Arabian Journal for Science and Engineering (2021) 46:5171–5178
https://doi.org/10.1007/s13369-021-05423-y

RESEARCH ARTICLE-CIVIL ENGINEERING

Strength and Durability Characteristics of Red Soil Stabilised with Foundry Sand and Cement

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Received: 3 December 2020 / Accepted: 28 January 2021 / Published online: 23 February 2021

Abstract

Utilisation of locally available marginal soil as a construction material is one wise choice when improve its characteristics. Foundry sand (FS) is an industrial by-product obtained from foundry industries. In the present project, an attempt has been made to enhance geotechnical characteristics of locally available marginal red soil (RS) by addition of FS in 10%, 30% and 50% to weight of dry soil. Further, the present project intends to blend a strong stabiliser like cement (C) to enhance the strength and durability of mix made with red earth and 30% FS In this regard, 2.5%, 5% and 7.5% of cement is added to above mix. Addition of 5% C mixed with 30% FS has shown unconfined compressive strength (UCS) of 1548.22 kPa. This strength has been achieved even after 12 cycles of alternate wetting–drying of specimens prepared by blending RS + 30%FS + 5%C mix. The addition of 5% C passing the required durability criteria. Moreover, UCS of 3442.02 kPa has been achieved even after 12 cycles of alternate wetting–drying of specimens prepared by blending RS + 30% + 7.5%C. FS is a sustainable material, and it can be used as an alternative to natural river sand for enhancing geotechnical characteristics of RS.

Keywords Red soil · Foundry sand · Cement · Unconfined compressive strength · Durability · Damage evaluation

1 Introduction

Red soils are usually found in the southern and semi-arid regions. RS are mostly found in South America, Central Africa, South and Southeast Asia, India and Australia [1]. Red fine-grained soils are present in many places, and they are not appropriate for of construction pavement courses. [2] used foundry sand blended with clayey soil for the application in sub-base and base layers. About 3 million tons of foundry sand generating from different foundry industries in the India. Foundry sand has potential for application in road construction. It can be used in the construction of sub-base layer of pavement [3, 4]. [5] advocated that soil-foundry sand mixes blended with cement/lime can be used in the construction of highway sub-base layer and as a fill material [6].

Soils can be stabilised by the addition of lime or cement [7]. [8] found that addition of lime has a significant effect on shear stress particularly beyond 28 days and in samples containing 8% lime for red soil tested. It has become general practice to stabilise earthen materials with strong stabiliser. The most commonly used stabiliser is cement, which reinforces earth by enhancing its strength and water resistance with chemical bonds [9]. [10] conducted tests to evaluate compressive strength by adding 0%, 4%, 6%, 8%, 10%, 12%, 15% or 20% of cement by weight of soil and found that the cement stabilisation increases the elastic modulus of the material increases from 1.89 GPa for un-stabilised soil to 2.51 GPa for soil stabilised with 10% cement. The cement added to red soil in 2.5%, 5.0% and 7.5% of dry weight of soil and observed that the UCS is directly proportional to cement content [11].

[12] has reported UCS value of 400 kPa for soil stabilised with 20% cement and 5% silica sand. [13] carried experimental study on blocks prepared with red earth and 8% cement and found that the prepared blocks cured for 28-days has shown the compressive strength of about 5000 kPa. [14] investigated the prospect of utilising red earth as alternative materials to river sand in the production of sandcrete blocks. Blocks were made with cement and red soil in mix ratio of 1:6, and the compressive strength test was performed on the samples at 7-days and 28-days curing in the laboratory, and it found to be about

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Table 1 Geotechnical properties of red soil

Property	Value
Specific gravity	2.69
Gravel (%)	0.1
Sand (%)	41.3
Fines (%)	58.6
Liquid limit (%)	37.29
Plastic limit (%)	18.06
Plasticity index (%)	19.22
Classification of soil (USCS)	Cl
Differential free swell index (%)	10
Degree of expansivity	Low
Modified compaction characteristics:	
Maximum dry density (Mg/m^3)	2.03
Optimum moisture content (%)	10.2

