

Swelling Pressure and Free Swell Behaviour of an Expansive Black Cotton Soil Treated with Nano-Silica, Lime and Fly Ash

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ABSTRACT

The damage that expansive soils inflict on light structures and pavements stems from their swelling pressure and free swell, so the suppression of these properties is the primary aim of any stabilisation aimed at volume-change control. This paper reports the swelling pressure, free swell index and plasticity of a black cotton soil from Wardha district, Maharashtra, treated with seven nano-silica–lime–fly ash blends. The untreated soil was strongly expansive, with a swelling pressure of about 120 kPa, a free swell index near 95% and a plasticity index of 34%. Treatment curtailed all three sharply: the swelling pressure fell to roughly 8 kPa, the free swell index to about 15% and the plasticity index to 9% in the high-dosage blends, effectively removing the soil from the dangerously expansive category. The reductions in swelling pressure and free swell moved in step with the fall in plasticity, and a single mechanism - the replacement of adsorbed sodium and the contraction of the diffuse double layer by calcium, followed by pozzolanic cementation - accounts for all three. The treated soil meets the criteria for a low-expansion subgrade, addressing the principal hazard that black cotton soils pose to construction.

Keywords- swelling pressure; free swell index; expansive soil; nano-silica; lime; fly ash; volume change.

I. INTRODUCTION

A black cotton soil is not weak, it is mobile. Its clay fraction consists of montmorillonite, which imbibes water between its layers, and when it is restrained, it exerts water pressure that can lift and crack a lightly loaded foundation or pavement, and on drying, shrinks and cracks again (Holtz and Gibbs, 1956; Chen, 1988; Nelson and Miller, 1992). This hazard is quantified by two laboratory indices, the swelling pressure and the free swell index, which are at the heart of stabilising such a soil for volume change control.

Lime has been a longstanding cure-all. It releases calcium ions which expels the sodium ions from the surface of the clay and reduces the swell of expansive clay by many folds; even a small percentage of lime can reduce the swell of expansive clay to a small fraction of original swell (Seed et al., 1962; Al-Rawas et al., 2005; Sivapullaiah et al., 2000). Fly ash helps in diluting the active clay as well as provide pozzolanic material, while nano-silica helps to speed up the cementation process that secures the contracted fabric (Phanikumar and Sharma, 2004; Sambre et al., 2024). The expansiveness classification of the soils from the index properties and the relationship between expansiveness and plasticity are well established (Sridharan and Prakash, 2000; Prakash and Sridharan, 2004; Sridharan and Gurtug, 2004). This study brings up a systematic documentation of the variation of the swelling pressure, free swell and plasticity of a graded series of ternary mixes of nano-silica, lime and fly ash for a highly expansive Deccan clay.

II. MATERIALS AND METHODS

2.1 Materials and Mixes: The expansive soil was obtained 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, from a depth of 1.0 to 1.5 m

below the existing ground surface, beneath the desiccated surface crust. In its natural state it is a clay of high plasticity (liquid limit 62%, plasticity index 34%) with a free swell index of about 95% and a swelling pressure near 120 kPa, placing it firmly in the very-high-expansion class. 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 proportioned by dry mass of soil 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: Swelling pressure was measured on specimens compacted at optimum moisture content and maximum dry density and inundated in the consolidation cell, following the constant-volume approach of IS 2720 Part 41 (IS 2720 (Part 41), 1977). The free swell index was determined to IS 2720 Part 40 (IS 2720 (Part 40), 1977), and Atterberg limits by the usual procedures. Five replicate determinations were made for each mix, and means with one standard deviation are reported. Because swelling pressure and free swell are governed by the soil's physico-chemical state, which is fixed at mixing, the values are reported by mix.

III. RESULTS AND DISCUSSION

3.1 Swelling Pressure: Figure 1 shows the swelling pressure of each mix, and the values are listed with the free swell and plasticity in Table 2. The untreated soil exerts about 120 kPa, more than enough to distress a lightly loaded footing or a pavement. The reduction with treatment is steep and immediate: the low-dosage blends already cut the pressure to roughly 60 kPa, and from the intermediate group onward it collapses, reaching a floor near 8 kPa in mixes M6 and M7—a reduction of better than 90%. At this level the soil can be regarded as practically non-expansive. The magnitude of the cut matches reports that 6% or more of lime can all but eliminate the swelling pressure of an expansive clay (Al-Rawas et al., 2005; Seed et al., 1962).

