

Influence of Nano-Silica, Lime and Fly Ash on the Compaction Characteristics of an Expansive Black Cotton Soil from Central India

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ABSTRACT

The compaction characteristics of a high-plasticity black cotton soil from Wardha district in Maharashtra were investigated after the addition of a ternary stabiliser (colloidal nano-silica, hydrated lime and class F fly ash). Each of the seven blended mixes (M1-M7) containing different amounts of nano silica (1-5%), lime (4-8%) and fly ash (10-20%) by dry mass was compared with the untreated soil using the standard proctor test; each soil mix had 5 replicate samples. The soil properties of the untreated soil were: Optimum moisture content (OMC) of 24.5% and Maximum dry density (MDD) of 1.564 g/cm³. The addition of stabiliser gave a consistent shift in the compaction curve to the left and up: the OMC decreased to as low as 19.5% while the MDD increased to 1.82 g/cm³ for the richest mix. Both the decrease in moisture requirement and the densification showed good correlation with the decrease in plasticity index caused by the cation exchange and pozzolanic flocculation. It has been found that the use of relatively small doses of nano-silica, in combination with lime and fly ash, is capable of changing the moulding properties of an otherwise difficult subgrade material that is a suitable form for field compaction.

Keywords- black cotton soil; nano-silica; lime; fly ash; compaction; optimum moisture content; maximum dry density.

I. INTRODUCTION

One of the most troublesome soils that a highway or foundation engineer encounters is the black montmorillonitic clay soils that cover most of the Deccan trap region of central and western India. Their attraction to water causes large seasonal volume changes, which often cause cracking of pavements and lightly-loaded structures built on these surfaces; this heave and shrinkage occur frequently (Chen, 1988; Nelson and Miller, 1992). Chemical stabilisation has historically proven to be the most economical remedy for the removal and replacement of these deposits, and has been the most commonly used treatment on Indian projects, with lime and fly ash being the two most commonly used reagents (Phanikumar and Sharma, 2004; Sambre et al., 2024).

Lime acts quickly. This release of calcium causes the weakly bound cations on the surface of the clay to be replaced, the diffuse double layer to shrink and the previously dispersed platelets to flocculate into larger, more granular sized aggregates (Eades and Grim, 1966; Bell, 1996). Fly ash provides extra silica and alumina, and as a fine non-plastic powder, reduces the amount of active clay fractions, and assists the pozzolanic reactions that form the matrix with time. Nano-silica has recently become a subject of interest because of its high reactivity as a supplement; with the high specific surface, nano-silica can cause the formation of calcium-silicate-hydrate gel, and can supply the silica component in a much more available form that is supplied by fly ash at a slow rate (Alshawmar, 2024; Ghavami and Naseri, 2025).

The strength, swelling or index behaviour of these reagents has been a major focus of the literature, while the compaction response has been reported only incidentally. However, the moulding properties are important in and of themselves as the OMC will determine the amount of water required in the field for the earthwork and the MDD will determine the density required as stated in the earthwork specification. Reagents that flocculate a clay generally raise its OMC and lower its MDD, whereas the addition of a denser, finer non-plastic filler tends to do the opposite; when several

reagents act together the net effect is not obvious in advance (Goutham and Krishnaiah, 2024). The present study therefore isolates the compaction behaviour of a single black cotton soil treated with a graded series of nano-silica–lime–fly ash blends, and relates the observed shifts in OMC and MDD to the accompanying change in plasticity.

II. MATERIALS AND METHODS

2.1 Soil and Additives: The expansive soil was retrieved from an open trial pit near Talegaon village in Wardha district, Maharashtra (approximately 20°44' N, 78°36' E), which lies within the black-cotton-soil tract of the Deccan trap. Sampling was carried out between 1.0 and 1.5 m below the existing ground surface, beneath the seasonally desiccated crust, where the deposit is comparatively undisturbed. The air-dried soil was pulverised and passed through a 4.75 mm sieve. Its measured index properties are listed in Table 1; with a liquid limit of 62.1% and a plasticity index of 34.0%, the material classifies as a clay of high plasticity (CH) and falls in the ‘very high’ degree-of-expansion band of IS 1498 (IS 1498, 1970; Sridharan and Prakash, 2000).

