



Use of Stabilized Lateritic and Black Cotton Soils as a Base Course Replacing Conventional Granular Layer in Flexible Pavement

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Abstract

The present work investigates the improved properties of lateritic and black cotton soils stabilized with ground granulated blast furnace slag (GGBFS) and alkali solutions. The alkali solution includes a mixture of sodium hydroxide and sodium silicate. The lateritic and black soils are treated with 30% GGBFS and the alkali solutions consisting of 6% Na₂O having silica modulus (*M_s*) of 0.5, 1.0 and 1.5 at a constant water binder ratio of 0.25. The treated samples were air-cured for 0 (immediately after casting), 3, 7 and 28 days at ambient temperature. The treated lateritic soil with 0.5 and 1.0 *M_s* is found durable after 3, 7, and 28 days curing. Whereas, the treated BC soil found durable with *M_s* 0.5 at modified Proctor density after 28 days curing. The formation of calcium silicate hydrate and calcium aluminosilicate hydrate structures resulted in a remarkable improvement of compressive strength, flexure and fatigue life of treated soils due to dissolved calcium ions from GGBFS, silicate and aluminium ions from alkali solutions. The microstructure image of the durable soil sample shows the crystal orientation of particles. The design of high and low volume roads is proposed by replacing the conventional granular layer with the durable stabilized soil and stress–strain analysis is carried out using pavement analysis software.

Keywords Lateritic soil · Black cotton soil · Alkali solutions · Durability · Stress–strain analysis · Microstructure

Introduction

Lateritic soil (*L*) is abundantly available in tropical and subtropical regions formed due to the prolonged weathering of the parent rock. In India, lateritic soil is predominantly available along the western coast [1] and black cotton (BC) soil is formed due to the decomposition and disintegration of rocks [2]. Due to the weathering, lateritic soil exhibits poor engineering properties such as high permeability, low density and low strength [3] and BC soil exhibits high swelling index ranging from 50 to 220% [2]. Hence, stabilization techniques need to be adopted to improve the engineering characteristics of the soil. The concept of geopolymerization involves the chemical reaction of aluminosilicate oxides with alkali poly-silicates yielding polymeric Si–O–Al bonds [4]. Many researchers worked on the stabilization of soil

using aluminosilicate materials such as ground granulated blast furnace slag (GGBFS) and Fly Ash [5, 6] with alkali poly-silicate materials such as sodium hydroxide (NaOH) [7], sodium silicate (Na₂SiO₃) and potassium hydroxide (KOH) [8]. Among many alkali solutions, the combination of NaOH and Na₂SiO₃ is found as the best combination for the stabilization of expansive soil [9]. In the present work, the geopolymerization technique is considered for the stabilization of lateritic and BC soils using GGBFS mixed with the combination of NaOH and Na₂SiO₃.

As the molarity of NaOH increases from 4 to 12 in the expansive soil stabilization, the unconfined compressive strength (UCS) increased to 1.5 times that of the ordinary portland cement (OPC) treated soil [10, 11] and similar work on fly ash-based geopolymer in stabilizing the expansive soil achieved 2.7 times more strength after 28 days curing [12]. It is observed that the 8% sodium oxide (Na₂O) dosage increases the strength of the expansive soil but further increase in Na₂O dosage decreases the mechanical strength and the same trend observed in the case of potassium oxide (K₂O) as well [5, 13, 14]. The high reactivity in alkali-activated fly ash is observed within 1–28 days of curing which is due to the high energy absorption [11, 15]. The optimum

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Table 1 The physical properties of the lateritic and BC soils

Properties	Lateritic soil	BC soil
Specific gravity	2.6	2.5
Grain sieve analysis		
Gravel (%)	24	2
Sand (%)	15	41
Silt (%)	20	32
Clay (%)	41	25
Atterberg limits		
Liquid limit (%)	66	42
Plastic limit (%)	32	22
Plasticity index (%)	34	20
Shrinkage limit (%)	–	10
Standard Proctor test		
OMC (%)	24	21.4
MDD (g/cc)	1.5	1.62
Modified Proctor test		
OMC (%)	22	17.2
MDD (g/cc)	1.72	1.7
CBR at standard Proctor density		
Unsoaked (%)	8	4
Soaked (%)	4	3
CBR at modified Proctor density		
Unsoaked (%)	20	13
Soaked (%)	10	7
UCS		
Standard Proctor (kPa)	433	155
Modified Proctor (kPa)	548	268

water binder ratio (w/b) of 0.25–0.35 in a fly ash-based geopolymer is showing better strength and a further increase in w/b ratio decreases the strength [16]. In case of pumice-based geopolymer composite the best mix was found at 0.36 w/b ratio, 0.68 silica modulus (M_s = ratio of Na_2O to SiO_2) and 10% Na_2O [17] and in case of fly ash-based geopolymer, the high strength is obtained at M_s 0.8–1.4, 8% Na_2O and curing for 72 h at 90 °C [18].

The lithomargic clay stabilized with the alkali-activated GGBFS and fly ash is found to be durable under extreme weather conditions [19, 20]. Similarly, the stabilization of BC soil with electrolytic lignin and fly ash [21] and high calcium fly ash binder [22] passed the durability tests with weight loss of less than 14%. The microstructure images of

the alkali-activated fly ash mortars [23] and geopolymerization on BC soil [24] shows the strong bond formation due to the polymerization.

Due to urbanization, the infrastructure construction demands the huge quantity of gravels which leads to the depletion of natural resources. To avoid the use of depleting gravels, naturally and abundantly available soil can be used. Therefore, the present work aims at replacing the granular materials with the lateritic and BC soil stabilized with GGBFS and alkali solutions such as NaOH and Na_2SiO_3 . The 30% GGBFS and the alkali solutions containing 6% Na_2O with the M_s of 0.5, 1.0 and 1.5 at a constant w/b of 1.25 are the parameters used for the investigation. The engineering properties of the stabilized soil is found by laboratory tests such as UCS, California bearing ratio (CBR) and durability under extreme weather conditions at both standard (S) and modified (M) Proctor densities cured at ambient temperature (25 °C) for 0 (immediately after casting), 3, 7 and 28-days curing as a base course in low and high-volume road construction. The stress and strain developed on the stabilized base course are analyzed using KENPAVE software and crystal orientation of the durable samples cured for 28 days was observed using scanning electron microscope (SEM).

