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ORIGINAL ARTICLE

Effect of fly ash, construction demolition waste and lime on geotechnical characteristics of a clayey soil: a comparative study

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Abstract Improvement of strength and subgrade characteristics of soil by stabilization is one of the popular techniques nowadays. The use of construction demolition (C&D) waste in soil stabilization is still under research as much work has not been done in this area. This paper presents a comparative study of utilization of fly ash, C&D waste and lime in soil stabilization. A number of tests such as differential free swell, pH, compaction, unconfined compressive strength (UCS) and California bearing ratio (CBR) were conducted to study the effect of addition of fly ash, C&D waste and lime on geotechnical characteristics of soil. Based on results, it is concluded that differential free swell and maximum dry density decrease, whereas pH, UCS and soaked CBR value increase with addition of fly ash, C&D waste and lime. The increase in UCS is almost the same for lime and C&D waste at 7 days which indicates that the usage of C&D waste compared with that of lime is economical, whereas if used in pavement subgrade lime is better material because of higher CBR value. The UCS at 28 days is more for fly ash compared with that for lime and C&D waste.

Keywords Fly ash · C&D waste · Lime · Geotechnical properties

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Introduction

Clayey soils often possess poor strength characteristics and pose serious construction problems resulting in large settlements detrimental to structures constructed over them. Many a times, it is not possible to abandon such sites because of non-availability of alternative locations having good load-bearing capacity. The stabilization of clayey soil at such locations is required using various materials so that the strength and subgrade characteristics of soil can be improved. Stabilization can be achieved by using either pozzolanic materials or chemicals each one of them having their own advantages and limitations. The fly ash, construction demolition (C&D) waste, rice husk ash, bagasse ash, saw dust ash and ground granulated blast furnace slag (GGBFS) are some of the pozzolanic materials which find use in soil stabilization. Lime, cement, calcium chloride, sodium chloride, sodium silicate, calcium carbide and lime sludge are some of chemicals used in the stabilization of soils.

In this paper, effect of use of fly ash, C&D waste and lime on geotechnical characteristics of clayey soil has been brought out. Fly ash has been extensively used to stabilize clayey soils, and a large number of researchers have conducted studies on its utilization and on various characteristics of fly ash-stabilized clayey soils. Phanikumar and Sharma (2004) showed that the addition of fly ash to expansive soil leads to decrease in plasticity, hydraulic conductivity and swelling properties, but the dry unit weight and strength increased. Prabakar et al. (2004) concluded that addition of fly ash improves the engineering properties of soil and is cost-effective material for stabilization of clayey soil. Sharma and Kalra (2006) showed that the chemical properties of soil are influenced significantly by the pH of both soil and fly ash. Kumar et al.

(2007) concluded that the expansive soil can be successfully stabilized by the combined action of fibers, lime and fly ash. Cetin and Pehlivan (2007) showed the effect of addition of fly ash on pH of soil. Chauhan et al. (2008) observed that optimum moisture content increases and maximum dry density decreases with increased percentage of fly ash mixed with locally available soil. Eskioglou and Oikonomou (2008) showed that the addition of ash increased the optimum moisture content in the compaction tests which contributes to increase in the stabilization capacity of soil. Phanikumar (2009) concluded that a fly ash content of 20 % showed significant reduction in swelling and secondary consolidation characteristics and resulted in increase in maximum dry density and shear strength. Compaction characteristics and unconfined compression strength improved at 4 % lime and reduced at 6 % lime. Sharma et al. (2012) concluded that UCS and CBR of soil increase substantially on addition of 20 % fly ash and 8.5 % lime. He et al. (2013) concluded that addition of paper sludge and fly ash caused neutral and weak alkaline pH which enhanced the phosphate removal from wastewater. Ramlakhan et al. (2013) concluded that the optimum moisture content and CBR value increase and maximum dry density decreases with increase in percentage lime and fly ash content. Sabat and Bose (2013) showed the combined effects of two industrial wastes fly ash and quarry dust on compaction, UCS, CBR, shear strength parameters and swelling pressure of an expansive soil. Umar et al. (2013) showed that up to 9 % of fly ash can be used to improve the CBR of the tested soil by more than 100 %. Gratchev et al. (2014) concluded that the ability of lime–fly ash–bentonite mixtures to neutralize acidic fluids was controlled by the lime content, whereas addition of bentonite to lime–fly ash mixtures could decrease the buffer capacity of soil and increases the dry density of mixtures at the optimum moisture content. Jia et al. (2014) revealed the importance of fly ash as a cover material to seal tailings compared with green liquor dregs and lime mud. Karthik et al. (2014) showed that addition of fly ash resulted in appreciable increases in the CBR of the soil which can be used to reduce the thickness of the pavement.

