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Use of Crystalline Silica Waste for Enhancement of Engineering Properties of Black Cotton Soil

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ABSTRACT

Construction of pavement layers on subgrade soil with excellent properties reduces the thickness of pavements and consequently reduces the initial cost of construction. However, construction of pavement on poor soil subgrade like black cotton soil is unavoidable due to several constraints. In such a situation, the enhancement of subgrade properties can be attained by the addition of foreign materials. The worldwide growing usage of cement has led to a larger collection of crystalline silica from the cement manufacturing plants. The disposal of the crystalline silica is extremely challenging and also causes an environmental impact. Hence this waste material can be used for enhancement of the strength of the weak soils. Chemical analysis has revealed that crystalline silica is rich in oxides such as silicon oxide, aluminium oxide and calcium oxide. In this study, the black cotton soil is blended with 8%, 12%, 16%, 18% and 20% crystalline silica by the weight of the dry soil. Laboratory tests, namely, standard proctor compaction test, California Bearing Ratio (CBR) test and Unconfined Compressive Strength (UCC) test were carried out to examine the performance of crystalline silica mixture in black cotton soil. The outcome suggests that a potential increase in crystalline silica content enhances the maximum dry density (MDD). The results also indicate there is a huge potential to use crystalline silica as an admixture to strengthen the black cotton soil. Moreover, the employment of crystalline silica might also benefit the environment and construction cost.

INTRODUCTION

Environmental pollution emanating from the industries is a serious cause of concern. Rapid industrialization and urbanization have increased the level of pollution significantly. Every year an enormous quantity of waste materials is being dumped on the valuable land resulting in degradation of the existing soil. Moreover, the developed nations tend to perceive the developing nations as a source of dump yards for the disposal of solid waste matter. Thus, solid waste management has become a serious issue for third world countries. Solid waste disposal is posing a threat for many countries in today's scenario and many investigations are being carried out to convert the industrial and domestic wastes into usable materials. One among them is to utilize the solid waste materials for the stabilization of the weak and expansive soils such as black cotton soil. The internal structure of the black cotton soil is provided in Fig. 1.

Expansive soil is a term that denotes any soil or rock that has a potential for shrinking and swelling under changing moisture conditions (Nelson & Miller 1992). Structures that are built on such soils are subjected to severe damages. Soil stabilization is a process of enhancing the soil material resulting in improved bearing capacity, soil strength, and durability under adverse moisture and stress conditions (Joel & Agbede 2011).

These solid wastes can be of various types, namely, industrial (fly ash, bottom ash, foundry ash, copper slag, blast furnace slag, etc.), agricultural (bagasse, groundnut shell, rice husk, coconut shells, etc.), mineral (quarry dust, marble dust, etc.) and domestic (waste tyres, incinerator ash, etc.) (Sabat & Pati 2014). The volume of industrial waste production surpasses the waste production from other sources such as domestic, agricultural and mineral wastes due to the rapid growth of industrialization in meeting the ever-demanding needs of the people. Hence, the focus of our study is the stabilization of the black cotton soil using crystalline silica, an industrial waste.

Fly ash has been added for the stabilization of various expansive soils. Among fly ash, there are many varieties like class-C, class-F, etc. Various researchers have explored the effect of class-F on expansive soils (Pandian et al. 2001, Ji-ru & Xing 2002, Phanikumar & Sharma 2004, Amu et al. 2005, Hakari & Puranik 2012, Maneli et al. 2013, Radhakrishnan et al. 2014). The effect of class-C on expansive

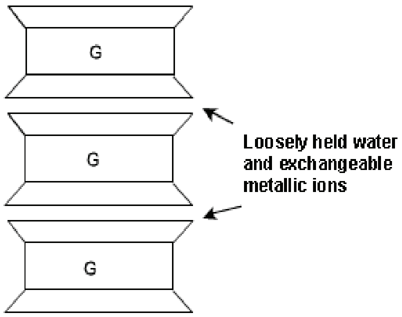

Fig.1: Internal structure of black cotton soil.