Table 2 Chemical properties of red soil

Property	Value
pH at 50%	6.80
Nitrogen (%)	< 0.01
Phosphorous (%)	< 0.01
Potassium (%)	2.80
Ferric oxide, Fe_2O_3 (%)	12.22
Aluminium oxide, $A1_2O_3$ (%)	2.70
Silicon dioxide, Si_2O_2 (%)	0.40
Titanium dioxide, TiO_2 (%)	< 0.01
Calcium oxide, CaO (%)	0.06
LOI (%)	3.20
Phosphorus pentoxide, P_2O_5 (%)	< 0.01
Manganese dioxide, MnO_2 (%)	0.09
Magnesium oxide, MgO (%)	0.04
Chromium oxide, Cr_2O_3 (%)	< 0.01
Dinitrogen pentoxide, N_2O_5 (%)	< 0.01

1000 kPa and 2000 kPa, respectively. Durability studies on stabilised material prepared with locally available red earth, sand, cement, lime, and enzyme was done by [15]. The previous studies are conducted on coarse-grained soils treated with FS. The major objective of the current study is to enhance the geotechnical characteristics of fine-grained RS with FS. Recycling of foundry sand can save energy and may reduce costs [16]. The primary interest of experiments is to arrive optimum foundry sand (OFS) for improving fine-grained RS. The present study also focusses on addition of cement for further improvement in the strength of RS + FS mixes. The significance of current work is to obtain optimum cement content (OCC) for improving the strength of fine-grained RS modified with FS. The utilisation of FS can resolve two major issues one is disposal of FS, and another one is overcoming the problems associate with fine-grained RS. As the red fine-grained soils are not having enough strength and stiffness. Further, durability studies are carried on RS + 30%FS mix with addition of 2.5%, 5.0% and 7.5% cement in order to determine the OCC from view point of durability.

2 Materials

2.1 Red Soil

The soil (See Fig. 1) used in the present study collected from a place near Nuzvidu (16° 47′ 0″ North, 80° 51′ 0″ East) which is about 50 km from Vijayawada, India. The grain size distribution curve of the soil is shown in Fig. 2. The geotechnical properties of the RS are presented in Table 1. The chemical properties of the RS are presented in Table 2.

Fig. 1 Red soil used in the present study

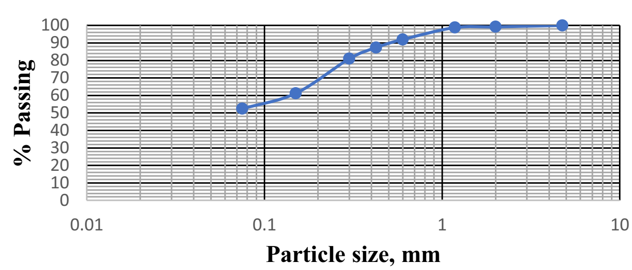


Fig. 2 GSD curve for red soil

2.2 Foundry Sand

Foundry sand (Fig. 3) is a waste material generated from local industry where natural sand is used as a moulding

Fig. 3 Foundry sand used in the present study

material which becomes unsuitable or waste after several cycles of use. The grain size distribution curve of the foundry sand is shown in Fig. 4.

2.3 Cement

The cement used in this investigation is an ordinary Portland cement (OPC) of 53 grade.

