

California Bearing Ratio of an Expansive Black Cotton Soil Stabilised with Nano-Silica, Lime and Fly Ash

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ABSTRACT

The California bearing ratio (CBR) of a subgrade is the most commonly used measure of its load bearing capacity, and in the expansive black cotton soils found in central India, it is poor. In this paper soaked and unsoaked CBRs of a black cotton soil from Wardha district, Maharashtra for 7 days to 90 days of curing with seven mixes of nano-silica, lime and fly ash are reported. The untreated soil gave a soaked CBR of only approximately 2.4% which is less than the value necessary for a pavement subgrade. Curing for 90 days increased soaked CBR by over ten times with the best mixture (M7) achieving a value of 25.3% and the unsoaked value was nearly 30%. The soaked and unsoaked ratios both increased with the amounts of reagent and the curing times and the ratio of soaked to unsoaked increased as reagent dosage reduced the sensitivity of the soil to soaking. A strong inverse relation between soaked CBR and free swell index confirmed that the strength gain and the loss of expansiveness are two faces of the same process. The treated soil comfortably satisfies subgrade and even sub-base expectations, allowing thinner, more durable pavement sections.

Keywords- California bearing ratio; expansive soil; nano-silica; fly ash; soaked CBR; pavement subgrade.

I. INTRODUCTION

Flexible pavement design in India leans heavily on the California bearing ratio of the subgrade, because the thickness of every overlying layer is keyed to it. Expansive black cotton soils sit at the bottom of the scale: in the soaked condition that the design codes insist upon, their CBR frequently lies between 2 and 3%, which forces either very thick pavement crusts or the importing of better material (Nelson and Miller, 1992; Sambre et al., 2024). The economic case for treating the soil in place, rather than replacing it, is consequently strong.

Lime and fly ash have been the workhorses of subgrade stabilisation for decades. Lime causes immediate cation exchange and flocculation and, with time, pozzolanic cementation, and fly ash provides the reactive silica and alumina to support the pozzolanic cementation and enhances the grading (Bell, 1996; Phanikumar and Sharma, 2004). The latest developments in such systems are driven by the high reactivity of nano-silica, which has a large surface area, allowing it to be used in small amounts of 1–5% to initiate the process of formation of calcium-silicate-hydrate and stiffen the matrix (Alshawmar, 2024; Ghavami and Naseri, 2025). There has been less systematic work on the combined effect of these three reagents on the bearing ratio, and especially the difference between the soaked and unsoaked values, which is what this study attempts to fill.

It is important for an expansive soil, but not so important for most soils. The unsoaked test is to see how strong the compacted material is as placed, the soaked test is to see how much remains after four days of inundation to soften the clay. In case of a swelling soil the soaked value becomes zero and it is the soaked value to which the engineer has to design. Thus, it is doing something useful—a treatment that reduces the difference between the two is making the material water resistant rather than dry strong, Goutham and Krishnaiah (2024); Wang et al. (2022).

II. MATERIALS AND METHODS

2.1 Soil, Additives and Mixes: The expansive soil was retrieved 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 where the deposit is comparatively undisturbed. The soil is a clay of high plasticity (liquid limit 62%, plasticity index 34%) with a free swell index of about 95% and a soaked CBR near 2.4%. The stabiliser comprised amorphous nano-silica (>99% SiO₂, 20–30 nm), hydrated lime and a Class F fly ash from a regional thermal power station. Seven blends, M1 to M7, were prepared 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 listed 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 Testing Programme: Specimens were compacted at the optimum moisture content of each mix in the standard CBR mould and cured under sealed, moist conditions at 27 ± 2 °C for 7, 14, 28, 56 or 90 days. At the end of curing, one set was tested in the as-cured (unsoaked) state and a companion set after the customary four-day soak, in accordance with IS 2720 Part 16 (IS 2720 (Part 16), 1987); compaction followed IS 2720 Part 7 (IS 2720 (Part 7), 1980). Penetration was applied at 1.25 mm/min and the CBR computed at 2.5 and 5 mm, the larger governing where relevant. Five replicates were tested for each condition, and results are reported as means with one standard deviation.