Several researchers used lime as a stabilizing material for clayey soil to improve its strength and subgrade characteristics. Davidson et al. (1965) proposed a minimum pH of 12.4 for pozzolanic reaction to take place between soil and lime, and thus, the minimum lime required for achieving this is regarded as a lime fixation point. Ola (1977) reviewed lime stabilization of lateritic soils and showed that plasticity indices of the soils were reduced, whereas the plastic limits increased, the liquid limits increased slightly, the maximum dry density decreased, and the optimum moisture content increased. From the results of durability and CBR tests, 6 % lime is recommended. Rahman (1986) presented the potentials of rice husk ash compared with lime and cement in lateritic soil stabilization and recommended the use of 7 % cement for base materials, 5 % lime for subbase materials and 18 % rice husk ash as a material to be used in subbase. Attoh-Okine (1995) investigated the use of lime in the treatment of lateritic soils and gravels. Bell (1996) concluded that addition of lime has influence on its plasticity as well as increases the OMC, decreases MDD and increases the CBR. Gay and Schad (2000) concluded that cement and lime increase the strength and stiffness, whereas with cement the improvement of cohesion was very large. Zhang and Cao (2002) showed that as amount of lime and fly ash increases there is reduction in maximum dry density and free swell, whereas optimum moisture content and CBR value increase. Hossain et al. (2007) established the use of locally available soils, volcanic ash and lime in the production of stabilized soils for applications in local construction industry. Kavak and Akyarli (2007) concluded that addition of lime increases the CBR values 16–21 times compared with initial soaked CBR values at the end of 28 days. The high increases observed in soaked CBR values would reduce the upper layer thickness of the roads. The similar improvements are also achieved in unconfined compression and plate loading tests. Yong and Ouhadi (2007) concluded lime as one of best stabilizing materials. Manasseh and Olufemi (2008) concluded liquid limit, plasticity index and maximum dry density reduced at 14 % lime content by dry weight of shale, whereas the plastic limit, unconfined compressive strength (UCS) and CBR value increased. Harichane et al. (2012) concluded that the soft soils can be successfully stabilized by the combined action of lime and natural pozzolana. The use of natural pozzolana instead of lime is an economical option to reduce construction cost. Ogundipe (2013) concluded that the addition of lime reduces the plasticity index at 8 and 10 % lime content. The California bearing ratio (CBR) of the lime-stabilized clay increases for lime content of 2–8 %, with the maximum value obtained at 8 %, while a reduction in the CBR was observed at 10 %. The reduction in the CBR at 10 % might be due to the excess lime in the clay not required for the early strength gain as a result of flocculation. Utami (2014) concluded that 10 % lime content is optimum for increasing CBR and to reduce swelling. Khalid et al. (2014) showed that mixing of 6 % lime with 3 % palm oil fly ash gives higher CBR value for soaked and un-soaked condition.

Many researchers used C&D waste as aggregates in pavements, but the use of C&D waste in soil stabilization is still under research. Ransinchung et al. (2012) reported that when fine crushed concrete cubes and cement were admixed, dramatic reduction in plasticity index was observed, whereas the UCS, soaked CBR values and split tensile strength improved.

Experimental investigation

Materials used

Soil

The soil used in this study was obtained from a site along national highway 88 at Sai near Hamirpur town in Himachal Pradesh, India. The soil sample was collected carefully considering the strata variation. The strata consisting of the soil was located at the formation level of highway. Representative soil samples were collected in polyethylene bags and preserved to avoid any moisture content variation. Soil was dried in the oven at a temperature of 105 °C, cooled in desiccators, pulverized and stored in airtight polyethylene bags. The soil can be classified as CH (clay with high compressibility) as per Indian standard soil classification system (IS 14981970), and its geotechnical properties are given in Table 1.

Appropriate ASTM standards (or relevant Indian standards) were followed to determine the index properties of different materials such as specific gravity (ASTM D854-14 2000), consistency limits (ASTM D4318-10 2000) and permeability (IS 2720-17 2000).

Fly ash

The fly ash (FA) used in this study was collected from Ropar thermal power plant. The physical and chemical characteristics of fly ash are represented in Tables 2 and 3, respectively. The fly ash is classified as MI (silt with intermediate compressibility) as per Indian standard soil classification system (IS 14981970).

Table 1 Geotechnical properties of soil

Characteristics	Value
Specific gravity	2.573
Liquid limit (%)	51.0
Plastic limit (%)	23.0
Plasticity index (%)	28.0
Indian standard soil classification	CH
Optimum moisture content (%)	16.0
Maximum dry density (g/cm^3)	1.75
Coefficient of permeability (cm/s)	3.54×10^{-8}
Unconfined compressive strength at 7 days (kN/m^2)	373.43
Differential free swell (%)	16.52
Soaked California bearing ratio (%)	1.61

Table 2 Geotechnical properties of fly ash

Characteristics	Value
Specific gravity	1.966
Liquid limit (%)	39.5
Coefficient of uniformity, Cu	4.909
Coefficient of curvature, Cc	0.930
Indian standard soil classification	MI
Optimum moisture content (%)	27.4
Maximum dry density (g/cm^3)	1.224
Coefficient of permeability (cm/s)	6.6×10^{-5}
Soaked California bearing ratio (%)	4.45

Table 3 Chemical composition of fly ash

Constituent	Percentage
Silica (SiO_2)	59.50
Alumina (Al_2O_3)	27.10
Iron oxide (Fe_2O_3)	7.36
Calcium oxide (CaO)	2.30
Magnesium oxide (MgO)	0.64
Sulfur trioxide (SO_3)	0.85
Loss of ignition	2.25

Construction demolition waste (C&D)

The production of C&D waste is increasing day by day due to development of infrastructure involving dismantling of old and obsolete buildings. The material is obtained free of cost from such buildings which otherwise is to be transported to disposal sites for proper disposal involving financial implications, and hence, its utilization solves the problem of disposal. Construction demolition (C&D) waste consists of primarily different types of materials such as concrete, brick, wood, steel, mortar and other materials which are required to be segregated into different constituents before utilization. The C&D waste for this research work was obtained from finishing layer of floor of a dismantled building in National Institute of Technology Hamirpur Campus. The floor finish layer mainly consists of cement concrete layer overlaid by cement–sand-rich mortar layer with tiling above. Out of these, the material from the cement sand layer which mainly consists of fine sand and hydrated mortar was used in this research work. The material so obtained was in the form of lumps which was crushed, dried, sieved through 4.75-mm sieve and then stored in polythene bags to control any moisture changes. The physical properties of C&D waste are given in Table 4. The C&D can be classified as SP (poorly graded sand) as per Indian standard soil classification system (IS 1498 1970).