Three additives were used. The nano-silica was a dry amorphous powder of better than 99% SiO₂ with a nominal particle size in the 20–30 nm range; the lime was laboratory-grade hydrated lime, Ca(OH)₂; and the fly ash was a Class F ash obtained from a thermal power station in the region. Seven blends were prepared by dry mass of soil, as set out in Table 2, the nano-silica varying from 1 to 5%, the lime from 4 to 8% and the fly ash from 10 to 20%.

Table 1: Index and physical properties of the untreated black cotton soil.

Property	Value	Property	Value
Liquid limit, LL (%)	62.1	Specific gravity, G	2.63
Plastic limit, PL (%)	28	Free swell index, FSI (%)	95.2
Plasticity index, PI (%)	34	OMC (%)	24.5
Classification (USCS)	CH	MDD (g/cm³)	1.564
Swelling pressure (kPa)	120	Soil group (IS 1498)	Very high swell

Table 2: Composition of the stabilised mixes (percentages by dry mass of soil).

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

2.2 Specimen Preparation and Testing: For each mix the dry soil and additives were blended to uniform colour, the target water added, and the moist mixture sealed and left to mellow for one hour before compaction. Compaction followed the light (standard Proctor) procedure of IS 2720 Part 7 (IS 2720 (Part 7), 1980), the soil being compacted in three equal layers in the standard 1000 cm³ mould under 25 blows of the 2.6 kg rammer falling through 310 mm. Moisture–density points were obtained over a range of water contents bracketing the optimum, and the OMC and MDD read from the fitted curve. Atterberg limits were determined to IS 2720 Part 5 (IS 2720 (Part 5), 1985). Five replicate determinations were made for every mix so that the scatter inherent in soil testing could be quantified; the values quoted below are means, with one standard deviation given as the measure of dispersion.

III. RESULTS AND DISCUSSION

3.1 Compaction Curves: Figure 1 compares representative values of moisture–density relationships of untreated soil and three of the blends. The curve for the untreated clay is the typical broad, flat curve typical of a montmorillonitic soil with a peak value at a water content of 24.5% and a value of 1.564 g/cm³. The curves shift more and more towards reduced water contents and higher doses of stabiliser and are increasingly well-defined, the optimal value of the parent soil being less

clearly marked than the well-defined optimum of mix M7. This is the typical behavior of a suppressed plasticity clay moving towards the left and upwards on the migration chart.

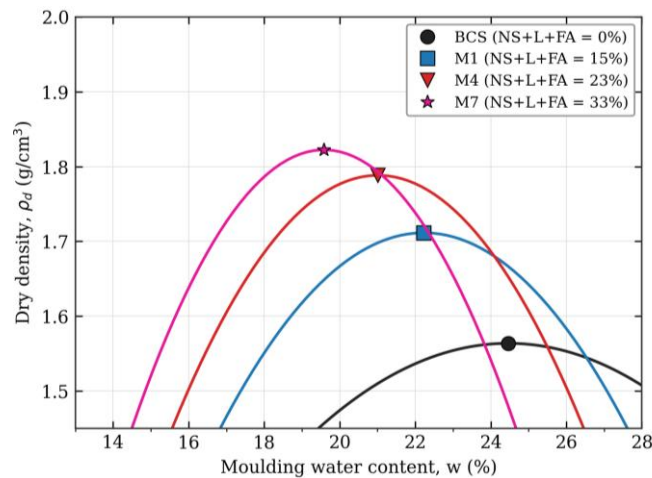


Figure 1: Standard Proctor compaction curves for the untreated soil and for mixes M1, M4 and M7, illustrating the upward and leftward shift of the optimum with increasing stabiliser content.

All the OMC and MDD values are summarized in Table 3 and presented in the figure mix by mix in Figure 2. There are two obvious trends. The value of OMC decreases gradually from 24.5 % in untreated soil to 19.5 % in M7 which is a decrease of one-fifth whereas the value of MDD increases gradually from 1.564 to 1.822 g/cm³ which is an increase of approximately 16 % in M7. The overall progression is monotonic with the content of additive, but not strictly linear, with the greatest single increase in density occurring from the low-dosage group (M1–M3) to the intermediate group (M4–M5) where the fly ash content increases from 10 to 15% and the lime content increases from 4 to 6%.