III. RESULTS AND DISCUSSION

3.1 Effect of Mix on Bearing Ratio: Figure 1 contrasts the soaked and unsoaked CBR of every mix at the 28-day curing age. The untreated soil barely registers, its soaked CBR of 2.4% lying at the level marked for a typical untreated expansive subgrade. Each successive blend lifts both bars, the climb steepening once the fly ash content reaches 15% in the intermediate group. By mix M7 the 28-day soaked CBR has reached almost 23% and the unsoaked value 27%. The full set of values at 7, 28 and 90 days is given in Table 2.

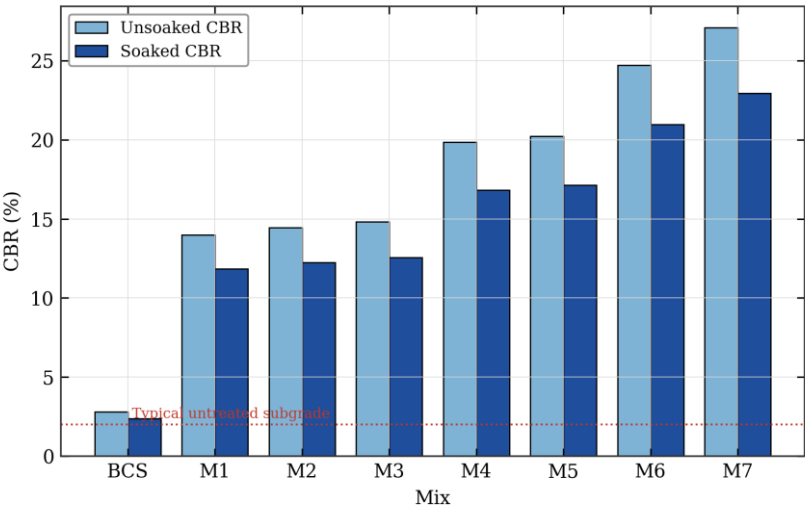


Figure 1. Soaked and unsoaked CBR of each mix at 28 days of curing; the dotted line marks the bearing level of a typical untreated expansive subgrade.

Mix	Soak 7d	Soak 28d	Soak 90d	Unsoak 7d	Unsoak 28d	Unsoak 90d
BCS	2.12 ± 0.04	2.36 ± 0.04	2.56 ± 0.01	2.50 ± 0.04	2.79 ± 0.05	3.02 ± 0.02
M1	10.32 ± 0.24	11.85 ± 0.18	12.95 ± 0.30	12.18 ± 0.28	13.98 ± 0.22	15.28 ± 0.35
M2	10.86 ± 0.29	12.24 ± 0.21	13.88 ± 0.14	12.82 ± 0.34	14.44 ± 0.25	16.38 ± 0.16
M3	11.47 ± 0.30	12.56 ± 0.16	14.18 ± 0.40	13.54 ± 0.35	14.82 ± 0.19	16.73 ± 0.47
M4	14.73 ± 0.34	16.82 ± 0.41	18.64 ± 0.36	17.38 ± 0.40	19.85 ± 0.48	21.99 ± 0.43
M5	15.58 ± 0.27	17.13 ± 0.55	19.04 ± 0.42	18.38 ± 0.32	20.22 ± 0.64	22.47 ± 0.49
M6	18.76 ± 0.46	20.96 ± 0.62	23.31 ± 0.40	22.14 ± 0.54	24.73 ± 0.73	27.50 ± 0.47
M7	20.14 ± 0.32	22.95 ± 0.68	25.26 ± 0.63	23.76 ± 0.38	27.09 ± 0.80	29.81 ± 0.74

The scale of the improvement is best appreciated as a multiple. The soaked CBR of M7 at 90 days, 25.3%, is more than ten times that of the untreated soil. Reported gains of this order are consistent with the combined lime–fly ash treatments documented for Maharashtra black cotton soils, although the inclusion of nano-silica appears to push the ceiling higher than lime and fly ash achieve alone (Sambre et al., 2024; Phanikumar and Sharma, 2004).

