Strengthening Low Plastic Soils Using MicroFine Cement Through Deep Mixing Methodology

Parth Shah, Manish Shah and Abhay Gandhi

Abstract The objective of the research work was to evaluate the settlement trait, modulus of subgrade reaction, elasticity, and shear strength of low plastic soil strengthened using Cement Deep Mixing technique. This is accomplished by performing modeled Plate Load and Unconfined Compression Test, respectively. For achieving the objective, a tank of size 75 cm × 75 cm × 75 cm was fabricated in which soil was compacted at different degree of saturation as 80 and 100% of optimum moisture content and using deep mixing assembly, soil–cement columns of different lengths as 100 and 200 mm were drilled and grouted. The assembly created comprised of cutter blade at the base of a solid pipe for facilitating drilling of the hole into the soil, and perforations all around the pipe facilitates grouting action during withdrawal. Filz theory (Geo-Front Congr ASCE 162(1):1–13, 2005) was adopted for deep mixing. Five columns of 5 cm diameter each out of which four columns at a spacing of 25 cm c/c and one under the footing were formed. Microfine cement slurry with water: cement ratio of 1.2 was used for grouting. Low plastic soil treated with microfine cement showed an appreciable reduction in the settlement as compared to untreated soil and was found to be adequate.

Keywords Cement deep mixing · Modulus of subgrade reaction · Modulus of elasticity · Shear strength

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1 Introduction

Deep soil mixing (DSM) technique is an in situ soil strengthening technique which delivers cement and/or other additives in either dry or slurry form using blades which lead to formation of soil–cement columns in different configurations. The aim of DSM technique was to minimize the settlement of soft ground, provide seismic resistance to soil against liquefaction, and reduce compressibility of soil and many more (CDIT 2002). There is a difference between jet grouting of the soil and DSM technique. Both the methods deal with penetrating the binder either in slurry or in dry form, but in case of jet grouting the main phenomena effecting its application is the pressure head which is created during injection of the slurry, whereas in case of DSM technique, static and the rotational head are the parameters that has an influence on the efficacy of the technique. DSM technique deals with penetrating the assembly into soil and filling up the hole with some suitable binder like cement, lime, flyash (Probaha 1988) during the withdrawal with the help of rotary motion of assembly; on the other hand, jet grouting deals with sealing up the hole with suitable binder at a certain higher injection pressure. DSM can be broadly classified as wet deep mixing method (WDMM) and dry deep mixing method (DDMM), the former being used for moisture content below 40% and the latter for moisture content above 60%. DSM technique mainly includes 23 different techniques. Cement deep mixing (CDM) is one among them which involves use of cements in either slurry or powder form to be used as a binder to be mixed with soil. CDM is further categorized in two different methods, namely CDM and CDM-LODIC method; the installation pattern of soil–cement column was adopted as suggested by Kitazume and Tersahi (2015). Ismail et al. (2002) suggested that Ordinary Portland Cement is best suited for the use as a binder material. Farouk and Shahein (2013) studied the effect of cement dosage, curing time, water-to-cement ratio on strength as well as the interaction between footing and soil. Carasca (2016) studied the strength characteristics of made up soil. The present research emphasizes on computing the settlement trait and shear strength of low plastic soil, subjected to variation in degree of saturation as 80 and 100% of optimum moisture content and at 90% of maximum dry density, soil–cement column length as 10 and 20 cm were strengthened using cement deep mixing technique. For shear strength test of deep mixed soil–cement, quantity was decided on the basis of method suggested by Federal Highway Administration Design Manual (2013), whereas for modeled Plate Load Test, CDM-LODIC method was employed which deals with replacing equivalent weight of soil by weight of cement at desired water-to-cement ratio.

2 Deep Mixing Assembly

The assembly created for facilitating the drilling of hole and its filling with cement slurry mainly comprised of a cutter blade whose width was so fixed that it drilled hole of exactly 50 mm in diameter. This blade was attached at the base of a solid pipe 25 mm in diameter; the main reason behind using solid pipe was from its stability point of view, so as it does not fail to meet its requirement. Filling of the hole by cement slurry was commenced during the withdrawal of the assembly. The assembly consisted of an inlet at the top and perforations over the circumference of the solid pipe, and these proved to be advantageous in achieving the desired mixing between the soil and the cement.

