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ORIGINAL CONTRIBUTION

Stabilization of Black Cotton Soil Using Micro-fine Slag

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Abstract This work presents the results of laboratory tests conducted on black cotton soil mixed with micro-fine slag. Different proportions of micro-fine slag, i.e., 3, 6, 9, 12 and 15 % were mixed with the black cotton soil to improve soil characteristics. The improvement in the characteristics of stabilized soil was assessed by evaluating the changes in the physical and strength parameters of the soil, namely, the Atterberg limits, free swell, the California Bearing Ratio (CBR), compaction parameters and Unconfined Compressive Strength (UCS). The mixing of micro-fine slag decreases the liquid limit, plasticity index and Optimum Moisture Contents (OMC) of the soil. Micro-fine slag significantly increases the plastic limit, UCS and CBR of the soil up to 6–7 % mixing, but mixing of more slag led to decrease in the UCS and CBR of the soil. The unsoaked CBR increased by a substantial amount unlike soaked CBR value. The swell potential of the soil is reduced from medium to very low. The optimum amount of micro-fine slag is found to be approximately 6–7 % by the weight of the soil.

Keywords Black cotton soil · Shrinkage · Micro-fine slag · Expansive soil · Strength · Compaction

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Introduction

Expansive soils cover a considerable part of various countries including India. These soils are also called as black cotton soil owing to their black color which is a result of high iron, humus and magnesium minerals derived from trap and basalt. It is mostly found in Maharashtra, Madhya Pradesh, Gujarat, Tamilnadu, Andhra Pradesh, and Karnataka states of India and covers almost 22 % of total land cover of the country [1]. Swelling and shrinkage are the key characteristics of these soils which cause threats to the foundations, structures, roadways, railways and various other life lines. These soils swell and shrink, respectively, with the increase and decrease in the water content. In the monsoon season, clay minerals attract water and causes the swelling and softening of soil whereas in the summer season, after evaporation of water, these soils shrink and produce cracks on it [2]. After absorption of water, soils become compressible and it leads to decrease in strength of the soil.

Swelling and contraction of the black cotton soil mainly occur owing to the presence of montmorillonite minerals in the soil [3]. Montmorillonite has a central octahedral sheet sandwiched among twofold tetrahedral sheets and it forms a three-layer element. A reason for swelling is the weak bond between the elements, which can be broken due to absorption of water. The researchers have found that the diffusion of water can be a main cause of swelling [4]. Swelling of soil comprises of two stages, first stage is inter-crystalline swelling and the second stage refers to double-layer repulsion [5].

Expansion of soil depends on the characteristics of water content, the initial dry density of soil, characteristics of clay minerals and type of cations present in the soil. If sodium is present in large amount, it can lead to high volume change after absorption of water. The thickness of the diffused double layer changes with change in the concentration of cations. The thickness of water layer decreases with the increase in the concentration of cations, hence various researchers had tried to find out an additive which increases the cation exchange capacity. The cation exchange capacity has a considerable influence on the process of clay expansion due to soil wetting [6].

Black cotton soil has proved itself as a source of damage to the property and economical loss. Expansion and contraction of black cotton soil causes various problems to the civil engineers not only at the time of construction but also throughout the life of structures. Uneven contraction and swelling reduce the serviceability of the structures. It causes the emergence of hairline cracks, differential settlements, and sometimes even severe cracks, which may initiate the collapse of structures, railway lines and roadways. Decrease in the availability of suitable soil for construction has forced researchers to search for an appropriate method to improve the performance of locally available problematic soil. During the last four decades, lots of research have been conducted on black cotton soil to reduce its expansion and contraction, and to save a lot of resources.

Literature Studies

Unavailability of suitable land for construction of roads, homes, railways, and other facilities have forced engineers to explore an appropriate and efficient method for ground improvement. Ground improvement has become an important and inevitable part of geotechnical engineering projects in developing countries due to significant progress in infrastructure, railways, roadways and unavailability of suitable land. Suitable remedial measures are to be considered before construction on the black cotton soil. A large number of solutions are available to improve the workability and minimize swelling and expansion of black cotton soil such as, removing the black cotton soil up to a particular depth, keeping the water table constant well below foundation level, reinforcing the soil, use of under reamed foundation or altering the properties with some additives. After certain depth, it is not feasible to the remove whole of the soil or retain the water table constant well below the expansive soil, so alternatively, additives can be used to alter the composition of soil and to improve the performance of soil.