soils has been studied by Amu et al. (2005), Cokca (2001), Nalbantoglu (2004), Pandian & Krishna (2003), Misra et al. (2005). Cement kiln dust has been used for stabilization of expansive soils (Peethamparan & Olek 2008, Moses & Saminu 2012). The effect of the addition of silica fume on geotechnical properties of expansive soils was analysed by Kalkan & Akbulut (2004) and Negi et al. (2013). Havanagi et al. (2006) mixed copper slag with fly ash in expansive soils in different proportions and investigated their suitability in embankment, sub base and basements. Kalkan (2006) stabilized expansive clay with red mud (a waste material generated during the production of alumina) and cement red mud and found increment in the strength and decrement in the swelling percentage. Apart from these, various other industrial waste materials have been used in the past such as granulated blast furnace slag (Sharma & Sivapullaiah 2012, Celik & Nalbantoglu 2013), ceramic dust (Sabat 2012, Sabat & Bose 2014), brick dust (El-Aziz & Abo-Hashema 2013), and polyvinyl waste (Oyekan et al. 2013). Hotti et al. (2019) used plastic bottle granules as an additive for the stabilization of black cotton soil at Nargund taluk, Karnataka state. Fauzi et al. (2016) evaluated the engineering properties of black cotton soil stabilized with high density polyethylene (HDPE) and waste crushed glass as additives for subgrade improvement. Kumar & Singh (2017) analysed the stabilization of black cotton soil with cement kiln dust and reported that the optimum moisture content increases and the maximum dry density decreases with the cement kiln dust content. From the above literature, it is evident that crystalline silica has not been used for the stabilization of the black cotton soil. In this study, an attempt has been made for the first time on the utilization of crystalline silica for the stabilization and enhancement of the strength of black cotton soil.

MATERIALS AND METHODS

Black cotton soil collected from a site in Erramanaickenpatti, Palani, Tamilnadu (Latitude 10°28’52’’ N and Longitude 77°35’02’’ E) has been used in this work. The soil sample was collected at a depth of 1m. The soil sample was prepared following IS-2720 Part 1. Crystalline silica sand of size less than 300 microns was collected from the ACC fly ash brick plant at Madukkarai in Coimbatore.

The chemical characterization of crystalline silica sand was found using Scanning Electron Microscopy (SEM) analysis. The results of the SEM test are given in Table 1.

From Table 1, it is evident that the element (O K) was found to be relatively high when compared with other elements.

Laboratory tests such as standard proctor compaction test, California Bearing Ratio (CBR) test and Unconfined Compressive Strength (UCC) test were carried out to examine the performance of crystalline silica mixture in black cotton soil.

RESULTS AND DISCUSSION

In Proctor compaction test, the compaction characteristics namely optimum moisture content and corresponding maximum dry density of the soil for a continuous increase in moisture content was determined as per IS 2720-7:1980. The variation of dry density with respect to water content is shown in Fig. 2.

With the addition of water to the black cotton soil, at low moisture content, it became easier for the soil particles to move over one another during the application of the compaction force. This caused the reduction of voids which subsequently increased dry density. As the water content

Table 1: Composition of crystalline silica.

S.No	Element	Concentration
1.	O K	36.15
2.	Al K	3.42
3.	Si K	6.37
4.	Ca K	17.35
5.	Fe K	1.11

increased, the soil particles were surrounded by larger water films around them. This increase in dry density continued until the stage where the water starts to occupy the space that could have been occupied by the soil grains. Thus the water at this stage impedes the closer packing of grains and reduces the dry unit weight. During compaction, removal of more void increases the density but it is impossible to remove all the air voids. So, practically the compaction curve cannot cross the zero air voids curve, therefore the void ratio is always greater than zero. From Fig. 2, it was also found that the optimum moisture content of the soil is 22% and the maximum dry density of the soil is 1.422g/cc.

In an unconfined compression test, we determined the unconfined compressive strength of the soil as per IS2720-10:1991 and the plot of the stress distribution is shown in Fig. 3. The plot also aids in the verification of the bulking of soil under various loading conditions.

California Bearing Ratio test was done for evaluating the bearing capacity of soil sample for the design of flexible pavement. Tests were carried out on natural or compacted soils under water-soaked and un-soaked conditions. The results obtained were compared with the curves of the standard test to have a conception of the strength of the underlying subgrade soil. While designing pavements, this CBR value governs the thickness of other layers, i.e. if CBR of soil is high, the layer thickness will be less.

Based on the standard formula and Fig. 4, the value of CBR of soil under un-soaked condition is 5.91%. The CBR test was performed on the soaked soil sample also. The sample was subjected to the soaking period of 96 hours before loading to ensure the worst field conditions.

