Sustainable Stabilization of Black Cotton Soil Using GGBS–Red Mud Blends for Pavement Subgrade Applications

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Abstract

Black cotton soil (BCS) is an expansive soil whose swelling, shrinkage and low soaked strength make it a poor pavement subgrade. This study evaluated blends of ground granulated blast furnace slag (GGBS) and red mud (RM), two industrial by-products, as stabilizers for a BCS from the Cuddapah–Kurnool section of NH-40 in Andhra Pradesh. Five GGBS:RM ratios (100:00, 70:30, 50:50, 30:70 and 00:100) were added to the soil, and mixtures with a total stabilizer content of 25% of the dry soil weight were tested for free swell index (FSI), unconfined compressive strength (UCS) and soaked California Bearing Ratio (CBR) after 0, 7, 14 and 28 days of curing, and for mass loss after four wetting–drying cycles. The untreated soil had an FSI of 52.28%, a UCS of 131 kPa and a soaked CBR of 1.5%. Stabilization reduced the FSI to 15–25%, with the lowest value for the 70:30 blend, a reduction of about 71%. UCS increased with curing for every blend; the 70:30 blend gave the highest UCS at every age, reaching 920 kPa at 28 days, about 7.0 times that of the untreated soil. The highest 28-day soaked CBR, 22.8%, was obtained with GGBS alone (100:00), while the 70:30 blend reached 11.5%, about 7.7 times the untreated value. The 70:30 blend also showed the lowest wet–dry mass loss (13.5%, against 18.5–21.0% for the other blends). Considering strength, swelling, bearing capacity and durability together, 25% stabilizer at a GGBS:RM ratio of 70:30 (soil:GGBS:RM = 75:17.5:7.5) was selected as the most favourable overall mixture. Field trials and environmental assessment of red mud are recommended before large-scale use.

Keywords: Black cotton soil; Expansive soil; GGBS; Red mud; Soil stabilization; Unconfined compressive strength; Soaked CBR; Free swell index; Wet–dry durability; Pavement subgrade

1. INTRODUCTION

Black cotton soil (BCS) covers large parts of central and southern India and is one of the most troublesome subgrade materials encountered in highway construction. Its clay fraction is dominated by expansive minerals, so it swells when wetted and shrinks and cracks when it dries. Under a pavement, these seasonal volume changes cause differential movement, longitudinal cracking and uneven riding surfaces, and the soil loses much of its bearing capacity when saturated [1]. Because flexible pavements are designed on the soaked CBR of the subgrade [2], a BCS subgrade with a very low soaked CBR leads to a thick and costly pavement crust unless the soil is improved.

Chemical stabilization with lime or cement is the conventional remedy, and IRC:SP:89 gives guidelines for stabilized subgrades [3]. Both binders, however, are energy-intensive, and there is growing interest in replacing them partly or wholly with industrial by-products [4]. Ground granulated blast furnace slag (GGBS), a by-product of iron-making rich in calcium, silica and alumina, is a latent hydraulic material that can form cementitious products in soil [5], [6]. Red mud (RM), the alkaline residue of alumina production by the Bayer process, is generated in very large quantities and stored in ponds; its use in soil stabilization would turn a disposal problem into a construction resource [7], [8].

Each material has limitations when used alone, and the proportion in which they are combined may control the performance of the stabilized soil. The present study therefore investigates GGBS–RM blends at five ratios for stabilizing an expansive BCS for pavement subgrades. Its objectives are (i) to evaluate the effect of the GGBS:RM ratio on the free swell, unconfined compressive strength (UCS) and soaked CBR of the soil; (ii) to evaluate the effect of curing period on strength and bearing capacity; (iii) to assess the durability of the stabilized soil under repeated wetting and drying; and (iv) to identify the most suitable blend for subgrade applications by considering these properties together.

2. LITERATURE REVIEW

Mai-Bade et al. reviewed the admixtures used to stabilize BCS, including lime, cement, fly ash and other industrial and agricultural wastes, and noted that the effectiveness of each depends on soil mineralogy, dosage and curing [1]. Jayanthi et al. examined sustainable materials for stabilizing fine-grained soils against desiccation cracking, a common problem in expansive soils that dry seasonally [4]. Sharma and Sivapullaiah showed that GGBS-amended fly ash can serve as a stabilizer for expansive soil, demonstrating the value of combining GGBS with another by-product [5]. Darsi et al. stabilized a BCS subgrade with GGBS and lime and reported improved subgrade properties [6], and Noolu et al. studied the strength and durability of BCS stabilized with a GGBS-based geopolymer [9].