Many researchers have used mechanical stabilization methods to modify the soil characteristics and minimize the expansion and shrinkage of soil. Thermal stabilization methods are also found useful for expansive soils. Chemical stabilization causes the reduction in the swelling and shrinkage characteristic of soil along with the reduction in the soil plasticity. Electrolytes have also been used as a stabilizer but the main problem involved in the use of electrolyte is the non-uniform mixing of chemicals which may give erratic outcomes. Another problem is that black cotton soils are very hard, and pulverization of clods for treatment remains a big task for engineers in the field [7].

At present, India, along with the world is producing billion tons of blast furnace slag every year which is creating various immense environmental problems. However, mix concrete industry is utilizing approximately nearly half of the amount [8]. Blast Furnace Slag (BBS) obtained from iron and steel manufacturing industries possess potential cementations reactivity. Various researchers have used Ground Granulated Blast furnace Slag (GGBS) to stabilize the various type of soils and have considered it as a potential soil stabilizer. Lime-GGBS can also be used as an alternative to cement. It increases the CBR and UCS of soil with and without the addition of gypsum [9]. A small amount of GGBS is sufficient to reduce the expansion of lime stabilized kaolinite which is exposed to water [10]. Earlier, investigators have determined the effect of mixing of GGBS on laterite soil. The amount of GGBS were varied between 0 and 15 % by weight of dry soil. Plastic limit and liquid limit were decreased with the addition of GGBS, while CBR, internal friction and cohesion values were improved with the increase in the GGBS content up to 10 % and furthermore addition caused reduction in these parameters. The addition of finer GGBS can lead to the early strength gain of mix and decrease in the erosion rate [11].

Neeraja and Rao (2010) [12] used various industrial wastes such as lime, GGBS, fly ash (FA) and rice husk ash (RHA) as stabilizing material for expansive clayey subgrade of flexible pavements. The optimum amount of lime, GGBS, FA and RHA was found to be 5, 15, 20 and 15 % respectively. It was reported that maximum improvement in the soil properties was achieved by adding lime up to 5 %, RHA and FA up to 20 % and GGBS up to 15 %. Sharma and Shivapullaiah [13] mixed GGBS with the expansive soil and found that the initial tangent modulus magnitude was improved with the increase in the quantity of GGBS in soil. The efficiency of additive depends more on the quantity of GGBS and less on the curing period. The un-soaked and soaked CBR value of soils increased significantly with incorporation of granulated blast furnace slag [14]. Patel and Joshi (2015) [15] used activated micro-fine slag cement grouts and found that UCS of soil samples improved by a significant amount. It has also been found that the compressive strength of soil was improved with the increase in the amount of micro-fine slag cement grout content and curing period [16]. Addition of micro-fine slag increased the performance of concrete. It also improved the workability, strength and durability of concrete [17].

Plasticity index, OMC and swelling pressure were decreased with the addition of GBFS. UCS, CBR and MDD were increased with the increase in the GBFS up to 9 % but further increase in the GBFS decreased the UCS, CBR and MDD value.

From the literature review, it is observed that most of the studies have determined the effect of GGBS on concrete pavements and some studies were conducted on GGBS stabilized black cotton soil. A few preliminary studies were also conducted to determine the effect of micro-fine slag on such soils. In this study, an attempt has been made to examine the effect of micro-fine slag on the black cotton soil characteristics. The improvement in the characteristics of micro-fine slag mixed soil were assessed by evaluating the changes in the physical and strength parameters of soil, namely, Atterberg limit, free swell, California bearing ratio, compaction parameters and unconfined compressive strength.

Material Used in the Study

The soil was collected from Guna, Madhya Pradesh which is black-grey in colour. The soil properties are determined as per Indian standard code and are presented in the Table 1.