2.1 Working of Deep Mixing Assembly

As can be seen from Fig. 1, top portion of the solid pipe is reduced to a diameter of 125 mm, the reason behind this is the top portion of reduced diameter gets fixed into the hand drill, and the hand drill facilitates the rotating of the assembly during drilling as well as during the withdrawal. Two-way drill machine was employed to achieve two-way movement of the assembly during drilling and withdrawal, i.e., if the assembly was rotated clockwise during the drilling operation, it would be rotated anticlockwise during the withdrawal and vice versa. The speed of the assembly during penetration as well as during the withdrawing operation plays an important role in achieving the purpose of the work. Higher rotation speed was employed during withdrawing than that during penetration, the reason for this was to cause cement slurry to flow to the maximum distance during withdrawal and to cause minimum disturbance to the soil during penetration.

3 Investigation of Shear Strength of Soil

There are various factors affecting the shear strength of soil among which one being degree of saturation of soil. To investigate the effect of the same on shear strength, low plastic clay was selected as type of soil. The soil was compacted at different degree of saturation as 80 and 100% of optimum moisture content keeping the cement dosage same as obtained using the guidelines provided in FHWA-HRT 13-046 and water-to-cement ratio as 1.2. Microfine cement was used as binder in order to prevent the disintegration of soil particles as well as for the proper interaction between the finer soil particles and the cement. FHWA consists of standard curve of relation between the desired Unconfined Compression Strength and Total water-to-binder ratio, and thus for the desired strength of soil, the total water to

Fig. 1 Deep mixing assembly

binder ratio can easily be obtained from the plot. After obtaining the total water to binder ratio, the equations which facilitate the determination of the dosage of cement as per FHWA are as follows:

$$\gamma_{d,\mathrm{slurry}} = \frac{G_b \times \gamma_w}{1 + (w : b)G_b} \tag{1}$$

$$\mathrm{VR} = \frac{w \times \gamma_{d,\mathrm{soil}}}{(w_T : b - w : b) \times \gamma_{d,\mathrm{slurry}}} \tag{2}$$

$$\mathrm{VR} = \frac{\alpha}{\gamma_{d,\mathrm{slurry}}} \tag{3}$$

3.1 Physical Properties of Soil

Prior to commencing the preparation of soil specimen, the physical properties of the soil were evaluated by conducting laboratory tests. Laboratory tests were conducted as per the Indian Standards. The soil was classified as low plastic clay as per IS classification method.

Table 1 Physical properties of soil

Properties	Results
Specific gravity	2.7
Liquid limit (%)	32
Plastic limit (%)	21
Soil classification (IS)	CL
Free swell index (%)	9
Cohesion (kg/cm^2)	0.5
Angle of internal friction (°)	23
Optimum moisture content (%)	13
Maximum dry density (kN/m^3)	19.5

3.2 Sample Preparation and Testing Procedure

Field efficiency as in DSM technique is 50–80% of the laboratory (EuroSoilStab 2002) and hence fixing the desired shear strength of soil on field and taking its equivalent shear strength to be achieved in the laboratory, total water-to-binder ratio is obtained from the standard curve and cement dosage is then worked out using Eqs. (1), (2), and (3) mentioned above. The cement dosages obtained for degree of saturation as 80 and 100% of optimum moisture content are provided in Table 1. The desired unconfined compression strength test on field was fixed to be 250 kPa, and hence, on the basis of efficiency standards suggested by EuroSoilStab (2002), laboratory strength to be achieved was kept to be 400 kPa. The samples were prepared with the obtained cement dosages at a water cement ratio of 1.2 in mold of 40 mm diameter and 80 mm in length. These samples were cured for 28 days in sealed plastic bags at room temperature, and the strength was evaluated by performing unconfined compression strength test at a strain rate of 1.5 mm/min (Table 2).

