

AHMED MAHMOUD ADAM IDRESS (ORCID: 0000-0002-2099-6605)¹

STABILIZATION OF EXPANSIVE ANKARA CLAY USING CONVENTIONAL, CHEMICAL, AND WASTE-DERIVED ADDITIVES. A TWO-STAGE EXPERIMENTAL INVESTIGATION

Expansive soils present major geotechnical challenges due to their pronounced swelling-shrink behaviour and associated volumetric instability, which can compromise foundations, pavements, and embankments. This study investigates the stabilization of expansive Ankara Clay using eight conventional, chemical, and waste-derived additives through a structured two-stage laboratory programme. In stage 1, all stabilizers were applied at a uniform dose of 30% by dry weight and evaluated in terms of index properties, standard proctor compaction characteristics, and one-dimensional swelling behaviour. The results show that the stabilizer type strongly governs the moisture–density relationship and the response to swelling. Composite systems, particularly concrete demolition waste (CDW) combined with lime or gypsum and cement-gypsum mixtures, achieved the greatest reductions in plasticity and swell potential, while gypsum alone showed limited effectiveness. Based on the performance of stage 1, lime and CDW were selected for stage 2 testing at 10% and 20% doses to assess moderate and intensive stabilization. A clear dosage-dependent behaviour was observed: at 10% content, CDW slightly outperformed lime due to mechanical restraint and particle interlocking, whereas at 20% content, lime exhibited marginally superior swell suppression through intensified physicochemical reactions. Both stabilizers significantly improved shear strength through different mechanisms. The findings demonstrate that well-designed waste-derived and hybrid stabilization strategies can effectively mitigate volumetric instability while promoting sustainable geotechnical practice.

1. INTRODUCTION

Expansive clay soils are characterised by pronounced volume changes in response to moisture fluctuations, often leading to severe structural distress on pavements, foundations, embankments, and retaining systems. expansive Ankara Clay is well known for its high swell potential, elevated plasticity, and low shear strength, significantly limit its suitability for geotechnical applications without prior treatment. Consequently, the effective

¹Department of Geological Engineering, Hacettepe University, 06800 Beytepe, Ankara, Turkey, email address: geoahmed1990@gmail.com

stabilization of expansive soils remains a critical research focus to ensure structural safety and long-term serviceability.

A wide range of stabilizing agents have been investigated to improve the engineering behaviour of expansive clays, including lime, cement, gypsum, and various industrial by-products. Among these, construction and demolition waste (CDW) has attracted increasing attention due to its availability, sustainability benefits, and ability to improve soil strength and reduce swelling through mechanical restraint mechanisms. Previous studies have demonstrated that CDW and demolition waste materials can markedly reduce plasticity and swelling potential while substantially improving strength characteristics, particularly unconfined compressive strength and friction resistance [1–3]. Similarly, lime-based stabilization has been consistently reported to be highly effective in suppressing swelling through physicochemical mechanisms such as cation exchange, flocculation, and pozzolanic reactions, resulting in significant improvements in plasticity, workability, and shear strength [4–6].

Gypsum has also been identified as a viable stabilizer for expansive soils, alone or in combination with other additives, which contributes to reductions in swelling potential and plasticity accompanied by moderate strengthening [7]. In parallel, several investigations have explored alternative industrial by-products and blended stabilization systems, including cement dust, fly ash, waste brick powder, ceramic dust, and multicomponent mixtures. These studies consistently indicate that hybrid stabilization approaches often outperform single additives by combining chemical bonding, pore filling, and mechanical reinforcement mechanisms [8–10].

More recently, increasing emphasis has been placed on sustainable and nontraditional soil stabilization methods to address environmental and engineering challenges associated with expansive soils. Agricultural waste-based additives have emerged as promising stabilizers due to their low cost, wide availability, and environmental benefits. Recent studies indicate that agricultural by-products, such as coffee husk, rice husk, sawdust, wheat straw, cornhusk, sugarcane bagasse and bamboo powder, can significantly improve geotechnical properties, including California bearing ratio, unconfined compressive strength, and plasticity characteristics, while reducing the swell potential and optimum moisture content [11–13]. Microstructural investigations using X-ray diffraction and scanning electron microscopy have further confirmed that these improvements are associated with changes in soil fabric, improved interparticle bonding, and partial pozzolanic activity induced by the organic and silica components of the waste materials [14,15].