Table 4 Geotechnical properties of C&D

Characteristics	Value
Specific gravity	2.57
Coefficient of uniformity, Cu	1.781
Coefficient of curvature, Cc	0.877
Indian standard soil classification	SP
Optimum moisture content (%)	12.4
Maximum dry density (g/cm^3)	1.675
Coefficient of permeability (cm/s)	4.26×10^{-4}
Soaked California bearing ratio (%)	17.07

Table 5 Physical properties and chemical constituents of lime

Characteristics	
Physical appearance	Dry white powder
Specific gravity	2.3
CaO	84.1
MgO	0.4
Fe_2O_3	1.8
Al_2O_3	1.3
SiO_2	2.4
SO_3	0.45
Na_2O	0.45
CO_2	3.1
$CaCO_3$	6.0

Lime

The lime used was commercially available lime typically used for construction works. The physical and chemical characteristics of lime are presented in Table 5.

Laboratory tests

A series of laboratory tests consisting of differential free swell, pH, compaction, UCS and CBR were conducted on soil, fly ash, C&D waste, lime and soil–admixture combinations. The sample preparation and laboratory tests were done as per the appropriate ASTM standards or equivalent Indian standards.

Differential free swell tests

Differential free swell tests (IS 2720-40 1977) were conducted to determine the swelling properties of soil and its combinations with admixtures. The oven-dried soil passing through 425μ IS sieve is added to the two cylinders one filled with water and other with kerosene. The volume of the soil after 24 h in two cylinders is noted as V_1 and V_k, respectively, to determine the differential free swell using the formula:

$$DFS = \left(\frac{V_1 - V_k}{V_k}\right) \times 100$$

pH tests

pH test (ASTM D 4972-13) was used to determine the optimum combinations of the composite materials used for conducting UCS tests and CBR tests. A 30 gm of soil passing through 425μ IS sieve is mixed in 75 ml of distilled water. The soil mixed with distilled water is allowed to stand for a period of 1 h and stirred once in every 15 min. After 1 h, the soil is stirred, and electronic pH meter is inserted in the beaker and pH is noted when it starts showing a constant reading.

Compaction tests

Standard Proctor compaction tests were conducted (ASTM D-698 2000) to determine optimum moisture content (OMC) and the maximum dry density (MDD). The soil and the composite mixes were thoroughly mixed for 1 h prior to compaction. Firstly, the compaction tests were performed to determine the compaction characteristics of unstabilized soil. Subsequently, tests were conducted on the composite mixes consisting of soil and admixtures. A soil sample weighing 2.5 kg passing through 4.75-mm sieve is taken for conducting the compaction test in a standard Proctor mold of capacity 1000 ml. The water is then added to soil and is mixed throughly without formation of any lumps. This sample is divided into three equal parts, poured in standard mold in three layers and compacted by applying 25 blows per layer using a standard rammer weighing 2.4 kg falling through a height of 300 mm. The test is repeated at different water contents. The dry density is determined corresponding to the various water contents, and a curve is plotted between dry density as ordinate and water content as abscissa. The maximum value of the dry density on the compaction curve gives the maximum dry density (MDD), and the water content corresponding to MDD is the optimum moisture content (OMC).

Unconfined compressive strength tests

Unconfined compressive strength tests were conducted (ASTM D-2166 2000) on cylindrical specimens of 38 mm diameter and 76 mm height at optimum moisture content compacted to maximum dry density. The specimens were prepared by compacting it in three equal layers in the standard mold. The specimens were cured by keeping them in plastic bags to prevent moisture loss. The UCS tests were conducted on the specimens at a strain rate of 1.25 mm/min. The stress and strain values were recorded, and a graph was plotted between stress as ordinate and strain as abscissa. The UCS of the sample is determined as the stress corresponding to the maximum load as:

$$\text{Stress, } \sigma = \frac{P}{A_c}$$

$$A_c = \frac{A}{1 - \varepsilon}$$

where P = load applied, A_c = corrected area, A = Area of sample, and ε = corresponding strain.

Unconfined compressive strength tests were performed at 7- and 28-day curing periods on soil and soil–admixture specimens. The UCS was determined as the average of values for two specimens.

California bearing ratio (CBR) tests

California bearing ratio (CBR) tests were conducted (ASTM D1883-05) on specimens of 150 mm diameter and 125 mm height compacted in three layer to maximum dry density at optimum moisture content. Soaked CBR tests were conducted after soaking the specimens for 96 h in water. A 50-mm-diameter and 100-mm-long metal plunger was allowed to penetrate the specimens at strain rate of 1.25 mm/min using computerized CBR testing machine. The CBR value was determined corresponding to 2.5- and 5-mm settlements.

Results and discussion

Particle size distribution

Particle size distribution (ASTM D6913-04 2000) curves for soil, fly ash and C&D waste are obtained by performing wet sieve analysis and hydrometer analysis (ASTM D422-63 2000). Figure 1 shows the particle size distribution curves of soil, fly ash and C&D waste.