3.2 Effect of Curing: Curing time is important, as the majority of strength is a result of slow pozzolanic reactions. The soaked CBR of some of the mixes is plotted versus curing time in Figure 2. The untreated soil is treated just like the flat sand, and doesn't get any cementing reaction, while each treated blend gains about half as much between 7 days and 90 days. The richer mixes not only initiate higher but increase at a greater rate, because of the greater supply of lime and reactive silica to drive the reaction. This relationship is direct and has practical implications: the early-age soaked CBR underestimates the value that the layer will provide in service (Wang et al., 2022).

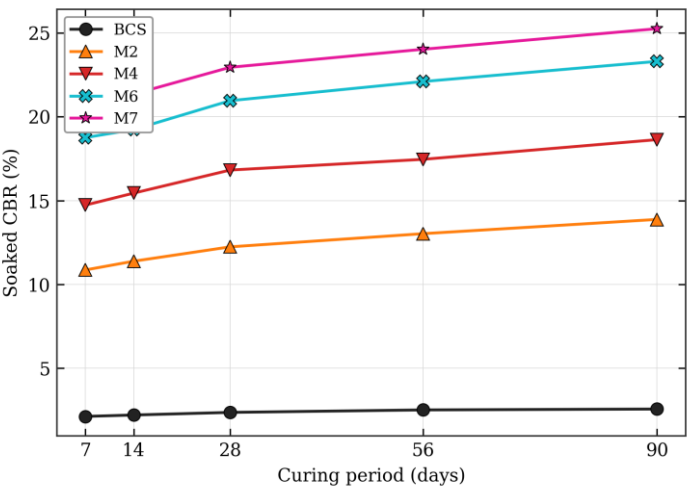


Figure 2: Development of soaked CBR with curing period for the untreated soil and for mixes M2, M4, M6 and M7.

3.3 Soaked Versus Unsoaked Response: The unsoaked CBR is always higher than the soaked CBR for each of the mixes, but there is a very good correlation between the two. Figure 3 shows the scatter graph for the two variables for the whole data set; the points are tightly grouped about a single straight line, with a coefficient of determination greater than 0.99. The unsoaked value is seen to be running about 18% higher than the soaked value throughout the range, as indicated by the slope. More significant than the slope is the behaviour of the absolute gap, in the untreated soil the soaking loss is proportionately severe while in the treated blends the soaked value mimics the closely the unsoaked one, a testament of the ability of the cementitious bond to withstand the softening effect of water. The treatment is therefore providing true water stability, rather than just dry stiffness.

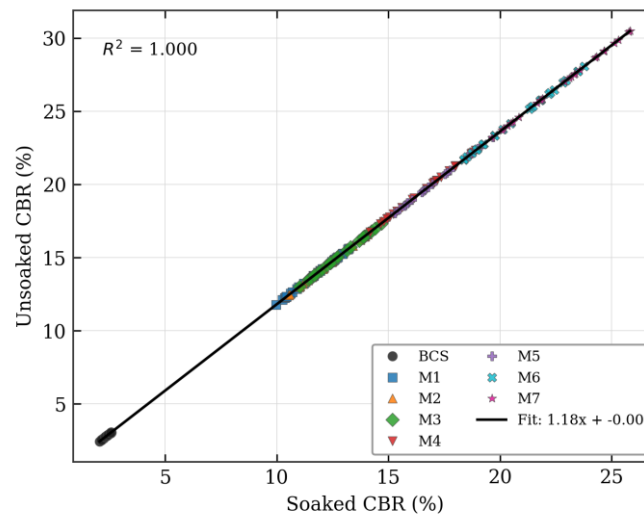


Figure 3: Correlation between soaked and unsoaked CBR across all mixes and curing ages.