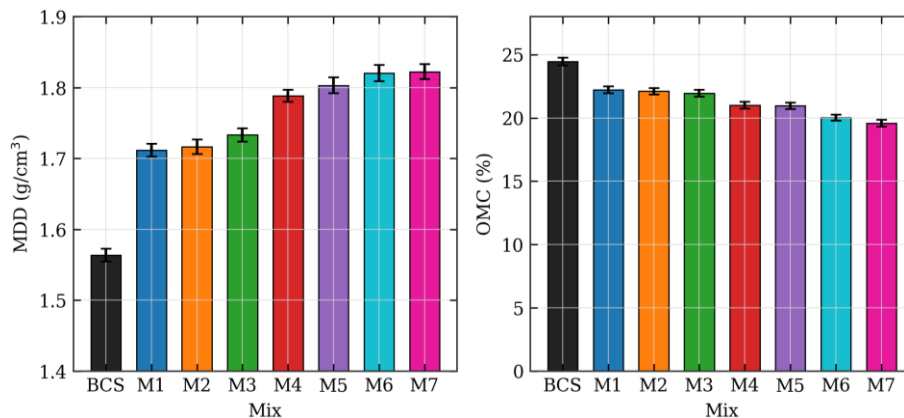


Figure 2: Maximum dry density (left) and optimum moisture content (right) for each mix; error bars denote one standard deviation about the mean of five replicates.

Table 3: Optimum moisture content and maximum dry density of each mix (mean ± one standard deviation, n = 5).

Mix	OMC (%)	MDD (g/cm ³)
BCS	24.46 ± 0.30	1.564 ± 0.009
M1	22.23 ± 0.28	1.711 ± 0.009
M2	22.11 ± 0.25	1.716 ± 0.010
M3	21.95 ± 0.26	1.733 ± 0.009
M4	21.01 ± 0.26	1.788 ± 0.009
M5	20.96 ± 0.25	1.803 ± 0.011
M6	20.02 ± 0.24	1.820 ± 0.011
M7	19.58 ± 0.26	1.822 ± 0.011

3.2 Mechanisms Behind the Density Gain: The increase in MDD may appear contradictory to the experience gained that lime is generally used to soften a clay and reduce its density. There are two conflicting influences. When the clay surface is treated with lime and/or nano-silica, flocculation occurs, which alone is expected to lower the MDD and raise the OMC; in testing where the "only" reagent is lime, the MDD tends to drop and the OMC tends to rise (Bell, 1996). In this case, however, there is a significant amount of fly ash—fine, hard, non-plastic powder with a higher specific gravity than the clay—that fills the voids between aggregates, and brings the grading toward a more closely packed mixture. The specific gravity of the solids decreased from 2.63 in the untreated soil to approximately 2.70 in the richest soil type, as the light clay minerals were progressively replaced by the heavier ash and reaction products. The densifying action of the fly ash filler dominates the loosening action from the flocculation and the overall effect is a lower water content for a higher MDD in these ternary blends.

The downward trend of OMC is more easily understood. Flocculation results in a decrease in the amount of surface area available to adsorb water molecules, which decreases moisture requirements for lubricating the particles for their densest packing. This is a similar mechanism to that of decreased plasticity. The two curves, as shown in Fig. 3, mirror each other about the body of the plot and the two extremes of MDD and OMC vary in opposite directions but in step with the overall additive content. It is consistent with combined lime–fly ash treatment of expansive subgrades which reduces moisture requirement and increases the density of the compacted material (Sambre et al., 2024; Phanikumar and Sharma, 2004).