ALCCOFINE 1203 is a very fine material mostly used in concrete industry as a supplementary cementitious material. It can be used in the place of silica fume, an important constituent of high performance concrete. It is an especially treated product with high workability and reactivity, produced through the process of controlled granulation. It was bought from Counto Micro-Fine Product Private limited, Goa, India, a division of Alcon Enterprises and JV with Ambuja Cements. It was used as an additive in present analysis. Chemical constituents and physical properties of micro-fine slag are shown in Tables 2 and 3 respectively.

Testing Methodology

Soil samples were collected from the field and preserved in desiccator for further testing. Firstly, index properties; Atterberg limits, in-situ moisture content, grain size distribution curve and maximum dry density of all the soil samples were determined in the laboratory as per the Indian standard codes. IS: 2720, Part IV [18] was used for determination of grain size analysis. The plastic limit and liquid limit of micro-fine slag mixed soil were determined using the thread rolling method and Casagrande percussion method respectively. The Atterberg limits of expansive soil samples were determined as per IS 2720-Part-V (1985) [19].

There are two methods available to estimate the shrinkage limit of fine-grained soil, namely, wax method and mercury method. The mercury device test method was used to assess the shrinkage limit. In this method, the total volume of specimen was determined when samples were dried out. Variation in the shrinkage limit of the soil samples were measured by changing the amount of micro-fine slag in the soil sample. The detailed procedure for the same is given in Indian standard code IS: 2720 (Part VI)-1972 [20].

The standard proctor tests were conducted on untreated soil and micro-fine slag mixed soil as per Indian standard IS 2720-Part-VII (1980) [21] and IS 4332-Part-III (1967) [22] respectively. Micro-fine slag content was varied from 3 to 15 % by weight of the soil. A sufficient quantity of water was added to the micro-fine slag mixed soil to enable smooth mixing and compaction. A metallic mould having inner diameter 38 and 76 mm length was used to prepare samples for the unconfined compressive strength tests. Samples were prepared for optimum moisture content and were compacted from both the ends to achieve a uniform compacted sample. The specimen was removed from the metallic mould using a hydraulic jack. The strain rate of 1.2 mm/min was selected for the UCS test.

Table 1 Physical properties of black cotton soil used

Property	Description, %	Property	Description
Silt + clay	67.3	Liquid limit, %	67.40 %
Fine sand	16.4	Plastic limit, %	44.20 %
Medium sand	12.1	Plasticity index, %	23.20 %
Coarse sand	4.2	Soil classification	MH
Shrinkage limit	13.1	UCS	191.20 kPa

Table 2 Chemical constituents of micro-fine slag used

Chemical constituent	Description, %
SiO_2	22
Al_2O_3	5.2
Fe_2O_3	4–5
CaO	62–63
SO_3	2.0–2.5
MgO	1–1.5

Table 3 Physical properties micro-fine slag used

Physical properties	Description
Fineness	12,000 cm^2/gm
Specific gravity	2.9 μm
Particle mean diameter	1.5 μm
D_{50}	5 μm
D_{90}	9.0 μm
Plasticity	Non plastic

The California bearing ratio tests were conducted as per IS 2720-Part-XVI (1987) [23]. The CBR tests were conducted on untreated soil as well as on micro-fine slag added soils. CBR depends on the state of soil at the time of testing so both unsoaked and soaked CBR were determined in the laboratory. Static compaction was used to compact the soil in the CBR mould. The amount of soil required to fill the mould was evaluated based on the maximum dry density and corresponding optimum moisture content. To minimize the friction between the soil and the mould wall, a thin coating of lubricant was applied on the inner surfaces of the CBR mould. The required mass of soil was placed in the mould in five layers. Each layer of soil was compacted with a rammer of 4.5 kg weight. The soil was compacted by free fall of rammer. After soaking the soil for 4 days, soil was tested. The load versus penetration curve was drawn for the untreated soil as well as for the micro-fine slag stabilized soils and the CBR values were determined from the curves.