3 Experimental Investigation

The present experimental study is planned to conduct laboratory tests in the series. In the first series of experimental programme intended to add FS in various proportions (10%, 30% and 50%) of dry weight of RS. In the second series, the cement of various proportions (2.5%, 5.0% and 7.5%) blended to dry weight of RS + FS mixes. Dynamic compaction tests, UCS tests and durability tests (alternate wetting–drying) are performed. Modified proctor compaction tests are conducted to determine the compaction characteristics. UCS tests are conducted on specimens prepared by compacting respective mix in layers by using a tamping rod inside a cylindrical mould having diameter of 36 mm and length of 72 mm. The required quantity of soil (untreated and treated) prepared at the respective OMC and compacted at MDD. The UCS tests are conducted in such a way that the compression load is applied to cause an axial strain at the rate of 0.5% to 2% per minute. Further, in this study, durability tests (alternate wetting and drying) are conducted on the soil. The reason for adopting wetting and drying of the specimens is mainly because of the soil falls in the semi-arid region. The specimens prepared with cement stabilised mixes are cured for 7-days. The wetting–drying tests are conducted as per [17] by immersing the samples in water for 5 h and subsequently oven-dried for a period of 42 h at a temperature of 70 °C. Each wetting and drying process constitutes one cycle.

4 Results and Discussions

4.1 Influence of FS and Cement on Compaction Characteristics of RS

The compaction characteristics namely maximum dry density (MDD) and optimum moisture content (OMC) are obtained by plotting compaction curves shown in Fig. 5.

