Strength and Stiffness Studies of Cement Stabilized Granular Lateritic Soil

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Abstract. A huge network of rural roads is being developed in India under the most ambitious Prime Minister's rural connectivity programme, *PMGSY (Pradhan Mantri Gramin Sadak Yojna)*. Under this programme, thousands of kilometers of rural roads are being constructed in the country, which require good quality pavement materials like crushed stone. The scarcity of natural aggregates has compelled to use marginal materials or locally available soils in structural layers of these pavements, which would reduced the cost of the project. Granular lateritic soils are widely available in many parts of India and presently, this is also used as sub-base material in different rural road projects, where it satisfies the code specifications. However, granular lateritic soils of some locations do not satisfy the strength and plasticity requirement of sub-base layer. But, they can probably be made suitable through stabilization. Though stabilization of soil by cement or lime is a well known process of improving the strength and stability of soil, the strength and stiffness parameters of stabilized lateritic soils in terms of modulus of rupture, resilient modulus, flexural modulus have very limited reference in literature. Therefore, in this study an attempt has been made to characterize the cement stabilized lateritic soils for use in sub-base and base layers in rural road pavements. A comprehensive laboratory testing programme has been conducted on cement stabilized granular lateritic soil samples collected from five different places of eastern India to study various strength parameters such as compressive strength, modulus of rupture and stiffness properties in terms of flexural modulus of cement stabilized granular lateritic soil. In this paper, strength and stiffness developments of cement stabilized granular lateritic soil in 7 days and 28 days have been studied and its suitability as a structural layer in rural roads has been investigated. Suitable modulus values of cement stabilized granular lateritic soils have been proposed which can be used as an input parameter for the input in mechanistic design of roads. Also relationships have been proposed to determine modulus of rupture and flexural modulus of cement stabilized granular lateritic soil from its compressive strengths.

1 Introduction

A huge network of rural roads is being developed in India under different schemes launched by the government including the Prime Minister's rural connectivity programme (*PMGSY)*. The requirement of enormous amount of good quality pavement

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materials like crushed stones (whose source is depleting day by day), is becoming a concern for the administrators and concerned authorities of the country. In this scenario, investigation of the use of marginal aggregates and locally available granular materials in structural layers of the pavement is timely justified. Granular lateritic soil (GLS) is available in many parts of India and presently being used as a sub-base material in various road projects, where this meets the code specifications. However, GLS from various sources do not satisfy the strength and plasticity requirement for sub-base and base layers (Biswal et al. 2016). Hence, these soils need to be modified or stabilized to make them suitable for sub-base and base layers of pavement. Traditionally, cement and lime or both are used to stabilize the soils for road construction purpose (Gidigasu 1976). Indian Roads Congress (2010) provides guidelines are available for cement and lime stabilization (IRC 2010) of soils. Though stabilization of soil by cement or lime is a very well known process of improving the strength of soil, very few studies are available on strength and stiffness properties of cement stabilized granular lateritic soils (CLS). For the mechanistic design of pavements with stabilized layers, the input parameters usually required are modulus and flexural strength. But, studies related to characterization of CLS in terms of modulus, flexural strength etc. under repeated loading condition is scarce. Therefore, in the present study, strength properties of CLS such as unconfined compressive strength (UCS), modulus of rupture (MOR) i.e., flexural strength and stiffness in terms of flexural modulus have been investigated.

1.1 Studies on Stabilized Lateritic Soil

The objective of stabilization is to improve plasticity characteristics, alteration of grain size distribution, increase in mechanical strength or stiffness and durability under adverse conditions which may be done by mixing cement or lime and cement, fly ash or with any chemical stabilisers. A brief summary on stabilization of lateritic soils by different researchers is presented in Table 1. Properties of cement or lime stabilized lateritic soils have been studied by many researchers. However, most of the papers have explained the improvement of the geotechnical properties e.g., OMC, MDD, liquid limit, plastic limit, UCS, CBR of stabilized lateritic soil. It needs to be emphasized that, studies regarding flexural modulus, flexural strength including compressive strength of stabilized lateritic soil is very scarce The study carried out by Joel and Agbede (2010) on stabilization of lateritic soil with cement and sand, revealed that 45% sand and 6% cement is the optimum content for the mix design. Similarly, Portelinha et al. (2012), Jaritngam et al. (2012), Ravi et al. (2008), Joel and Agbede (2010) investigated the potential of stabilized lateritic soils of Brazil, Thailand, India and Nigeria respectively. It may be observed that cement and lime proves to be good modifiers or stabilizers for lateritic soils in order use as a base or sub-base course material.

