

Unconfined Compressive Strength Development in an Expansive Black Cotton Soil Treated with Nano-Silica, Lime and Fly Ash

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ABSTRACT

The most direct laboratory test for the cementation that a cement can provide to a clay is unconfined compressive strength (UCS). The present study investigates the development of UCS under various treatment conditions such as seven nano-silica–lime–fly ash combinations and curing periods ranging from 7 to 90 days in a black cotton soil from Wardha district in Maharashtra. The untreated soil's strength increased only slightly over time (182 - 389 kPa), which indicates that no cementing agent was present. By contrast, each stabilised blend exhibited significant and steady strengths at both the time and the 90-day mark: the strongest blend (M7) had an early-age strength of 770 kPa and exceeded the 90-day strength of the untreated soil by nine times and more than four times that of the untreated soil's 90-day strength. As the dosage of the reagent increased, and as curing time increased, strength increased, which indicates that the time dependence is greatest for the pozzolanic reaction. The distribution of UCS was very closely linked to the triaxial cohesion intercept and confirmed that the extra strength is added in the form of inter-particle bonding, and not in the form of frictional resistance. The results indicate that nano-silica (in addition to lime and fly ash) can transform a weak expansive clay into a firm and cemented material for use as a structural fill and treated subgrade with nano-silica content as low as 10%.

Keywords- unconfined compressive strength; expansive soil; nano-silica; lime; fly ash; pozzolanic reaction; curing.

I. INTRODUCTION

The unconfined compression test is considered useful in stabilisation work because it is fast, confining apparatus is not required and it provides one number that is related to the degree of cementation that a treatment has provided. In expansive black cotton soils, which have relatively weak strength when no treatment has been applied and large volume change, UCS is used as a test of the completion of the chemical reactions that go on in the soil (Nelson and Miller, 1992; Chen, 1988).

With such a clay and the addition of lime, two processes are occurring on vastly different time scales. The first is fast – the calcium ions are taken up by the clay surface, the double layer contracts and the platelets flocculate, thereby gaining strength immediately, although not much. The second one is slow; under the alkaline environment created by the lime, silica and alumina dissolve and re-combine to form calcium-silicate-hydrate and calcium-aluminate-hydrate gels that bind the flocculated fabric over weeks and months (Eades and Grim, 1966; Bell, 1996; Sivapullaiah et al., 2000). Fly ash feeds the second process by supplying additional reactive aluminosilicate, while nano-silica, because of its extraordinary surface area, accelerates and amplifies it, providing readily soluble silica exactly where the calcium-silicate-hydrate gel forms (Alshawmar, 2024; Ghavami and Naseri, 2025; Hasan, 2025).

Although the individual reagents are well studied, the way UCS evolves under a graded series of ternary nano-silica–lime–fly ash mixes, across a curing window long enough to capture the slow reaction, is less fully documented. The present work reports that evolution and relates it to the additive dosage and to the cohesion measured independently in triaxial tests (Goutham and Krishnaiah, 2024).

II. MATERIALS AND METHODS

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

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 Specimen Preparation and Testing: Cylindrical specimens 38 mm in diameter and 76 mm tall were prepared at the optimum moisture content and maximum dry density of each mix, sealed to prevent moisture loss, and cured at 27 ± 2 °C for 7, 14, 28, 56 or 90 days. They were then tested in unconfined compression to IS 2720 Part 10 (*IS 2720 (Part 10), 1991*) at a strain rate of 1.25 mm/min, the peak axial stress being taken as the UCS. Five replicate specimens were tested for each mix and age; means and standard deviations are reported. Companion unconsolidated-undrained triaxial tests furnished the cohesion intercept used in the correlation of Section 3.4.

III. RESULTS AND DISCUSSION

3.1 Strength Development with Curing. All the materials have their UCS plotted against curing period in Figure 1 and the values listed in Table 2. The lowest (and flattest) trace is the untreated soil, which starts at 182 kPa and moves to 389 kPa after 90 days, which is mainly due to consolidation and ageing of the soil, but not due to any cementation. Each treated blend is above it and rises much more precipitously. The ranking is approximately in line with the order of reagents; mix M7 is the highest throughout, with a pressure of 1713 kPa after 90 days, and 770 kPa after 7 days.