Red mud has been used with other additives in expansive soils. Sridevi et al. stabilized an expansive soil with red mud and lime [7]. Sahoo et al. treated a BCS (UCS 48.78 kPa, free swell index 27.7%) with red mud, phosphogypsum and lime, and obtained the highest UCS of 223.5 kPa with 5% lime added to a 60:40 soil–red mud mix [8]. Dwivedi and Kumar combined fly ash and red mud for stabilizing BCS and assessed the mixtures experimentally and through a performance-index approach [10].

These studies show that GGBS and red mud can each improve expansive soils, usually when combined with lime, fly ash or chemical activators. Few studies, however, have combined GGBS and red mud directly, varied their ratio systematically, and evaluated swelling, UCS, soaked CBR and wet–dry durability together for the same BCS. Since a mixture that gives the highest strength may not give the highest CBR or the lowest swelling, the present study evaluates all of these properties to select a blend for pavement subgrades.

3. MATERIALS AND METHODOLOGY

3.1 Materials

The black cotton soil was collected near Hussainapuram on the existing Cuddapah–Kurnool National Highway (NH-40), Andhra Pradesh (Fig. 1(a)). It was air-dried, pulverized to remove lumps, mixed to obtain a representative sample and sieved as required for each test. GGBS was obtained from Chettinad Cement, Visakhapatnam (Fig. 1(b)); its major constituents are SiO_2, CaO, Al_2O_3 and MgO. Red mud was collected from the storage pond of National Aluminium Company Limited (NALCO) at Damanjodi, Odisha, where it is generated by the Bayer process (Fig. 1(c)). The materials are summarised in Table 1.



(a) BCS sampling, Hussainapuram **(b)** GGBS **(c)** Red mud

Fig. 1. Materials used in the study

Table 1. Materials used in the investigation

Material	Source / description
Black cotton soil (BCS)	Hussainapuram, Cuddapah–Kurnool NH-40, Andhra Pradesh
GGBS	Chettinad Cement, Visakhapatnam, Andhra Pradesh
Red mud (RM)	NALCO storage pond, Damanjodi, Odisha
GGBS:RM blend ratios	100:00, 70:30, 50:50, 30:70 and 00:100

3.2 Experimental programme

The experimental programme followed the sequence shown in Fig. 2. Five GGBS:RM ratios were prepared by mass, and each blend (GGRM) was added to the soil at 5, 10, 15, 20, 25 and 30% of the dry soil weight, giving 30 combinations with three specimens per combination. Strength trends over this range showed that strength generally increased up to 25% stabilizer and decreased beyond it, so the detailed comparison of blend ratios reported here is for a total stabilizer content of 25%. For the 70:30 blend this corresponds to soil, GGBS and RM proportions of 75%, 17.5% and 7.5% by dry mass. Specimens were cured for 7, 14 and 28 days, and the untreated soil served as the reference (Table 2).