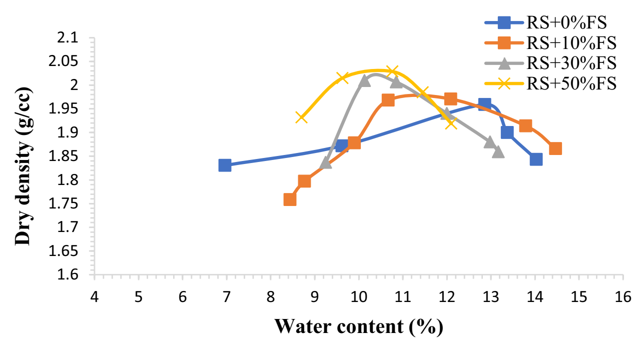


Fig. 5 Compaction curves for RS modified with FS

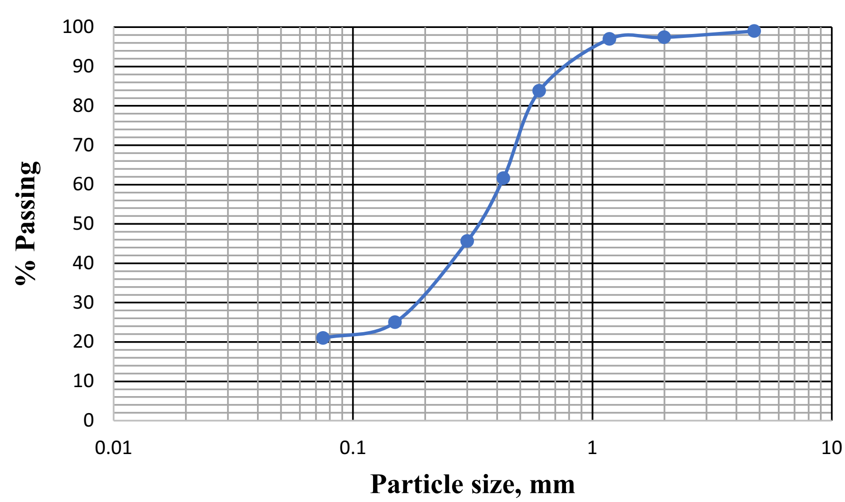


Fig. 4 GSD curve for foundry sand

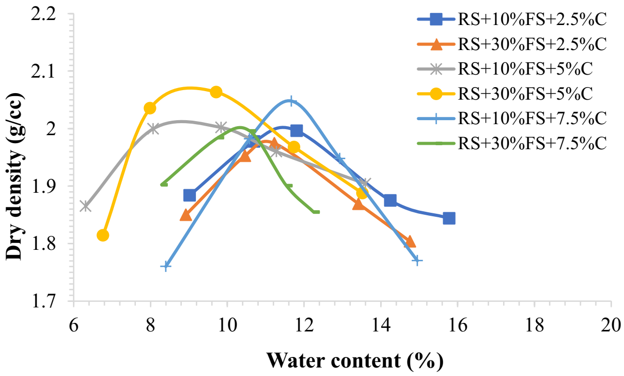


Fig. 6 Compaction curves for cement stabilised RS + FS mixes

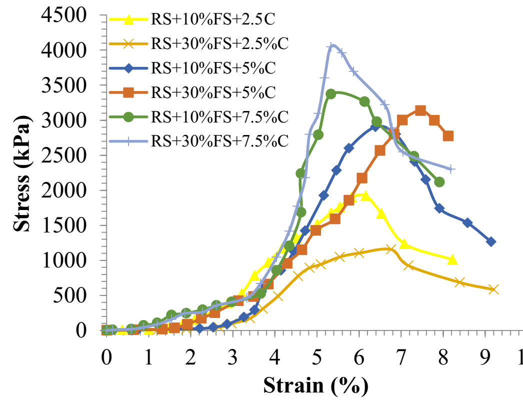


Fig. 8 Stress–strain plots for FS + RS + C mixes

MDD increases and OMC decreases with addition of FS to RS. The reason for reduction in OMC is may be owing to the presence of coarser particles in FS which in turn reduces the affinity for water. Increase in MDD is may be due to filling the voids of the RS with FS particles. Figure 6 shows the compaction curves for cement stabilised RS modified with FS. It is observed that with the addition of 2.5% cement to RS treated with different percentages of FS (10% and 30%) shows reduction in both MDD and OMC. It is observed that with the addition of 5.0% cement to RS treated with different percentages of FS (10% and 30%) shows increase in MDD and reduction in OMC. It is interesting to note that with the addition of 7.5% cement to RS treated with 10% and 30% FS shows reduction in MDD and increase in OMC. The decrease in MDD is may be owing to flocs formation. The increase in OMC is may be due to more amount of water required for mixing higher percentage of cement and FS to RS.

4.2 Influence of Foundry Sand and Cement on UCS

The stress–strain plots obtained from UCS tests that are drawn for different proportions of FS added to RS (See Fig. 7). UCS values reported in this study are determined by taking the average results of three specimens. From Fig. 7, it is observed that RS alone attained low peak at high strain whereas RS + 10%FS mix shows high peak at low strain. The peak stress and the corresponding strain are found to be low for RS added with 30% and 50% of FS. This is because of more sand proportion which in turn results failure of the specimens at early stage due to lack of confinement. The stress–strain plots are drawn for RS + FS mixes stabilised 2.5%, 5.0% and 7.5% cement (See Fig. 8). From Fig. 8, it is noted that with addition of small quantity of cement i.e. 2.5% to RS + 30%FS results in high percentage of increase in peak stress and marginal increase in strain corresponding to peak stress. It is noted that with addition of 7.5% cement to RS + 30%FS results in very high percentage of increase in peak stress and significant decrease in strain corresponding to peak stress. The value of strain is about 5% for RS + 30%FS + 7.5%C mix.