Strength of Cement Stabilized Soils

As already mentioned, stabilization of soil by cement and lime is a well known process, and use of stabilized soil in pavements has also been in practice for decades. However, the proper characterisation of cement stabilized soil as sub-base and base course

Table 1. Some studies on stabilised lateritic soil

Location of laterite sample	Reference	Optimum content (%)	7 day UCS
Nigeria	Joel and Agbade (2010)	45% sand and 6% cement	2702 kPa, 270% improvement
Brazil	Portelinha et al. (2012)	3% cement or 3% lime	600 kPa for lime (118% improvement) 1000 kPa for cement (233% improvement)
Thailand	Jaritngam et al. (2012)	3% cement	2220 kPa
India	Ravi et al. (2008)	4% cement with pond ash	1000 kPa, 440% improvement

material is required as the mechanistic design of pavements requires input parameters like elastic modulus and Poisson's ratio etc. Unconfined compressive strength is one of the accepted methods for determining the strength of bound materials. UCS is used for determining the suitability of the mix to perform satisfactorily as a bound sub-base and base layer (Paige 1998; Vorobeiff 2004; Austroads 2008; Yeo et al. 2011). Addition of small percentage of stabiliser may improve the strength and plasticity properties of soil, but it may lack the required tensile strength and behave as an unbound granular (Vorobeiff 2004). A criteria developed by Austroads (2013) to differentiate modified soil from stabilized soil is given in Table 2.

Table 2. Typical properties of modified and bound materials (Austroads 2013)

Classification	Testing criteria	Test conditions
Modified	0.7 MPa < UCS < 1.5 MPa	28 day moist curing and 105 mm diameter and 115.5 mm height mould and 4 h soaking prior to testing
Bound	UCS > 1.5 MPa	

Many research reports and standard specifications have put the requirement of minimum strength in terms of UCS of stabilized soil for use in sub-base and base layer of pavement. As per Indian Road Congress (IRC:37-2012) guidelines, the minimum requirement of 7 day UCS value for cement stabilized soils are 4.5 MPa and 0.75–1.5 MPa for base and sub-base respectively. However, in case of low volume roads the minimum UCS value for stabilized or bound base is 3 MPa which has been mentioned in Table 3. Further, wet-dry durability tests need to be conducted on stabilized materials to assess the suitability of these materials for use as sub-base or base layer. The assessment is done in terms of mass loss after 12 wet-dry cycles. As per PCA (Portland Cement Association) (1992), the maximum permissible mass loss after 12 wet-dry durability cycles are 14% and 7% for granular materials and cohesive clays respectively Similarly, the performance of stabilized materials is studied by conducting shrinkage tests and load induced fatigue tests. However, durability tests, shrinkage tests and fatigue tests of cement stabilized lateritic soil are not within the scope of this paper. Table 3 summarises the strength requirement for stabilized layers for different types of pavement. Test conditions and sample size for determination of *UCS* vary as shown Table 3.

Table 3. Criteria in terms of UCS for suitability of stabilised subbase and base

References	UCS (MPa)		Curing period	Sample size
	Medium to high volume roads	Low volume roads		
Portland Cement Association (1992)	2.068 (for subbase/base)			
Gass (1993)	2.068 (for subbase/base)			
MEPDG (2004)	1.72 (for subbase) and 5.17 (for base)	1.72 (for subbase) and 5.17 (for base)	7 days for cement and 28 days for lime-flyash or cement-flyash	100 mm (d) × 115 mm (h)
Austroads (2008)	2	1–2	28 days curing and 4 h soaking prior to testing	105 mm (d) × 115.5 mm (h)
IRC 37 (2012)	0.75–1.5 (for subbase) and 4.5–7 (for base)	1.7 (for subbase) and 3 (for base)	7 days for cement and 28 days for lime-flyash	50 mm (d) × 100 mm (h)
Syed and Scullion (2001)	1.38 (for subbase/base)			

The strength criteria for lightly trafficked or low volume roads is low as compared to high volume roads, as there is less concern on fatigue cracking causing damaging effects on the life of thin bituminous surfacing. It can be observed that, the minimum 28 day *UCS* for stabilized materials for use in rural road is 1–2 MPa as per Austroads (2008). The minimum *UCS* value of 1.7 MPa and 3 MPa is considered suitable for sub-base and base course as per IRC:SP-72 (2015).

As the bound material is capable of developing tensile stress, which allows it to resist and transfer the traffic load to layers below, the *MOR* needs to be evaluated. Though bending tensile stress developed in bound layers due to traffic load is below the tensile strength of bound materials, the *MOR* is an important tensile strength parameter which is required for determination of cumulative fatigue damage of stabilized layer. The default value of *MOR* of soil cement and cement treated aggregate are taken as 0.69 MPa corresponding to minimum 28 days UCS value of 5.17 MPa (ARA 2004).

Stiffness of Cement Stabilized Soils
Elastic modulus of stabilized materials is an important parameter required in elastic layered analysis for determination of stresses and strains at critical locations of a pavement. Although elastic modulus of cemented materials can be estimated by monotonic compression test, third point flexure test is better for determination of modulus due to the similarity in development of stress-strain gradient generated in a pavement (Wen et al. 2014; Austroads 2008; Arulrajah et al. 2015; Yeo et al. 2011). Laboratory determination of stiffness or modulus values of cement stabilized materials depends on the type of test. The modulus values obtained under monotonic compression testing differs from that obtained from cyclic compression testing (Fall et al. 2008) which also differs with flexural modulus determined from beam testing. The modulus of cemented materials which influences development of tensile strain is the flexural modulus and therefore, this may be used as the design modulus. For the elastic analysis of pavement structure having soil-cement base layer, elastic modulus and Poisson's ratio are two important input material parameters. Though, the elastic modulus of cement stabilized base material depends on so many factors, the design elastic modulus have been presumed to be 5000 MPa, 3447 MPa and 3500 MPa by Austroads (2012), ARA (2004), IRC (2012) respectively. As the laboratory determination of elastic modulus is a tedious process, generally UCS of stabilized materials is used to determine the modulus value of cemented materials. Equations 1, 2 and 3 presents the models used to determine the design modulus values of soil cement by IRC (2012), ARA (2004), Austroads (2012) respectively.