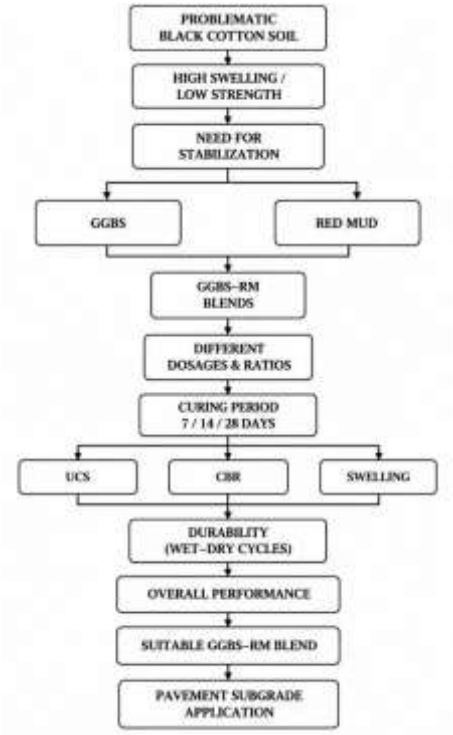


Fig. 2. Methodology of GGBS–red mud stabilization of black cotton soil

Table 2. Experimental programme

Parameter	Details
GGBS:RM ratios	100:00, 70:30, 50:50, 30:70, 00:100
Stabilizer contents (% of dry soil)	5, 10, 15, 20, 25, 30 (detailed results at 25%)
Number of blend combinations	30 (three specimens each)
Curing periods	0 (initial), 7, 14 and 28 days
Reference specimen	Untreated black cotton soil
Main tests	Compaction, free swell index, UCS, soaked CBR, wet–dry durability

3.3 Test methods

The soil was characterized for specific gravity, particle-size distribution, consistency limits, free swell and swelling pressure as per IS 2720 Parts 3, 4, 5, 40 and 41 [11]–[15]. The moisture–density relationship of each mixture was determined by light compaction as per IS 2720 (Part 7) [16], and specimens for the other tests were prepared at the corresponding compaction condition. The dry soil and the GGRM blend were first mixed thoroughly, water was added and mixed to a uniform moisture content, and the mixture was compacted or moulded as required by each test. The UCS was determined as per IS 2720 (Part 10) [17] and the soaked CBR as per IS 2720 (Part 16) [18]. The free swell index (FSI) was determined as per IS 2720 (Part 40) [14] from the equilibrium sediment volumes of 10 g of oven-dried soil passing the 425 μm sieve in distilled water (V_d) and in kerosene (V_k):

$$FSI\ (\%) = 100 \times (V_d - V_k) / V_k \quad (1)$$

Wet–dry durability was evaluated on specimens cured for 28 days in airtight bags (Fig. 3). Each cycle consisted of wetting for 5 hours at ambient temperature followed by oven-drying for 42 hours at 70 ± 2 °C. After four cycles, the mass loss was calculated as

$$\text{Mass loss (\%)} = 100 \times (M_0 - M_4) / M_0 \quad (2)$$

where M_0 is the initial dry mass of the specimen and M_4 its dry mass after four cycles. The improvement of a stabilized mixture over the untreated soil was expressed as an improvement ratio, $R = X_{\text{stabilized}} / X_{\text{untreated}}$, where X is the UCS or soaked CBR.

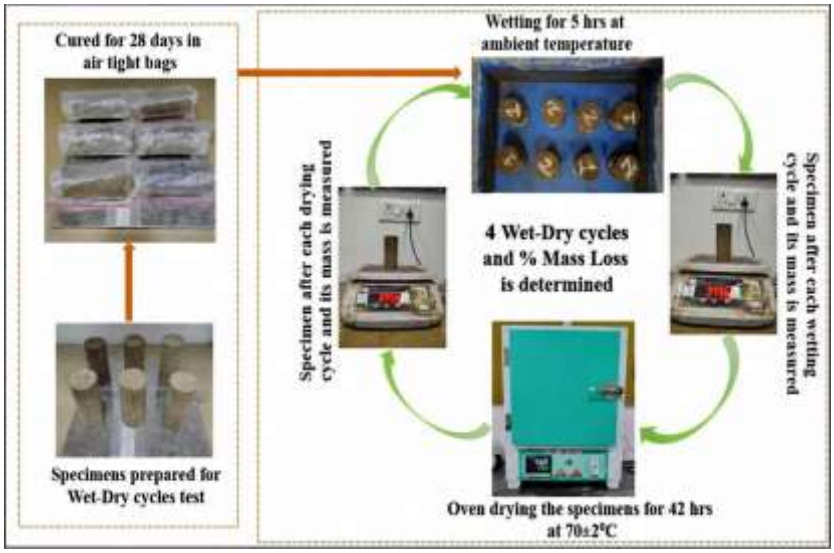


Fig. 3. Wet–dry durability procedure: curing, wetting for 5 h, oven-drying for 42 h at 70 °C and mass measurement

4. RESULTS AND DISCUSSION

4.1 Untreated black cotton soil

The untreated soil had a free swell index of 52.28%, the mean of trial values of 50.00% and 54.55%, a UCS of 131 kPa and a soaked CBR of 1.5% (Table 3). The high free swell confirms a strongly expansive soil, and the very low soaked CBR shows that the soil provides little bearing support when saturated, so it needs improvement before it can serve as a pavement subgrade [2]. When wetted in the durability test, the compacted untreated soil disintegrated rapidly during the first wetting cycle, so its mass loss could not be measured over four cycles.