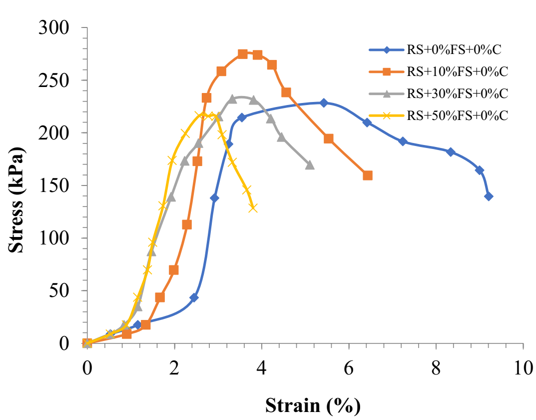


Fig. 7 Stress–strain plots for different proportions of FS added to RS

Relative strength gain number (RSGN) for various mixes is calculated and presented in Table 3. RSGN value for RS + 10% + 2.5%C mix is 7.39 and that of RS + 30%FS + 2.5%C mix is 4.06. It can be clearly noticed that only 10%FS can be utilised when 2.5% cement is added. When 5% cement added to RS + 30%FS mix, the RSGN value is found to be 12.73, and it indicates better gain in strength. RSGN value is found to be more when 7.5% cement added to RS + 30%FS mix. Addition of 5.0% and 7.5% cement to red soil shows UCS of 1300 kPa and 1600 kPa, respectively [11]. After curing the blocks for 7 days, the blocks made with the mixture of cement, red earth, river sand and laterite (1:2:2:2) have the average compressive strength of 750 kPa [14]. The UCS obtained for RS + 10%FS + 2.5%C is 1917.26 kPa which is much higher than results reported by earlier researchers those added cement to red soil. Moreover, the gain in strength is much pronounced for RS + 30%FS + 5%C mix. The addition of cement increases the strength which is may be due

Table 3 RSGN values for foundry sand treated Red soil

Mix	UCS of treated soil, A (kPa)	UCS of untreated soil, B (kPa)	Strength ratio (A/B)	RSGN (A-B)/B
RS + 0%FS	228.43	228.43	1	0
RS + 10%FS	274.65	228.43	1.2	0.2
RS + 30%FS	232.16	228.43	1.02	0.02
RS + 50%FS	216.47	228.43	0.95	− 0.05
RS + 10%FS + 2.5%C	1917.26	228.43	8.39	7.39
RS + 30%FS + 2.5%C	1154.81	228.43	5.06	4.06
RS + 10%FS + 5.0%C	2905.12	228.43	12.72	11.72
RS + 30%FS + 5.0%C	3136.44	228.43	13.73	12.73
RS + 10%FS + 7.5%C	3370.03	228.43	14.75	13.75
RS + 30%FS + 7.5%C	4047.42	228.43	17.72	16.72

to aluminous and silicious minerals in the soil react with the cement to produce calcium silicates and aluminates that bond the particles together. The similar observation reported by earlier researchers [9].

4.3 Damage Evaluation Process

Progressive damage behaviour of the material is expressed by damage variable (D). The material strength and the damage variable also subject to statistical distribution, so, the Weibull's distribution formula of two parameters is expressed in Eq. (1), and it can be expressed as

$$D = \left(1 - \left(e^{-\left(\frac{\varepsilon}{\varepsilon_s}\right)^n}\right)\right) \tag{1}$$

Conferring to elementary relationship of continuous damage mechanics, stress (σ) can be written as

$$\sigma = E(1 - D)\varepsilon \tag{2}$$

where, E = Young's modulus.

ε is axial strain, n is shape parameter, both are non-negative.

Substituting Eqs. (1) in (2) which gives following equation

$$\sigma = E\varepsilon e^{-\left(\frac{\varepsilon}{\varepsilon_s}\right)^n} \tag{3}$$

When $\varepsilon = \varepsilon_c, \sigma = \sigma_c$

$\varepsilon_c =$ Peak axial strain; $\sigma_c =$ Peak compressive strength = UCS

$$\frac{\sigma_c}{E\varepsilon_c} = \left(e^{-\left(\frac{\varepsilon_c}{\varepsilon_s}\right)^n}\right) \tag{4}$$

By applying logarithm on both the sides of Eq. (4)

$$\text{Shape parameter} = n = \frac{1}{\ln \frac{E\varepsilon_c}{\sigma_c}} \tag{5}$$

$$\text{Scale factor} = \varepsilon_s = \varepsilon_c\left(\frac{1}{n}\right)^{\frac{1}{n}} \tag{6}$$

Substituting Eqs. (6) in (1)

$$\text{Damage variable} = D = \left(1 - e^{-\frac{1}{n}\left(\frac{\varepsilon}{\varepsilon_c}\right)^n}\right) \tag{7}$$

