Nanomaterial and Biopolymer Catalyst Addition for Improving Expansive Clay Soil

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Abstract

Expansive clays shrink and swell under wet–dry cycles, cracking and differentially deforming the roads, bridges and housing built on them. Such clays cover about 20% of Indonesia's land area, from Sumatra to Papua.

This study stabilises a montmorillonite-rich clay of very high plasticity (CV) with nano-lime and nano-silica. Chitosan, a biopolymer, acts as a binder between the nanomaterials and the soil. Four conditions were compared: untreated CV, CV + 0.05% chitosan (CV+B), CV + 3% nano-lime + 1% nano-silica (CV+N), and CV+N + 0.05% chitosan (CV+N+B).

Micro- and macro-scale tests show that the plasticity index (PI) fell from 52.88% to 25.49–36.24%. Swelling pressure fell by up to 98.9% (447.83 → 4.91 kPa for CV+N). CV+N+B reached an unconfined compressive strength (UCS) of ≈924 kPa at <24 h and kept it after 7 days.

Keywords: expansive clay, nano-silica, nano-lime, chitosan, montmorillonite.

Introduction

Problematic clay occurs in almost every region of Indonesia (Badan Geologi, 2019). Much of the infrastructure in the national medium-term plan (roads, bridges, settlements) is built on it. Such damage is costly: in Louisiana, USA, expansive soil caused losses of about US$66 million by 2010 (Bi et al., 2022).

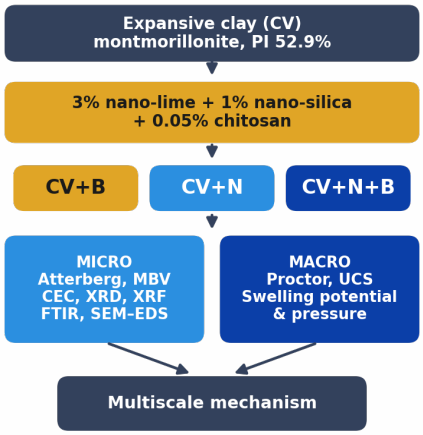
Swelling is driven by active clay minerals such as smectite and montmorillonite. Scanning electron microscopy (SEM) shows pores of only ~100–200 nm, while clay particles are 100–10,000 nm, so an effective additive must be at or below the pore size. Nano-lime gives a much higher compressive strength than ordinary lime, and nano-silica raises strength and density while reducing swelling.

Improvement is expected through crystallisation, flocculation–agglomeration between soil and nanomaterial. Chitosan, a biopolymer, is added as a binder to bond the nanoparticles to the soil and fill the pores.

Objective: to characterise the micro- and macro-scale behaviour of an expansive clay before and after the addition of nanomaterials and a biopolymer.

Research Method

The base soil (CV) is an expansive clay of very high plasticity: 76.82% clay fraction, liquid limit (LL) 80.23%, plastic limit (PL) 27.35%, PI 52.88%, methylene blue value (MBV) 35.96 and cation exchange capacity (CEC) 134.62 cmol/100 g. X-ray diffraction (XRD) indicates montmorillonite. X-ray fluorescence (XRF) gives Si 44.2%, Al 20.9%, Fe 18.3% and Ca 12.2%. Nanomaterial dosages of 1–5% and biopolymer dosages of 0.05–0.2% were screened to select the mixes (Picture 1).

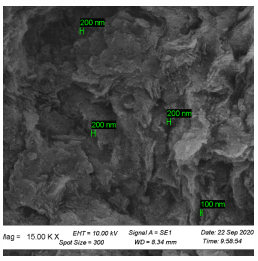


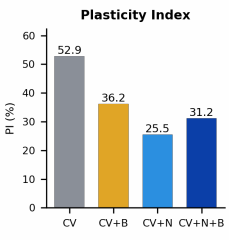
Picture 1. Research flow and testing programme

Micro-scale tests track changes in mineral activity, chemistry, bonding and pore structure: Atterberg limits, MBV, CEC, XRD, XRF, Fourier-transform infrared (FTIR) and SEM–EDS with image-based pore analysis.

Macro-scale tests give the engineering properties: standard Proctor compaction, UCS, and swelling potential and pressure. UCS and swelling were measured at <24 h and after 7 days of curing.

Linking the two scales explains *why* each additive works: chemistry → bonding and microstructure → plasticity → swelling, compaction and strength.





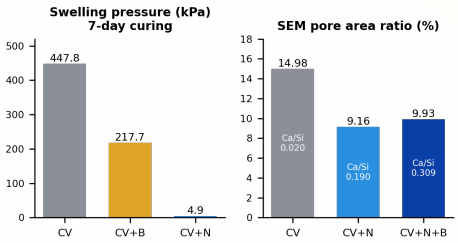
Picture 2. SEM of untreated expansive clay (left); PI of the four mixes (right)

Discussion & Result

CV+B (chitosan only). PI drops to 36.24%. Chitosan's –NH_2 and –OH groups coat and bridge particles into aggregates. Swelling pressure falls to 119.10 kPa (–73.4%) at <24 h but rises to 217.69 kPa after 7 days as the polymer film thins.

CV+N (nano-lime + nano-silica). PI drops to 25.49%. $Ca(OH)_2$ supplies Ca^{2+} for pozzolanic calcium silicate and aluminate hydrates (C–S–H/C–A–H), while the nanoparticles fill pores and cause flocculation. Swelling pressure is only 4.91 kPa after 7 days (–98.9%).

CV+N+B (hybrid). PI is 31.20%. The microstructure is denser and more homogeneous. Ca/Si rises from 0.020 to 0.309, and FTIR shows altered bonding. UCS reaches 923.98 kPa at <24 h and 912.50 kPa after 7 days: high early strength from an organo-mineral network.



Picture 3. Swelling pressure after 7 days of curing; SEM pore area ratio and EDS Ca/Si ratio

Conclusion

1. The CV soil is highly expansive (PI 52.88%, swelling pressure 447.83 kPa) because of its montmorillonite content and open, sheet-like pore structure.

2. Nano-lime + nano-silica (CV+N) is the most effective at suppressing swelling (–98.9% at 7 days) and reducing plasticity, through pore filling, flocculation–agglomeration and C–S–H/C–A–H cementation.

3. Chitosan alone gives a fast but time-dependent improvement, so it is best used as a binder rather than as a stand-alone stabiliser.

4. The hybrid CV+N+B forms an organo-mineral system with a denser matrix, a higher Ca/Si ratio and high early strength (UCS ≈ 924 kPa) that is maintained over curing.

5. Stabilisation performance must be judged at several scales, not by a single parameter. Nanomaterial–chitosan treatment is promising for expansive clay subgrades.