Table 3. Engineering properties of the untreated black cotton soil

Property	Untreated BCS
Free swell index	52.28%
Unconfined compressive strength	131 kPa
Soaked CBR	1.50%
Reference condition	0 days / untreated
Application considered	Pavement subgrade

4.2 Free swell index

Stabilization reduced the free swell index substantially (Fig. 4, Table 4). With 25% GGRM, the FSI fell from 52.28% to between 15% and 25%, below the 50% reference line, for all five blends. The 70:30 blend gave the lowest FSI of 15%, a reduction of 71.3%, followed by the 50:50 (19%), 30:70 (21%), 00:100 (23%) and 100:00 (25%) blends. Partial replacement of GGBS by red mud therefore reduced swelling more than GGBS alone, with the best result at 30% red mud in the blend; beyond this, the FSI increased again as the red mud proportion rose.

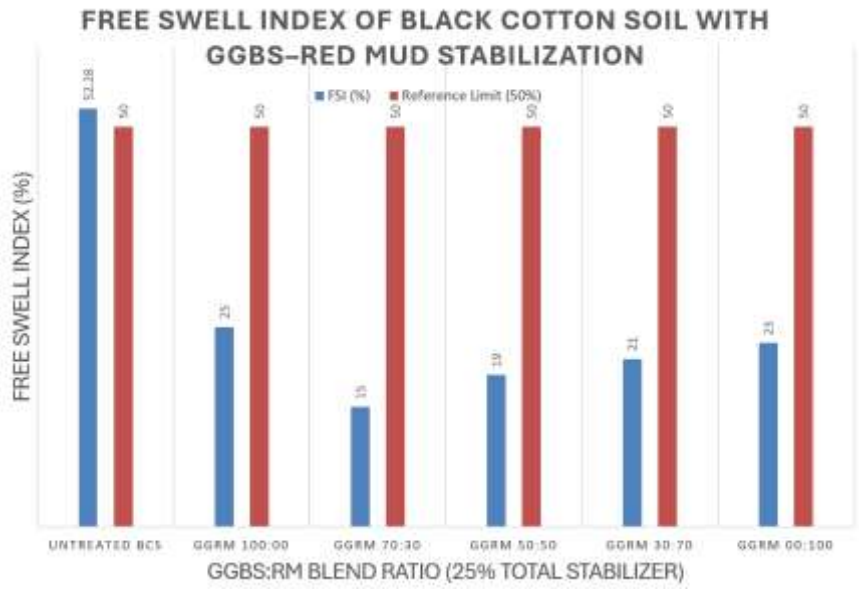


Fig. 4. Free swell index of black cotton soil with 25% GGBS–red mud stabilizer

Table 4. Free swell index of untreated and stabilized soil (25% GGRM)

Soil mixture	FSI (%)	Reduction relative to untreated soil (%)
Untreated BCS	52.28	—
GGRM 100:00	25	52.18
GGRM 70:30	15	71.31
GGRM 50:50	19	63.66
GGRM 30:70	21	59.83
GGRM 00:100	23	55.93

4.3 Unconfined compressive strength

All stabilized mixtures were stronger than the untreated soil at every age, and their UCS increased steadily with curing (Table 5, Fig. 5). Immediately after mixing, the UCS rose only modestly, from 131 kPa to 140–168 kPa, which shows that most of the strength gain comes from reactions that develop with time rather than from the immediate effect of the added solids. After 7 days, the 70:30 blend reached 450 kPa, an increase of 243.5%; after 14 days it reached 680 kPa (+419.1%); and after 28 days it reached 920 kPa, 7.02 times the untreated UCS (+602.3%). The ranking of the blends was the same at 14 and 28 days:

70:30 > 50:50 > 100:00 > 30:70 > 00:100

Table 5. Age-wise UCS (kPa) of BCS stabilized with 25% GGRM

GGBS:RM	0 days	7 days	14 days	28 days
Untreated BCS	131	131	131	131
100:00	145	350	520	686
70:30	**168**	**450**	**680**	**920**
50:50	151	390	570	780
30:70	142	320	470	650
00:100	140	250	360	500