$$E_f = 1000\,UCS \tag{1}$$

$$E_f = 1200\,UCS \tag{2}$$

$$E_f = 1000\,to\,1250\,UCS \tag{3}$$

Where,

E = Flexural Modulus in MPa
UCS = Unconfined Compressive Strength in MPa

As, a range of stabilized materials are being used as bound layer in pavements, modulus of elasticity and strength cannot be uniquely related, (Williams 1972) which encourages to study the relationship between UCS and modulus values of stabilized granular lateritic soils.

2 Materials and Methods

2.1 Materials

The materials used in the present investigation are GLS collected from five different locations of Eastern India as shown in Fig. 1 which are marked as A, B, C, D and E. The physical properties of five different GLS are summarised in Table 4 and the chemical compositions of the soils are summarised in Table 5. The lateritic soils

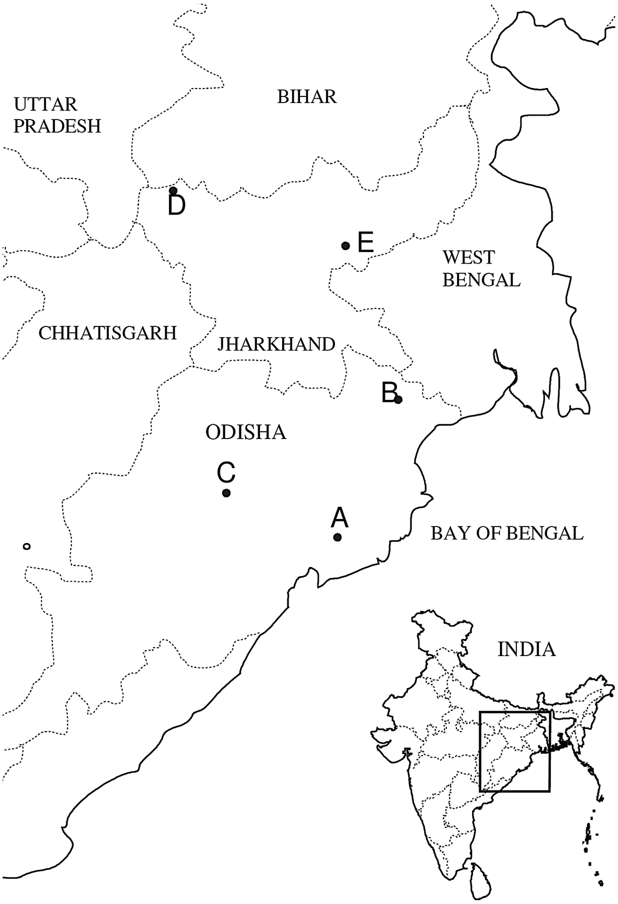

Fig. 1. Location map of collected granular lateritic soils in eastern India.

Table 4. Summary of the engineering properties of soil

Sample no	Region	Gravel	Sand	Silt & Clay	w_{omc} (%)	MDD (kN/m^3)	Soaked CBR (%)	UCS (kPa)	LL	PI	Soil type (ISCS)
A	Khurdha, Odisha	35	60	4	13	21			48	15	SW
B	Baripada, Odisha	95	4	0	9	22	20	760	34	10	GW
C	Sonepur, Odisha	42	37	17	9	22	27	950	68	38	SW
D	Hussainabad, Jharkhand	33	67	0	10	21	23	410	47	19	SW-SM
E	Bokaro, Jharkhand	24	75	0	8	21	24	360	52	29	SW

Table 5. Chemical Compositions of granular lateritic soil and cement used in this study.

Constituents	Lateritic Soil (% by mass)					Cement
	A	B	C	D	E	
Fe_2O_3	21.6	32.49	8.47	7.61	31.82	1.67
Al_2O_3	18.59	14.26	12.51	14.44	17.73	4.41
SiO_2	50.32	44.05	64.06	55.02	48.97	16.33
MgO	0.95	1.02	0.76	0.95	1.14	5.49
K_2O	2.1	1.34	1.69	7.69	2.45	1.09
CaO		1.03	0.3	0.82	0.66	67.99
TiO_2	2.49	2.97	1.36	1.34	3.62	
CuO						0.166
SO_2						0.53

selected under this study have a wide range of plasticity characteristics and gradation, in order to get a practical range of strength and stiffness properties of GLS. The lateritic soils have been air dried prior to testing or sample preparation. The gradation and plasticity characteristics of the studied soils suggests that both cement and lime can be used for stabilization of this soil as per IRC: SP89 (2010), However, cement has been chosen for the study of the stabilization of lateritic soils in the present study. The cement used in this study is bagged ordinary portland cement (OPC).