Particle size distribution curve for soil shows that most of the particles are finer than 75 micron size and about 32 % of particles are finer than clay size (2 microns). The liquid limit of the soil is 51 %, its plastic limit is 23 %, and plasticity index is 28 %. The plasticity index divided by the percentage of the particles finer than 2 μ size gives the activity of the soil. The activity of the soil is 0.92 which indicates a normally active soil. The particle size distribution curve of fly ash shows the poorly graded nature having coefficient of uniformity C_u as 4.909, and having coefficient of curvature C_c as 0.930. The most of the particles of fly ash are of silt size.

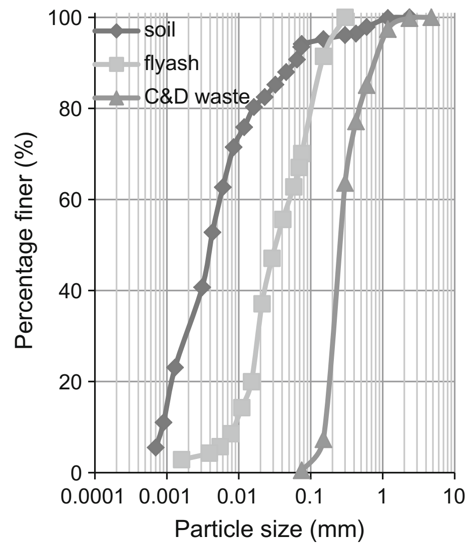

Fig. 1 Particle size distribution for soil, fly ash and C&D waste

The particle size distribution curve of C&D waste shows its poorly graded nature having coefficient of uniformity, C_u as 1.781 and coefficient of curvature, C_c as 0.877. The particles of C&D waste lie mostly in the fine sand range.

Differential free swell

The differential free swell (DFS) tests were used to determine the swelling characteristics of soil and soil–admixtures combinations. The material combinations that are used for conducting differential free swell test are soil/fly ash: 94:6, 88:12, 86:14, 84:16 and 78:22; soil/C&D waste: 96:4, 92:8, 88:12, 84:16, 82:18, 80:20, 78:22, 76:24 and 64:36; and soil/lime: 97:3, 96:4, 95:5 and 94:6. The effect of addition of fly ash on swelling properties of soil is illustrated in Fig. 2. The differential free swell of the soil is 16.52 % which on addition of fly ash reduces drastically at 6 % fly ash content and becomes zero at 12 % fly ash content. Addition of increased fly ash content does not cause any swelling. The reduction in differential free swell

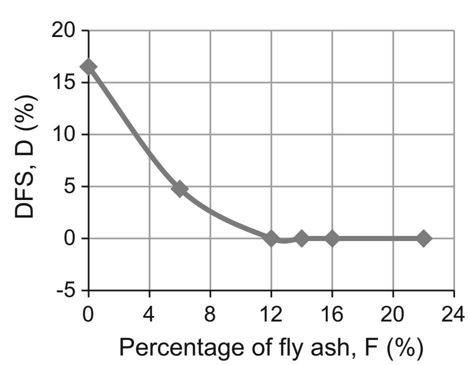

Fig. 2 Variation of DFS of soil–fly ash mixes

due to addition of fly ash has been reported by other researchers (Prabakar et al. 2004; Phanikumar and Sharma 2004; Phanikumar 2009; Sharma et al. 2012).

With the addition of fly ash to soil, the percentage of coarse particles increases and specific surface area is reduced which tends to decrease differential free swell. Also, decrease in differential free swell of the soil by addition of fly ash is due to partial replacement of soil particles by fly ash particles which are pozzolanic and non-swelling in nature.

The addition of C&D waste to soil resulted in decrease in differential free swell as shown in Fig. 3. The differential free swell of soil decreases with the addition of increased C&D waste content and becomes zero at 22 % C&D waste content. This may be attributed to increase in coarser particle content in soil–C&D mix resulting in decrease in surface activity, and differential free swell is reduced.

The effect of addition of lime on the differential free swell is shown in Fig. 4. The addition of lime decreases differential free swell of soil–lime mix up to 4 % lime content, and then it increases. The decrease in differential free swell up to 4 % lime content is due to flocculation of the soil particles on addition of lime, thus increasing the particle size and resultant decrease in the specific surface (Chen 1988; Zhang and Cao 2002; Phanikumar 2009). The increase in differential free swell after 4 % lime content may be due to the presence of free lime in the soil–lime mix.

The addition of fly ash, C&D waste and lime reduces differential free swell of soil. But addition of little amount of fly ash, i.e., 12 % fly ash content will reduce its swelling to zero, whereas 22 % C&D waste is required to achieve the same. Thus, fly ash is better material compared with C&D waste to reduce swelling. In case of lime, swelling reduces to zero at 4 % lime content and again increases with further addition of lime, but lime is a costly material, whereas fly ash and C&D waste are waste materials whose disposal is a problem and which are free of cost. Thus, fly ash is the best stabilizing material to reduce swelling, but if large quantity of C&D waste is available, the use of C&D waste is best suited because it will solve the disposal problems.