For preparing a sample for UCS testing, initially, a predetermined quantity of micro-fine slag was mixed with air-dried black cotton soil. Water equal to OMC of soil was added to the soil and the components were uniformly mixed for homogeneity. A metallic split mould was used to prepare the sample of 38 mm diameter and 76 mm height. Three specimens were prepared and tested for a certain quantity of micro-fine slag. More details of the testing procedure, calculation and other guidelines are given in Indian standard IS 2720 (Part XI): 1983 [24]. Swelling potential was determined using the consolidation test apparatus (fixed ring). Oven dried soils and micro-fine were used to prepare the specimen at desired density. Static compaction was applied to prepare the sample. An air dried porous stone was placed on oedometer and then a filter paper was placed on the top of stone to avoid invasion of soil into the porous stone. Testing was performed under a seating pressure of 7 kPa. The change in the height of soil sample was directly determined from the vertical dial gauge reading. The final reading, which remains constant for a considerable time was used to determine the percentage change in the height of soil. Detailed method to determine the swell potential is given in Seed et al. [25]. The swelling potential can also be determined based on the plastic properties of soil. A number of empirical relations are available in literature to determine the swelling potential of soil [3, 7, 26].

Results and Discussion

The effect of micro-fine slag on different properties of expansive soil was determined as per Indian standards and discussed in the following sections, namely, the Atterberg limit, compaction parameters, CBR, UCS tests and swelling characteristics. The results of present study are compared with the results of earlier investigations [27]. The researchers have used fly ash to stabilize the black cotton soil (Fig. 1).

Atterberg Limits

Atterberg limits are index properties frequently used directly and indirectly to assess the activity and the frost susceptibility of fine grained soil. The effect of slag content on Atterberg limits is shown in Fig. 2.

Liquid limit indicates compressibility of the soil. Higher the liquid limit, higher the compressibility of the soil. Figure 2a shows that the liquid limit of the soil has continuously decreased with the increase in the micro-fine slag up to 6 % but further increase in the slag content increased the liquid limit of the soil mix. Decrease in the liquid limit with the addition of micro-fine slag indicates that the compressibility of black cotton soil is decreasing with increase in the amount of micro-fine slag in the soil.

Plastic limit increased with the increase in the slag content up to 6 % but additional mixing of slag with the black cotton soil resulted in the decrease in the plastic limit. The variation of plastic limit with micro-fine slag is shown in Fig. 2b. Increase in the plasticity of soil indicates that micro-fine slag added soil can be in plastic state even at higher water content.

Liquid limit and plastic limit are progressively decreasing and increasing respectively with the addition of fly ash, whereas in the case of micro-fine slag, liquid limit and plastic limit started increasing and decreasing respectively after a certain amount of additive. Rate of change in the liquid limit and plastic limit is higher in case micro-fine slag as compared to fly ash used.

The shrinkage limit is a valuable parameter for the soil which undergoes large volume changes with change in the moisture content. Shrinkage of soil cannot occur at water