2.2 Methods

Unconfined Compressive Strength

The strength properties have been determined in two stages. In the first stage, UCS tests have been conducted on all soil samples at various cement content such as 2, 3, 4, 5, 6 and 8%. The air dried soil samples have been mixed with calculated amount of cement and water and samples of size 38 mm in diameter and 76 mm in height have been prepared and cured for 7 and 28 days. All the soil samples have been prepared at optimum moisture content and modified dry density at respective dosed state for the strength and stiffness study.

Flexure Test

The flexure test is conducted for determination of modulus of rupture. In this study, the test has been conducted as per ASTM D 1635. Beam samples of size 75 mm × 75 mm × 290 mm have been prepared for all five GLS mixed with two different cement content i.e., 2% and 5% to prepare stabilized materials for sub-base and base course respectively. The beam samples have been cured for a period of 28 days prior to the flexure test. Three specimens have been tested for each soil samples and the average value of the result has been used for analysis. The flexure test arrangement is shown in Fig. 2.

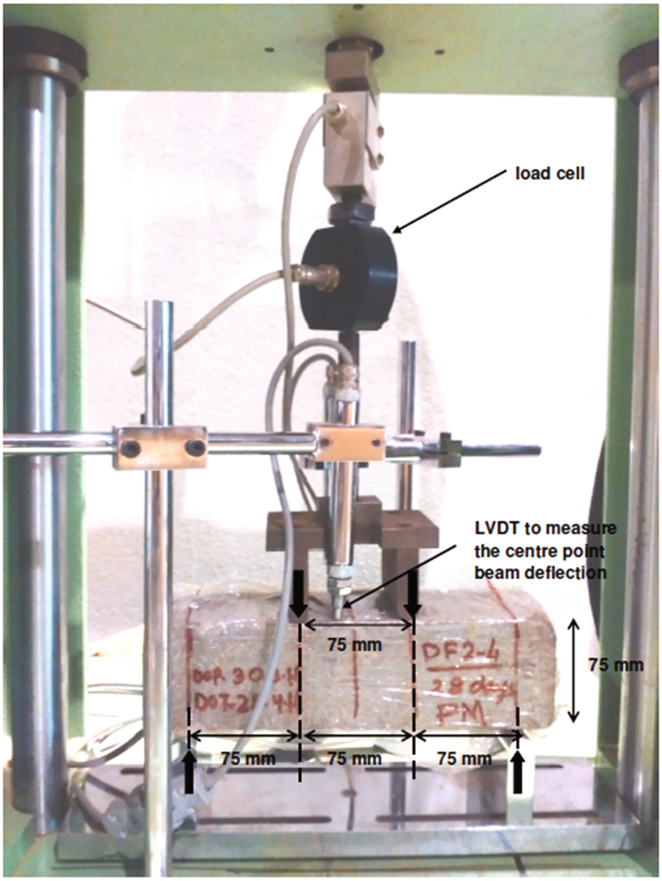

Fig. 2. Flexural Modulus test of beam sample

Flexural Modulus Test

In the absence of a standard method for determination of flexural modulus of stabilized beam samples, the protocol developed by Yeo et al. (2011) has been adopted for determination of flexural modulus. The flexure test arrangement which is shown in Fig. 2 has also been used for flexural modulus test. Two linear variable differential transformers (LVDTs) have been used for measuring deflection of the beam centre. The beam specimen have been subjected to haversine cyclic load of 100 cycles having a peak load which is equal to 20%, 30% and 40% of failure load of beam samples determined from flexure test. Modulus value corresponding to 40% of failure load have been taken for determination of flexural modulus (Wen et al. 2014; Yeo et al. 2008). The first 50 loading cycles are considered as conditioning stage and the average value of modulus calculated in last 50 cycles is reported and considered as modulus value of CLS. Following Equation has been used for determination of flexural modulus.

Flexural Modulus,

$$E_f = \frac{\sigma_t}{\varepsilon_t} = \frac{\frac{Pl}{bd^2}}{\frac{108\delta_d d}{23l^2}} = \frac{23Pl^3}{108bd^3\delta_d} \tag{4}$$

Where,

σ_t = Maximum bending stress corresponding to failure load P
ε_t = Maximum bending strain corresponding to failure load P
P = Cyclic load in kN
b = Width of beam in mm
d = Thickness of beam in mm
l = Span from centre to centre of support in mm
δ_d = Vertical deformation at midpoint in mm

3 Results and Discussions

3.1 Compressive Strength of CLS

The use of stabilized materials or soils for their suitability as a sub-base or base is generally decided by their UCS values (Yeo et al. 2011). Minimum requirement of UCS values for stabilized soils to satisfy the strength criteria are summarized in Table 3. UCS values are also used for differentiating mixtures of soil cement, lime, fly ash or other soil-chemical mixtures as modified soil, lightly bound or heavily bound soil. According to NAASRA (1986), stabilized material with 7 day UCS value of 0.8 MPa or higher can be used as a structural layers as per the strength criteria. As per IRC 37-2012, stabilized materials having UCS value more than 1.5 MPa can be used as a sub-base material and those having UCS value more than 4.5 MPa can be used as base material as per strength criteria. However, the durability, shrinkage and fatigue properties of stabilized granular lateritic soils are not within the scope of this paper. The 7 day and 28 day UCS values of CLS of samples A, B, C, D are shown in Figs. 3 and 4 respectively. As the UCS value of CLS with 3% cement is more than 1.5 MPa, it can be used as sub-base layer in low and high volume roads. UCS values of LSC of samples A, C, D and E at 5% cement content satisfies the requirement of base layer *i.e.,* UCS > 4.5 MPa. However, granular lateritic soil sample B needs minimum 6% cement to satisfy the IRC requirement for base layer. Further, as per IRC SP: 72-2015, a minimum laboratory UCS of 3 MPa is required for base whereas, minimum laboratory UCS of 1.7 MPa is required for sub-base for rural roads. Hence, CLS with 5% cement can be used for base layer in rural roads and CLS with 2% cement content can be used as sub-base layer in rural roads.