Materials and Methodologies

Materials

For the present work, the lateritic and BC soils were procured from Dakshina Kannada district, Karnataka, India. The engineering properties and chemical composition of these soils are tabulated in Tables 1 and 2, respectively. The chemical composition of both soils was found as per the relevant code. The GGBFS is a by-product of steel industries

Table 3 Physical properties of GGBFS

Properties	Results
Specific gravity	2.87
Size (micron)	< 75
Water content (%)	24.4
Loss of ignition (%)	0.05

Table 2 Chemical properties of the lateritic and BC soils

Oxides	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Sulfate	pH	Electrical conductivity ($\mu\text{s}/\text{cm}$)
Quantity (%)								
Lateritic soil	69.3	10.3	5.2	0.11	0.004	0.02	5.02	13.37
BC soil	55.3	9.3	7.2	0.0042	0.012	0.087	8.16	1.17

Table 4 Chemical properties of GGBFS

Oxides	CaO	SiO ₂	Al ₂ O ₃	MgO	Fe ₂ O ₃	MnO
Amount (%)	37.5	37.6	14.4	8.5	0.98	0.01

procured from Jindal Steel Works (JSW). The physical and chemical properties of GGBFS are tabulated in Tables 3 and 4, respectively. The NaOH is available in the form of flakes having a molecular weight of 40 g/mole with a specific gravity of 2.14. The Na₂SiO₃ is in the form of liquid consisting of 18.8% Na₂O, 32.4% silica oxide (SiO₂) and 48.6% water and having a molecular weight of 285.1 g/mole and the specific gravity of 1.52 with *M_s* of 1.76. The procured alkali materials were industrial grade with a purity level of 95–99%.

Methodologies

The relevant codes were followed for conducting the experiments in the laboratory and are tabulated in Table 5. Three samples were prepared at both standard and modified Proctor densities for each test. The variance of three replicates

Table 5 The standards followed for the laboratory tests

Name of the tests	Confirming codes
Specific gravity	IS 2720: Part 3: Sec 1: 1980
Grain sieve analysis	IS: 1498–1970
Atterberg limits	IS 2720: Part 5: 1985
Proctor tests	
Standard Proctor test	IS 2720: Part 7: 1980
Modified Proctor test	IS 2720: Part 8: 1983
Unconfined compressive strength test	IS 2720: Part 10: 1991
California bearing ratio test	IS: 2720–16 1987
Durability test	
Wetting and drying test	ASTM 559-D
Freeze and thaw test	ASTM 560-D
Flexure strength test	IS 4332: Part 6: 1972
Chemical composition	
SiO ₂ , Fe ₂ O ₃ and Al ₂ O ₃	IS 2720: Part 25: 1982
CaO and MgO	Titration

was verified with the relevant standards. From the sieve analysis, the lateritic soil is classified as Silty soil with high compressibility (MH) and BC soil as clayey soil with medium compressibility (CI) as per Indian Standards (IS) classification.

Result and Discussions

Proctor Tests

The optimum moisture content (OMC) and maximum dry density (MDD) of treated soils are obtained from standard and modified Proctor tests. The lateritic and BC soil samples are replaced with 30% GGBFS and alkali solution consisting of 6% Na₂O and *M_s* of 0.5, 1.0 and 1.5. The OMC and MDD of the treated soil at different *M_s* are tabulated in Table 6.

Unconfined Compressive Strength Test

The UCS samples of treated lateritic and BC soils at both standard and modified Proctor densities are air-cured for 0, 3, 7 and 28 days when the relative humidity was 55–60%. The variation in UCS values of treated soils to different curing periods and *M_s* are shown in Figs. 1 and 2.

In the case of lateritic soil, the treated samples having *M_s* of 1.0 cured for 28 days are giving the maximum UCS of 6341 and 9901 kPa which are 13.6 and 17.1 times that of the natural soil at standard and modified Proctor densities, respectively. Whereas, in the case of treated BC soil having *M_s* of 0.5 cured for 28 days achieved the maximum UCS of 1225 and 1723 kPa which are 7 and 5.4 times of the natural soil at standard and modified Proctor densities, respectively.

Table 6 The OMC and MDD of the treated samples from standard and modified Proctor tests

Silica modulus	Lateritic soil				BC soil			
	Standard Proctor test		Modified Proctor test		Standard Proctor test		Modified Proctor test	
	OMC (%)	MDD (g/cc)	OMC (%)	MDD (g/cc)	OMC (%)	MDD (g/cc)	OMC (%)	MDD (g/cc)
0.5	20.5	1.72	17	1.82	17.3	1.69	13.1	1.72
1.0	20	1.7	17	1.82	17	1.67	12.8	1.71
1.5	21.8	1.65	17.7	1.8	16.8	1.66	12.6	1.7

Fig. 1 The variation in UCS of treated soil to different curing periods

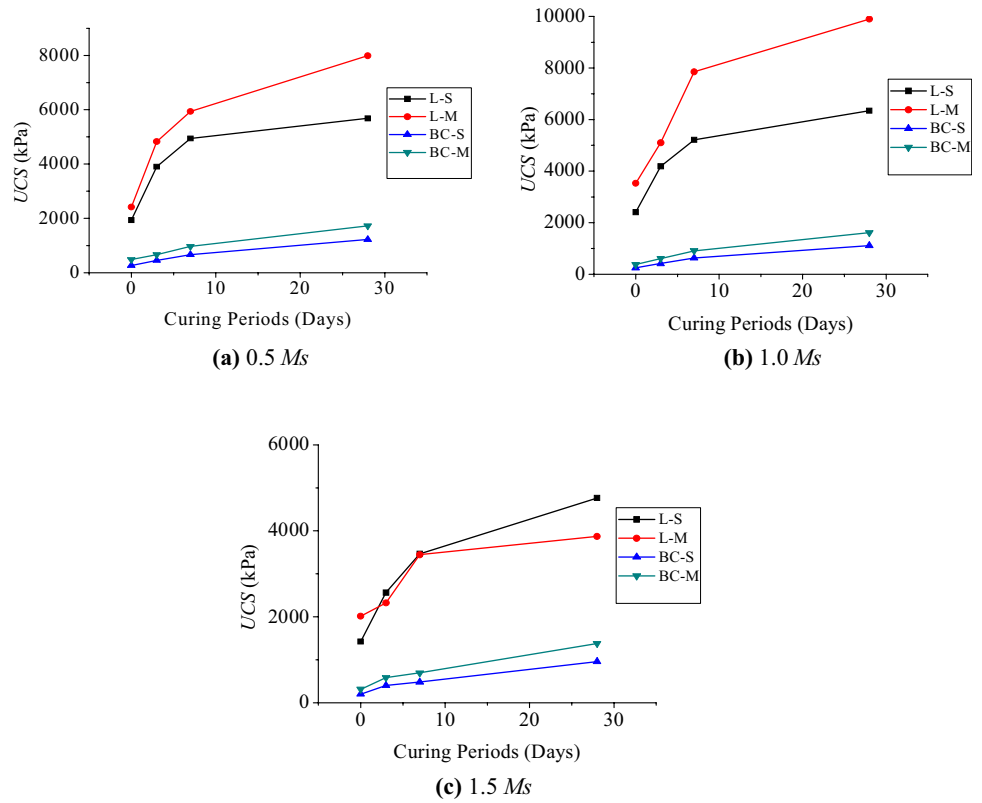
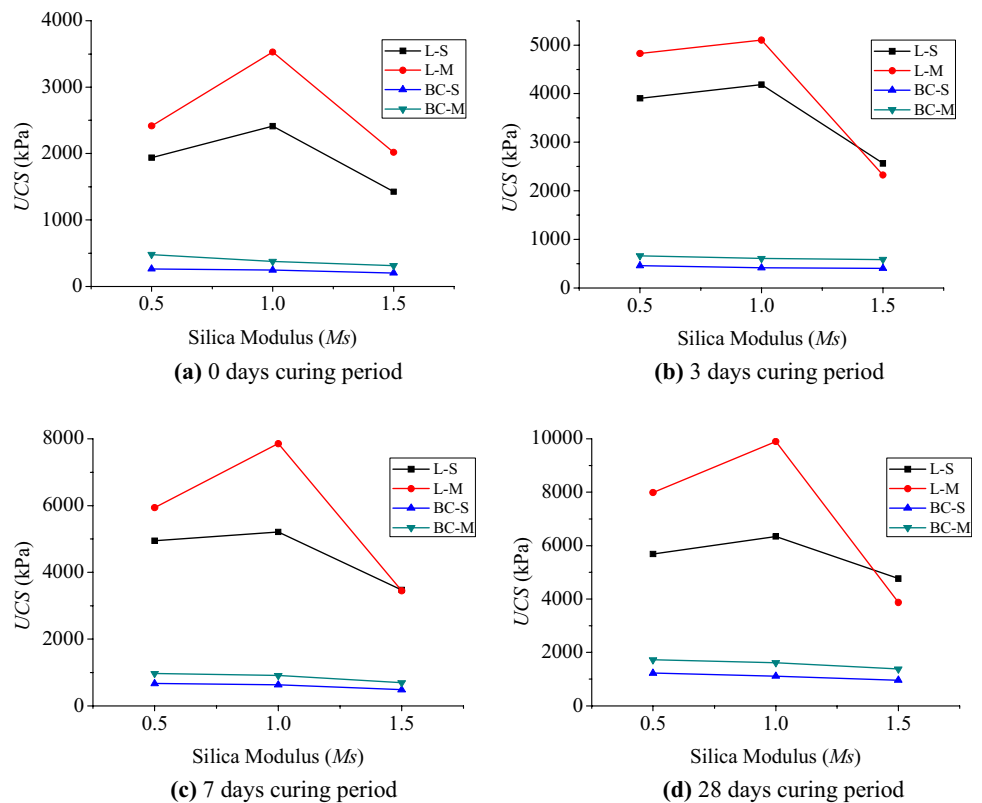


