

Triaxial Shear Strength of an Expansive Black Cotton Soil Stabilised with Nano-Silica, Lime and Fly Ash

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ABSTRACT

The shear strength parameters that govern the stability of embankments and foundations on expansive soils are best obtained from triaxial testing. This paper reports the cohesion intercept and the angle of internal friction of a black cotton soil from Wardha district, Maharashtra, treated with seven nano-silica–lime–fly ash blends and cured for 7 to 90 days. The untreated soil was weakly frictional and modestly cohesive, with a cohesion of about 45 kPa and a friction angle near 14°. Stabilisation transformed both parameters: in the richest mix (M7) the cohesion rose to 129 kPa and the friction angle to almost 29° after 90 days of curing. The cohesion gain was the larger in proportion and continued throughout the curing period, identifying cementitious bonding as the principal source of strength, while the rise in friction angle reflected the coarser, flocculated and better-packed fabric of the treated material. Mohr–Coulomb failure envelopes for the treated soil stood far above that of the parent clay. The strengthened parameters substantially enlarge the bearing and slope-stability margins available to the designer, and the dominance of cohesion is consistent with the calcium-silicate-hydrate cementation responsible for the strength gain.

Keywords- triaxial test; shear strength; cohesion; angle of internal friction; expansive soil; nano-silica; Mohr–Coulomb.

I. INTRODUCTION

The shear strength of a soil, expressed through the Mohr–Coulomb parameters of cohesion and friction angle, underlies almost every geotechnical stability calculation. For expansive black cotton soils the unstabilised parameters are unflattering: the friction angle is low because the clay is fine and platy, and although there is appreciable apparent cohesion when the soil is dry, much of it is lost on wetting (*Nelson and Miller, 1992; Chen, 1988*). Reliable, water-resistant shear strength is therefore one of the chief objectives of chemical stabilisation.

Lime, fly ash and nano-silica improve shear strength through a sequence of mechanisms. The immediate cation exchange and flocculation that lime induces convert the dispersed clay into a granular, aggregated fabric, which raises the friction angle by giving the assemblage a coarser effective grading (*Eades and Grim, 1966; Bell, 1996*). The slower pozzolanic reactions then deposit calcium-silicate-hydrate gel at inter-particle contacts, and it is this cementation that supplies the large gain in cohesion. Nano-silica, by virtue of its reactivity, intensifies the cementing reaction, while fly ash both contributes reactive aluminosilicate and improves the packing (*Sivapullaiah et al., 2000; Hasan, 2025; Alshawmar, 2024*).

Studies of lime- and silica-treated clays have generally found that cohesion responds far more strongly than the friction angle, the latter sometimes barely changing (*Hasan, 2025; Wang et al., 2022*). Whether the same holds for a ternary nano-silica–lime–fly ash system applied to a highly expansive Deccan clay, and how the two parameters evolve over an extended curing period, is the question examined here through consolidated triaxial testing across a graded series of mixes.

II. MATERIALS AND METHODS

2.1 Materials and Mixes: The soil was collected from an open trial pit near Talegaon village in Wardha district, Maharashtra (approximately 20°44' N, 78°36' E), within the Deccan trap black-cotton-soil belt, at a depth of 1.0 to 1.5 m below the existing ground surface. It is a clay of high plasticity (liquid limit 62%, plasticity index 34%). The stabiliser comprised amorphous nano-silica (>99% SiO₂, 20–30 nm), hydrated lime and a Class F fly ash drawn from a regional thermal power station. Seven blends, M1 to M7, were proportioned by dry mass of soil as listed in Table 1, the nano-silica ranging from 1 to 5%, the lime from 4 to 8% and the fly ash from 10 to 20%.

Table 1. Composition of the stabilised mixes (percentages by dry mass of soil).

Mix	Nano-silica (%)	Lime (%)	Fly ash (%)	Group
BCS	0	0	0	Control
M1	1	4	10	Low
M2	2	4	10	Low
M3	3	4	10	Low
M4	2	6	15	Intermediate
M5	3	6	15	Intermediate
M6	4	6	20	High
M7	5	8	20	High

2.2 Triaxial Testing: Cylindrical specimens 38 mm in diameter and 76 mm tall were compacted at the optimum moisture content and maximum dry density of each mix, sealed and moist-cured at 27 ± 2 °C for 7, 14, 28, 56 or 90 days. They were then sheared in triaxial compression following IS 2720 Part 11 (*IS 2720 (Part 11), 1993*), each mix and age being tested at three cell pressures so that the Mohr–Coulomb envelope could be fitted. The cohesion intercept and friction angle were read from the best-fit failure line. Five replicates were tested for each condition, and the results are reported as means with one standard deviation.

III. RESULTS AND DISCUSSION

3.1 Cohesion: Figure 1 plots the cohesion intercept against curing period for all eight materials, and the values appear in Table 2. The untreated soil holds an almost constant cohesion of 42–46 kPa, with no curing trend, because nothing in it reacts. Each mix that's been treated starts above it and continues to rise: The mix numbers in between are parallel, but a little lower than mix M7, which starts at 114 kPa at 7 days and climbs to 129 kPa at 90 days. The calcium-silicate-hydrate gel slowly binding the individual particles together is the characteristic of pozzolanic cementation, which steadily increases with curing. The pattern is similar to the cohesion development reported for lime – Silica fume treated clays (Hasan, 2025; Sivapullaiah et al., 2000) but on a wider parent soil.