The damage variable is vital to study damage evolution process of stabilised soils. Figures 9 shows the Damage variable-strain curves of 2.5%, 5.0% and 7.5% cement stabilised RS + 30%FS mixes. The damage variable rises with the rise of axial strain. With the increase in stress, damage variable is increasing and reaches approximately 0.99 at failure. $D = 0$ indicates undamaged state, and $D = 1$ indicates failure state; and $0 < D < 1$ shows damaged intermediate state. From Fig. 9, when the axial strain is small it is found that the damage variable is high which can reflect strain hardening phenomenon, and it is much pronounced for RS + 30%FS + 7.5%C mix.

4.4 Prediction of UCS of RS added with FS and cement

In the present study, a mathematical model has been proposed to predict UCS of RS added with FS and cement. Proposed model is developed based on multiple nonlinear polynomial regression analysis. The model developed by considering UCS as dependent variable and FS, C are independent variables. The prediction performance of the model has been checked, and a plot is drawn between observed UCS and predicted UCS (see Fig. 10). From the Fig. 10, it is observed that best fit exists between observed UCS and

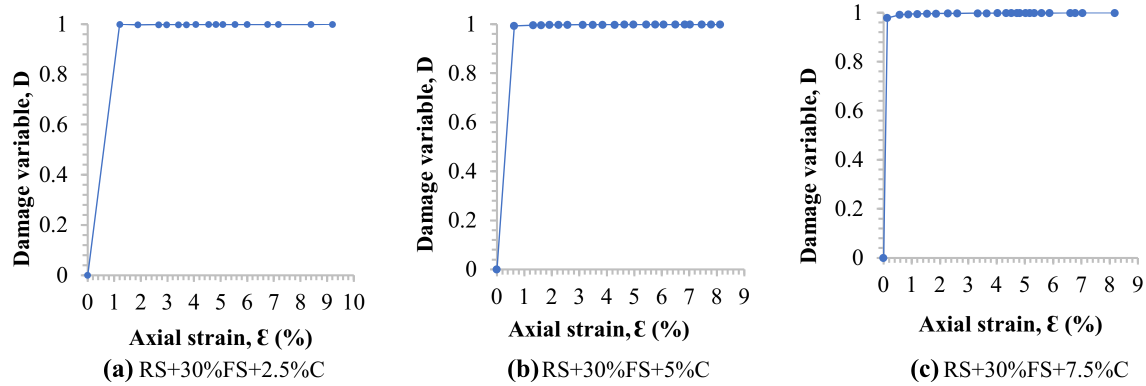


Fig. 9 Plots drawn between Damage variable vs. axial strain

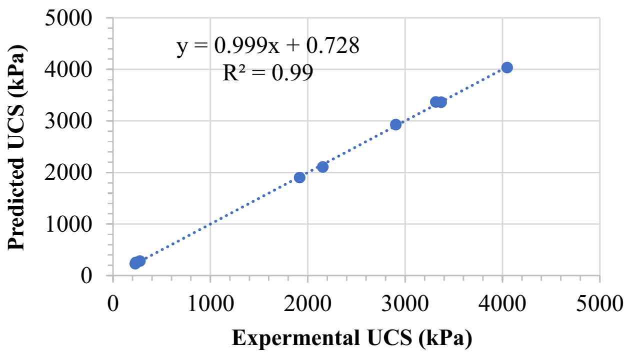


Fig. 10 Predicted versus experimental UCS values of RS *added with FS and C*

predicted UCS. The coefficient of determination (R^2) is found to be 0.99.

$$UCS = -0.218x_1^2 + 4.667x_1x_2 - 47.386x_2^2 + 7.297x_1 + 719.683x_2 + 228.430 \quad (8)$$