The relationship between MOR and UCS of 28 days cured cement stabilized granular lateritic soil samples is shown in Fig. 5 and presented by Eq. 5. A comparison of MOR predicted from UCS obtained by Eq. 4 (present study), Eq. 5 (Wen et al. 2014) and Eq. 6 (ARA 2004) have been illustrated in Fig. 6. The MOR of CLS having 2% cement and 5% cement varies in the range of 0.27–0.74 MPa and 0.74–1.69 MPa

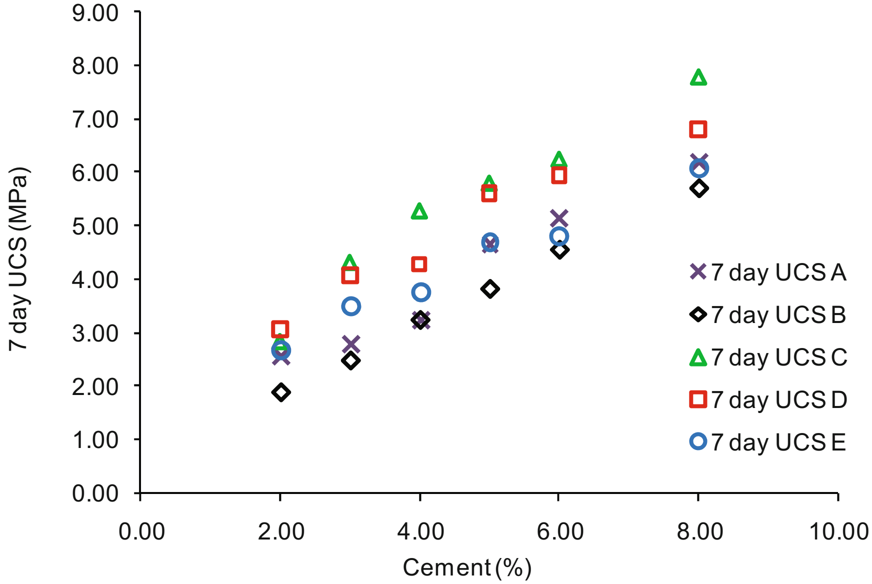

Fig. 3. 7 day UCS values of CLS (specimen size 38 mm diameter and 76 mm height)

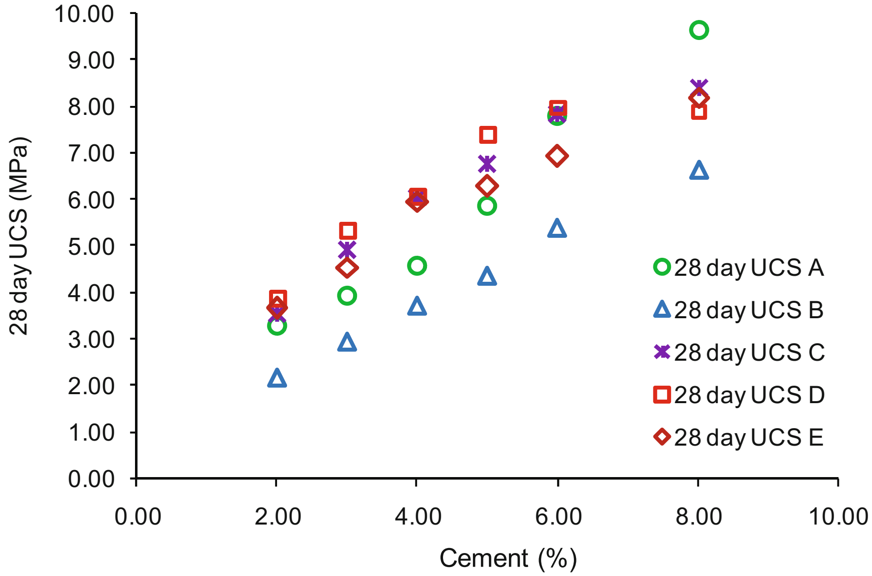

Fig. 4. 28 days UCS values of CLS (size 38 mm diameter and 76 mm height)

