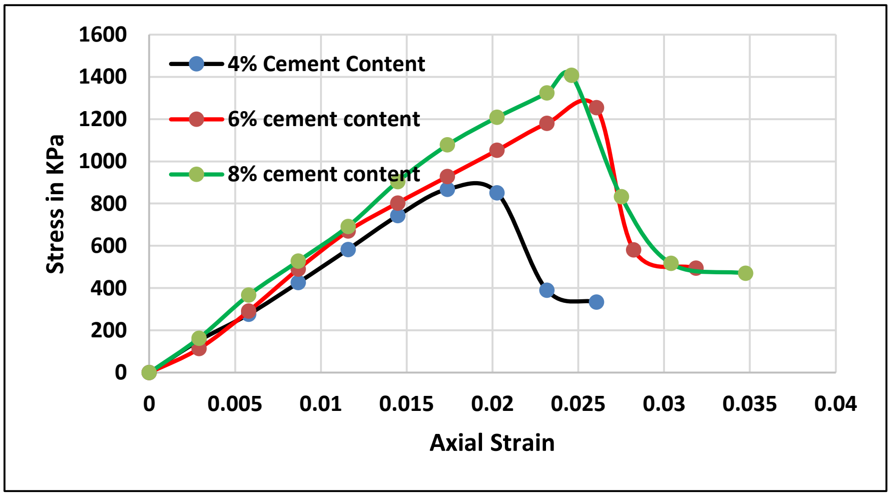


Figure11. UCS at 14 days

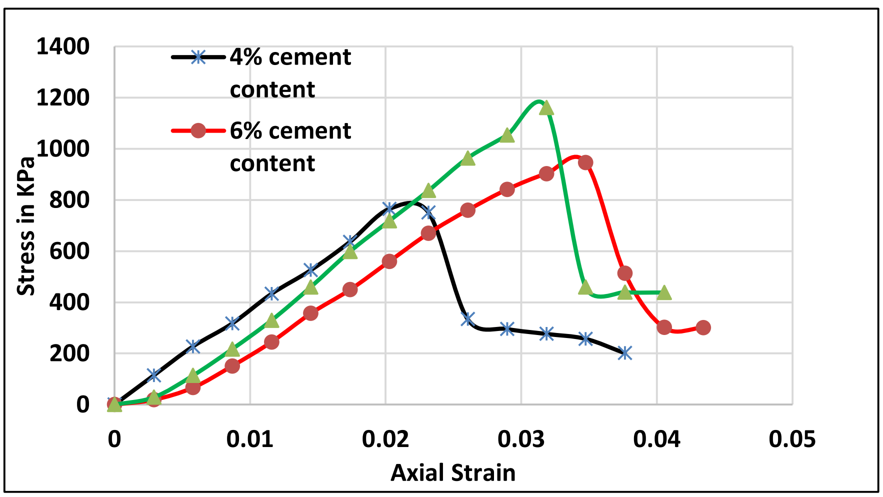


Figure 12. UCS at 28 days

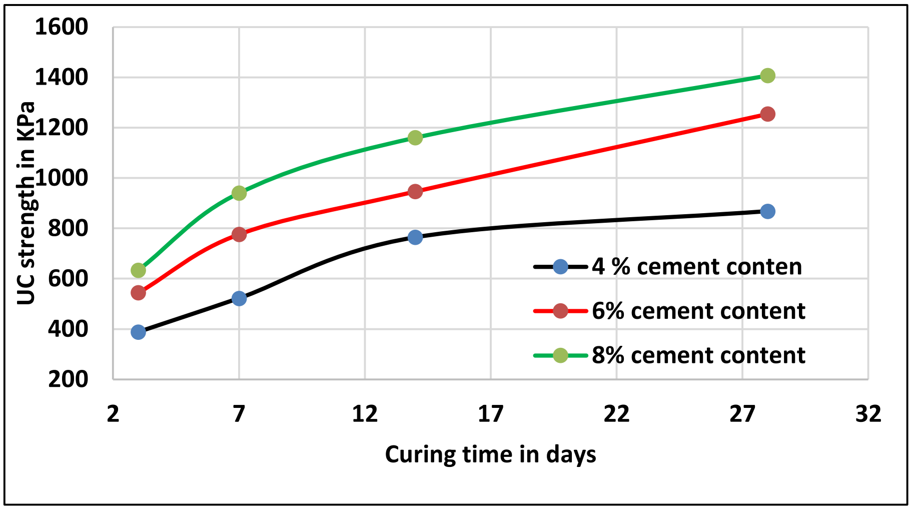


Figure 13. Variation of UCS with curing time

Part II: Design and Modeling of Cross section of Pavement:

The natural soil was stabilized with cement and the CBR and UCS value are used for Part II of the study. The design catalogue by DOR and IRC are only limited to subgrade CBR of 2%. Therefore, for lower CBR the pavement needs to be modelled and designed based on critical compressive and tensile strain. The modelling was done varying depth of layers in pavement and cross section until the resulting tensile and compressive strain from analysis are safe for both fatigue and rutting criteria. The strain and number axle for designed cross section of road for 30 and 50 msa from Kenpave is summarized below:

Table 5. Strain and Failure criteria from model

Traffic (msa)	Compressive strain		Tensile strain		Nr (msa)		Nf (msa)	
	Type I	Type II	Type I	Type II	Type I	Type II	Type I	Type II
30	0.0002174	0.0002074	0.0002760	0.0002356	34.33	42.39	425.48	716.28
50	0.0001929	0.0001975	0.0002606	0.0002043	58.65	52.78	513.97	1145.04

The modeling with Kenpave was done to determine ideal cross section for the Insitu soil with CBR 1% in subgrade layer. The road with CSS as interface layer between subbase and subgrade showed significant reduction in total thickness of pavement because of large elastic modulus of CSS layer. The designed cross section shown in figure below:

Table 6. Reduction in pavement thickness

Traffic (msa)	Total thickness (cm)		Reduction in thickness	%Reduction
	Type I Pavement	Type II pavement		
30	99	112	13	11.6
50	105	114	9	7.9