In addition to biobased stabilizers and polymeric materials have also been explored as alternative ground improvement techniques. While rigid and flexible polyurethane foams have been shown to improve soil compaction and shear behaviour, their application is often constrained by high material cost and technical complexity. Recent experimental investigations demonstrate that semi-rigid foam systems used alone or in combination with cement provide a more practical and economical solution. Although foam alone offers limited improvement, its combined application with cement results in a pronounced synergistic effect, significantly increasing soil cohesion, internal friction angle, and bearing capacity when

optimal mix proportions are adopted [16,17]. These improvements are mainly attributed to mechanical interlocking, filling of voids, and improved cementation within the soil matrix.

At the infrastructure scale, expansive soils remain a major challenge for transportation networks, particularly pavements subjected to cyclic moisture variations. Advanced stabilization strategies employing chemical additives, including geopolymers and silica-based materials, along with innovative geosynthetic systems such as geocells and wicking geotextiles, have been reported to effectively mitigate the distress caused by shrink–swell behaviour. Field applications and case studies highlight that these methods improve moisture regulation, stress distribution, and long-term pavement performance while offering favourable sustainability and lifecycle cost benefits [18].

Geopolymer stabilization using industrial by-products has further expanded the range of sustainable soil treatment technologies. Fly ash-red mud geopolymer systems have demonstrated significant potential as low-carbon alternatives to conventional cement stabilization. Recent studies emphasise that the combined use of fly ash and red mud enhances geopolymerization reactions, leading to improved soil strength, durability, and resistance to adverse environmental conditions compared to single-precursor systems [19].

Despite the extensive body of existing literature, limited studies have conducted systematic comparisons of conventional binders, industrial by-products, and waste-derived stabilizers at consistent dose levels while simultaneously evaluating their combined effects on index properties, compaction behaviour, swelling response, and shear strength. Moreover, staged experimental frameworks aimed at identifying optimal stabilizers for expansive Ankara Clay remain unexplored enough. These gaps motivate the present study, in which expansive Ankara Clay is stabilized using multiple conventional and waste-based systems applied at consistent dosage levels, with the objective of identifying effective and sustainable stabilization strategies and providing practical guidance for geotechnical engineering applications.

2. MATERIALS AND METHODS

Expansive Ankara Clay. The expansive clay investigated in this study was obtained from an old construction site in Ankara, Türkiye, at coordinates 39°53'46.47"N and 32°44'50.15"E. Undisturbed soil blocks were collected from the ground surface to a depth of approximately 50 cm to ensure representative sampling of the active clay zone (Fig. 1). The sampling area is characterised by clay-rich deposits typical of the Ankara region. The soil exhibits a brown to reddish colouration with occasional lime bands, indicating the partial presence of natural carbonate and heterogeneity in the mineral composition. Particle size analysis revealed that the soil consists predominantly of clay and silt fractions, with a minor sand content and negligible gravel. The clay fraction exceeds 65%, confirming the fine-grained and highly plastic nature of the material. Index property tests show

high limits for liquid and plastic, resulting in a large plasticity index. According to the Unified Soil Classification System (USCS), soil is classified as high-plasticity clay (CH), consistent with its pronounced swelling potential and low inherent shear strength.