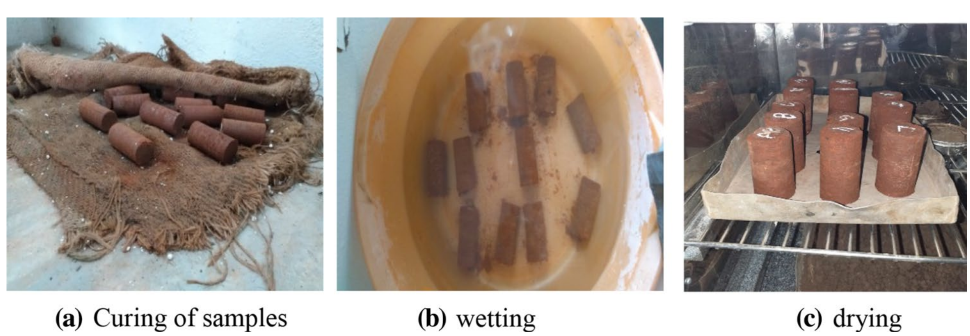
where x_1 = % foundry sand, x_2 = % cement.

4.5 Durability Studies on Cement Stabilised Foundry Sand Treated Red Soil

Durability is the capability of the material to continue its functionality over period. CBR values for stabilised soils found to be more than 100% which is unrealistic, and the durability tests are conducted in order to ensure the strength of stabilised soil as pavement course material [18]. [19] confirmed that the strength of a cement stabilised soil base should be measured using the UCS. Alternate wetting and drying are conducted on the specimens prepared with cement stabilised mixes are cured for 7-days. The wetting–drying of specimens are performed by immersing the samples in water for 5 h and followed by oven-drying for a period of 42 h at 70^{0}C. Figure 11 shows the process of conducting durability tests on cured samples.

Figure 12 shows the % loss of soil for RS + 30%FS added with different proportions of cement. UCS for RS + 30%FS added with different proportions of cement is presented in Fig. 13. The % loss of soil for RS + 30%FS blended 2.5%C is about 31.57% for 9th cycle and samples not able to stand once 5-cycles of wetting–drying. The % loss of soil is about 11.57% for 1st Cycle, and it is about 15.05% for 12th cycle for RS + 30%FS + 5%C. UCS value for RS + 30%FS + 5%C after 12 cycles of wetting–drying is 1548.22 kPa. The % loss of soil is about 11.03% for first cycle, and it is about 11.61% for 12th cycle for RS + 30%FS + 7.5%C mix and found that the % loss of soil is almost negligible. UCS value after 12 cycles of wetting–drying for RS + 30%FS + 7.5%C mix is 3442.02 kPa, and the reduction in UCS value is almost negligible. Similar observations made by [10], and they reported that for water resistance, dynamic compaction is the best