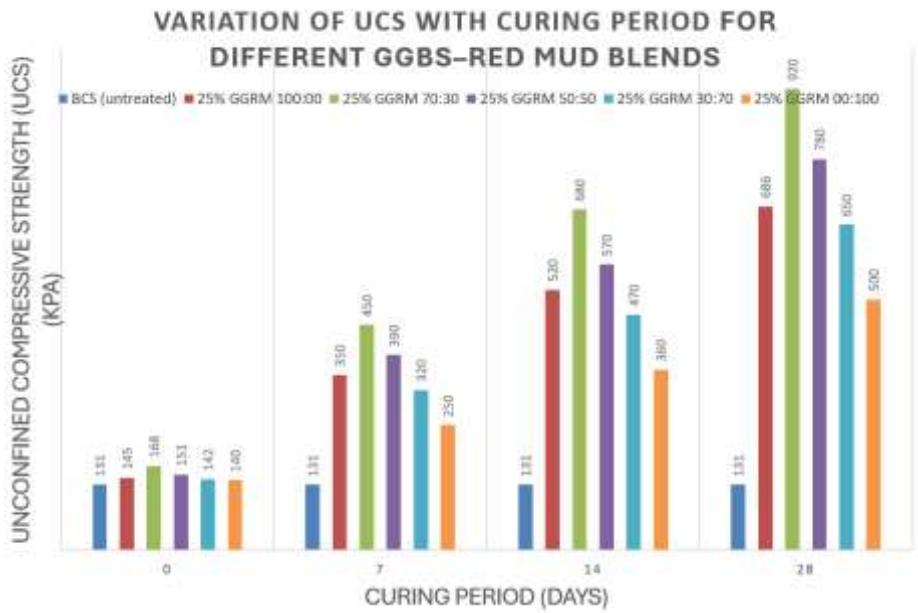


Fig. 5. Variation of UCS with curing period for different GGBS–red mud blends

The 28-day UCS ranged from 500 kPa for red mud alone to 920 kPa for the 70:30 blend. GGBS alone (686 kPa) produced a substantial gain, but replacing 30% of it with red mud raised the strength by a further 34%, whereas larger red mud proportions lowered it. A plausible explanation is that the alkaline red mud promotes the reaction of the slag, while too much red mud dilutes the reactive GGBS; this interpretation is consistent with the trends but could not be confirmed, because no microstructural tests were carried out. Across the range of stabilizer contents, strength generally increased up to 25% GGRM and decreased beyond it, so increasing the dose further does not produce a proportional gain.

4.4 Soaked California Bearing Ratio

The soaked CBR of all stabilized mixtures increased with curing period (Table 6, Fig. 6). For the 70:30 blend it rose from 3.8% immediately after mixing to 7.3%, 8.8% and 11.5% after 7, 14 and 28 days, an increase of 202.6% over its initial value; the 100:00 blend rose from 4.5% to 22.8% and the 50:50 blend from 3.3% to 9.8% over the same period. Unlike the UCS, the soaked CBR was highest for GGBS alone at every age, and it fell steadily as the red mud proportion increased. The 28-day ranking was:

100:00 > 70:30 > 50:50 > 30:70 > 00:100

Table 6. Soaked CBR (%) of BCS stabilized with 25% GGRM

GGBS:RM	0 days	7 days	14 days	28 days
Untreated BCS	1.5	1.5	1.5	1.5
100:00	4.5	8.8	13.2	22.8
70:30	3.8	7.3	8.8	11.5
50:50	3.3	6.4	8.0	9.8
30:70	2.9	5.1	7.2	8.4
00:100	2.1	4.7	5.9	6.2