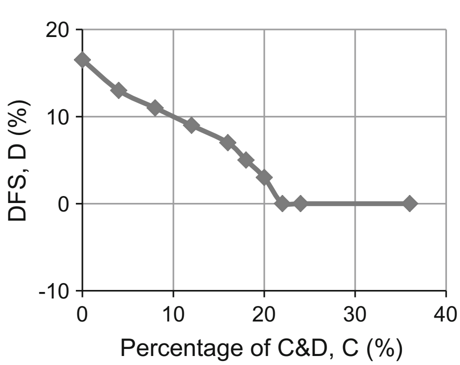

Fig. 3 Variation of DFS of soil-C&D waste mixes

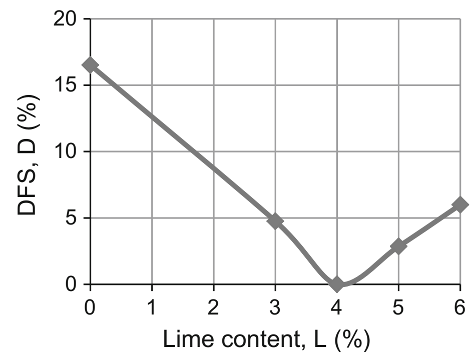

Fig. 4 Variation of DFS of soil–lime mixes

pH tests

The material combinations that are used for conducting pH tests are soil/fly ash: 94:6, 88:12, and 84:16; soil/C&D waste: 84:16, 82:18, 80:20, 78:22, 76:24 and 64:36; soil/lime: 99:1, 98:2, 97:3, 96:4, 95:5, 94:6, 93:7, 92:8 and 91:9. pH of soil is 6.7 which is slightly acidic in nature, and pH of fly ash is 8.9 being slightly alkaline. When fly ash is added to soil, pH of the composite increases and becomes neutral (pH = 7) at 12 % fly ash content (Fig. 5) and goes on increasing with further increase in fly ash content. Similar behavior of increase in pH of soil with addition of increased fly ash content has been reported by many researchers (Sharma and Kalra 2006; Cetin and Pehlivan 2007). For the purpose of fixation in soil–fly ash mix 12 % fly ash content may be chosen because the mix becomes neutral at this fly ash content. The increase in pH of the mix by addition of fly ash is due to the higher pH of fly ash compared with that of soil.

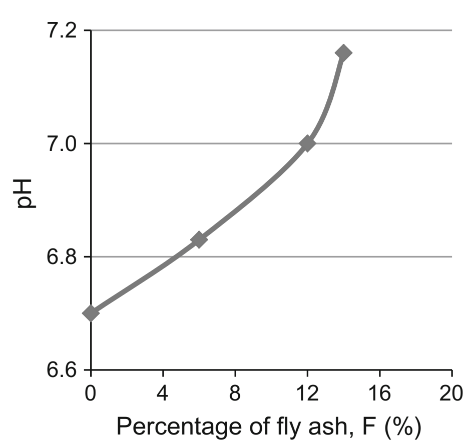

Fig. 5 pH of soil–fly ash mixes

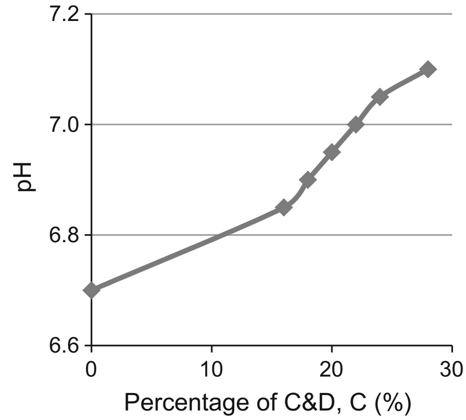

Fig. 6 pH of soil–C&D mixes

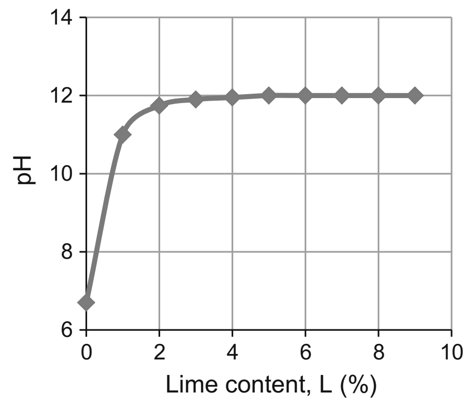

Fig. 7 pH of soil–lime mixes

The addition of C&D waste to soil tends to increase pH of soil composite with increasing C&D waste content. The pH is neutral (pH = 7) for 22 % C&D waste content (Fig. 6), and therefore, 22 % C&D waste content may be selected as fixation point. Further addition of C&D waste content (beyond 22 %) to soil makes the mix alkaline. The increase in pH of the mix by addition of C&D waste is due to the higher pH of C&D waste (pH = 8.6) as compared to that of soil.

pH of soil–lime composite increases with increase in lime content as shown in Fig. 7. The increase in pH by addition of lime is due to alkaline nature of lime. The maximum pH of 12 (pH of commercial lime used in this study, which contains some impurities) was achieved for 4 % lime content in soil–lime mixture, and hence, this may be used for fixation in soil stabilization. ASTM-C977 (1992) indicated that in soil stabilization using lime, if the pH reading is 12.40 or higher, the lowest percentage that gives a pH of 12.40 is the required amount of lime. As the lime is added to clay, reaction takes place between lime and soil particles resulting in cation exchange up to certain lime content, and the pH attains maximum value after which further dosage of lime does not cause any increase in pH (Davidson 1965; Yong and Ouhadi 2007; Sharma et al. 2012). Thus, 4 % lime content may be fixed as optimum lime content for soil stabilization.

The addition of fly ash and C&D waste to soil changes the acidic nature of soil to neutral, thus increasing its stability. The addition of lime to soil changes its nature from acidic to alkaline, though the resulting soil–lime mix is stronger, but it may not be durable.