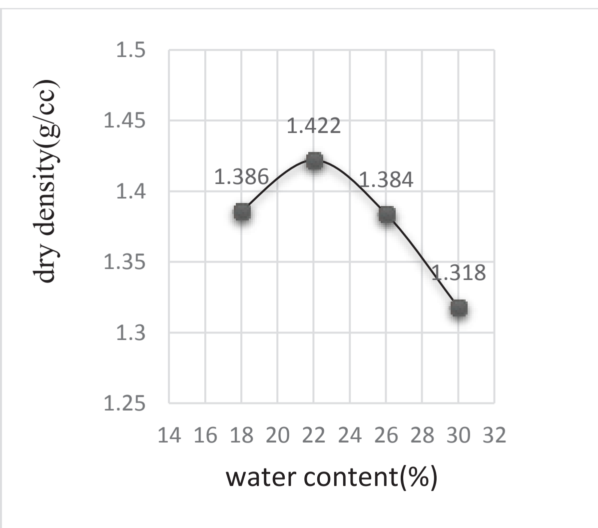

Fig. 2: Variation of dry density with water content.

Based on standard formula and Fig. 5, the value of CBR of soil in soaked condition is 1%. It is observed from the obtained values that the CBR value will generally be higher for the dry soil because the shear strength of dry soil is higher than the shear strength of wet soil. Moreover, since CBR is mostly associated with mechanical strength, the CBR (un-soaked value) will be higher than the CBR soaked value and a similar conclusion can be arrived here. Soaked CBR is used for the design of pavement as the earth beneath the pavement crust does not exactly remain dry throughout the year after the construction of the pavement. Some water does eventually reach the subgrade having percolated through interconnected voids, present either due to inadequate compaction, faulty mix design or potholes or by infiltration through the unpaved shoulders. The water affects the shear strength and bearing capacity

(CBR is the index of bearing capacity) of the subgrade, and weakens the subgrade, when moisture content exceeds the optimum moisture content (OMC). The various indexes and engineering properties of the soil are given in Table 2.

The compaction test was done with black cotton soil with the addition of crystalline silica to determine the optimum percentage of crystalline silica that would increase the dry density. With this optimum percentage, the unconfined compressive strength test and the California bearing ratio test were performed.

Effect of Crystalline Silica on Black Cotton Soil

The black cotton soil was added with 8%, 12%, 16% and 20% of crystalline silica and different percentages of water were added to determine the maximum dry density and the optimum moisture content.

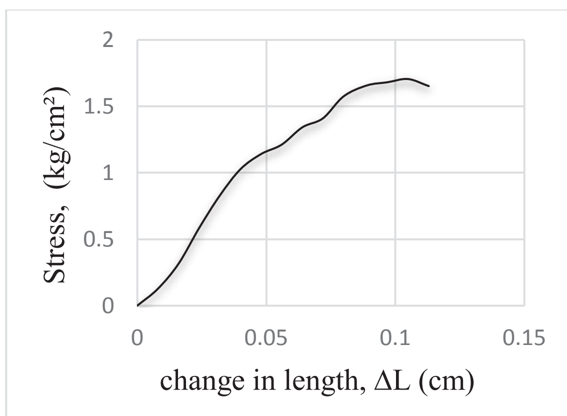

Fig. 3: Variation of stress with the change in length in UCC test for virgin soil.

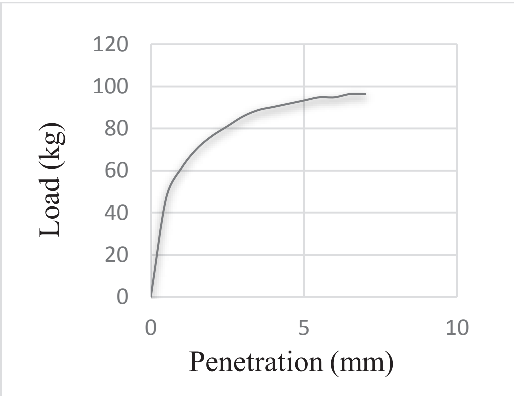

Fig. 4: Variation of load with penetration in CBR test during the un-soaked condition.

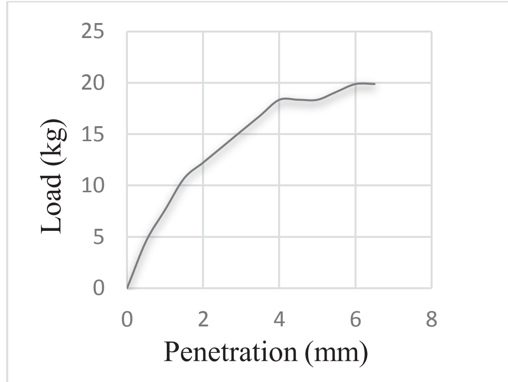

Fig. 5: Variation of load with penetration in CBR test during the soaked condition.