Fig. 2 The variation in UCS values of treated soil samples at different silica modulus (M_s)



Effect of Curing Periods

From Fig. 1a–c, it is observed that at both standard and modified Proctor densities, the UCS increases with an increase in curing period from 0 to 28 days at all M_s . When calcium oxide (CaO) rich GGBFS reacts with alkali solution generates heat and for M_s calcium silicate hydrate (CSH) bond. The generated heat rapidly increases the rate of polymerization initially and as the curing period further increases, at ambient temperature, the gradual polymerization helps to form calcium aluminosilicate hydrate (aluminosilicate structure or CASH) and hence the UCS increases [25].

Effect of Silica Modulus

From Fig. 2a–d, it is noticed that the treated lateritic soil achieved the maximum UCS at M_s of 1.0 at both densities which may be due to the equal concentration of SiO_2 and Na_2O helps in polymerization reaction and form aluminosilicate structure which increases the UCS whereas, in case of treated BC soil samples, the maximum UCS is achieved at M_s of 0.5 at both densities. This may be due to the increased fines in the BC soil contribute enough SiO_2 content to form an aluminosilicate structure. When M_s further increases to 1.5 in both treated soils, the UCS decreases as the increased SiO_2 content precipitates causing detrimental effects such as efflorescence and reduction in pH. And thus, decreases the UCS [26].

California Bearing Ratio (CBR)

The treated CBR soil samples are cured and tested under both soaked and unsoaked conditions. The cured samples kept for 4 days soaking found moisture absorption only 15%. The plunger could not penetrate into the soil as it was hard due to the high density, and resistant to the penetration was very high. The obtained CBR values were more than 100% which is unrealistic and hence, the correlation between UCS and CBR could not be established.

Durability

The treated samples should maintain the stability and integrity in the mixture when exposed to extreme weather conditions. The durability test consists of the wetting and drying (WD) and freeze and thaw (FT) test. The WD test is conducted by keeping the samples in water for 5 h and drying in an oven at 72 °C for 42 h. The weight loss at every cycle of WD is noted and percentage weight loss after 12 cycles of WD is found and it should be less than 14%. The FT test is conducted by keeping the cured treated samples in the freezer at –23 °C for 24 h and thawing at a temperature of 21 °C for 23 h. The weight loss at each cycle of the FT

test is noted and percentage weight loss after 12 cycles of the FT test should not exceed 14%. Figure 3a–d depicts the percentage weight loss at every cycle of the WD and FT test of lateritic soil at both densities.

From Fig. 3a–c, it is noticed that all treated samples of lateritic soil at both densities could able to withstand 12 cycles of FT with weight loss of less than 14%. The treated lateritic samples having M_s 0.5 and 1.0 at both densities cured for 3, 7 and 28 days sustained 12 cycles of WD test but samples prepared with alkali solution having M_s of 1.5 at both densities and in all curing periods collapsed within 12 cycles and are shown in Fig. 3 and failed samples are represented as samples with a 14% weight loss limit. At 1.5 M_s , the increased SiO_2 content demands higher Na_2SiO_3 and hence, water content increases. The increased water content in the mixture leads to a reduction in mechanical strength and integrity cannot be achieved, Hence, the samples collapsed within 12 alternate cycles of WD test [16].

In case of treated BC soil, the samples prepared at both densities found durable in FT test with weight loss less than 14% and the treated BC samples having M_s 0.5 cured for 28 days at modified Proctor density could withstand 12 cycles with percentage weight loss of 7.7% and the results are depicted in Fig. 4a–d. All treated samples at standard Proctor density collapsed within 12 cycles of the WD test. Samples compacted at modified Proctor density found durable in the WD test, it may be due to high density achieved from heavy compaction. As the GGBFS and BC soil are rich in SiO_2 content, the mechanical strength of the mixture will be more and hence, the durability is achieved. The samples L–S–0.5, L–M–0.5, L–S–1.0, L–M–1.0, and BC–M–0.5 have passed the durability test and hereafter these samples cured for 28 days are considered for flexure and fatigue tests and microstructure analysis.

Flexure Strength

The soil samples were cast into a shape of the rectangular beam having dimension 300 × 75 × 75 mm and tested under two-point loading. The failure load at which the crack occurs on the samples was noted and the modulus of resilient is calculated using the Eq. (1) where the weight of the beam is neglected.

$$M_R = \frac{Pl}{bd^2} \quad (1)$$

where, P is the maximum applied load in N , l is the span length in mm, b is the average width of the specimen in mm, d is the average depth of the specimen in mm, M_R is the modulus of rupture in MPa.