Compaction characteristics

Based on the differential free swell and pH tests, the material combinations and their proportions for conducting the compaction tests were fixed as: soil/fly ash: 92:8, 88:12 and 84:16; soil/C&D waste: 88:12, 78:22, 76:24 and 64:36; and soil/lime: 97:3, 96:4, 95:5 and 94:6. The compaction tests are used for determining the maximum dry density (MDD) and optimum moisture content (OMC). The compaction curves for soil and the optimum mixes containing 78 % soil + 22 % C&D waste, 88 % soil + 12 % fly ash and 96 % soil + 4 % lime are shown in Fig. 8. The addition of admixtures to the soil results in decrease in the maximum dry density with largest decrease observed in case of lime followed by fly ash and C&D waste. The optimum moisture content of the composite mixes decreases with addition of C&D waste but increases when fly ash and lime are added to soil, the increase being more in case of lime. The effect of addition of fly ash, C&D waste and lime on optimum moisture content and maximum dry density of soil is shown in Figs. 9, 10 and 11, respectively.

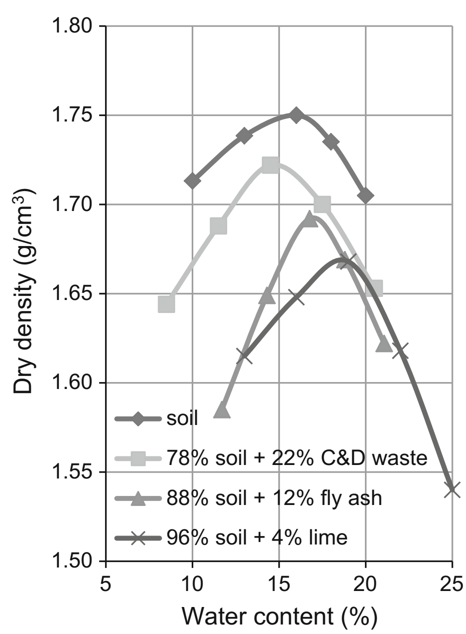

Fig. 8 Compaction curves for soil and optimum mixes

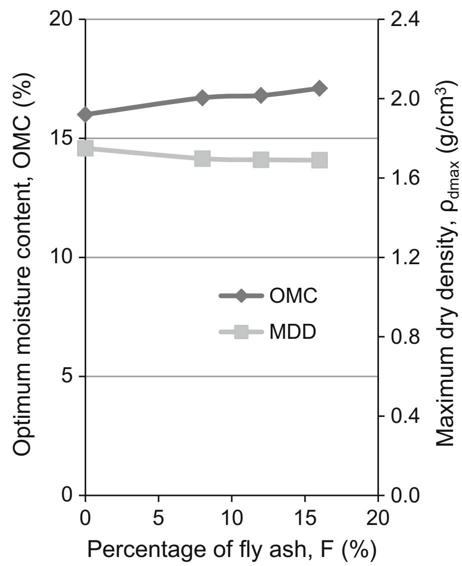

Fig. 9 Variation of OMC & MDD with fly ash

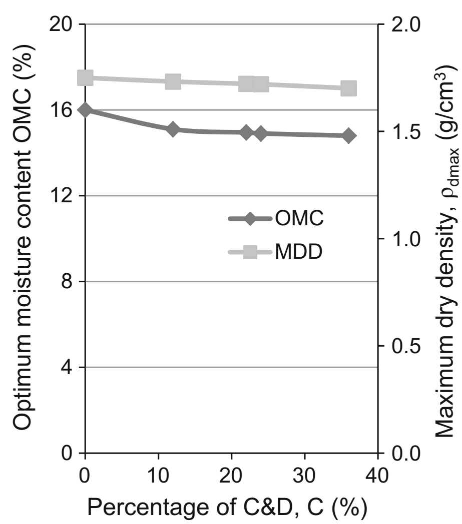

Fig. 10 Variation of OMC & MDD with C&D waste

The addition of fly ash to soil increases the optimum moisture content from 16 to 17.1 % and decreases the maximum dry density from 1.75 to 1.69 g/cm^3 when fly ash content increases to 16 % as shown in Fig. 9. Several researchers reported similar behavior for soil–fly ash composite (Kumar et al. 2007; Chauhan et al. 2008; Eskioglou and Oikonomou 2008; Umar et al. 2013). The decrease in maximum dry density is because of low specific gravity of fly ash compared with that of soil. The increase in optimum moisture content occurs due to higher optimum moisture content of fly ash compared with that of soil.

The addition of C&D waste decreases both optimum moisture content and maximum dry density as shown in

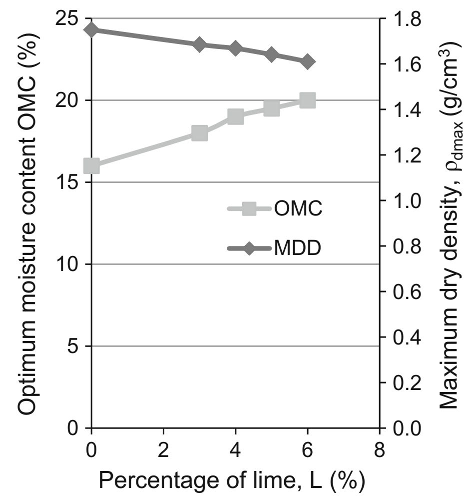

Fig. 11 Variation of OMC & MDD with lime

Fig. 10. As the C&D waste content increases to 36 %, the optimum moisture content decreases from 16 to 14.8 % and the maximum dry density decreases from 1.75 to 1.70 g/cm^3 The decrease in optimum moisture content is due to the presence of sand which is having lower specific surface area compared with that of soil used resulting in lower optimum moisture content. Two reasons for decrease in maximum dry density are as follows: Firstly, the decrease in maximum dry density is due to less specific gravity of C&D waste compared with that of soil. Secondly, the maximum dry density decreases due to flocculation/aggregation of un-reacted cement as flocculation/ aggregation provides resistance to densification.