The unconfined compressive strength of the soil was carried out at an optimum percentage of 16% crystalline silica sand mixed with black cotton soil to determine the bulking characteristic of modified soil since the dry density is maximum at about 1.486 g/cc for the addition of 16% of silica sand when compared to others. A graph was plotted between stress and change in length for the addition of 16% of silica and the same has been illustrated in Fig. 6 to verify the bulking characteristics.

It can be inferred from Fig. 6 that the shear strength of the soil increases with the decrease in water content and an increase in dry density. Undisturbed soil can exist with either flocculent or dispersed structures depending upon mineralogy, the ion concentration of the pore fluid and the stress history. The structure is a principal factor of shear strength since a flocculent structure will tend to exhibit higher strength than a dispersed structure. The higher strength in the flocculent soil was probably because a greater number

Table 2: Obtained values for various properties of soil.

S. No	Test Conducted	Value
1.	Natural moisture content (Oven Drying Method)	33%
2.	Specific Gravity (Density Bottle Method)	2.07
3.	pH	8.9
4.	Organic content	16.66%
5.	Ash content	83.33%
6.	Differential free swell	40%
7.	Colour	Dark grey
8.	Atterberg's limits: Liquid Limit(W_L) Plastic Limit(W_P) Shrinkage Limit(W_S) Plasticity Index(I_P) Consistency Index(I_C) Shrinkage Ratio(R) From Plasticity chart (soil type)	68% 22.78% 15.23% 41.29% 0.85 1.48% MH type
9.	OMC MDD	22% 1.422g/cc
10.	Unconfined compressive strength	175.6 kN/m^2
11.	Fine-grained particles Coarse-grained particles	98.64% 1.36%
12.	CBR test: Unsoaked condition Soaked condition	5.91% 1%

of interparticle contacts would have disrupted during the shearing process. As the natural water content increases, which increases void ratio and degree of saturation, the shear strength of the black cotton soil decreases since the particles are forced apart, thereby decreasing the magnitude of the attractive forces. This indicates that the shear strength parameters, i.e., cohesion and angle of internal friction decrease with increasing water content.

With reference to shear strength, emphasis can be made on compacted samples. The states of particle arrangement (structure) that exist at various phases of compaction are shown in Fig.7. The changes in the arrangement of soil particles are explained as follows. At point A, the electrolyte concentration is very high due to the low water content and prevents the diffuse double layer of ions encompassing every particle from developing absolutely. The depression of the diffuse layer leads to low interparticle repulsion resulting in a tendency towards flocculation of the colloids. If the water content is increased to point B, the electrolyte concentration is reduced, resulting in an expansion of the double layer, increased repulsion between particles and a lower degree of agglomeration, which is an increased degree of particle orientation. Further increase in water content to an extent C, increases the sequel and ends up in a still higher increase in particle orientation. The mineralogical composition of the black cotton soil will determine the magnitude of variation of structure with moisture content. The above discussion explains the effect of moisture content and mineralogy on the shear strength of remoulded samples of the cohesive soil. The shear strength of the black cotton soil increases to a maximum and then decreases with increasing water content. The increase in strength at low water content indicates the need for some amount of water before the diffuse double layer is satisfied. Additional water added above optimum then reduces the electrolyte concentration, thereby, allowing changes in particle orientation which decrease the shear strength.

The CBR value of the black cotton soil with the addition of the optimum percentage of crystalline silica in the unsoaked and soaked condition was determined, and the values are plotted in Fig. 8 and Fig. 9.

Based on the results obtained from the compaction test, unconfined compression test and California bearing ratio test, the following remarks could be proposed for stabilizing weak soil using crystalline silica. Addition of crystalline silica into the black cotton soil changed the proctor compaction parameters as given in Table 3. The maximum dry density increased with increase in crystalline silica content while the optimum moisture content decreased. From Fig. 10, it is noted that the inclusion of crystalline silica in the black cotton soil causes an improvement in maximum dry density up to 16%.