From Fig. 5, it is noticed that the lateritic samples having 1.0 M_s are showing better flexure strength of 0.69 and 1.33 MPa at standard and modified Proctor densities,

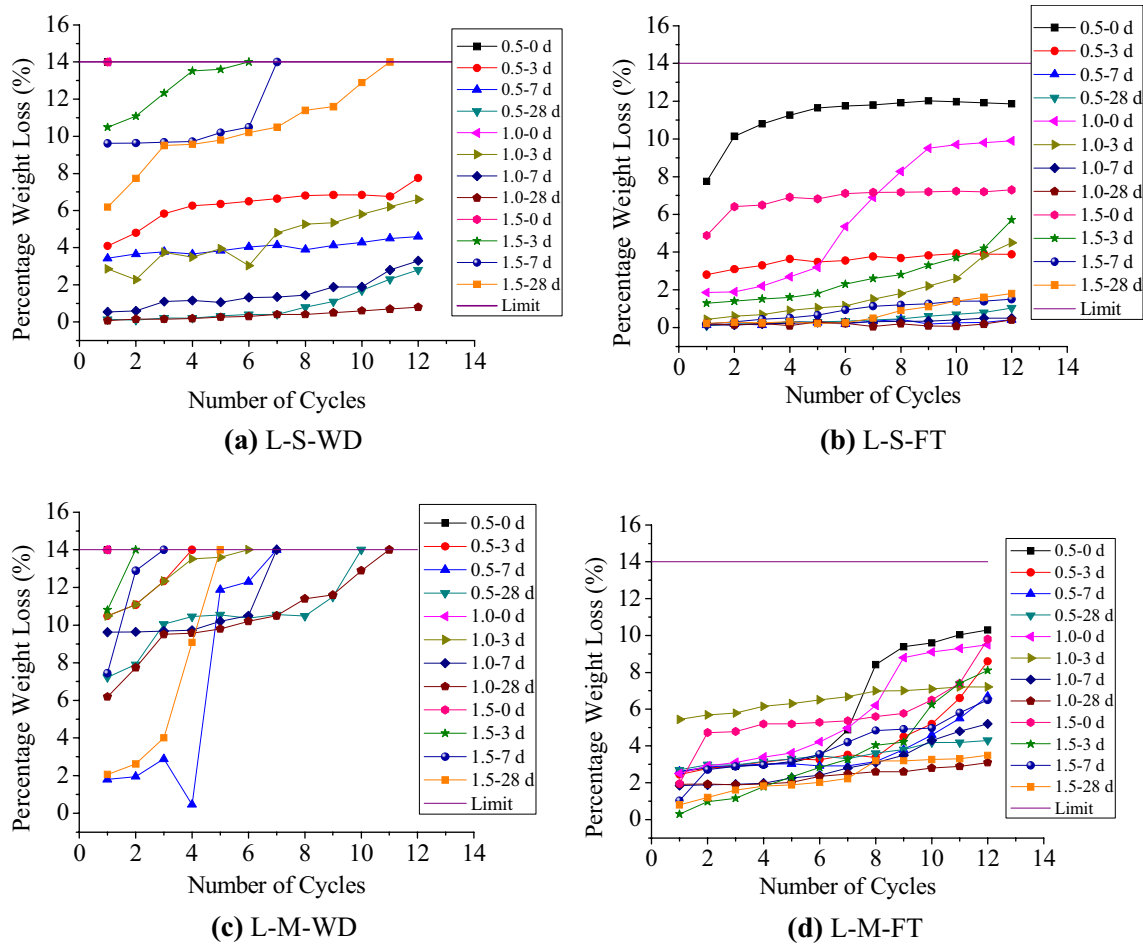


Fig. 3 The percentage weight loss of treated lateritic soil samples during a durability test at both densities

respectively. Whereas, in the case of BC soil, the samples having 0.5 M_s compacted at modified Proctor density has achieved 0.87 MPa. The correlation between UCS and flexure strength of lateritic soil samples is established and the R-squared (R^2) value is found to be 0.97. The correlation is represented by Eq. (2). The graph plotted between UCS and flexure strength is depicted in Fig. 6

$$\text{Flexure strength} = (0.1803 \times \text{UCS}) - 0.4987 \quad (2)$$

Fatigue Test

The fatigue test is conducted to know the number of cycles that the pavement can sustain. The fatigue cycles cause structural damage to the pavement leads to the development of cracks. The cylindrical sample of soil having dimension 38×76 mm cured for 28 days is considered for fatigue test. The $\frac{1}{3}$ rd (0.33), $\frac{1}{2}$ (0.5) and $\frac{2}{3}$ rd (0.66) of the minimum UCS load obtained is applied to the samples. In the case of treated lateritic soil, the minimum UCS load of 20 kN at

standard Proctor density and 26 kN at modified Proctor density are found. Whereas, in the case of BC soil the minimum UCS load is 2.9 kN at modified Proctor density. The number of cycles sustained by soil for different M_s is depicted in Fig. 7 and it is evident that in the case of lateritic soil, the fatigue repetitions of 4×10^5 and 4.5×10^5 at standard and modified Proctor densities, respectively, are achieved for the sample having M_s of 1.0 cured for 28 days. Whereas, in the case of treated BC soil, the sample consisting of 0.5 M_s at modified Proctor density sustains of 0.74×10^5 repetitions. The sustained repetitions are due to the enhanced UCS.

Microstructure Analysis

The soil samples are scanned under the electron microscope and surface images of the atom are collected at various resolutions. The microscopic images of resolution 2 K and the ten micron are obtained from the technique of scanning electron microscope (SEM) using a high focussed beam electron. The microstructure images of lateritic soil samples are depicted in Fig. 8a–d.