4 Investigation on Settlement Trait of Strengthened Soil

One of the main advantages of CDM technique is the reduction in settlement of strengthened soil, this research deals with evaluating the percentage reduction in settlement of low plastic soil compacted at different degree of saturation and strengthened using different soil–cement column lengths. To achieve the objective

Table 2 Cement dosages at different degree of saturation

Degree of saturation (%)	$\gamma_{d,\text{slurry}}$ (kN/m^3)	VR	α (kg/m^3)
80	6.6	10^{-1}	65.6
100	6.6	1.3×10^{-1}	85.3

of the study, a deep mixing assembly comprising of cutter blade and perforations all around was created. Cutter blade was attached to base of solid pipe which facilitated drilling of hole in the soil and perforations all around the pipe facilitated filling of cement slurry in hole so created by rotational motion of the assembly during its withdrawal. The width of blade was so set that it exactly facilitated in drilling the hole which is 5 cm in diameter and of the desired length. Four columns were formed at a distance of 25 cm c/c and one exactly beneath the footing.

4.1 Test Setup

4.1.1 Preparation of Soil-Cement Columns

On the basis of trial and error, a water to cement ratio of 1.2 was found to be producing a workable mixture. Hence, a water-to-cement ratio of 1.2 was used and cement dosages for studying the settlement trait were fixed on basis of CDM-LODIC method which mainly involves replacing the weight of soil excavated from the hole by equivalent weight of cement. The soil–cement columns were installed in a steel tank of dimension 75 cm × 75 cm × 75 cm using deep mixing assembly by the procedure as described by Filz (2005). Deep mixing assembly was penetrated into the soil up to the desired depth and during its withdrawal slurry of microfine cement was poured in the inlet provided at the top of assembly, once the assembly was filled up with the slurry the assembly was rotated in the direction opposite to that during penetration. Due to higher rotating speed, cementious particles got well mixed with the soil particles, thus improvising the soil. Four columns each of diameter 50 mm and spaced at 250 mm c/c and one exactly under the footing of the same dimension. The replacement area ratio defined as the ratio of total cross-sectional area of column to the area loaded by steel plate. Replacement area ratio of 8.7% was kept fixed and degree of saturation of soil and soil–cement column length was varied to evaluate their combined effect on the percentage reduction in settlement (Fig. 2).

4.1.2 Preparation of Soil Bed

The soil bed was prepared in a steel tank supported on a loading frame specially fabricated for this purpose. The steel tank had internal dimensions of 750 mm 750 mm × 750 mm. In order to prohibit the movement of the tank as well as frame during the preparation of the soil bed and when during the installation of soil–cement columns, both the frame and the tank were fixed on a rigid support. The tank was also stiffened by diagonally placed angles to avoid its movement under the load. The soil was compacted at density corresponding to 90% of the maximum dry density with moisture content varying as 80 and 100% of optimum moisture content. In order to execute modeled plate load test on the treated as well as the untreated soil, a

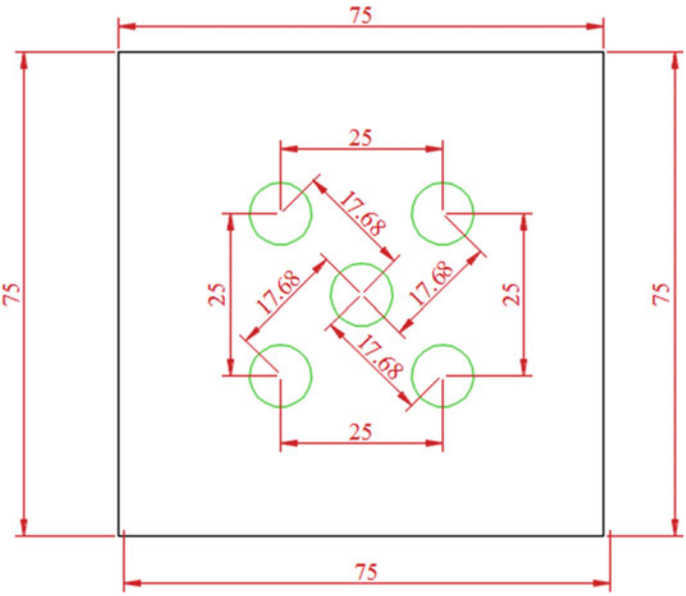

Fig. 2 Schematic plan of arrangement soil–cement columns

strip footing of size 150 mm × 150 mm (i.e., one fifth of the tank dimensions) was fabricated. The entire setup is schematically shown below in Fig. 3.