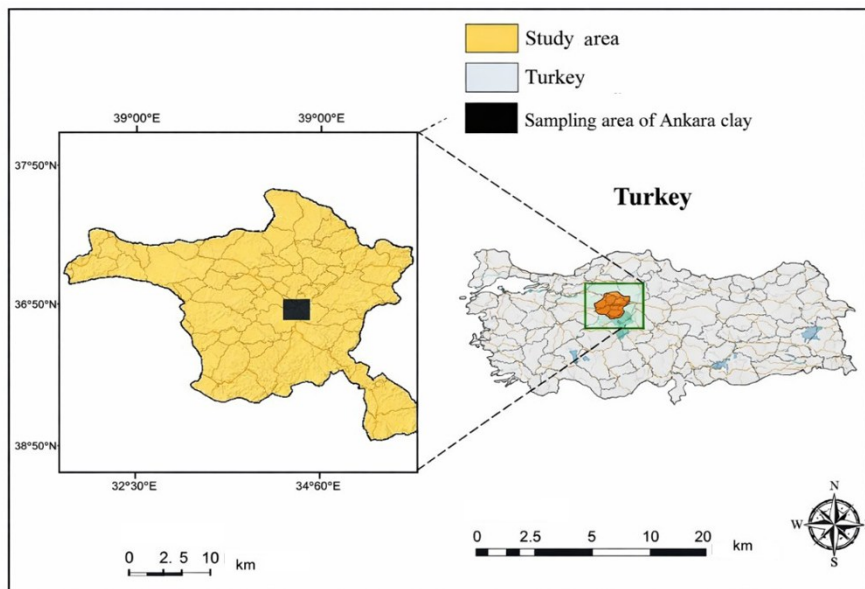


Fig. 1. Location map of the sampling area for Ankara Clay

Stabilization materials. Four stabilization materials were selected to improve the engineering behaviour of expansive Ankara Clay: lime, ordinary Portland cement, gypsum and concrete demolition waste. These additives represent a combination of conventional chemical stabilizers and waste-derived materials and were chosen to enable a systematic comparison of their chemical, mechanical and sustainability-related stabilization mechanisms. All additives were incorporated at a uniform dose of 30 wt % of soil during the stage 1 screening programme.

Lime was selected because of its well-established effectiveness in stabilizing expansive clays through physicochemical mechanisms such as cation exchange, particle flocculation, and pozzolanic reactions, which lead to reductions in plasticity and swelling and improvements in soil structure and strength. Ordinary Portland cement (OPC) was used as a conventional cementitious stabilizer. Its hydration reactions and subsequent formation of cementitious compounds contribute to increased stiffness, bonding, and volumetric stability of treated soils. Gypsum was included as a sulphate-based additive capable of modifying plasticity and influencing swelling behaviour through the formation of calcium-sulphate-related reaction products. Its role was evaluated as both as a standalone stabilizer and in blended systems. Concrete demolition waste (CDW) was obtained from a demolished construction site in Ankara province at coordinates 39°56'37.95"N and

32°49'04.09"E. The material represents a sustainable stabilization alternative, providing mechanical improvement through particle replacement, densification, and interlocking, as well as residual cementitious activity.

In addition to individual additives, four blended systems were examined: CDW with lime, CDW with gypsum, cement with gypsum, and cement with lime. At this stage, each additive in the mixed systems was used at 30% by weight (by dry weight of the soil). These combinations were selected to assess the potential synergistic effects arising from the interaction between recycled materials and conventional binders, enabling a comprehensive evaluation of hybrid stabilization strategies.

Experimental design and testing philosophy. The experimental programme was structured in two stages to systematically evaluate stabilization strategies for expansive Ankara Clay.

Stage 1 served as a comparative screening programme to assess the effectiveness of conventional stabilizers and waste-derived stabilizers under identical conditions. Eight systems were investigated: lime, ordinary Portland cement (OPC), gypsum, concrete demolition waste (CDW), and four mixed formulations (lime + CDW, gypsum + CDW, cement + gypsum, cement + lime). All stabilizers were incorporated at a uniform dosage of 30 % by dry weight of soil. The evaluation focused on key geotechnical parameters, defined and measured as follows.

Liquid limit (LL). The water content at which the soil changes from the plastic state to the liquid state, determined using the Casagrande apparatus according to ASTM D4318 (expressed in %).

Plasticity index (PI). The numerical difference between LL and PL ($PI = LL - PL$), representing the range of plastic behaviour (determined by ASTM D4318, expressed in %).

Shrinkage limit (SL). The lowest water content at which further drying does not cause volume reduction, measured using the shrinkage dish and mercury displacement method (ASTM D427) and reported in %.

Compaction characteristics. Optimum moisture content (OMC) and maximum dry density (MDD) obtained from Standard Proctor compaction tests (ASTM D698) using a Proctor mould and rammer (OMC reported in %, MDD in g/cm^3).

Swelling behaviour. The percentage calculated as $(\Delta h/h_0) \times 100$, where Δh is vertical expansion was measured on the oedometer under confined conditions (ASTM D4546).

Stage 2 focused on a detailed evaluation of lime and CDW, selected based on stage 1 performance and their contrasting stabilization mechanisms. To capture both moderate and intensive effects, these additives were incorporated at 10 and 20% by dry weight of soil. The testing programme followed the same methodology as stage 1, with the addition of shear strength assessment.