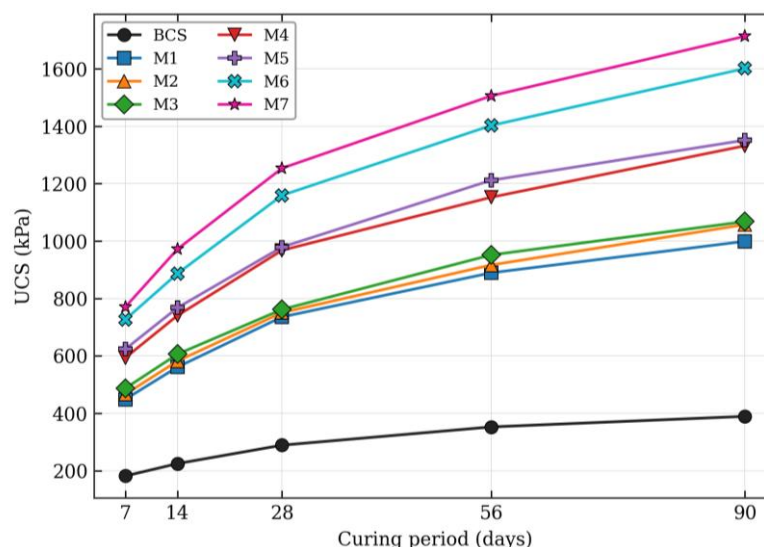


Figure 1. Unconfined compressive strength versus curing period for the untreated soil and the seven stabilised mixes.

Table 2. Unconfined compressive strength (kPa) at each curing age (mean $\pm$ one standard deviation, n = 5).

Mix	7 d	14 d	28 d	56 d	90 d
BCS	182 $\pm$ 3	225 $\pm$ 5	289 $\pm$ 5	353 $\pm$ 7	389 $\pm$ 2
M1	449 $\pm$ 10	561 $\pm$ 15	736 $\pm$ 11	889 $\pm$ 26	999 $\pm$ 23
M2	466 $\pm$ 13	582 $\pm$ 12	751 $\pm$ 13	916 $\pm$ 35	1057 $\pm$ 10
M3	487 $\pm$ 13	606 $\pm$ 16	762 $\pm$ 10	951 $\pm$ 30	1068 $\pm$ 30
M4	593 $\pm$ 14	741 $\pm$ 20	968 $\pm$ 24	1152 $\pm$ 26	1332 $\pm$ 26
M5	623 $\pm$ 11	768 $\pm$ 23	979 $\pm$ 31	1211 $\pm$ 36	1351 $\pm$ 30
M6	726 $\pm$ 18	887 $\pm$ 22	1159 $\pm$ 34	1402 $\pm$ 17	1601 $\pm$ 27
M7	770 $\pm$ 12	972 $\pm$ 28	1253 $\pm$ 37	1505 $\pm$ 45	1713 $\pm$ 43

However, the best evidence of pozzolanic activity is the sustained growth from 28 to 90 days. Cation exchange and flocculation are complete in hours and the strength they provide is measured at 7 days; the additional strength in the richer mixes over the weeks that follow is only due to the continuing precipitation of the cementitious gel. The behavior is similar to that of expansive clays treated with lime–silica fume and lime–fly ash where strength continues to increase as long as the soluble silica and free lime can react (Hasan, 2025; Sivapullaiah et al., 2000).

3.2 Effect of Dosage: Plotting the 90-day strength against the total additive content, Figure 2, brings out the dose response. A positive and slightly concave relationship exists, with the strength of the relationship increasing with the dosage level, up to the high dosage group. The jump is largest in the interval of increasing fly ash content from 10 to 15% and increasing lime content from 4 to 6% (between the low and intermediate group), indicating that lime available in these materials is primarily used in cation exchange reactions and that when the need for cation exchange is satisfied, the excess causes significant cementation. This is in line with the classical idea of a 'lime fixation point', where the strength of the concrete remains constant as the amount of reagent is increased, but its plasticity is enhanced (Bell, 1996; Phanikumar and Sharma, 2004).

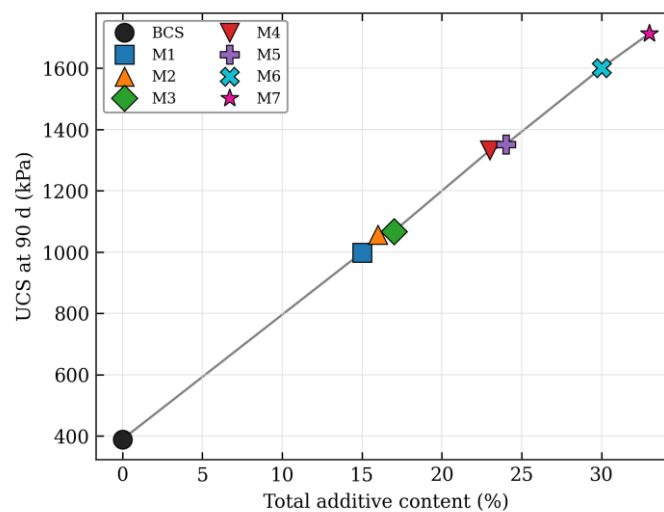


Figure 2. 90-day unconfined compressive strength as a function of total additive content (nano-silica + lime + fly ash).