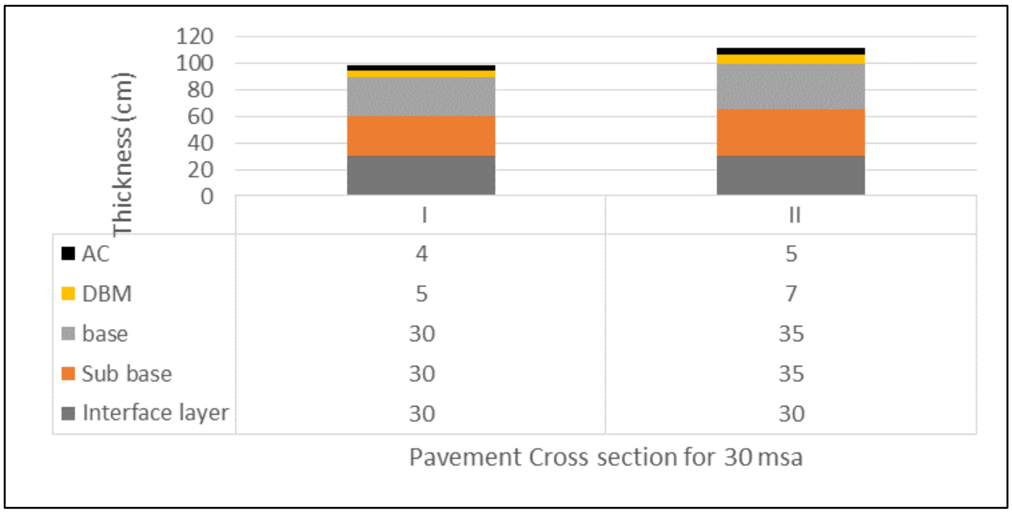


Figure 14. Design cross section for 30 msa

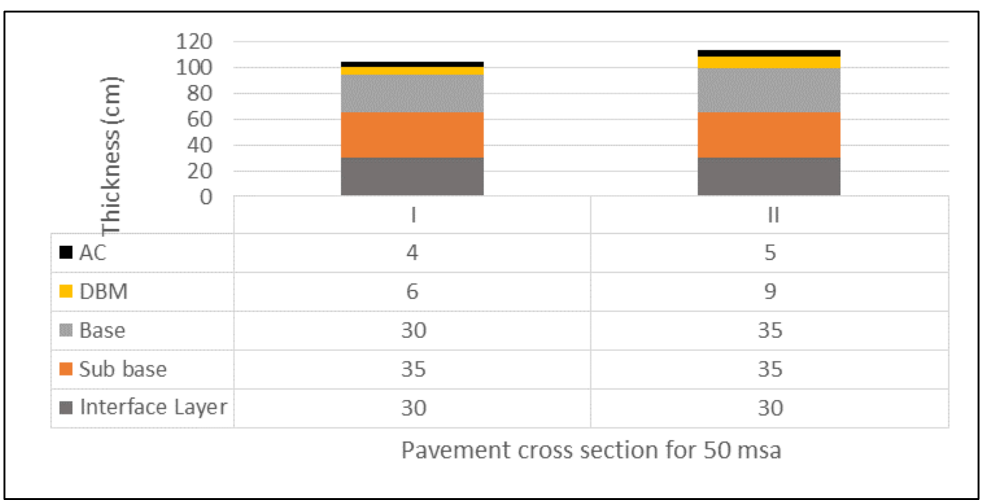


Figure 15. Design cross section for 50 msa

Table 7. Layer wise cost for 1 km road stretch of 3.5 m width

Traffic (msa)	Pavement Type	Cost of Disposal of soil (NRs.)	Cost of Interface layer (NRs.)	Sub base layer cost (NRs.)	Base Layer Cost (NRs.)	DBM cost (NRs.)	AC Cost (NRs.)	Total Cost (NRs.)
30	I	0	2,691,150	2,430,750	3,116,400	2,898,000	2,593,920	13,730,220
	II	94,500	952,350	2,835,875	3,635,800	4,057,200	3,242,400	14,818,125
50	I	0	2,691,150	2,835,875	3,116,400	3,477,600	2,593,920	14,714,945
	II	94,500	952,350	2,835,875	3,635,800	5,216,400	3,242,400	15,977,325

The cost of pavement is summarized in table below:

Table 8. Cost Estimation and Comparison

Traffic (msa)	Cost of Type I Pavement (NRs.)	Cost of Type II Pavement(NRs.)	Cost Difference (NRs.)	% Reduction
30	13,730,220	14,818,125	1,087,905	7.34
50	14,714,945	15,977,325	1,262,380	7.90

The cost determined in the abo ve table are construction cost and are determined for a road stretch of 1 km with 1 lane i.e. 3.5 m width. The cost used the rates of item specified by District and norms and standard set by DOR. The reduction in the cost due to use of CSS is due to the fact that foreign material is not required and the Insitu material is used as the interface layer with stabilization. Furthermore, the reduction of thickness of subbase, base and the surface course significantly reduced the cost of construction compared to convention method.

4. CONCLUSION

1. Plasticity index was reduced for all proportion of cement. LL shows increasing trend for low cement content followed by gradual fall after 4% cement content. On the other hand, PL shows falling trend for all content of cement.

2. The stability and strength of natural soil increased significantly. Addition of 6% cement content shows the 1450% increment to the initial value of soaked CBR for natural soil after 7 days curing period. The UCS also shows the significant increment in initial value. It shows increment in both condition of increasing cement content and curing period.

3. The increment of strength of natural soil with cement makes the soil competent

enough to be used as supporting layer above natural soil subgrade.

4. The thickness of each layer and total thickness of pavement was determined using Kenpave and Pavement design guidelines for 30 and 50 msa traffic load. The result showed that the overall thickness of type I pavement is small compared to type II pavement. The percentage reduction in thickness accounted for 11.6 % and 7.9% for 30 and 50 msa respectively which means type I material requires less material than type II pavement.

5. The cost was determined for both type of pavement for assumed traffic loadings. Type I pavement is found to be 7.34 % and 7.9 % cheaper than Type II pavement. This could lead to significant saving in construction of road in soft soil subgrade. Although the cost of cement stabilization is high for per cubic meter rate but the overall reduction of pavement thickness is the reason for cost reduction in whole pavement compared to pavement using capping layer.