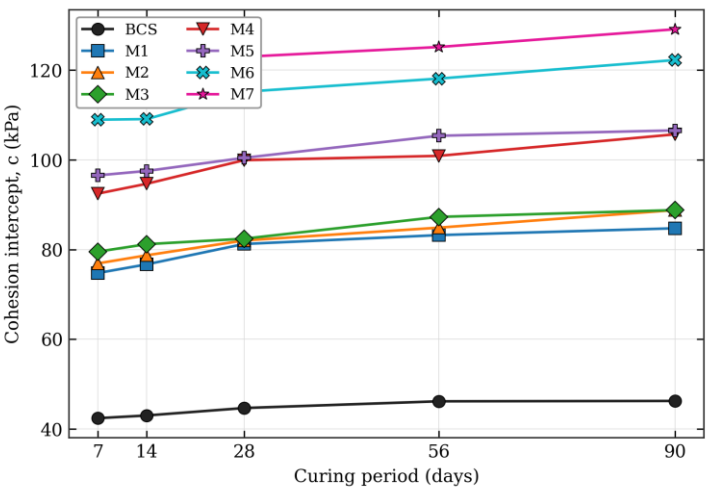


Figure 1. Cohesion intercept versus curing period for the untreated soil and the seven stabilised mixes.

Table 2. Cohesion intercept c (kPa) at 7, 28 and 90 days and the span of friction angle ϕ over curing (mean values, $n = 5$).

Mix	c , 7 d	c , 28 d	c , 90 d	ϕ range (deg)
BCS	42.4 ± 0.7	44.7 ± 0.8	46.3 ± 0.3	14.2–13.9
M1	74.8 ± 1.7	81.2 ± 1.3	84.7 ± 2.0	20.7–20.9
M2	76.9 ± 2.1	82.0 ± 1.5	88.8 ± 0.9	21.3–21.1
M3	79.5 ± 2.1	82.4 ± 1.0	88.8 ± 2.5	21.6–21.7
M4	92.5 ± 2.1	99.9 ± 2.4	105.7 ± 2.0	24.2–24.3
M5	96.5 ± 1.7	100.4 ± 3.2	106.6 ± 2.4	24.8–24.5
M6	108.9 ± 2.7	115.2 ± 3.4	122.2 ± 2.1	27.4–27.7
M7	114.0 ± 1.8	123.0 ± 3.6	129.1 ± 3.2	28.7–28.9

3.2 Angle of Internal Friction: The friction angle, summarised by mix at 28 days in Figure 2, tells a complementary story. It rises from about 14° in the untreated soil to nearly 29° in mix M7, but, unlike cohesion, it changes little with curing once a mix is set—the values for a given blend span barely a degree across the whole curing window. This separation of behaviour is diagnostic. The friction angle is governed by the texture and packing of the soil skeleton, which are fixed almost immediately by flocculation and remain stable thereafter; the cohesion is governed by cementation, which continues to grow as the slow reaction proceeds. The near-time-invariance of ϕ alongside a steadily rising c has been observed in other stabilised clays and supports the same interpretation here (Wang *et al.*, 2022; Bell, 1996).

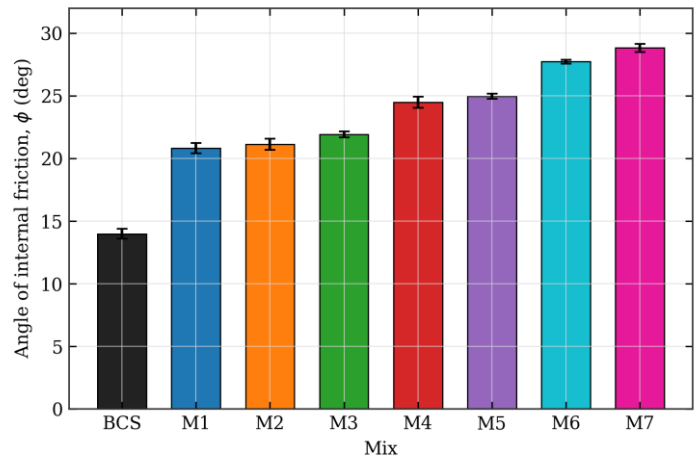


Figure 2. Angle of internal friction of each mix at 28 days of curing; error bars denote one standard deviation.

3.3 Failure Envelopes: The combined effect of the two parameters is seen most vividly in the Mohr–Coulomb diagram of Figure 3, which compares the failure envelopes of the untreated soil and mix M7 at 28 days, with representative stress circles. The treated envelope is lifted bodily upward by the larger cohesion intercept and rotated to a steeper inclination by the higher friction angle, so that at every normal stress the shear strength of M7 is more than double that of the parent clay. The widening separation of the two envelopes with increasing normal stress shows that the frictional component of the improvement becomes more valuable as confinement grows, while the raised intercept benefits the soil even at shallow depth and low stress.