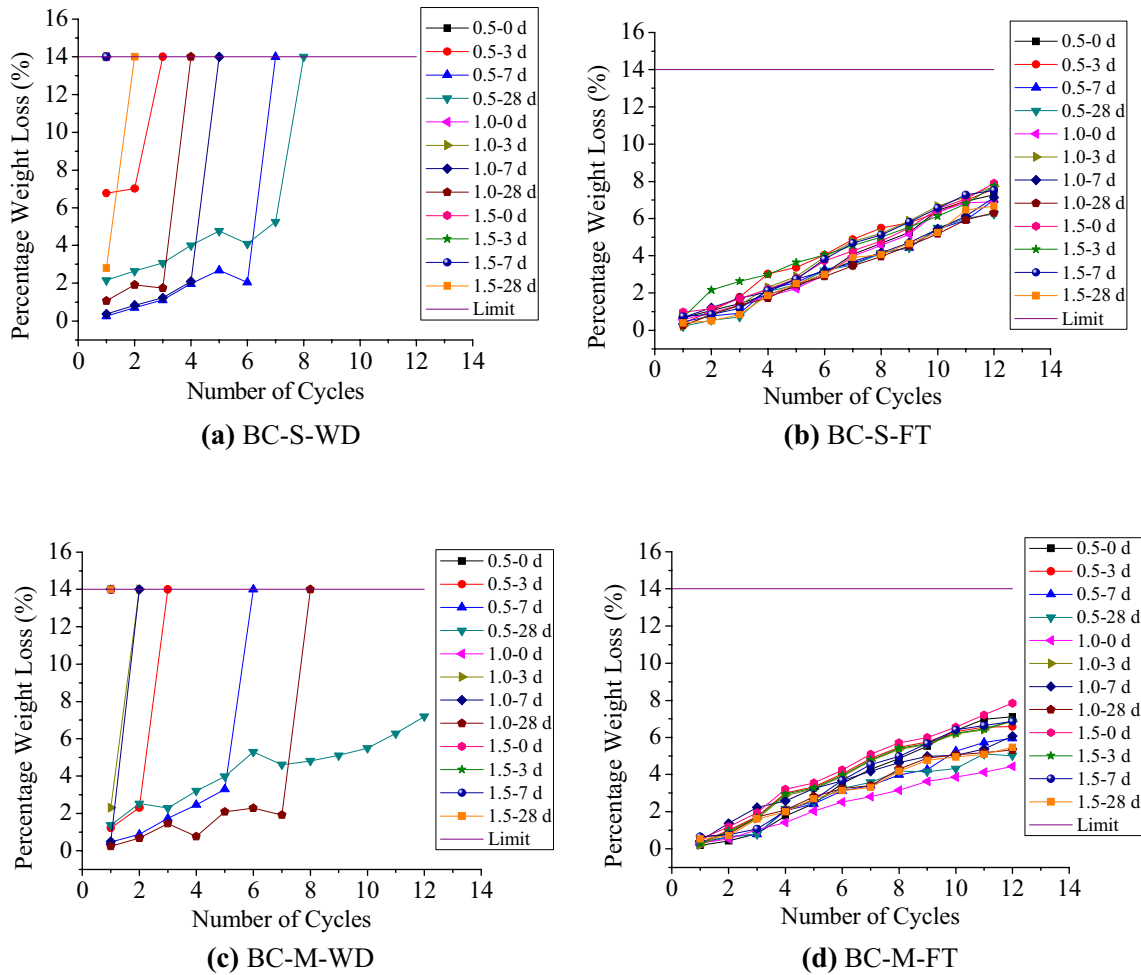


Fig. 4 The percentage weight loss of treated BC soil during a durability test at both densities, at various M_s and curing periods

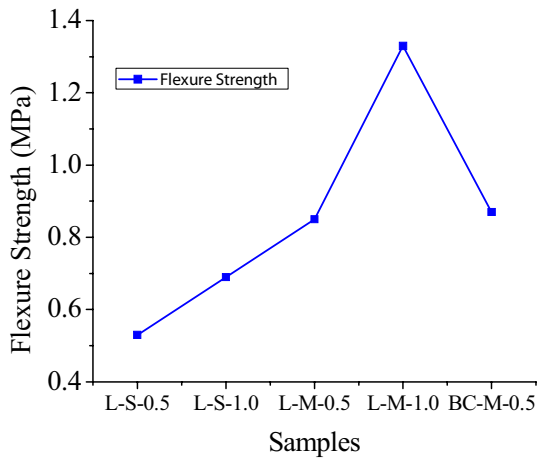


Fig. 5 The variation in flexure strength of the durable treated lateritic and BC soils

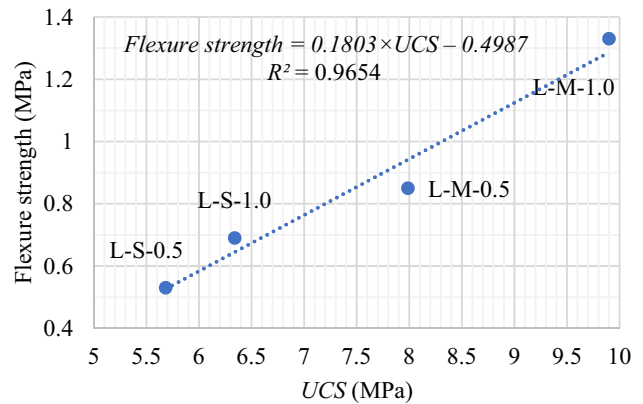


Fig. 6 The correlation between UCS and flexure strength

From Fig. 8a–d, it can be observed that the grey coloured, closely packed, the flake-like structure represents the formation of an aluminosilicate structure. The formation of an aluminosilicate structure is may be due to the polymerization

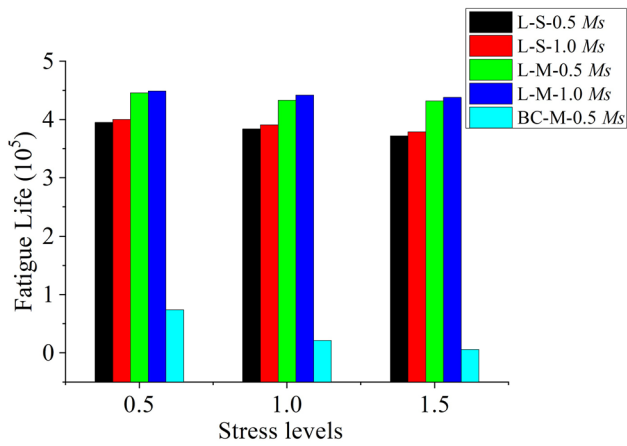


Fig. 7 The fatigue life of durable stabilized lateritic and BC soils

reaction between the GGBFS and alkali solution which binds soil with fewer voids. The black dark spots represent the unreacted voids. The samples prepared at modified Proctor density are showing a densified structure with very few voids due to the heavy compaction.

From Fig. 9, the microstructure image shows many voids due to the increased fines in soil. It is also observed that at modified Proctor density, treated lateritic soil samples are showing compact images than BC soil which may be due to the more fines.