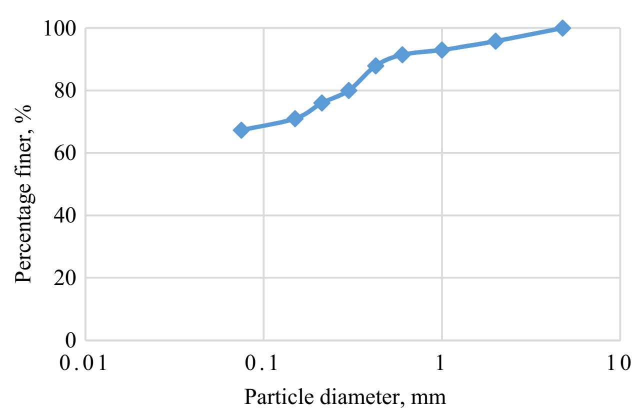

Fig. 1 Grain size distribution of soil used

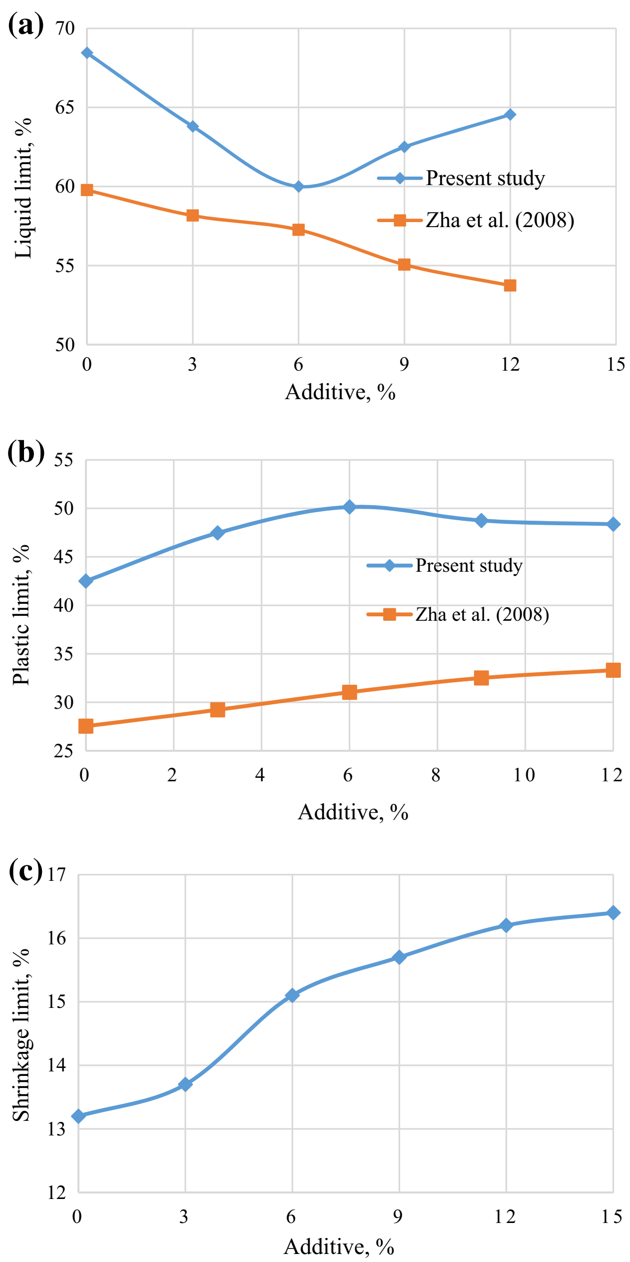

Fig. 2 Effect of slag content on Atterberg limits: **a** liquid limit; **b** plastic limit and **c** shrinkage limit

content below or equal to the shrinkage limit of soil. Variation of the shrinkage limit with micro-fine slag is shown in Fig. 2c. The shrinkage limit is increasing with the increase in the quantity of micro-fine slag. Increase in the shrinkage limit after the addition of micro-fine slag indicates that expansive soil can preserve its solid state even at higher water content and the volume of soil mass cannot reduce further for a water content less than or equal to 16.4 %. Initially, for this soil, it was essential to maintain water content less than or equal to 13.1 % and any water content more than 13.1 % could have led to swelling in soil

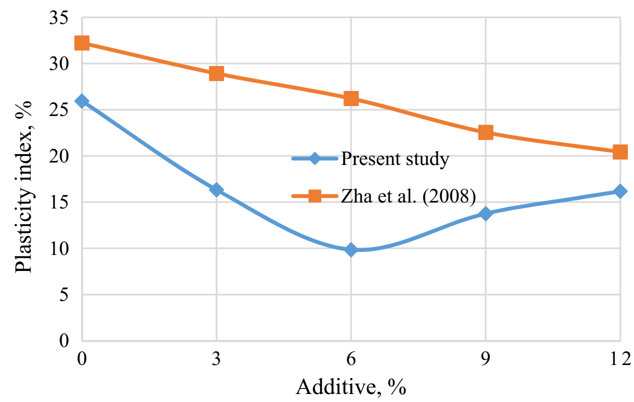

Fig. 3 Effect of fine slag on the plasticity index

but after the addition of micro-fine slag in the soil mass, water content can be varied between 0 and 16.4 % without worrying about soil expansion and contraction.