6. In model of pavement for both type of pavement, it can be seen that pavement I requires lesser thickness of surface layer i.e. BDM and AC. Hence, use of cement stabilization in pavement reduced the use of bitumen in pavement which is an imported material for adopted traffic intensity. This can be taken as an indirect benefit of the proposed pavement with CSS layers.in comparison to bitumen, cement is produced within the country so it can be beneficial to use cement stabilization to reduce use of bituminous layer. The study can be extended for other level of traffic intensity to ensure the direct and indirect benefits of cement stabilization of subgrade in pavement.

The results obtained from the above study are from controlled laboratory tests. It is difficult to replicate exact results on field but strict quality control measure can replicate the results to the maximum possible level. Furthermore, it is recommended to conduct field test to verify the results in ground. Other combination of stabilization technique such as lime + cement or pozzolanic material + cement can be evaluated in the same way as carried in the above study for best stabilization technique that can be used in road construction practices in Nepal. It is also recommended that this study is for particularly type of soil as characterized by properties in above study, so for other soil varying in property series of laboratory test must be conducted in order to recommend any stabilization technique.

REFERENCES:

(1) Dill, H. G.; Kharel, B. D.; Singh, V. K.; Piya, B.; Busch, K.; Geyh, M. Sedimentology and Paleogeographic Evolution of the Intermontane Kathmandu Basin, Nepal, during the Pliocene and Quaternary. Implications for Formation of Deposits of Economic Interest. *J. Asian Earth Sci.* **2001**, *19* (6), 777–804.

(2) Tang, X.; Stoffels, S. M.; Palomino, A. M. Mechanistic-Empirical Approach to Characterizing Permanent Deformation of Reinforced Soft Soil Subgrade. *Geotext. Geomembranes* **2016**, *44* (3), 429–441.

(3) Wanyan, Y.; Abdallah, I.; Nazarian,

S.; Puppala, A. J. Expert System for Design of Low-Volume Roads over Expansive Soils. *Transp. Res. Rec.* **2010**, *2154* (1), 81–90. https://doi.org/10.3141/2154-07.

(4) Lotfi, H. A.; Schwartz, C. W.; Mitczak, M. W. *Compaction Specification for the Control of Pavement Subgrade Rutting*; 1988.

(5) Seco, A.; Ramírez, F.; Miqueleiz, L.; García, B. Stabilization of Expansive Soils for Use in Construction. *Appl. Clay Sci.* **2011**, *51* (3), 348–352. https://doi.org/10.1016/j.clay.2010.12.027.

(6) Halsted, G. E.; Adaska, W. S.; Mcconnell, W. T. Guide to Cement-Modified Soil (CMS). *Portl. Cem. Assoc.* **2008**, 20. https://doi.org/10.1182/blood-2010-03-272153.

(7) Croft, J. B. Theinfluence of Soilmineralogical on Cement Stabilization. *G&echni~ue* **1967**, *17*, 119–135.

(8) Bell, F. G. Cement Stabilization and Clay Soils, with Examples. *Environ. Eng. Geosci.* **1995**, *I* (2), 139–151. https://doi.org/10.2113/gseegeosci.I.2.139.

(9) Parsons, R. L.; Milburn, J. P. Engineering Behavior of Stabilized Soils. *Transp. Res. Rec.* **2003**, *1837* (1), 20–29.

(10) Little, D. N.; Nair, S. Recommended Practice for Stabilization of Subgrade Soils and Base Materials. **2009**.

(11) Pedarla, A.; Chittoori, S.; Puppala, A. J. Influence of Mineralogy and Plasticity Index on the Stabilization Effectiveness of Expansive Clays. *Transp. Res. Rec.* **2011**, *2212* (1), 91–99.

(12) IRC. *Guidelines for the Design of Flexible Pavements*; 2012.

(13) *Pavement Design Guidelines*.

(14) Dahal, B. K.; Zheng, J. J.; Zhang, R. J. Experimental Investigation on Physical and Mechanical Behavior of Kathmandu Clay. *Adv. Mater. Res.* **2018**, *1145*, 112–116. https://doi.org/10.4028/www.scientific.net/amr.1145.112.

(15) *Cement-Modified Soil Integrated Paving Solutions*; Illinois.

(16) Ferrier, S. K. Soil Cement Roads; 2016.