4.2 Testing Procedure

The test was initially commenced on untreated soil and latter on the strengthened soil in order to evaluate the percentage reduction in settlement of soil after strengthening. Strip footing of size 15 cm × 15 cm was loaded using a mechanical jack, and load was applied in equal increments. To ensure that footing model is subjected to a concentrated load, the rod is fixed at its base with the help of a cap having the same internal diameter as that of the rod. The rod is connected to the proving ring which in turn is attached to the mechanical jack. The settlement was recorded by mechanical dial gauge. Two dial gauges were installed at 180° in order to obtain average settlement. The loading was continued up to settlement of 25 mm or when the soil stops taking the load, whichever is earlier.

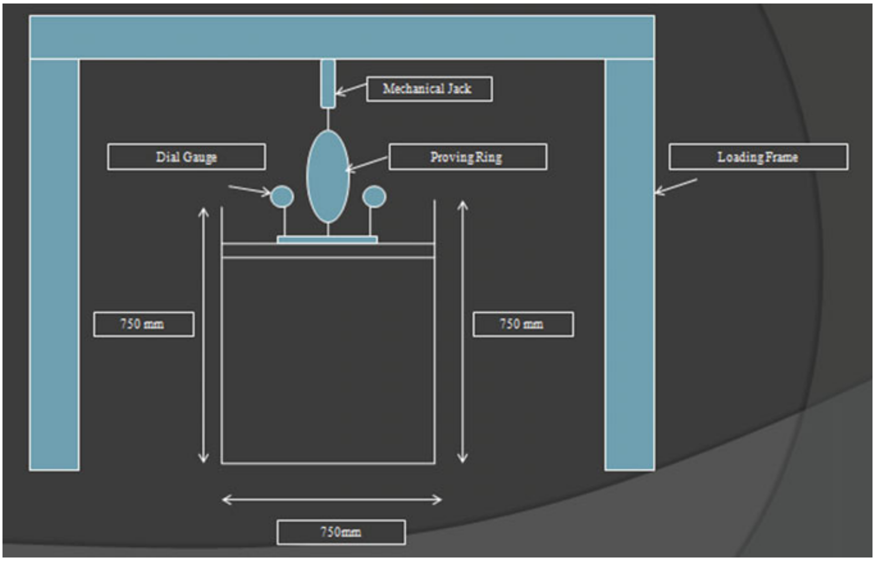

Fig. 3 Schematic diagram of modeled plate load test setup

4.3 Extracted Soil–Cement Columns

After completion of the modeled plate load test, soil–cement columns were extracted in order to check the extent up to which the cement particles grab the soil particles. On extraction it was found that cement particles were able to grab the soil particles in the range of about 3.5 times the diameter of column. Figure 4 shows the extracted soil–cement columns which depicts the influence zone of 3.5 times the diameter of column which nearly simulates the influence zone that is achieved in the field.