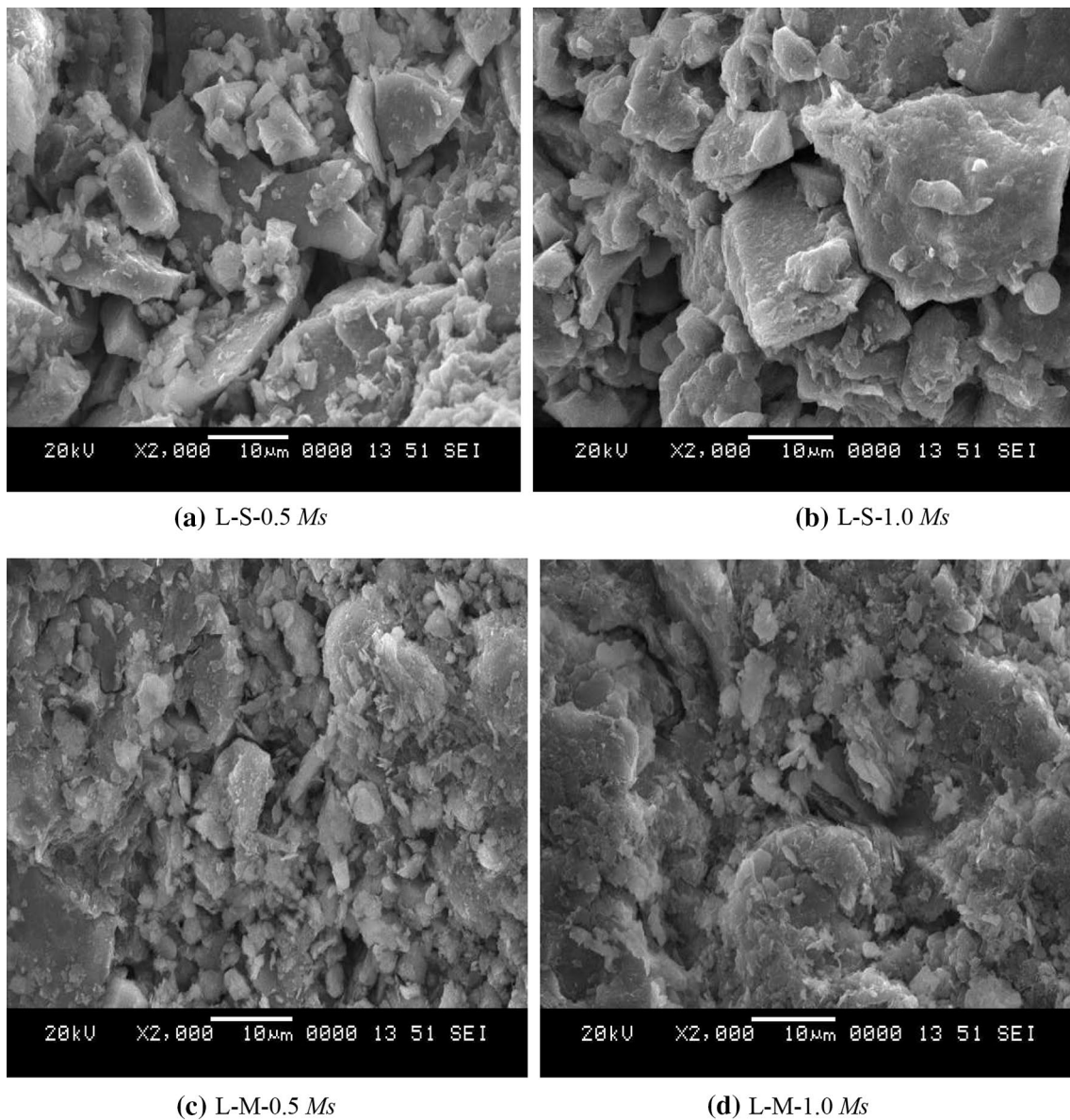


Fig. 8 The microstructure images of the durability passed lateritic soil samples

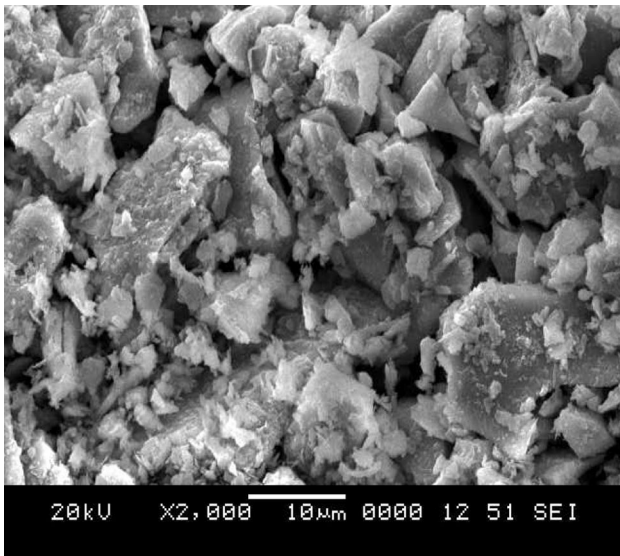


Fig. 9 The microstructure image of the BC-M-0.5 Ms

Application of Stabilized Soil in Road Construction

The design of high and low volume roads is carried out as per the Indian Roads Congress (IRC): 37-2012 and IRC: SP:72-2007, respectively, by replacing conventional granular material with the treated lateritic and BC soils.

Low Volume Roads

Lateritic Soil

The low volume roads are designed when the cumulative number of standard axle load repetitions is less than one million standard axles (MSA (this has to be in lowercase e.g. msa)). The pavement cross-section consists of a subgrade layer followed by granular sub base (GSB), water bound macadam (WBM) and premix carpet with seal coat/mix seal surface (MSS)/surface dressing (SD). The designed layer

Table 7 The thickness values for the low volume flexible pavement as per IRC: SP:72-2007

Subgrade CBR (%)	Traffic ($\times 10^3$)	Thickness (mm)			
		Gravel base	Modified soil	Granular sub base (GSB)	Water bound macadam (WBM)
4	10–30	200	–	–	–
4	30–60	275	–	–	–
4	60–100	–	–	150	150
4	100–200	–	100	100	150
4	200–300	–	150	100	150
4	300–600	–	150	100	225
4	600–1000	–	150	150	225

thickness for the conventional flexible pavement for low volume roads suggested by IRC: SP:72-2007 is tabulated in Table 7. The CBR of the subgrade soil was considered as 4%. As per the IRC: SP:72-2007, on the top of subgrade, 100 mm thick modified subgrade soil having CBR more than 10% has to be laid and compacted. In this investigation, modified subgrade soil is replaced with stabilized lateritic soil of 15–4–0.5. The conventional WBM layer was replaced with stabilized lateritic soil of 30–6–0.5 which satisfies the sub-base criteria. The design details are tabulated in Table 8 and the cross-section details are given in Fig. 10.

BC Soil

The CBR of the subgrade is considered as 3% for the design. As per IRC: SP:72-2007, the top 100 mm thick modified subgrade soil will be replaced with treated BC soil of 25–5–0.5 combination. The designed layer thickness for the conventional flexible pavement for low volume roads suggested by IRC: SP:72-2007 is tabulated in Table 7. The conventional WBM layer was replaced with stabilized BC soil of 30–6–0.5. The design details are tabulated in Table 9 and the cross-section details are given in Fig. 11.

Table 8 The designed values of the low volume flexible pavement using stabilized lateritic soil

Traffic ($\times 10^3$)	Thickness (mm)		
	Stabilized soil 15–4–0.5	GSB	Stabilized soil 30–6–0.5
10–30	150	–	–
30–60	175	–	–
60–100	225	–	–
100–200	–	100	150
200–300	–	125	150
300–600	–	150	150
600–1000	–	150	225

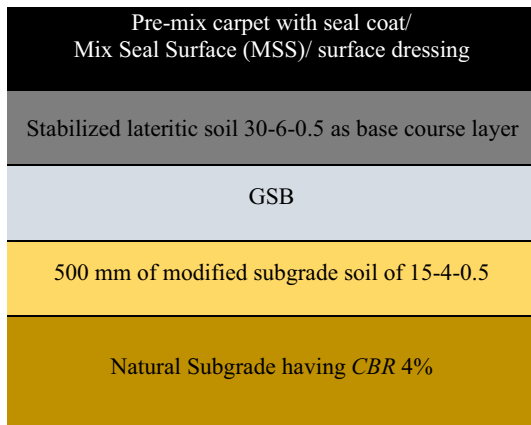


Fig. 10 The suggested cross-section of low volume flexible pavement using stabilized lateritic soil