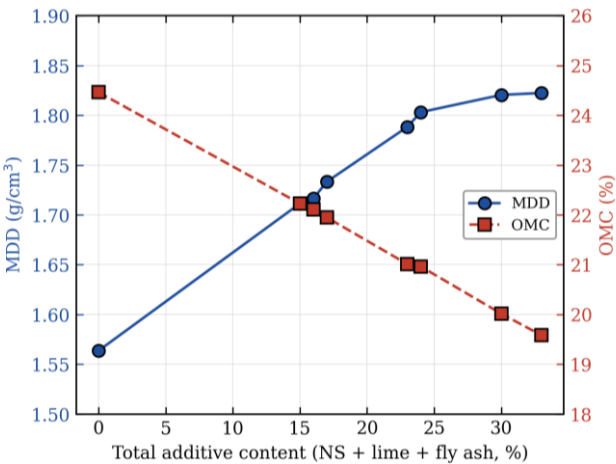


Figure 3: Variation of MDD and OMC with total additive content (nano-silica + lime + fly ash), showing the mirror-image trends.

The link between compaction and plasticity is made explicit in Figure 4, where MDD is plotted against plasticity index. The points fall along a tight descending band: as the plasticity index drops from 34% in the untreated soil to about 9% in M7, the dry density rises correspondingly. Because the plasticity reduction is itself a direct consequence of cation exchange and the early pozzolanic reaction, the figure ties the improved moulding behaviour back to the underlying physico-chemical changes rather than to mere dilution. A similar dependence of compacted density on plasticity has been noted for nano-silica-amended clays elsewhere (Alshawmar, 2024; Ghavami and Naseri, 2025).

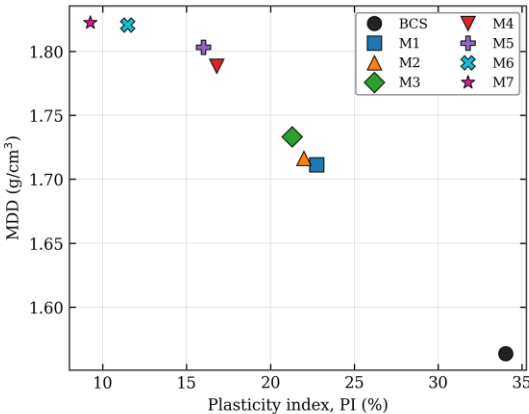


Figure 4: Relationship between maximum dry density and plasticity index across all mixes; lower plasticity is associated with higher attainable density.

3.3 Practical Implications: From a construction standpoint the changes are favourable on every count. A lower OMC means less water need be carried to and worked into the soil, an advantage in the dry pre-monsoon window when much earthwork in the region is done. A higher MDD translates directly into a stiffer, less permeable and more durable compacted layer. Because compaction is performed at the moment of placement, before the slow pozzolanic reactions have run their course, it was reassuring to find that OMC and MDD were effectively independent of the subsequent curing period in the dataset; the moulding targets a contractor must meet are therefore fixed by the mix alone and can be specified without reference to curing time. The expansive soils literature has long stressed that the state in which such a clay is compacted governs much of its later behaviour (*Seed et al., 1962; Holtz and Gibbs, 1956*), so the ability to place these blends drier and denser is itself a meaningful gain.

IV. CONCLUSIONS

- The compaction property of the black cotton soil of Wardha was systematically improved by increasing the percentage of nano-silica, lime and fly ash in the soil, which resulted in the optimum moisture content decreasing from 24.5% to 19.5% while the maximum dry density increased from 1.564 to 1.822 g/cm³ for the soil series from untreated to mix-M7.
- The compaction curve became more compact and to the left, and more acute, with the dosage, indicating the suppression of the plastic properties of the clay, by the cation exchange and flocculation properties with the formation of floccule structures and the void filling effect of the fly ash.
- The maximum dry density was found to be closely and inversely related to the plasticity index, indicating that it is not only a dilution effect that leads to an increase in the density of the clay, but the physico-chemical change taking place in the clay as well.
- Moisture content and maximum dry density were determined by the mix composition, and were negligibly affected by curing time, meaning that a field compaction target can be established based on the mix proportions, with the curing time ignored.
- The intermediate blends (M4-M5) achieved most of the potential gains attainable without compromising performance with a reasonable compromise on reagent costs for subgrade applications.

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