The variation of maximum dry density with varying optimum moisture content in the crystalline silica treated black cotton soil is shown in Fig.11

The variation of unconfined compressive strength in the black cotton soil before and after the addition of crystalline silica is shown in Fig.12. The unconfined compression strength has increased from 174 kN/m^2 (natural soil) to 341.9kN/m^2 (treated soil). The CBR values have increased for both soaked and unsoaked condition for the soil treated with silica content. (Table 4). Unsoaked CBR value has increased by more than 1.4 times when compared to the initial CBR value. Although the CBR value has increased for the soaked condition also, the change is not significant due to loss of cohesion and additional softening of soil due to soaking.

The variation of CBR value in the black cotton soil before and after the addition of crystalline silica are shown in Fig. 13 and Fig. 14.

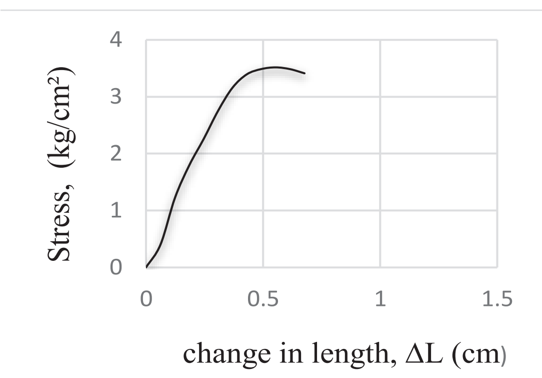

Fig. 6: Variation of stress with the change in length for the addition of 16% of silica.

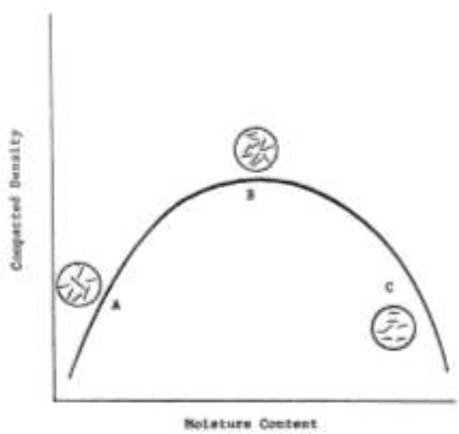

Fig. 7: Variation of compacted density with moisture content.

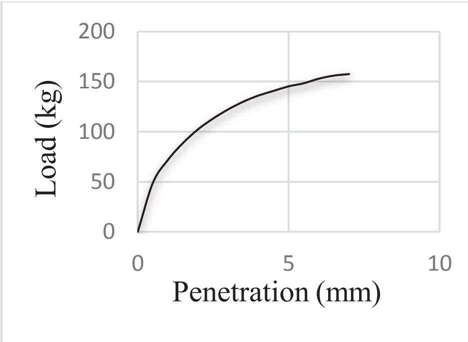

Fig. 8: Variation of load with penetration in CBR test during the un-soaked condition for treated soil.

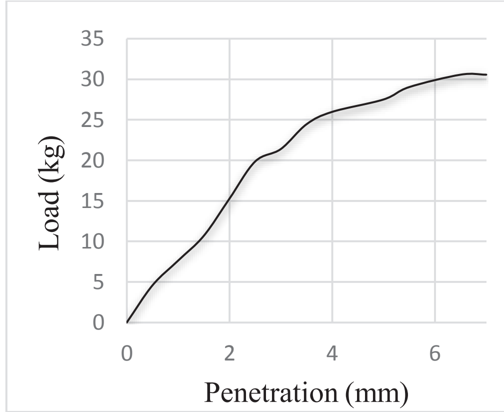

Fig. 9: Variation of load with penetration in CBR test during the soaked condition for treated soil.

CONCLUSION

The optimum content of crystalline silica waste was found to be 16% as the mixture attained an increase in UCS value when compared with the virgin soil. CBR value also increased under both un-soaked as well as soaked condition for the silica treated soil. The results of this study confirm Crystalline Silica Sand (CSS) as a potential stabilizer in improving engineering qualities of black cotton soil. Crystalline Silica, a waste material from the cement manufacturing plant is cost-effective, environmentally sustainable and can be gainfully used in pavement engineering construction. This application will enable the nation in achieving economic growth and industrialization if employed as part of the green growth development strategy.

Table 3: Variation of MDD and OMC of stabilized black cotton soil.

Soil Type	OMC	MDD (g/cc)
Black Cotton soil	22%	1.42
BC + 8% crystalline silica	22%	1.42
BC + 12% crystalline silica	20%	1.426
BC + 16% crystalline silica	18%	1.482
BC + 18% crystalline silica	14%	1.439
BC + 20% crystalline silica	14%	1.438

Table 4: CBR value.