3.4 Link with Swelling: The mechanism tying these observations together is the suppression of the soil's expansiveness. Figure 4 plots the 90-day soaked CBR against the free swell index of each mix. The relationship is strongly inverse: as the free swell index falls from about 95% in the untreated soil to roughly 15% in the high-dosage blends, the soaked CBR rises across the full range. A soil that no longer takes up water and swells also no longer loses its strength on soaking, so the same flocculation and cementation that curtail swelling are responsible for the bearing improvement (Sridharan and Prakash, 2000; Prakash and Sridharan, 2004).

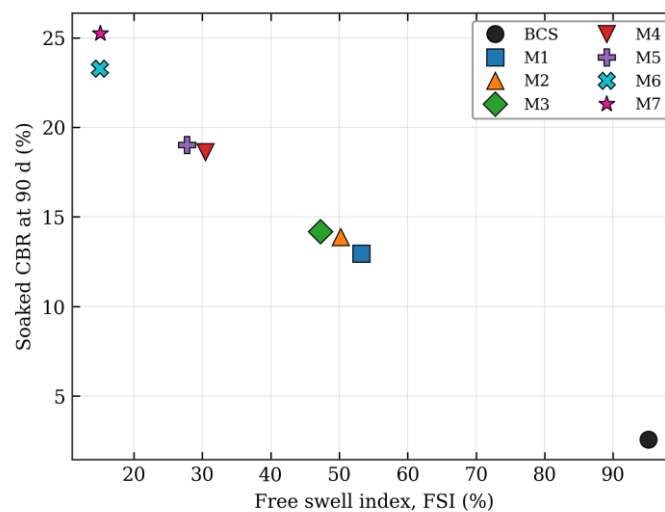


Figure 4. Inverse relationship between 90-day soaked CBR and free swell index across the mixes.

3.5 Pavement Implications: A subgrade soaked CBR of 2.4% would, under the prevailing Indian design guidance, demand a very thick pavement crust and would still leave the structure vulnerable to moisture-driven distress. Lifting the soaked CBR into the 13–25% band achieved by the intermediate and high-dosage blends moves the treated layer from ‘poor subgrade’ into the range associated with a competent subgrade or even a lower sub-base, with a corresponding reduction in the required thickness of granular and bituminous layers. The economic and durability gains that follow have been demonstrated for comparable stabilised expansive subgrades (Sambre et al., 2024; Perigalla et al., 2026). For routine work the intermediate blends, which already deliver a soaked CBR near 17–19%, represent a sensible target; the high-dosage blends are justified where the thinnest possible section or the greatest moisture resilience is sought.

IV. CONCLUSIONS

- Treatment of the Wardha black cotton soil with nano-silica, lime and fly ash raised its soaked CBR from about 2.4% to as much as 25.3%, an increase exceeding an order of magnitude.

- Both soaked and unsoaked CBR increased with reagent dosage and with curing period, the treated blends gaining roughly 50% in soaked strength between 7 and 90 days while the untreated soil remained unchanged.
- Soaked and unsoaked CBR are very closely correlated ($R^2 > 0.99$) and the progress of the reduction of the difference between the two against treatment indicates that it is the stabiliser which gives resistance to soaking, and not dry strength.
- The correlation between the 90-day soaked CBR and free swell index was negative, indicating that the increase in the CBR was due to the same flocculation and pozzolanic cementation process that reduced the swelling.
- The intermediate blends already raise the soil to the competent-subgrade zone and represent the least expensive target for pavement operations, while high-dosage blends are only used in situations where the greatest possible soil thickness reduction, or moisture resistance, is required.

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