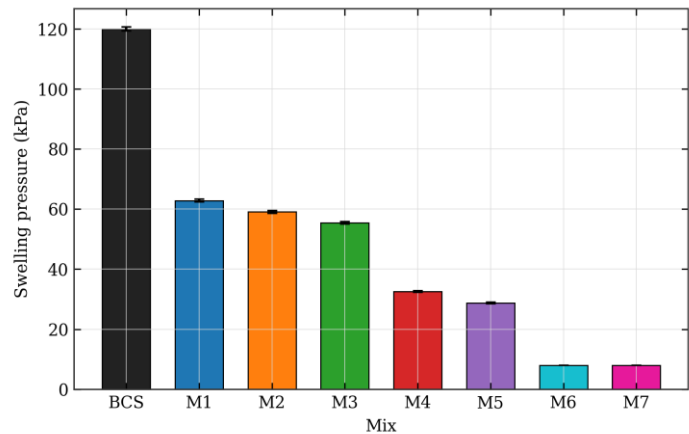


Figure 1: Swelling pressure of each mix; error bars denote one standard deviation about the mean of five replicates.

Table 2: Swelling pressure, free swell index and plasticity index of each mix (mean ± one standard deviation, n = 5).

Mix	Swelling pressure (kPa)	Free swell index (%)	Plasticity index (%)
BCS	120.0 ± 0.7	95.2 ± 1.6	34.0 ± 0.4

Mix	Swelling pressure (kPa)	Free swell index (%)	Plasticity index (%)
M1	62.9 ± 0.5	53.2 ± 0.8	22.8 ± 0.2
M2	59.1 ± 0.4	50.2 ± 0.8	22.0 ± 0.2
M3	55.5 ± 0.4	47.2 ± 0.9	21.3 ± 0.3
M4	32.5 ± 0.2	30.4 ± 0.5	16.8 ± 0.2
M5	28.7 ± 0.2	27.7 ± 0.5	16.0 ± 0.2
M6	8.0 ± 0.0	15.0 ± 0.3	11.5 ± 0.1
M7	8.0 ± 0.0	15.1 ± 0.3	9.3 ± 0.1

3.2 Free swell index: The free swell index (Figure 2) continues the downward trend. It starts at about 95% well above the 50% threshold between high and moderate swell, and drops below that threshold by the intermediate group, down to the high dosage blends where it reaches roughly 15%. The 50% mark is important as it represents a shift from the category that requires special foundation precautions to one that does not. The free swell is a little more sluggish to respond as it is recorded on remoulded material and thus corresponds to the change in the intrinsic affinity of the clay towards water, as opposed to the response of a confined specimen (Sridharan and Gurtug, 2004; Prakash and Sridharan, 2004).

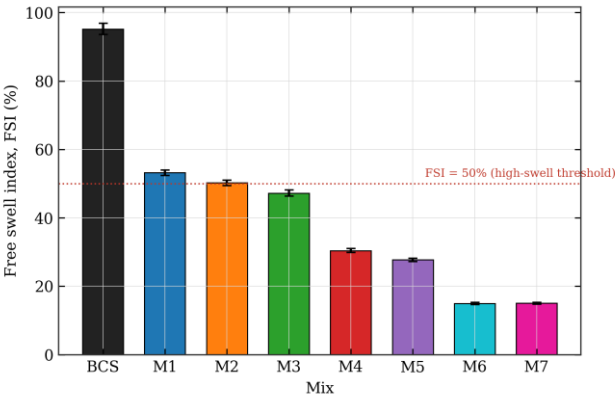


Figure 2. Free swell index of each mix; the dotted line marks the 50% high-swell threshold.

3.3 Combined Trend with Dosage: Plotting swelling pressure and free swell together against total additive content, Figure 3, shows the two indices descending in close company. Both fall most steeply through the low-to-intermediate range and then flatten as they approach their respective floors, the swelling pressure levelling at about 8 kPa and the free swell at about 15%. The parallel decline indicates that a single underlying change—the conversion of the clay from a sodium-dominated, highly dispersive state to a calcium-dominated, flocculated one—drives both, with the pozzolanic cementation that follows then fixing the low-swell fabric permanently (Sivapullaiah et al., 2000; Sambre et al., 2024).