Fig. 4 Extracted soil–cement columns

5 Analysis and Discussion of Results

5.1 Strength of Treated Soil

The shear strength of untreated as well as treated soil was evaluated by performing unconfined compression strength test. The soil was compacted at 90% of maximum dry density with varying degree of saturation as 80 and 100% of optimum moisture content and was treated with cement dosages as obtained by employing the procedure given in FHWA. Since for unconfined compression strength test, the length-to-diameter ratio of specimen must vary between 2 and 2.5, and the diameter of soil–cement column was fixed as 50 mm, the effect of soil–cement column length was not being undertaken in evaluating the shear strength of strengthened soil. The results achieved for degree of saturation as 80 and 100% of optimum moisture content are presented in Table 3. The results clearly depict that although the cement dosage was fixed taking the desired strength value as 400 kN/m^2, in place of 250 kN/m^2, taking into account guidelines provided in EuroSoilStab, as the moisture content approaches toward the optimum the strength reduces although the cement dosage is fixed based on that particular moisture content. Thus, deep soil mixing technique is more preferable when the soil is compacted at the dry side of optimum. It can be clearly seen from the results presented in Table 3 that as the moisture content of soil approaches optimum moisture content, the strength of soil reduces even below the desired strength on the field. An increase in the moisture content of soil by 20% tends to reduction in strength by 10–15%. Thus, wet deep mixing method (WDMM) is more feasible when soil is compacted at dry side of its optimum; however, dry deep mixing method (DDMM) might turn out to be feasible at higher moisture content of soil, since it involves use of binder in dry form. It can be observed from the below tabulated values that with rise in the cement dosage strength reduces reason for which can be given as, since the cement dosage is entirely dependent on degree of saturation of soil and with the increase in degree of saturation the strength is reducing, it follows the same trend with cement dosage as well.

The stress–strain curve for samples at degree of saturation as 80% and 100% of optimum moisture content is presented in Fig. 5.

The values of unconfined compression strength obtained at 80 and 100% of optimum moisture content are compared graphically as shown in Fig. 6.

Table 3 Unconfined compression strength for different degree of saturation

Degree of saturation (%)	Unconfined compression strength test (kPa)			Average unconfined compression strength (kPa)
	1	2	3	
80	254.4	253.7	291	266.4
100	193	242.3	272	235.7

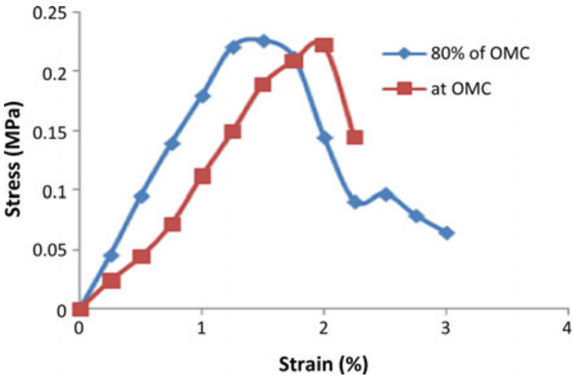

Fig. 5 Stress strain relationship at 80 and 100% of optimum moisture content

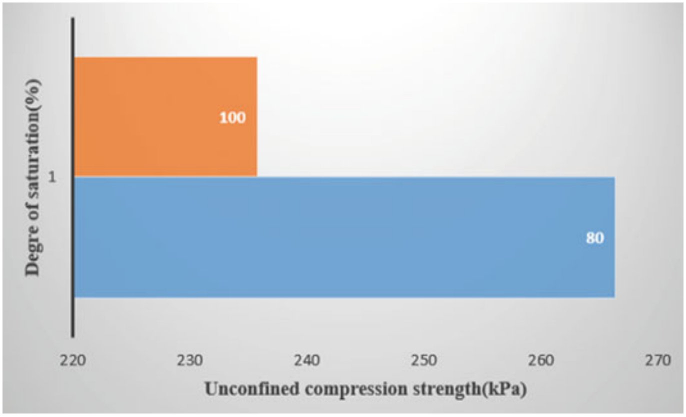

Fig. 6 Comparison between unconfined compression strength at 80 and 100% of optimum moisture content

5.2 Settlement Trait of Treated Soil

5.2.1 Effect of Degree of Saturation

The effect of degree of saturation on settlement trait of strengthened soil for soil–cement column length of 100 and 200 mm is illustrated in Figs. 7 and 8, respectively. As expected, for a given length of soil–cement column, the soil compacted on dry side of optimum showed about 10–15% greater reduction in the settlement as compared to those compacted at optimum moisture content.