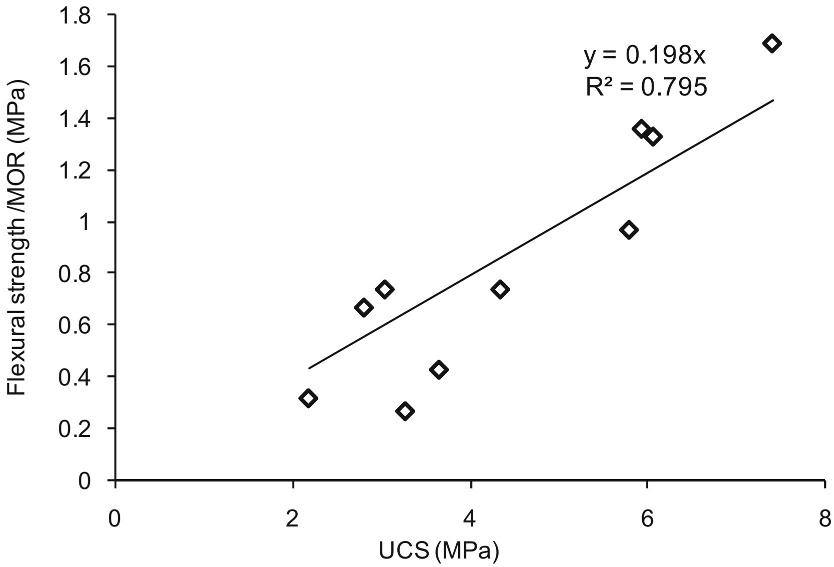

Fig. 5. MOR versus UCS

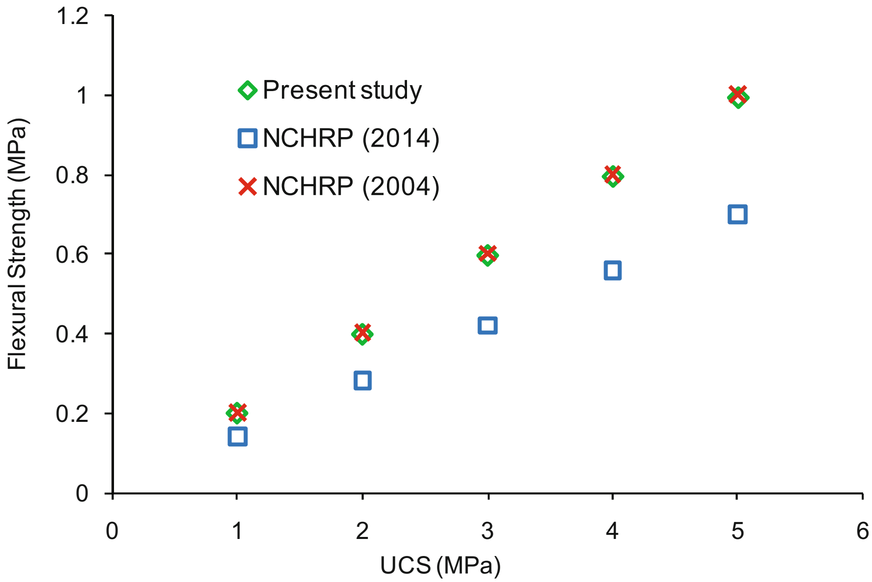

Fig. 6. MOR predicted from UCS using different correlations

respectively. The default value of MOR of soil cement adopted by IRC 37: 2012 and MEPDG for fatigue analysis is 0.7 MPa for UCS value of 5.17 MPa is very conservative for CLS as the predicted MOR obtained from Eq. 2 is 1.02 MPa. However, minimum value of MOR of CLS with 5% cement which is 0.74 MPa can be used as the design value of MOR for CLS.

$$MOR = 0.1985 \times UCS \quad R^2 = 0.79 \tag{5}$$

$$MOR = 0.14 \times UCS \tag{6}$$

$$MOR = 0.2 \times UCS \tag{7}$$

3.2 Flexural Modulus of CLS

Flexural moduli of 28 day cured lateritic soil samples with 2% cement and 5% cement at stress ratios of 0.2, 0.3 and 0.4 are illustrated in Fig. 7. It may be observed that, the modulus increases with stress ratio. This behavior of CLS is in line with gravel-cement, silt-cement and clay-lime (Wen et al. 2014). As already mentioned, flexural modulus at a stress ratio of 0.4 have been taken as the modulus of that sample as per the study of Austroads (2008).

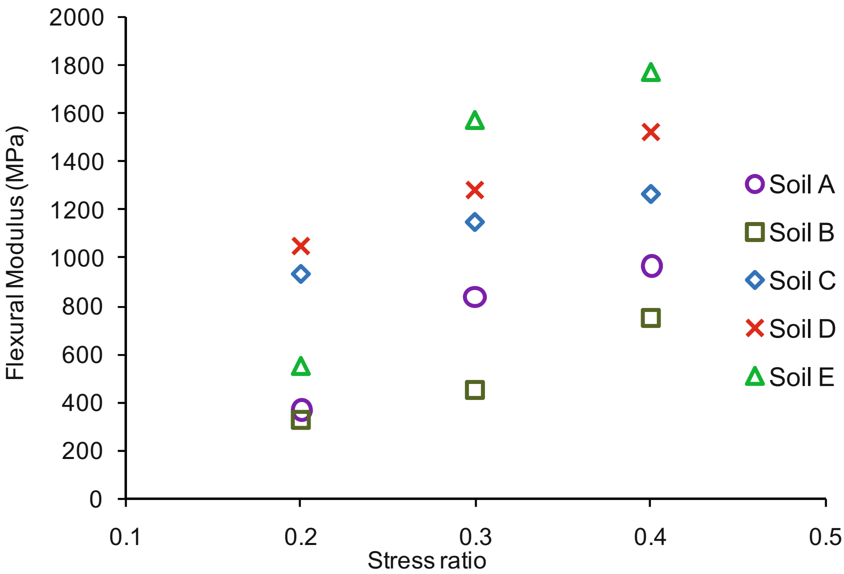

Fig. 7. Flexural modulus at various stress ratios

The relationship between flexural modulus and UCS is shown in Fig. 8 and presented in Eq. 8. However, more samples having wide a range of stiffness or strength values needs to be studied to develop a good correlation between flexural modulus and UCS. Similarly, the relationship between flexural modulus and UCS is shown in Fig. 9