Figure 3 shows that plasticity index decreases with the increase in the slag content up to 6 %, though, furthermore mixing of slag in the soil caused an increase in the plasticity index. Plasticity index indicates the water content range over which the soil can maintain its plastic state. Plasticity of soil reduced from medium plastic to slight plastic. As per the literature [28], swelling potential of the soil decreased from high ($22 < PI < 48$) to low ($PI < 18$) with the addition of micro-fine slag. The rate of change in the plasticity index is higher in case of micro-fine slag as compared to fly ash used by the investigators [27]. The plasticity index decreased progressively with increase in the quantity of fly ash, whereas in case of micro-fine slag, plasticity index started increasing after a certain amount.

The increase in the concentration of electrolyte or chemicals causes a reduction in the thickness of the double layer and consequently led to an increase in the shearing resistance between soil particles [1, 28–30]. This increase in the shearing resistance between particles has decreased the plasticity index and liquid limit. But after a certain amount of slag (6–7 %), there is an increase in the plasticity index and liquid limit, and this shows that cation exchange capacity is reducing with the addition of excessive slag. Overcrowding of cations on the clay particles can be a possible cause of this behaviour.

Compaction Parameters

Relationship between optimum moisture content and dry density is shown in Fig. 4. Increase in the slag content in the black cotton soil increased and decreased the dry density and water content respectively. In all cases, slope of the curves is steeper on the dry side of optimum. It indicates that a little increase in the water content can lead

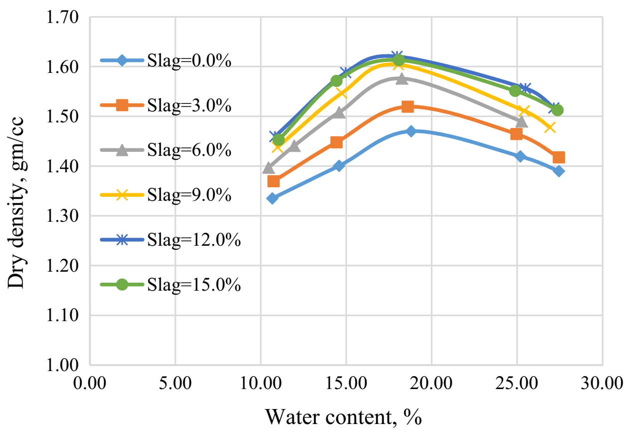

Fig. 4 Water content and dry density relationship

to improvement in the density of soil on the dry side of optimum. The effect of micro-fine slag on the maximum dry density and water content are shown separately in Fig. 5a, b respectively. Figure 5a shows that optimum water content decreased linearly with increase in the amount of slag. Figure 5b shows that the slope of graph is high up to slag content of 6 % which indicates that the rate of increase in density is high up to this slag content and later dry density continued to increase but at a slower rate. It shows that efficiency of additive started reducing after a certain amount of micro-fine slag. For large amount of micro fine slag, there is a little change in the density of micro-fine mixed soil which may be due to increase in the finer content in the soil. The addition of additive reduces the thickness of diffused double layer of water around the clay particles and consequently increases the density of the soil along with reducing the OMC of soil [30, 31].

Effect of micro-fine slag and fly ash on the OMC of black cotton soil is very much similar. The maximum dry density reduces with increase in the quantity of fly ash, whereas in case of micro-fine slag maximum dry density is increasing with increase in the quantity. This difference in behaviour can be attributed to the difference in the specific gravity of micro-fine slag and fly ash.