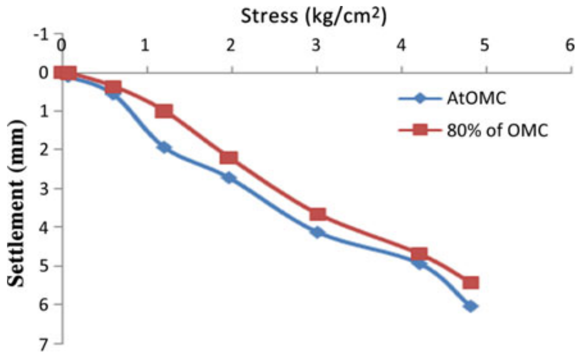

Fig. 7 Stress–settlement curve for 100 mm soil–cement column length at different degree of saturation

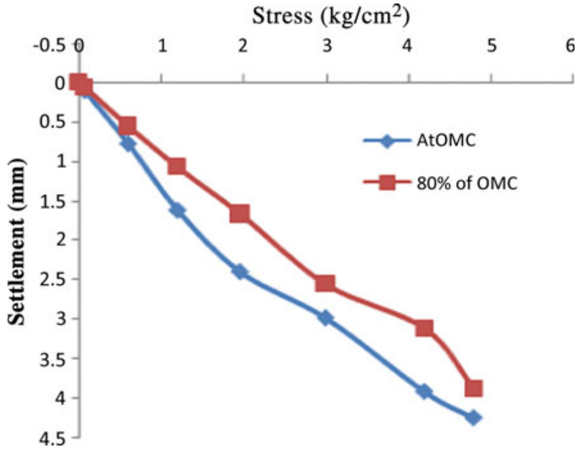

Fig. 8 Stress–settlement curve for 200 mm soil–cement column length at different degree of saturation

5.2.2 Effect of Soil–Cement Column Length

Figures 9 and 10 depict the settlement trait of soil for different length of soil–cement column length for soil compacted at 80 and 100% of optimum moisture content, respectively. For a given degree of saturation, increasing the column length showed about 35% more reduction in settlement.

5.2.3 Stress–Settlement Curves for Untreated and Strengthened Soil

The stress–settlement curve for untreated soil as well as for the soil treated with different soil–cement column lengths and compacted at different degree of saturation as 80 and 100% of optimum moisture content and treated with different soil–cement column lengths as 100 and 200 mm are illustrated in Fig. 11. Figure clearly depicts that under the same load untreated soil undergoes a settlement of 29.9 mm, whereas treated soil undergoes a maximum settlement of 6 mm.

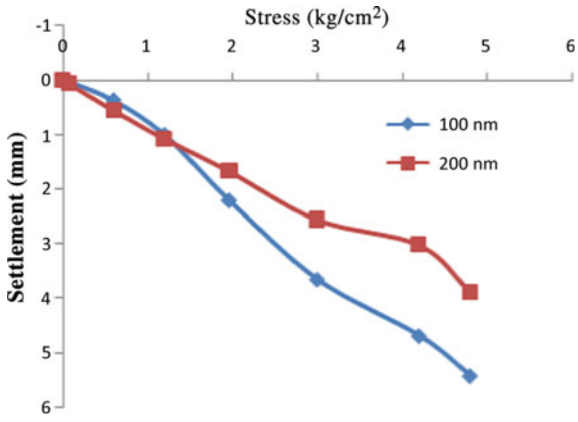

Fig. 9 Stress–settlement curve for soil compacted at 80% of OMC with different soil–column length

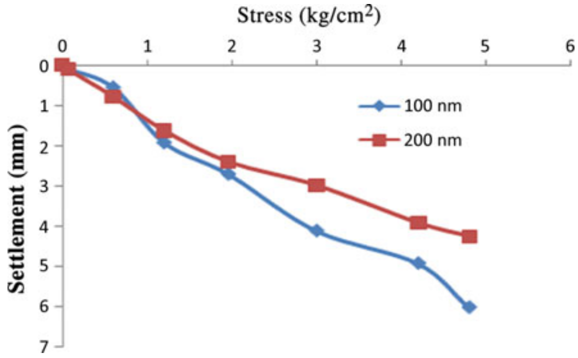

Fig. 10 Stress–settlement curve for soil compacted at OMC with different soil–column length