The effect of addition of lime on optimum moisture content and maximum dry density is shown in Fig. 11. As the lime content increases to 6 %, the optimum moisture content increases from 16 to 20 % and the maximum dry density decreases from 1.75 to 1.61 g/cm^3. Similar behavior has been reported by several researchers (Gay and Schad 2000; Zhang and Cao 2002; Hossain et al. 2007; Kavak and Akyarli 2007; Manasseh and Olufemi 2008; Harichane et al. 2012).

The reasons for the decrease in maximum dry density are due to aggregation of the particles which occupy larger spaces altering the gradation of soil, and decrease in density is due to replacement of soil particles by given volume of lime of comparatively low specific gravity. However, the increase in optimum moisture content is due to increase in desire for water by addition of lime and also the increase in optimum moisture content is due to pozzolanic reaction between clay particles in soil and the lime.

The addition of fly ash causes reduction in the maximum dry density, whereas addition of C&D waste causes less reduction. The maximum dry density is reduced more in case of lime, but optimum moisture content increases due

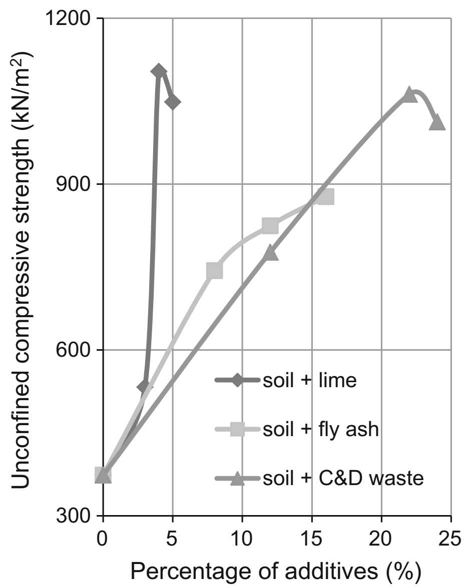

Fig. 12 7-day UCS of soil, soil–lime, soil–fly ash and soil–C&D waste

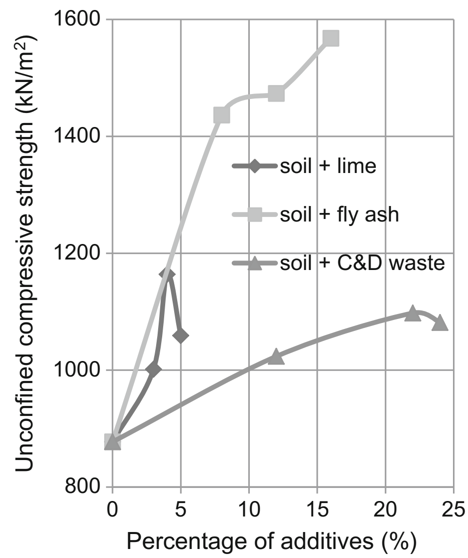

Fig. 13 28-day UCS of soil, soil–lime, soil–fly ash and soil–C&D waste

to more water requirement for cation exchange reaction and also increases the cost of construction. The maximum dry density achieved with C&D waste is more than that achieved for fly ash and lime.

Unconfined compressive strength tests

The UCS tests were conducted on soil and different material combinations such as: soil/fly ash: 92:8, 88:12 and 84:16; soil/C&D waste: 88:12, 78:22 and 76:24; soil/lime: 97:3, 96:4 and 95:5. The effect of addition of fly ash, C&D waste and lime on UCS of soil is shown in Figs. 12 and 13 at 7-day and 28-day curing period, respectively. The 7-day UCS of soil is 373.44 kN/m^2 which increases to 743.39 kN/m^2 for 8 % fly ash, 824.41 kN/m^2 for 12 % fly ash and 877.38 kN/m^2 for 16 % fly ash. The 28-day UCS is 877.38 kN/m^2 for soil which increases to 1436.37 kN/m^2 for 8 % fly ash, 1473.34 kN/m^2 for 12 % fly ash and 1569.72 kN/m^2 for 16 % fly ash. Thus, the addition of fly ash to soil increases the UCS of composite mix. The increase is due to the pozzolanic reaction between the soil and fly ash resulting in formation of cementations compounds and good bonding between soil and fly ash particles. Similar behavior was observed by several researchers (Sabat and Bose 2013, Karthik et al. 2014).

The 7-day UCS of soil stabilized with C&D waste is: 776.68 kN/m^2 for 12 % C&D waste, 1062.32 kN/m^2 for 22 % C&D waste and 1012.38 kN/m^2 for 24 % C&D waste. The results of 28-day UCS tests are: 1023.59 kN/m^2 for 12 % C&D waste, 1097.71 kN/m^2 for 22 % C&D waste and 1081.55 kN/m^2 for 24 % C&D waste. Thus, the addition of C&D waste to the soil increases the UCS of the mix. This increase is due to the pozzolanic reaction between soil and C&D waste. Similar behavior was reported by (Ransinchung et al. 2012).