Condition	Natural Soil	Treated Soil
Unsoaked	5.91%	8.3%
Soaked	1%	1.45%

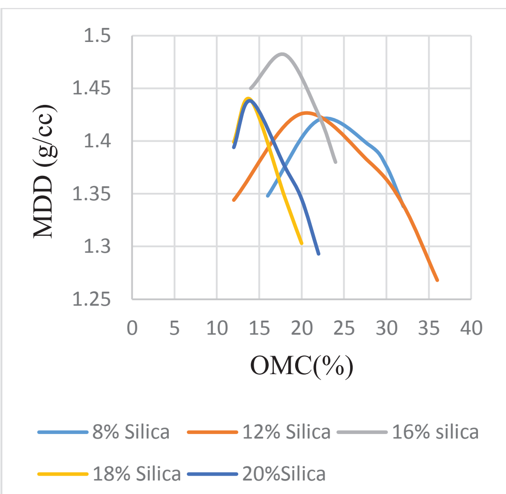

Fig. 10: Variation of OMC and MDD with various percentages of silica content.

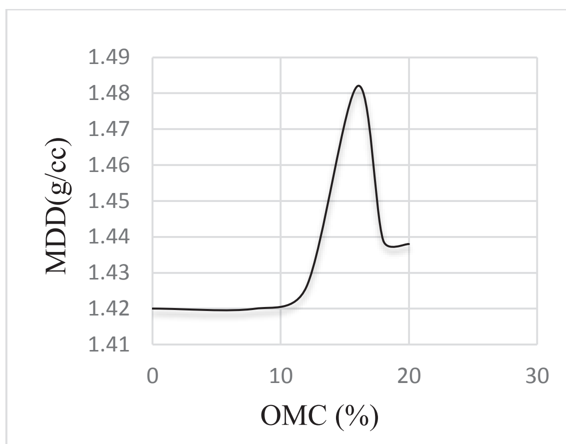

Fig.11: Variation of MDD and OMC of stabilized black cotton soil.

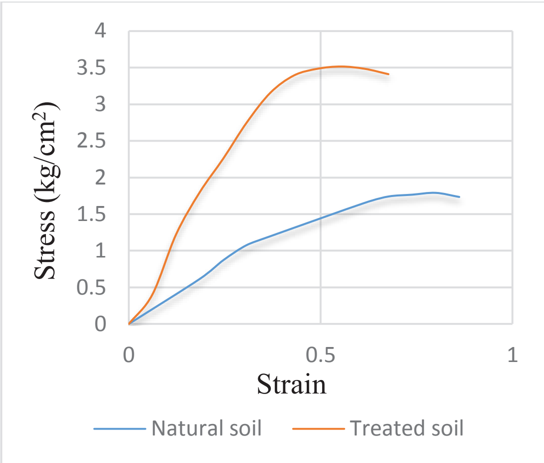

Fig.12: Variation of UCS with the addition of silica.

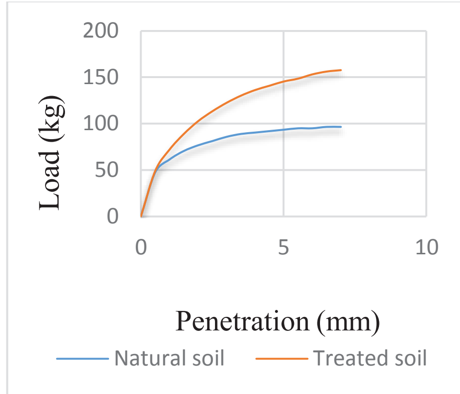

Fig.13: Variation of CBR with the addition of crystalline silica (un-soaked).

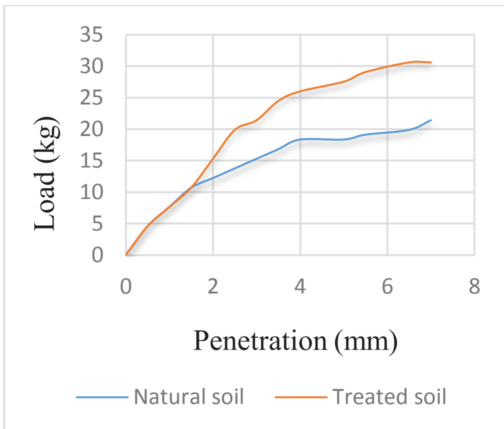

Fig. 14: Variation of CBR with the addition of crystalline silica (soaked).

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