Fig. 11 Durability tests on cured samples



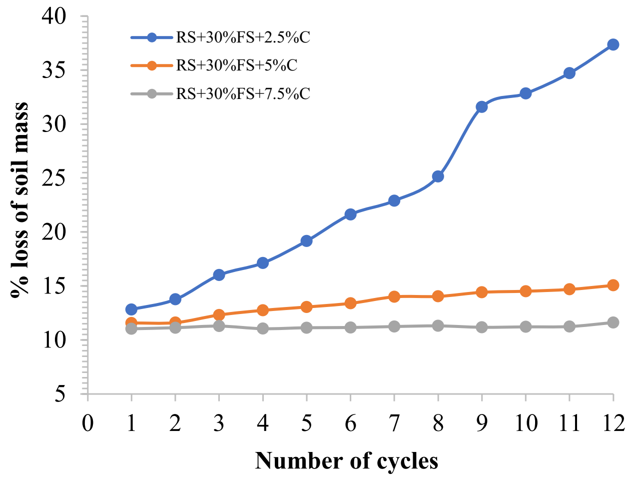


Fig. 12 % loss of soil for RS + 30%FS added with different proportions of cement

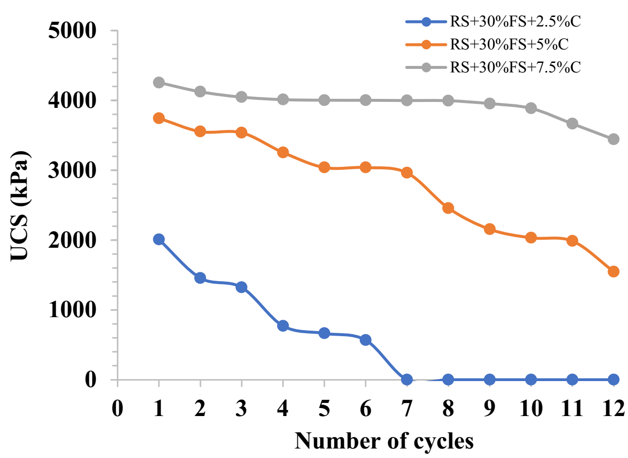


Fig. 13 UCS for RS + 30%FS added with different proportions of cement

method of compaction, as it offered higher strength more than 2000 kPa for in excess of 6% of cement content. As compared with results from previous study better compressive strength achieved even after 12 cycles of alternate wetting and drying. With higher amount of cement addition retains the strength and it may be due to the pozzolanic reaction between soil and cement. The minimum UCS required for subgrade, sub-base and base course is 245 kPa, 700 kPa and 1717 kPa, respectively [20]. This criterion is well satisfied for RS + 30%FS + 5%C mix. The cementitious sub-base should have a 7-day UCS of 1.5 to 3.0 MPa as per [21]. As this criterion is satisfied by RS + 30%FS + 5.0%C mix and RS + 30%FS + 7.5%C mix.

5 Conclusions

The following conclusions can be drawn be drawn from the present study:

- Locally available marginal red soil is treated with addition of FS in 10%, 30% and 50% to weight of dry soil. It is observed that 10% addition of FS can slightly enhanced the UCS, and the OFS is found to be 10%.
- It can be found that addition of cement can increase the strength. In this regard, 2.5%, 5% and 7.5% of cement is added to RS + 10%FS, RS + 30%FS and RS + 50%FS mixes. From the view point of rate of gain in the strength, RS + 30%FS + 5%C mix is the optimum mix. The OFS is found to be 30% when cement added to RS + FS mixes.
- The optimum cement content (OCC) is 7.5% from strength point of view. Damage variable is evaluated for RS + 30%FS mix added with different proportions of cement, and it shows strain hardening behaviour.
- A model presented below is proposed for estimating the UCS of RS added with FS and cement.

$$\mathrm{UCS} = -0.218x_1^2 + 4.667x_1x_2 - 47.386x_2^2 + 7.297x_1 + 719.683x_2 + 228.430$$

- The % loss of soil is about 11.57% for 1st cycle, and it is about 15.05% for 12th cycle for the RS + 30%FS + 5%C. The % loss of soil is almost insignificant for RS + 30%FS + 7.5%C mix exhibited to 12 cycles of alternate wetting and drying.
- Addition of 5% cement to RS + 30%FS gives UCS of 1548.22 kPa after 12 cycles of alternate wetting and drying. The addition of 5% cement passing the required durability criteria also.
- Moreover, UCS of 3442.02 kPa has been achieved even after 12 cycles of alternate wetting–drying of specimens prepared RS + 30% FS + 7.5%C mix.
- The OCC is 5% from cost point of view and whereas OCC is 7.5% from view point of durability and bulk utilisation of FS.

Acknowledgements Authors are highly thankful to Dr. K. Mallikarjuna Rao, Professor, Department of Civil Engineering, SVU College of Engineering, Tirupati, Andhra Pradesh, India for his valuable suggestions. Authors are thankful to Er. Y. Tirumala, PG scholar at VR Siddhartha Engineering College for his constant support during this study.

Funding No funding received.

Compliance with Ethical Standards

Conflict of interest The authors declare that there is no conflict of interest.

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