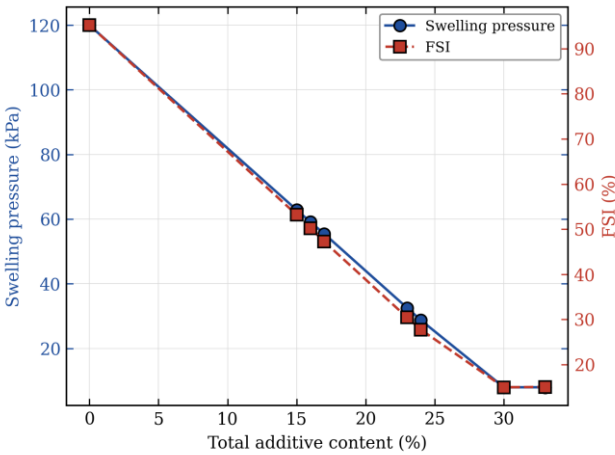


Figure 3. Swelling pressure and free swell index as functions of total additive content.

3.4 Relation to Plasticity: Because the swelling of a clay and its plasticity both arise from the same water-holding capacity of the active mineral surface, the two should fall together, and Figure 4 confirms that they do. Swelling pressure is plotted against plasticity index for all mixes, and the points trace a clear positive band: as the plasticity index drops from 34% in the untreated soil to 9% in M7, the swelling pressure declines across the full range. The relationship is useful in practice, since the plasticity index is far quicker to measure than the swelling pressure and can serve as a first screen for the adequacy of a treatment (Sridharan and Prakash, 2000; Holtz and Gibbs, 1956).

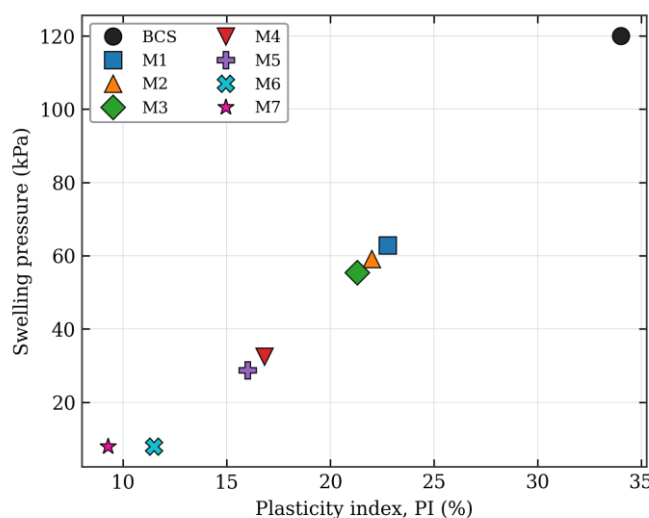


Figure 4: Relationship between swelling pressure and plasticity index across the mixes.

3.5 Practical Significance: The practical implications are quite clear. If an untreated swelling pressure of 120 kPa is found and a free swell index of 95%, a designer would be forced to take expensive precautions which include deep foundations, moisture barriers or complete removal and replacement of the soil. By reducing the swelling pressure below 10kPa and the free swell below 15%, the hazard of volume change is eliminated at its source, and conventional shallow construction and ordinary pavement sections are permissible on this type of soil that was once considered a hostile soil. The intermediate blends reduce the free swell to below the high swell level and the swelling pressure to approximately one-third of nature, and are thus an economic option for routine applications; the high dosage blends are suitable for situations where it is required to get the residual movement as close to zero as possible (Sharmila et al., 2021; Phanikumar and Sharma, 2004).

IV. CONCLUSIONS

- Nano-silica–lime–fly ash treatment sharply reduced the expansiveness of the Wardha black cotton soil, the swelling pressure falling from about 120 kPa to roughly 8 kPa and the free swell index from about 95% to about 15% in the high-dosage blends.
- The reductions were steepest through the low-to-intermediate dosage range and then approached a floor, indicating that the available calcium had largely satisfied the cation-exchange demand by the intermediate group.
- Swelling pressure, free swell index and plasticity index declined together, all three governed by the conversion of the clay from a dispersive, sodium-dominated state to a flocculated, calcium-dominated one fixed by pozzolanic cementation.
- Swelling pressure correlated positively with plasticity index, so the readily measured plasticity index can serve as a practical first screen for the effectiveness of treatment.
- The treated soil meets low-expansion subgrade criteria; the intermediate blends bring the free swell below the high-swell threshold economically, while the high-dosage blends drive the residual swelling pressure close to zero.

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