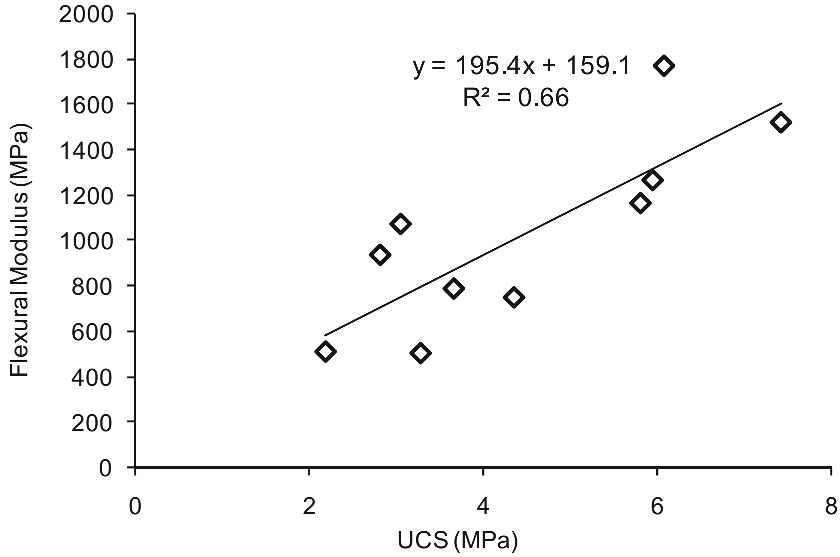

Fig. 8. Flexural modulus versus UCS

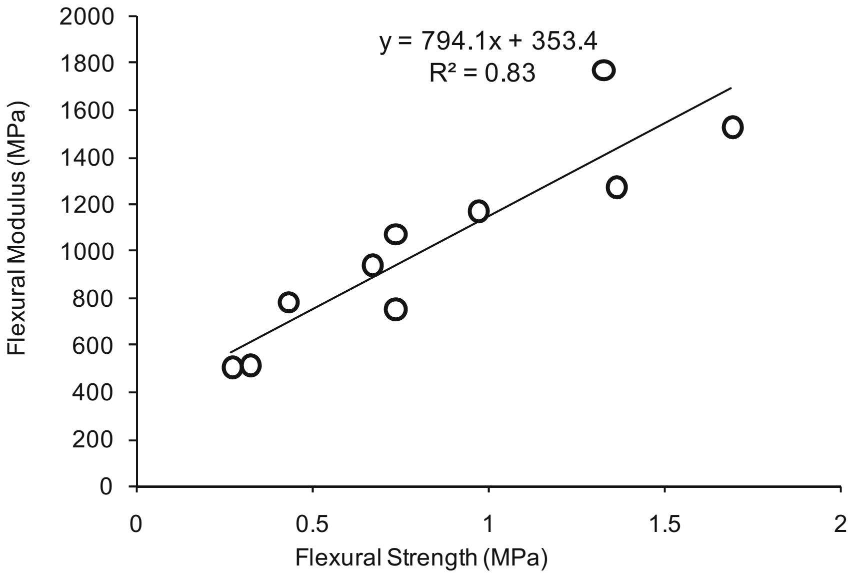

Fig. 9. Flexural modulus versus MOR

and presented in Eq. 9. It may be observed that the flexural modulus and MOR increases with increase in UCS which is in consistent with the earlier studies (Wen et al. 2014; Arulrajah et al. 2015; Austroads 2008).

Figure 10 shows a comparison between predicted flexural modulus and measured flexural modulus of CLS after 28 days curing periods. Figure 11 illustrates a comparison of predicted flexural modulus determined from UCS using various models such as Eq. 8 (present study), Eq. 1 (IRC 2012), Eq. 2 (ARA 2004) and Eq. 10 (Wen et al. 2014). It may be observed from Fig. 11 that the elastic modulus predicted from the relationship developed in present study is very close to the elastic modulus predicted from Eq. 10 (Wen et al. 2014). However, the design elastic modulus predicted from Eq. 1 (IRC 2012) is four times more than the elastic modulus predicted from the relationship developed in present study. Similarly, the design elastic modulus predicted from Eq. 2 (ARA 2004) are five times more than the elastic modulus predicted from the relationship developed in present study. Hence, it is very important to determine the elastic modulus value of cement stabilized soils by using appropriate laboratory of filed test which simulated the behaviour of stabilized layer in pavement

$$E_f = 195.43 \times UCS + 159.17 \quad R^2 = 0.66 \tag{8}$$

$$E_f = 794.1 \times MOR + 353.4 \quad R^2 = 0.83 \tag{9}$$

Where,

E_f = flexural modulus in MPa
UCS = Unconfined Compressive strength in MPa
MOR = Modulus of Rupture in MPa