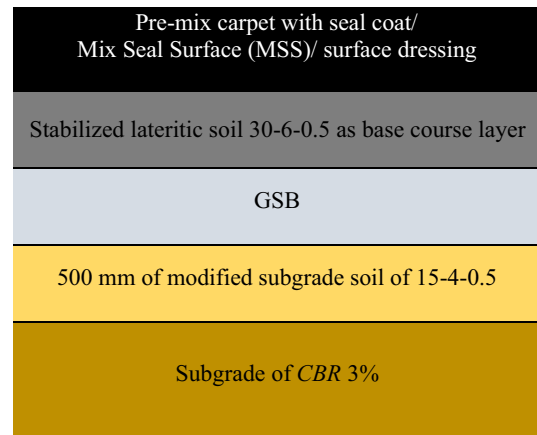


Fig. 11 The suggested cross-section of low volume flexible pavement using stabilized BC soil

High Volume Roads

The design chart of conventional high-volume roads suggested as per IRC: 37-2018 and the design values are tabulated in Table 10. The resilient modulus of the natural subgrade soil is calculated using the Eq. (3) suggested by IRC: 37-2018 and is found to be 40 MPa.

$$M_R = 10 \times \text{CBR} \tag{3}$$

The horizontal tensile strain (ϵ_t) at the bottom of the surface course and vertical compressive strain at the top of the subgrade (ϵ_z) are evaluated using software and are tabulated in Table 11. The elastic modulus (E) of the GSB and base course are considered as 400 and 450 MPa, respectively. The surface course layer consists of dense bituminous macadam (DBM) and bituminous concrete (BC). The grade of VG 30 bitumen is used and the elastic modulus considered for BC and DBM as 3000 MPa at 25 °C.

Table 9 The designed values of the low volume flexible pavement using stabilized BC soil

Traffic ($\times 10^3$)	Thickness (mm)		
	Stabilized soil 15-5-0.5	GSB	Stabilized soil 30-6-0.5
10-30	150	-	-
30-60	175	-	-
60-100	225	-	-
100-200	-	100	150
200-300	-	125	150
300-600	-	150	150
600-1000	-	150	225

The subgrade CBR considered for the pavement design is 4%. As per the IRC: 37-2018, the top 500 mm of the subgrade has to be removed and filled with a new material having CBR more than or equal to 10%. In this case, the treated lateritic soil of 15-4-0.5 having CBR 48% was referred. The effective CBR was obtained from Fig. 12 and found to be 21%. The resilient modulus of the modified subgrade soil is calculated using the Eq. (4) and is found to be 123.5 MPa

$$M_R = 17.6 \times (\text{CBR})^{0.64} \tag{4}$$

For the design purpose, 70% of the laboratory UCS values were used and it should not be less than 4.5 MPa. Among durable samples, the treated lateritic soil such as 30-6-0.5 and 30-6-1.0 compacted at modified Proctor density and cured for 28 days gave UCS values of 5.6 and 6.9 MPa, respectively. The sample 30-6-0.5 is recommended as M_s is 0.5 and it may be economical to use as alternate road material. The strains were calculated using KENPAVE software and the results are tabulated in Table 11. The elastic modulus of the base course for treated soil was found to be 4500 MPa using the Eq. (5) suggested by IRC: 37-2018. As per IRC, the laboratory strengths will be much higher than field values and suggested to use 600 MPa. The elastic modulus values of GSB and surface course (DBM and BC) considered as 400 and 3000 MPa, respectively

$$E = 1000 \times \text{UCS} \tag{5}$$

An aggregate layer of 100 mm thick should be provided above the base course when stabilized soil is used to arrest the propagation of the cracks and the aggregate layer will not be considered as a structural layer. Figure 13 shows the cross-section of high-volume flexible pavement using stabilized lateritic soil as a base course layer.

Table 10 The thickness chart of conventional high-volume roads

Traffic (msa)	E (MPa)	Thickness (mm)				Strains	
		GSB	Base course	DBM	BC	$\epsilon_z (10^{-4})$	$\epsilon_t (10^{-4})$
2–5	40	335	250	60	25	3.166	1.217
6–10	40	380	250	90	40	2.278	0.9233
11–20	40	380	250	120	40	1.810	0.8445
21–30	40	380	250	130	40	1.680	0.8216
31–50	40	380	250	140	40	1.561	0.8002
51–100	40	380	250	145	50	1.403	0.7705
101–150	40	380	250	170	50	1.184	0.7269

Table 11 The designed values of high-volume roads using the stabilized lateritic soil as a base course layer

Traffic (msa)	M_R of sub-grade (MPa)	Thickness (mm)				Strains	
		GSB	Base course, stabilized soil 30–6–0.5	DBM	Bituminous concrete	$\epsilon_z (10^{-4})$	$\epsilon_t (10^{-4})$
2–5	123.5	335	250	60	25	2.654	1.064
6–10	123.5	380	250	90	40	1.972	0.8434
11–20	123.5	380	250	120	40	1.774	0.5799
21–30	123.5	380	250	130	40	1.469	0.7751
31–50	123.5	380	250	140	40	1.366	0.7602
51–100	123.5	380	250	145	50	1.229	0.7393
101–150	123.5	380	250	170	50	1.023	0.6951

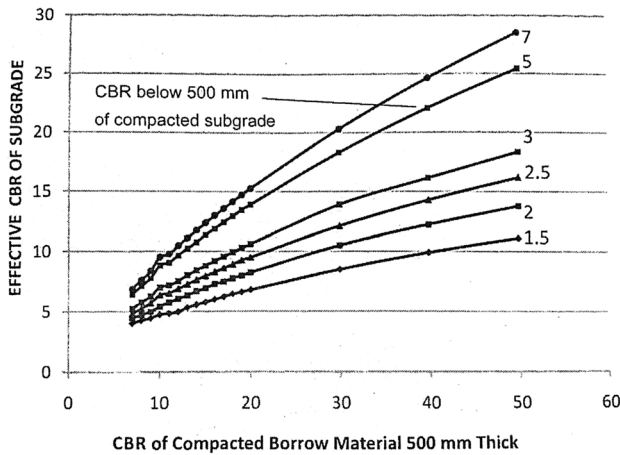


Fig. 12 The effective CBR of the subgrade suggested by IRC: SP:72-2007

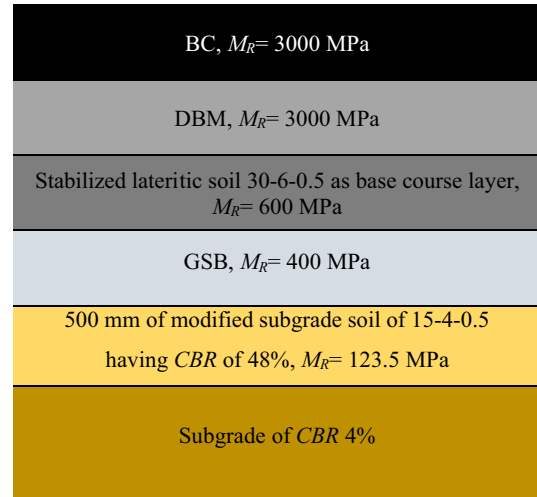


Fig. 13 The suggested cross-section of high-volume flexible pavement using stabilized lateritic soil

Conclusions

The following conclusions are drawn from the results.