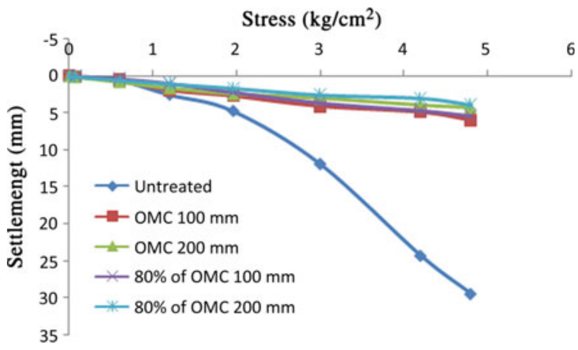

Fig. 11 Stress–settlement curve for untreated and treated soil

5.3 Modulus of Subgrade Reaction and Modulus of Elasticity

The stress–settlement curve obtained after commencement of the modeled plate load test helps in determining the modulus of subgrade reaction of the soil. The modulus of subgrade reaction was worked out corresponding to a settlement of 1.25 mm as well as to load of 0.7 kg/cm^2.

$$k = \frac{p}{0.125}\ \text{kg/cm}^2/\text{cm} \tag{4}$$

$$k = \frac{0.70}{d}\ \text{kg/cm}^2/\text{cm} \tag{5}$$

Equations (4) and (5) represent the equation employed for evaluating the modulus of subgrade reaction corresponding to settlement of 1.25 mm and an average displacement d (in cm), respectively. After applying corrections for the plate size, degree of saturation and for the load settlement curve, least of the above two values is taken as the modulus of subgrade reaction for the soil.

From the relation available between the modulus of elasticity and modulus of subgrade reaction of the soil as given by Eq. (6), modulus of elasticity of the treated as well as the untreated soil was worked out.

$$k = \frac{0.65E_s}{B(1-\mu^2)}\sqrt[12]{\frac{B^4E_s}{EI}} \tag{6}$$

FHWA (2013) suggests that the ratio of modulus of elasticity to unconfined compression strength at 28 days varies as 75–300; this relation is presently used to validate the experimental results. The ratio of experimentally obtained modulus of elasticity of treated soil to unconfined compression strength test of deep mixed soil at 28 days works out to be 146 (<300) for 80% degree of saturation, and 162 (<300) for 100% degree of saturation. It can be observed from the values of modulus of subgrade reaction and modulus of elasticity tabulated in Table 4 that there is a drastic improvement in their values as compared to untreated soil as well as when the degree of saturation is varied from 100 to 80% at a particular soil–cement column length.

Table 4 Modulus of subgrade reaction and modulus of elasticity of treated and untreated soil

Degree of saturation (%)	Soil-cement column length (mm)	Modulus of subgrade reaction; k (kg/cm^2/cm)	Modulus of elasticity; E (kg/cm^2)
At OMC (Untreated)	0	4.44	161.01
80% of OMC (Treated)	100	7.4	258.01
	200	7.7	267.65
At OMC (Treated)	100	5.0	179.67
	200	5.3	189.6

6 Conclusion

The important conclusions that can be derived from this study are listed below:

- As the moisture content of the soil approaches the optimum moisture content, strength of the treated soil reduces.
- For a given degree of saturation of the soil, with the increase in the soil–cement column length about 30–35% more reduction in settlement was observed.
- For a given soil–cement column length, with the increase in the degree of saturation of soil, the percentage reduction in settlement was recorded to decline by 10–15%.
- At same degree of saturation, with the increase in the soil–cement column length modulus of subgrade reaction was found to increase by 5–7%.
- For the same column length, with decrease in degree of saturation modulus of subgrade reaction was found to increase by 45–50%.
- At same degree of saturation, with the increase in the soil–cement column length modulus of elasticity of soil was found to increase by 4–6%.
- For the same column length, with decrease in degree of saturation modulus of elasticity of soil was found to increase by 45–50%.

It can thus be concluded that cement deep mixing (CDM) technique when applied on low plastic soils subjected to variation in degree of saturation gives satisfactory results. Use of microfine cement as a binder for low plastic soils was found to be adequate for a suitable water to cement ratio selected. Various assumptions regarding the length of soil–cement column were made in the study due to lack of ample amount of Indian Codal guidelines on CDM technique, the assumptions made provided adequate results, thus indicating the feasibility of CDM technique as a modern ground improvement technique for low plastic soil.

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