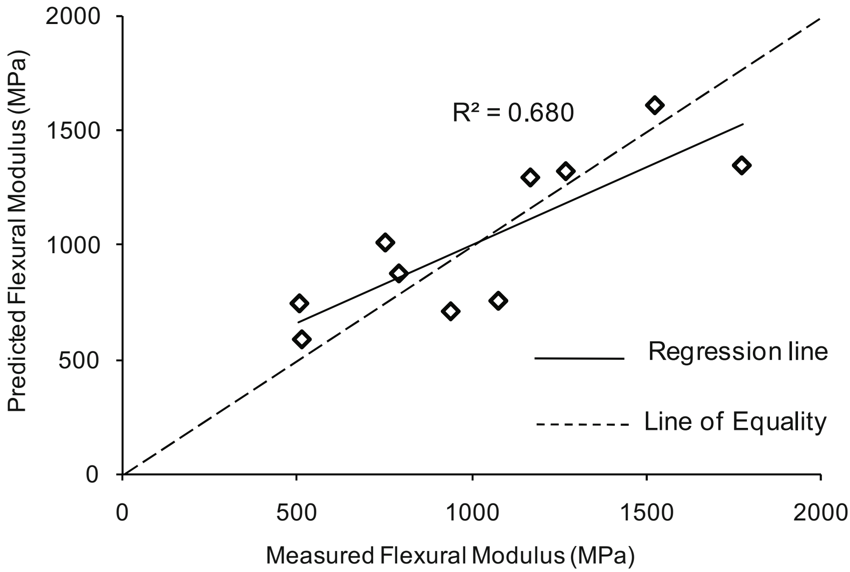

Fig. 10. Predicted verses measured flexural modulus values determined from UCS

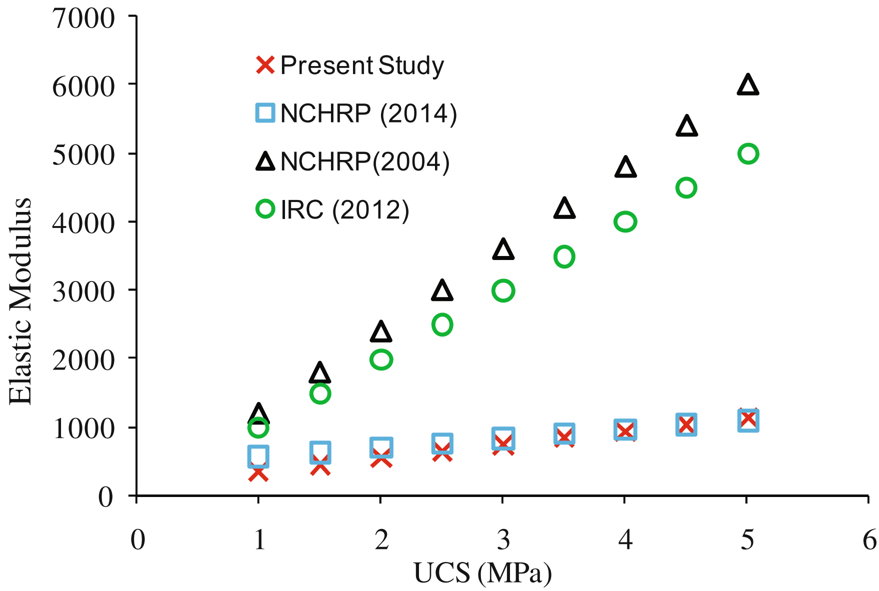

Fig. 11. Comparison of design modulus predicted from UCS

$$E_F^* = 131.08 \times UCS^* + 62382 \tag{10}$$

E_f^* = flexural modulus in psi
UCS^* = Unconfined Compressive strength in psi

4 Conclusions

A detailed laboratory testing programme have been conducted on cement stabilized granular lateritic soils collected from five different locations of eastern part of India to investigate the compressive strength, modulus of rupture and flexural modulus or design modulus. Cement stabilized granular lateritic soil at 2% cement is found suitable for sub-base layer from compressive strength criteria in both low. However, Cement stabilized granular lateritic soil at 5% cement content is found adequate for base layer of rural roads as per IRC:SP 7-2015. The relationship between modulus of rupture and UCS observed in this study is consistent with ARA (2004), Austroads (2012). Comparison has been made between predicted modulus of rupture and modulus determined from UCS of stabilized granular lateritic soil. Relationships have been developed to determine modulus of rupture of cement stabilized granular lateritic soil samples from UCS of CLS, for practical use. Design value of modulus of rupture, mentioned in IRC (2012), ARA (2004) is very close to the minimum modulus of rupture of CLS determined from this study. A relationship has also been established to determine the modulus of CLS from UCS. However, further study is required with more number of samples having a range of stiffness and/or strength values to develop a good correlation between flexural modulus and UCS. However, further studies of some important aspects like, shrinkage, durability and fatigue shall be conducted to assess the performance of stabilized granular lateritic soils, which are not within the scope of this paper.

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