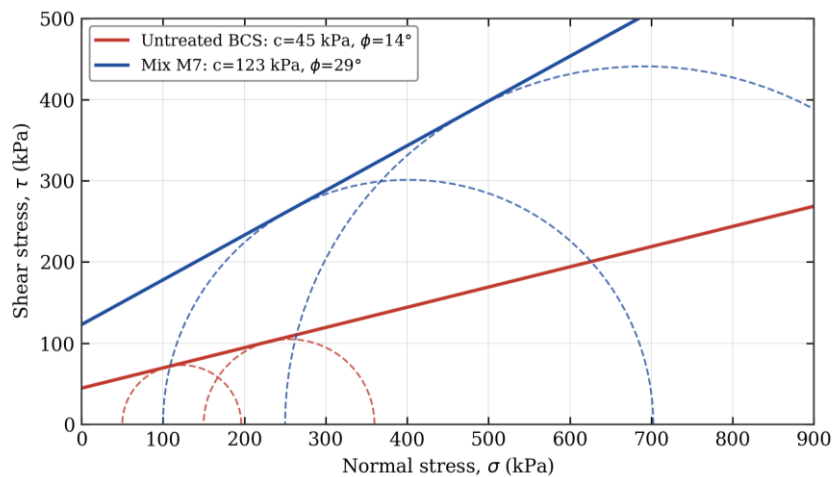


Figure 3. Mohr–Coulomb failure envelopes and representative stress circles for the untreated soil and mix M7 at 28 days.

3.4 Relative Roles of Cohesion and Friction. Plotting both parameters against total additive content, Figure 4, makes the relative contributions explicit. The friction angle increases by about 15° and the cohesion increases nearly 3 times from the untreated case to M7; the increase in friction angle is relatively insignificant compared to the increase in the cohesion of well over 80 kPa. The predominance of cohesion is precisely what the cementation mechanism for the strength of the cement would suggest and is consistent with the companion unconfined compression tests in which strength increased linearly with cohesion. The majority of work is carried out by the cohesive, cemented bonding; not friction (Ghavami and Naseri, 2025; Sridharan and Prakash, 2000).

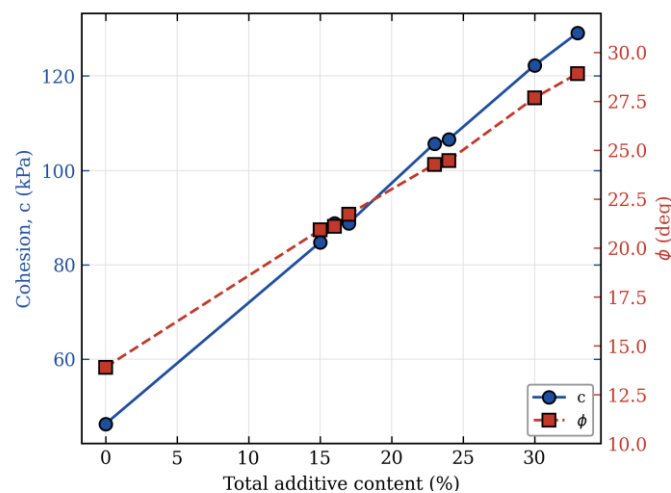


Figure 4. Variation of cohesion and friction angle with total additive content at 90 days of curing.

3.5 Design implications: The higher the parameters become the higher the factor of safety will be for the practising engineer. The treated material has a cohesion of approximately 130 kPa with a friction angle of about 29° which is much greater than the untreated clay, and since the cohesion is provided by water-resistant cementitious bonds rather than by suction, the material will not lose its cohesion if the soil is wet. The intermediate blends, which already achieve a cohesion greater than 100 kPa and a friction angle higher than 24° , already bring a lot of these benefits at moderate reagent costs; the high dosage blends are warranted in cases where the steepest slopes or the highest contact pressures need to be carried (Sambre et al., 2024; Perigalla et al., 2026; Phanikumar and Sharma, 2004).

IV. CONCLUSIONS

- Nano-silica–lime–fly ash treatment resulted in the increase of both shear strength parameters of Wardha black cotton soil, the cohesion from around 45 to 129 kPa and the friction angle from around 14° to 29° for the richest blend at 90 days.

- Cohesion increased consistently during curing, attributed to pozzolanic cementation, while friction angle set rapidly at an early stage and remained relatively constant during curing and attributed to flocculation.
- Mohr–Coulomb envelopes for the treated soil were much higher than for the parent clay and the shear strength of mix M7 was more than twice that of the untreated soil for all of the normal stresses tested.
- In absolute terms the cohesion gain dominated the strength improvement, consistent with calcium-silicate-hydrate bonding and with the parallel unconfined compression results.
- The strengthened, water-resistant parameters markedly enlarge bearing and stability margins; the intermediate blends capture most of the benefit economically, with high-dosage blends reserved for the most demanding conditions.

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