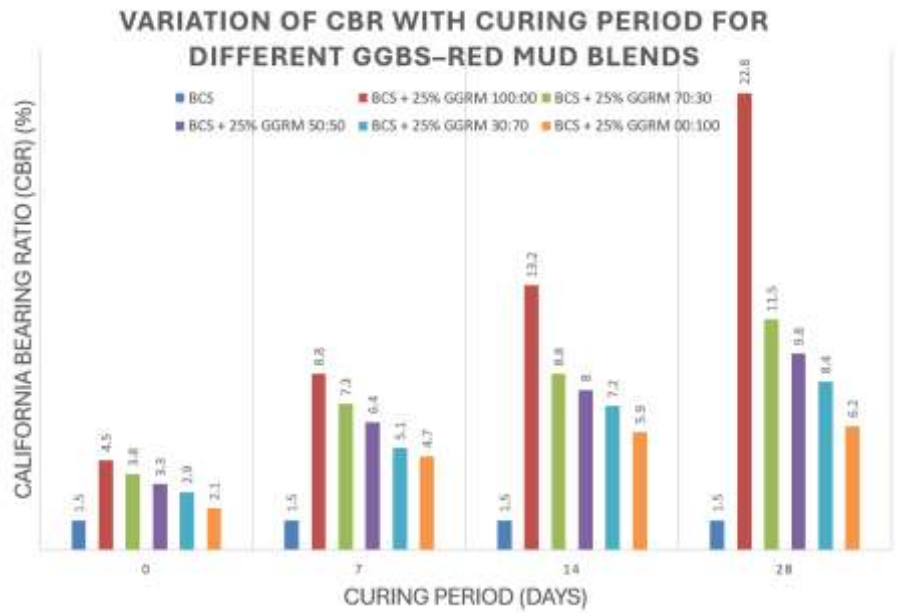


Fig. 6. Variation of soaked CBR with curing period for different GGBS–red mud blends

Relative to the untreated soil, the 28-day soaked CBR increased by 1420% for the 100:00 blend, 666.7% for 70:30, 553.3% for 50:50, 460% for 30:70 and 313.3% for 00:100. GGBS therefore played the main role in improving the soaked bearing capacity, while red mud contributed more to swelling control and compressive strength.

4.5 Comparison of UCS and soaked CBR

Table 7 compares the 28-day UCS and soaked CBR. The two tests identify different best mixtures: the 70:30 blend gave the highest UCS (920 kPa) with the second-highest CBR (11.5%), whereas GGBS alone gave the highest CBR (22.8%) with the third-highest UCS (686 kPa). Both properties decreased once the red mud proportion exceeded 30%, and red mud alone gave the lowest values of both. For the 70:30 blend, the improvement ratios were 920/131 = 7.02 for UCS and 11.5/1.5 = 7.67 for soaked CBR. Since a subgrade must resist both compression and soaked penetration, and must also control swelling, the optimum cannot be chosen from a single test.

Table 7. Comparison of 28-day UCS and soaked CBR

GGBS:RM ratio	UCS (kPa)	Soaked CBR (%)	CBR increase over untreated
Untreated BCS	131	1.5	—
100:00	686	22.8	1420%
70:30	920	11.5	666.7%
50:50	780	9.8	553.3%
30:70	650	8.4	460%
00:100	500	6.2	313.3%

4.6 Wet–dry durability

The untreated soil disintegrated during the first wetting, whereas all stabilized specimens survived four complete wet–dry cycles. Their mass losses are given in Table 8 and Fig. 7. The 70:30 blend lost the least mass (13.5%), followed by the 50:50 (16.8%), 100:00 (18.5%), 30:70 (19.2%) and 00:100 (21.0%) blends. As with the UCS, replacing 30% of the GGBS with red mud improved the resistance to cyclic moisture changes, while larger red mud proportions reduced it.