The 7-day UCS of soil–lime mixes is: 532.58 kN/m^2 for 3 % lime content, 1103.63 kN/m^2 for 4 % lime content and 1048.45 kN/m^2 for 5 % lime content. The increase in UCS results was observed with curing period, i.e., the 28-day UCS is 1001.6 kN/m^2 for 3 % lime, 1163.8 kN/m^2 for 4 % lime and 1059.2 kN/m^2 for 5 % lime. Addition of lime increases the UCS values significantly up to certain lime content (4 %) after which it decreases slightly. Similar results have been reported by Ola (1977), Rahman (1986), Attoh-Okine (1995), Bell (1996) and Manasseh and Olufemi (2008). The increase in UCS value by addition of lime is due to the chemical reaction between soil particles and lime resulting in bonding.

The addition of fly ash, C&D waste and lime increases the UCS at 7 days. The increase in strength is more in case of lime compared with fly ash and C&D waste, but the difference in strength by addition of lime and C&D waste is very less. Thus, C&D waste can be used for soil stabilization, whereas lime that attains slightly more strength is costlier. The increase in 28-day strength by addition of fly ash is much more compared with that by addition of C&D waste and lime. Thus, fly ash can be utilized for soil stabilization when long-term strength is of primary requirement, whereas short-term strength gain is secondary.

California bearing ratio

The CBR tests were conducted on soil and the optimum mixes such as soil/fly ash: 88:12, soil/C&D waste: 78:22

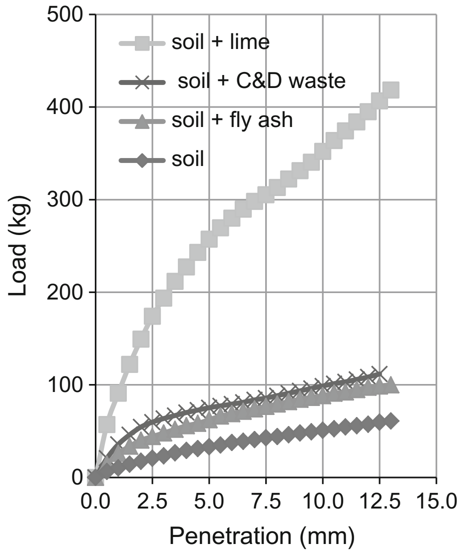

Fig. 14 Laboratory result for CBR value under soaked condition

Table 6 Soaked CBR values for soil and soil–admixture mixes

Material	Soaked California bearing ratio
Soil	1.612
Soil + 16 % fly ash	3.22
Soil + 22 % C&D waste	4.36
Soil + 4 % lime	12.7

and soil/lime: 96:4 which were obtained from UCS tests. The trend of change in CBR with addition of fly ash, C&D waste and lime is shown in Fig. 14. The effect of addition of fly ash, C&D waste and lime on soaked CBR of soil is given in Table 6. The addition of fly ash increases the CBR value which occurs due to interlocking of the coarser particles and variation in the cohesive nature of the soil–fly ash composite. Similar behavior was observed by several researchers (Prabakar et al. 2004, Ramlakhan et al. 2013). The addition of C&D waste to soil increases the CBR value of mix. The increase in CBR is due to the presence of sand particles in the C&D waste which mobilizes the angle of internal friction resulting in increase in strength.

The addition of lime to the soil increases the CBR value significantly. The increase in CBR is due to the cation exchange reaction between soil and lime resulting in bonding of soil particles. Similar behavior was observed by several researchers (Ogundipe and Olumide Moses 2013; Khalid et al. 2014; Utami 2014).

The CBR is a useful parameter for design of pavements. For rural roads, a CBR value of at least 5 is recommended. Thus, this soil is unsuitable to be used as subgrade for pavement, but with addition of lime it can be used as subgrade material. Though addition of fly ash and C&D waste improves CBR, but it is not sufficient to be used as subgrade material for pavement. Thus, lime is a better stabilization material compared with fly ash and C&D waste to be used in pavements.

Conclusions

1. The addition of 12 % fly ash, 22 % C&D waste and 4 % lime to soil individually decreases the differential free swell to zero. Addition of more fly ash and C&D waste does not cause any change in DFS, whereas further addition of lime increases the swelling.
2. pH of soil increases with addition of fly ash, C&D waste and lime. The increase is more in case of lime (as compared to fly ash and C&D waste) because commercial lime used has pH 12.
3. Maximum dry density decreases with addition of fly ash, C&D waste and lime. The decrease is more in the case of lime compared with fly ash and C&D waste, and decrease in maximum dry density is less in case of C&D waste.
4. Optimum moisture content increases with addition of fly ash and lime and decreases with increase in C&D waste. The decrease is due to the presence of fine sand in C&D waste.
5. 7-day UCS increases with addition of fly ash, C&D waste and lime. The increase in strength is more in case of lime which is a little higher than that of C&D waste. Thus, C&D waste can be used for soil stabilization, whereas lime that attains slightly more strength is costlier.
6. 28-day UCS is more in the case of fly ash compared with C&D waste and lime.
7. Soaked CBR of soil increases with addition of fly ash, C&D waste and lime. Increase in soaked CBR is more in case of lime which can be used as subgrade material in pavements. The other two materials are not satisfying requirements of subgrade material.
8. For this particular soil, lime is the best stabilizer to be used as subgrade material. C&D waste is economical where early gain of strength is of primary importance. For sites located in the vicinity of thermal power plants and where long-term strength is the primary criteria, fly ash is best suited stabilizing material.

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