UCS Test

Figure 6 shows the variation in the unconfined compressive strength of soil samples for different proportions of micro-fine slag for 3 and 7 days curing period. The unconfined compressive strength increased with the increase in the micro-fine slag content up to 6–7 % but further addition of micro-fine slag led to decrease in the strength of the soil. The slopes of the curve on both the side of peak indicates that the rate of change of strength with change in slag content are steeper in the case of higher curing period. The unconfined compressive strength is increasing with a

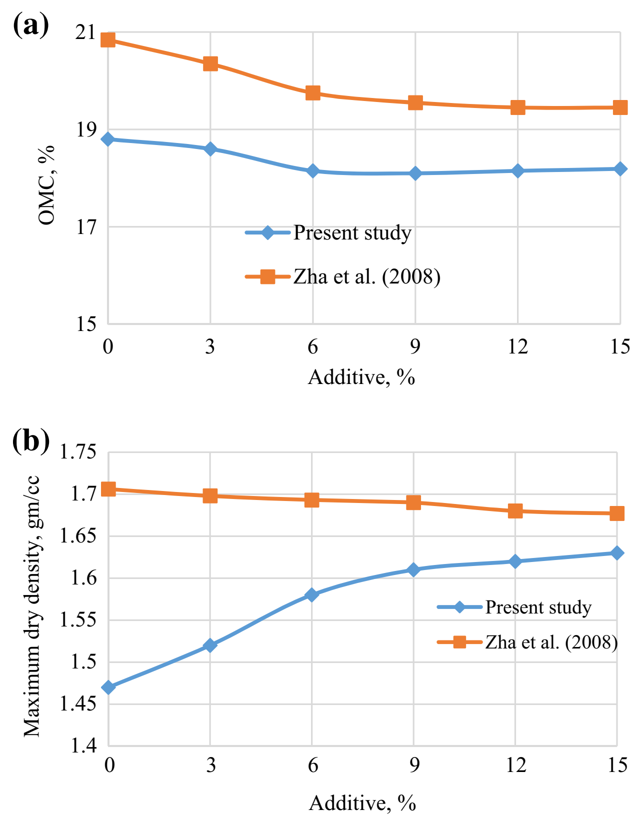

Fig. 5 Effect of slag content on **a** optimum moisture content, **b** maximum dry density

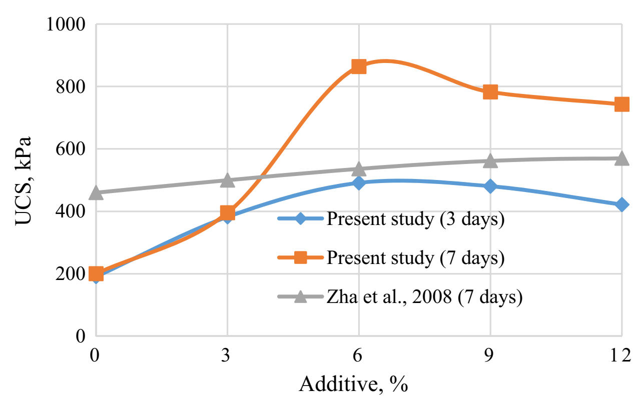

Fig. 6 Unconfined compressive strength of black cotton soil for 3 and 7 days curing

higher rate in case of micro-fine slag as compared to fly ash. Compressive strength of clay soil is very sensitive to the water content and increase in the UCS can be related to the decrease in the OMC of soil and increase in the density of soil with the addition of micro-fine slag.

Contrary to earlier researches [18, 32], it has been found that efficiency of an additive depends on the amount of additive as well as on the curing period. This variation in the results with those of former studies may be observed due to difference in the characteristics of soil and additive