3.3 Normalised Strength Gain: Figure 3 normalises each material's UCS value to the 7-day value of the material, in order to separate the rate of reaction and the absolute strength. When treated this way, the treated blends outperform, proportionally, the untreated soil during the curing span and the strongest blend increases early strength by about a factor of two in 90 days. The untreated soil also increases in "relative" terms, but not chemically but by consolidation, and its absolute strength is an order of magnitude below. The normalised plot is helpful for the design as it shows the degree of reserve strength which the layer will gain after measurement of the early-age value.

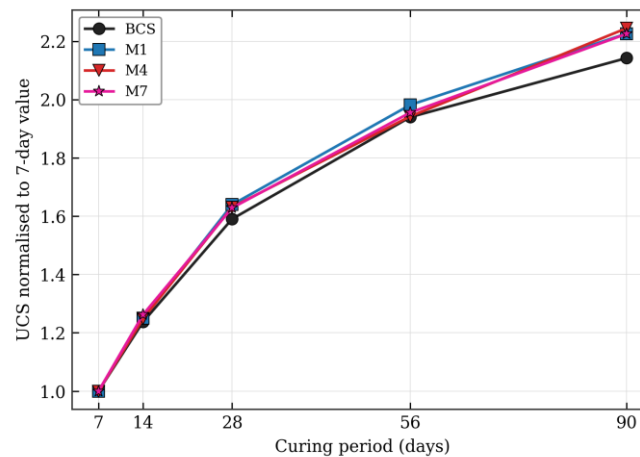


Figure 3. Unconfined compressive strength normalised to the 7-day value, showing the relative rate of strength gain.

3.4 Relation to Cohesion: In principle, the UCS is double the undrained shear strength of a purely cohesive material, and should therefore follow the cohesion intercept from the triaxial compression test. It does, indeed, it is confirmed in Figure 4; both quantities are on the same straight line for the whole dataset with a coefficient of determination of greater than 0.95. This suggests that the increased strength the treatment provides is not primarily in the form of frictional resistance but in cohesion, in other words, the ability to bond the particles together, a cementitious bond. This is typical of the behavior of cementation by calcium-silicate-hydrate cement and is consistent with that observed in lime and silica treated expansive clays (Hasan, 2025; Goutham and Krishnaiah, 2024).

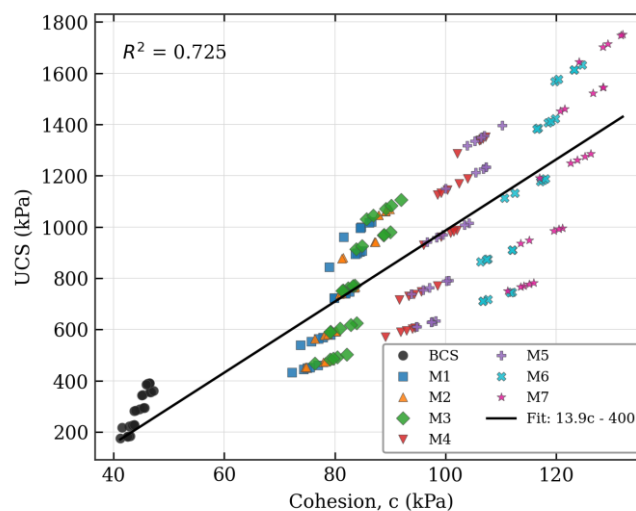


Figure 4. Correlation between unconfined compressive strength and triaxial cohesion intercept across all mixes and curing ages.

3.5 Practical Significance: A UCS between 1000 and 1700 kPa is sufficient for the treated material to be considered to be in the range usually considered suitable for a stabilized subgrade or capping layer and at the upper end of the range, it approaches the UCS that would be expected for a lightly cemented fill material. The treatment is economical and environmentally sound because both reagents are industrial by-products or used in small amounts, and can be achieved from an engineering perspective with a parent soil of only 180, kPa. The strong growth after the traditional 28 days age further provides a margin of reserve which simple tests at early ages do not demonstrate (Perigalla et al., 2026).

IV. CONCLUSIONS

- The unconfined compressive strength of the Wardha black cotton soil was significantly improved after treatment with Nano-silica–lime–fly ash, the highest value being 1713 kPa attained after 90 days compared to 389 kPa for untreated soil after the same period.

- The strength was found to increase with the dose of reagents and curing time, with the residual strength gain after 28 days pointing to slow pozzolanic cementation as the primary source of strength in the late age.
- The 90-day strength increased in a more dramatic fashion as the additive content was shifted from the low to intermediate group, as is expected with a cementation threshold, after which excess reagent promotes cementation.
- The unconfined compressive strength was correlated almost linearly with the triaxial cohesion intercept ($R^2 > 0.95$), indicating that there is no increase in strength due to friction, but only due to inter-particle bonding.
- The treated material achieves properties appropriate for stabilised subgrade and capping applications and the material strengthens beyond 28 days, offering a long term benefit of practical use.

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