- The treated lateritic soil samples having silica modulus of 0.5 and 1.0 cured for 28 days at modified Proctor density achieved maximum compressive and flexure strength with better fatigue life and durability.
- It is recommended to use treated lateritic soil as a base course layer replacing conventional gravel materials for high volume roads as it satisfies the requirements of the base course material.
- An aggregate interface layer of 100 mm thick should be provided above treated soil.
- The BC soil treated with 0.5 silica modulus at modified Proctor density cured for 28 days was found to be dura-

ble, and hence, its use is recommended for low volume pavements as a modified subgrade layer because its CBR value is more than 10%.

References

- Sekhar DC, Nayak S (2018) Utilization of granulated blast furnace slag and cement in the manufacture of compressed stabilized earth blocks. *Constr Build Mater* 166:531–536. <https://doi.org/10.1016/j.conbuildmat.2018.01.125>
- Gidigasu SSR, Gawu SKY (2013) The mode of formation, nature and geotechnical characteristics of black cotton soils—a review. *Stand Sci Res Essays* 1(14):377–390
- Mengue E, Mroueh H, Lancelot L, Eko RM (2017) Mechanical improvement of a fine-grained lateritic soil treated with cement for use in road construction. *J Mater Civ Eng* 29:1–22. [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0002059](https://doi.org/10.1061/(ASCE)MT.1943-5533.0002059)
- Davidovits J, Quentin S (1991) Geopolymers inorganic polymeric new materials. *J Thermal Anal Calorim* 37:1633–1656
- Qureshi MN, Ghosh S (2013) Effect of alkali content on strength and microstructure of GGBFS paste. *Global J Res Eng* 13(1), Retrieved from <https://engineeringresearch.org/index.php/GJRE/article/view/721>
- Obuzor GN, Kinuthia JM, Robinson RB (2011) Enhancing the durability of flooded low-capacity soils by utilizing lime-activated ground granulated blastfurnace slag (GGBS). *Eng Geol* 123:179–186. <https://doi.org/10.1016/j.enggeo.2011.07.009>
- Olaniyan OS, Olaoye RA, Okeyinka OM, Olaniyan DB (2011) Soil stabilization techniques using sodium hydroxide additives. *Int J Civ Environ Eng IJCEE-IJENS* 11:9–22
- Stempkowska A, Mastalska-pop J, Izak P et al (2017) Stabilization of kaolin clay slurry with sodium silicate of different silicate moduli. *Appl Clay Sci* 146:147–151. <https://doi.org/10.1016/j.clay.2017.05.046>
- Review AL, Force AIR, Directorate M (2012) AFRL-RX-TY-TR-2010-0097, Retrieved from <http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.909.9357&rep=rep1&type=pdf>
- Thomas A, Yadu RKTLK (2018) A laboratory investigation of soil stabilization using enzyme and alkali-activated ground granulated blast-furnace slag. *Arab J Sci Eng* 43:5193–5202. <https://doi.org/10.1007/s13369-017-3033-x>
- Ghadir P, Ranjbar N (2018) Clayey soil stabilization using geopolymer and Portland cement. *Constr Build Mater* 188:361–371. <https://doi.org/10.1016/j.conbuildmat.2018.07.207>
- Parhi PS, Garanayak L, Mahamaya M, Das SK (2018) Stabilization of an expansive soil using alkali activated fly ash based geopolymer. In: Hoyos L, McCartney J (eds) *Advances in characterization and analysis of expansive soils and rocks*. GeoMEast 2017. Sustainable civil infrastructures. Springer, Cham. https://doi.org/10.1007/978-3-319-61931-6_4
- Allahverdi A, Kani EN, Esmailpoor S (2008) Effects of silica modulus and alkali concentration on activation of blast-furnace slag. *Iran J Mater Sci Eng* 5(2):32–35
- Yang G, Liu H, Lv P, Zhang B (2012) Geotextiles and geomembranes geogrid-reinforced lime-treated cohesive soil retaining wall: case study and implications. *Geotext Geomembr* 35:112–118. <https://doi.org/10.1016/j.geotexmem.2012.09.001>
- Joel M, Agbede IO (2011) Mechanical-cement stabilization of laterite for use as flexible pavement material. *J Mater Civ Eng* 23(2):146–152. [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0000148](https://doi.org/10.1061/(ASCE)MT.1943-5533.0000148)
- Patankar SV, Jamkar SS, Ghugal YM (2013) Effect of water-to-geopolymer binder ratio on the production of fly ash based geopolymer concrete. *Int J Adv Technol Civ Eng* 2(1):79–83
- Yadollahi MM, Benli A, Demirbog R (2015) The effects of silica modulus and aging on compressive strength of pumice-based geopolymer composites. *Constr Build Mater* 94:767–774. <https://doi.org/10.1016/j.conbuildmat.2015.07.052>
- Cho Y, Yoo S, Jung S et al (2017) Effect of Na₂O content, SiO₂/Na₂O molar ratio, and curing conditions on the compressive strength of FA-based geopolymer. *Constr Build Mater* 145:253–260. <https://doi.org/10.1016/j.conbuildmat.2017.04.004>
- Amulya S, Shankar AUR, Praveen M (2018) Stabilisation of lithomargic clay using alkali activated fly ash and ground granulated blast furnace slag. *Int J Pavement Eng*. <https://doi.org/10.1080/10298436.2018.1521520>
- Sekhar DC, Nayak S, Preetham HK (2017) Influence of granulated blast furnace slag and cement on the strength properties of lithomargic clay. *Indian Geotech J* 47:384–392. <https://doi.org/10.1007/s40098-017-0228-8>
- Lekha BM, Sarang G (2015) Effect of electrolyte lignin and fly ash in stabilizing black cotton soil. *Transport Infrastruct Geotechnol*. <https://doi.org/10.1007/s40515-015-0020-0>
- Coudert E, Paris M, Deneele D et al (2019) Use of alkali activated high-calcium fly ash binder for kaolin clay soil stabilisation: physicochemical evolution. *Constr Build Mater* 201:539–552. <https://doi.org/10.1016/j.conbuildmat.2018.12.188>
- Chi M (2015) Effects of modulus ratio and dosage of alkali-activated solution on the properties and micro-structural characteristics of alkali-activated fly ash mortars. *Constr Build Mater* 99:128–136. <https://doi.org/10.1016/j.conbuildmat.2015.09.029>
- Murmu AL, Dhole N, Patel A (2018) Stabilisation of black cotton soil for subgrade application using fly ash geopolymer. *Road Mater Pavement Des*. <https://doi.org/10.1080/14680629.2018.1530131>
- Nurrudin MF, Haruna S, Mohammed BS, Galal I (2018) Methods of curing geopolymer concrete: a review. *Int J Adv Appl Sci*. <https://doi.org/10.21833/ijaas.2018.01.005>
- Firdous R, Stephan D (2019) Effect of silica modulus on the geopolymerization activity of natural pozzolans. *Constr Build Mater* 219:31–43. <https://doi.org/10.1016/j.conbuildmat.2019.05.161>

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