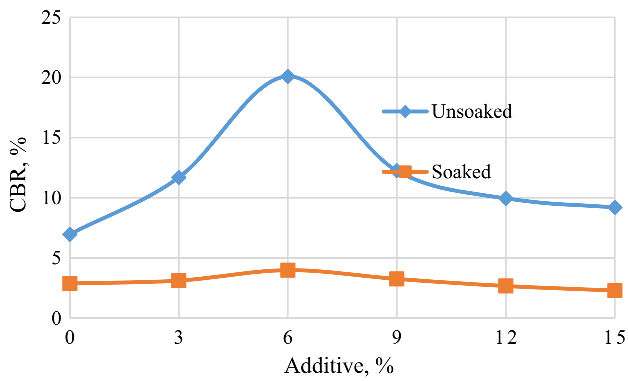

Fig. 7 Effect of micro-fine slag on soaked and unsoaked CBR

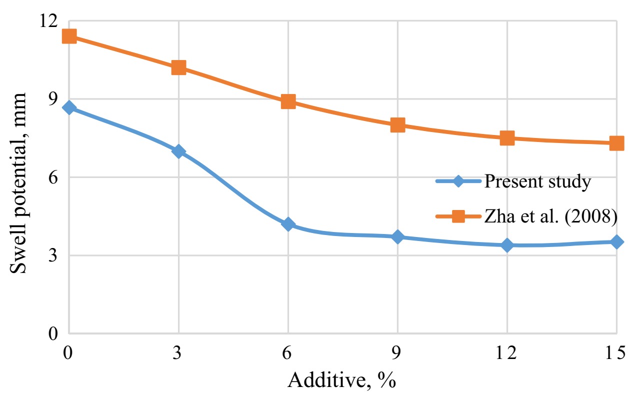

Fig. 8 Variation of swell potential with micro-fine slag

used in the study. Result of the present study indicate that the effectiveness of micro-fine slag increased significantly with increase in the curing period which agrees with the findings of previous researchers [32].

CBR Test

CBR can be related to modulus of subgrade reaction, strength, plasticity index and modulus of resilience. The variation of soaked and unsoaked CBR with micro-fine slag content is shown in Fig. 7. Soaked CBR remained unaffected for different quantity of slag content, but un-soaked CBR increased with increase in the slag content up to 6 %. Though, further increasing the slag content causes drastic decrease in the unsoaked CBR. This behaviour can be attributed to the change in soil skeleton after mixing of micro-fine slag. It was reported in the earlier studies that skeleton of soil-admixture is well formed for admixtures and soil being kept in a fixed proportion but any variation in this proportion can adversely affect the integrity of the skeleton which eventually leads to decreased strength of soil mix [33].

Un-soaked CBR value is increased to more than three times of initial CBR value. Although, soaked CBR increased as well but change is not significant which can be due to loss of cohesion and additional softening of soil due to soaking.

Swelling Characteristics

Expansivity of soil was determined from oedometer test as well as from index properties of soil, such as liquid limit, shrinkage limit, plasticity index and shrinkage index. Soil used in the study has liquid limit 67.4 % and plasticity index 23.20 %, based on which it can be predicted that the soil has high degree of expansivity [3, 26]. Based on shrinkage index and shrinkage limit, the soil can be classified as high swelling potential soil [7, 26].

Figure 8 shows that both micro-fine slag and fly ash are reducing the swell potential of soil and trend of the graphs is almost similar for both the additives. Swelling potential can be assessed using plasticity index of soil. Under a surcharge of 7 kPa, swell of soil in oedometer was found to be 8.67 % and based on this value, soil can be termed as of medium swell potential [25, 34]. The swelling of soil is reduced to half due to addition of micro-fine slag and consequently, the swelling potential of soil is reduced from medium to low.

Conclusion

All the tests were conducted in the laboratory. The study results reveales that micro fine slag can also be used as an additive to stabilize the black cotton soil. Free swelling of the soil is decreased with the addition of micro fine slag. Mixing of micro-fine slag decreased the liquid limit, plasticity index and optimum moisture contents of the expansive soil used. Micro-fine slag also significantly increased the plastic limit, unconfined compressive strength, maximum dry density and unsoaked CBR of the soil when mixed up to 6–7 % of the soil weight, but further increase in the slag content can decrease the UCS and CBR of micro fine slag mixed soil as evident from the tests. The unconfined compressive strength of black cotton soil increased significantly with increase in the curing period. The 3 and 7 days curing increased the UCS, respectively by 2.5 and 4 times to that of the untreated soil. Change in soaked CBR value is insignificant with addition of Micro-fine slag as compared to the un-soaked CBR value of the soil. The swell potential of soil is reduced from medium to very low. The effects of slag treatment very much depend upon the amount of micro-fine slag that is mixed with the black cotton soil. The optimum amount of micro-fine slag was found to be approximately 6–7 % by the weight of the soil.

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