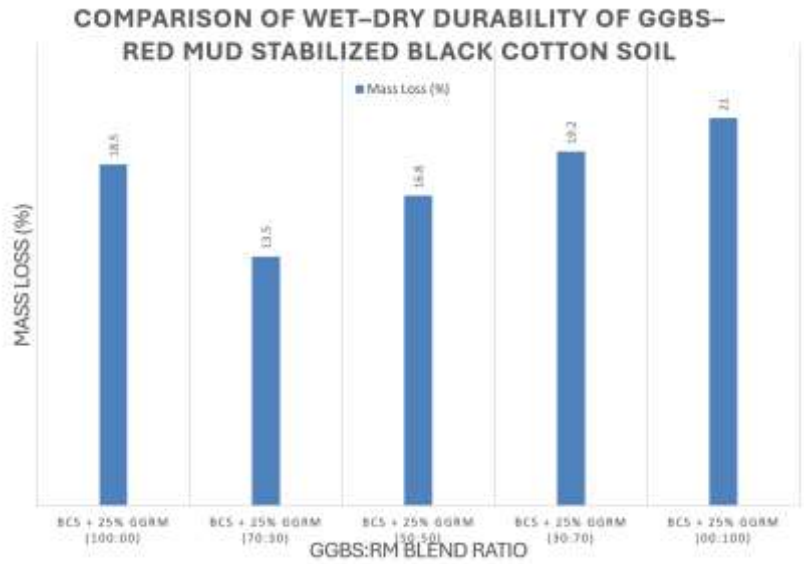


Fig. 7. Wet–dry durability (mass loss) of GGBS–red mud stabilized black cotton soil

Table 8. Mass loss after four wet–dry cycles (25% GGRM)

GGBS:RM ratio	Mass loss (%)
100:00	18.5
70:30	13.5
50:50	16.8
30:70	19.2
00:100	21.0

4.7 Selection of the optimum blend

Table 9 summarises the best results. The 70:30 blend gave the highest UCS at every curing age, the lowest free swell index and the lowest wet–dry mass loss, together with the second-highest soaked CBR, which at 11.5% is still more than seven times that of the untreated soil. GGBS alone gave the highest soaked CBR but weaker swelling control, lower strength and greater mass loss. On the combined basis of strength, swelling, bearing capacity and durability, 25% GGRM at a GGBS:RM ratio of 70:30, that is, soil, GGBS and red mud in the proportion 75:17.5:7.5 by dry mass, was selected as the most favourable overall mixture. It should be described as the best overall mixture rather than the best for every property; where the soaked CBR alone governs the design, GGBS alone may be preferred.

Table 9. Overall performance of the investigated mixtures

Parameter	Untreated BCS	Best result	Corresponding mix
Free swell index	52.28%	15%	25% GGRM 70:30
UCS at 28 days	131 kPa	920 kPa	25% GGRM 70:30
Soaked CBR at 28 days	1.5%	22.8%	25% GGRM 100:00
Wet–dry mass loss	disintegrated	13.5%	25% GGRM 70:30
Overall selected blend	—	70:30	25% total GGRM

4.8 Practical implications and limitations

For field use, the selected mixture of 75% BCS, 17.5% GGBS and 7.5% red mud could be applied through site preparation, pulverization of the soil, proportioning and dry mixing of GGBS and red mud, moisture conditioning, mixing, spreading, compaction, curing and quality control. The approach improves a poor subgrade while using two industrial by-products, and the higher soaked CBR would permit a thinner pavement crust under the IRC:37 design method [2]. The study, however, used one soil source and one source each of GGBS and red mud, whose properties vary between locations. Detailed results are reported for 25% stabilizer only, laboratory specimens may differ from field-mixed material, and microstructure, leaching of red mud constituents and long-term field performance were not studied. Field trials and environmental assessment are therefore required before large-scale use.

5. CONCLUSIONS

The following conclusions are drawn from the laboratory investigation:

1. The untreated black cotton soil was highly expansive and weak, with a free swell index of 52.28%, a UCS of 131 kPa and a soaked CBR of 1.5%, and it disintegrated on first wetting.
2. GGBS–red mud stabilization at 25% reduced the free swell index to 15–25%; the 70:30 blend gave the lowest value, a reduction of about 71%.
3. The UCS of all blends increased with curing. The 70:30 blend was the strongest at every age and reached 920 kPa at 28 days, about 7.0 times the untreated UCS; strength fell when the red mud proportion exceeded 30%.
4. The soaked CBR also increased with curing. GGBS alone gave the highest 28-day CBR of 22.8%, and the 70:30 blend reached 11.5%, about 7.7 times the untreated value.
5. All stabilized mixtures survived four wet–dry cycles; the 70:30 blend had the lowest mass loss (13.5%) and red mud alone the highest (21.0%).
6. Considering all properties together, 25% stabilizer at a GGBS:RM ratio of 70:30 (BCS:GGBS:RM = 75:17.5:7.5) was the most favourable overall mixture for pavement subgrades.

Future work should include field trial sections with long-term monitoring, microstructural and mineralogical analysis, leaching and environmental assessment of red-mud-stabilized soil, tests on other black cotton soils and by-product sources, and life-cycle cost assessment.

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