Direct shear test. Conducted according to ASTM D3080 using a shear box apparatus at a constant displacement rate of 0.05 mm/min. Stress–strain curves were recorded and peak shear stress–normal stress data were used to construct failure envelopes.

Shear strength parameters. Cohesion (c , in kPa) and friction angle (ϕ , in deg) derived from the Mohr–Coulomb theory based on failure envelopes.

This staged approach enabled a direct comparison between chemically dominated stabilization (lime) and mechanically driven modification (CDW), providing insight into their relative effectiveness and practical applicability.

The plasticity index (PI) was determined in accordance with ASTM D4318 (*Standard Test Methods for Liquid Limit, Plastic Limit, and Soil Plasticity Index of Soils*). PI, expressed as percentage, represents the numerical difference between the liquid limit (LL) and the plastic limit (PL), that is, $PI = LL - PL$. Measurements were made in remoulded samples prepared at the same additive dosage and curing conditions used for swelling tests to ensure consistency in comparative evaluation.

3. RESULTS AND DISCUSSION OF STAGE 1

3.1. CHARACTERIZATION OF NATURAL ANKARA EXPANSIVE CLAY

The particle size analysis showed that the natural clay consists of 66.6% clay, 23.5% silt, and 10.5% sand, with negligible gravel content. The soil has a liquid limit of 94.5%, a plastic limit of 39.3%, and a plasticity index of 55.2%, and is classified as CH according to the *Unified Soil Classification System*. The particle size distribution and index properties are presented in Fig. 2 and Table 1.

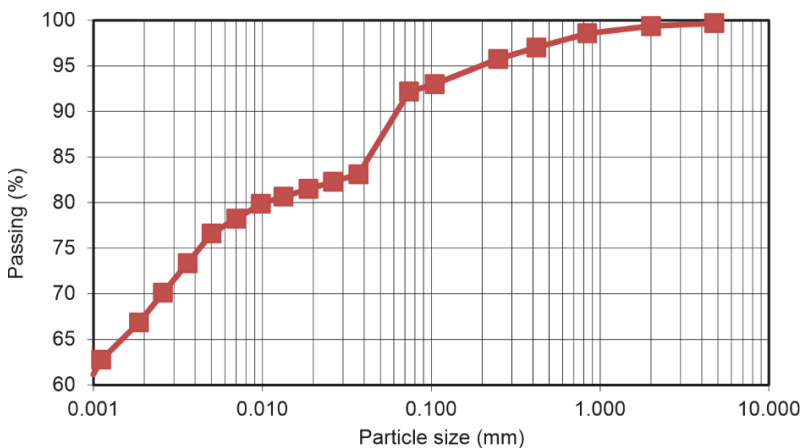


Fig. 2. Particle-size distribution of Ankara Clay

Table 1

Properties of expansive Ankara Clay

Test	Values	ASTM Standards
Particle size analysis		[20]
Gravel, wt %	0	
Sand, wt %	10.5	
Silt, wt %	23.5	
Clay, wt %	66.6	
Atterberg limits/consistency limits		[21]
Liquid limit, %	94.5	
Plastic limit, %	39.3	
Plasticity index, %	55.2	
Shrinkage limit, %	15	
Other index properties		[22]
Maximum dry density, g/cm ³	1.25	
Optimum moisture content, %	35	
Specific gravity	2.51	[23]
Modified free swell index (MFSI)	105	[24]
Soil classification		[25]
USCS classification	CH	

Mineralogical analysis using XRD identified smectite as the dominant clay mineral, with illite and kaolinite also present, together with quartz, feldspar, and calcite (Table 2). The soil shows the characteristics of an active expansive clay, with a modified free-swell index exceeding 100%. Representative XRD patterns are shown in Figs. 3 and 4.

Table 2

Summary of semi-quantitative analysis of non-clay and clay minerals for soil sample

Non-clay and clay minerals			Clay minerals		
Mineral	Quantitative value	Mineral ratio [%]	Clay mineral	Quantitative value	Clay mineral ratio [%]
Clay	256.025	68	smectite	2.7	49.54
Quartz	47.25	12.55	illite	1.5	27.52
Calcite	56.98	15.135	kaolin	1.25	22.94
Feldspar	16.2	4.303	total	5.45	100
Total	376.455	99.9			

The clay mineral ratios are expressed relative to the clay fraction (100%).

All tests were performed according to ASTM standards, except for the modified free swelling index test, which followed Indian standards.

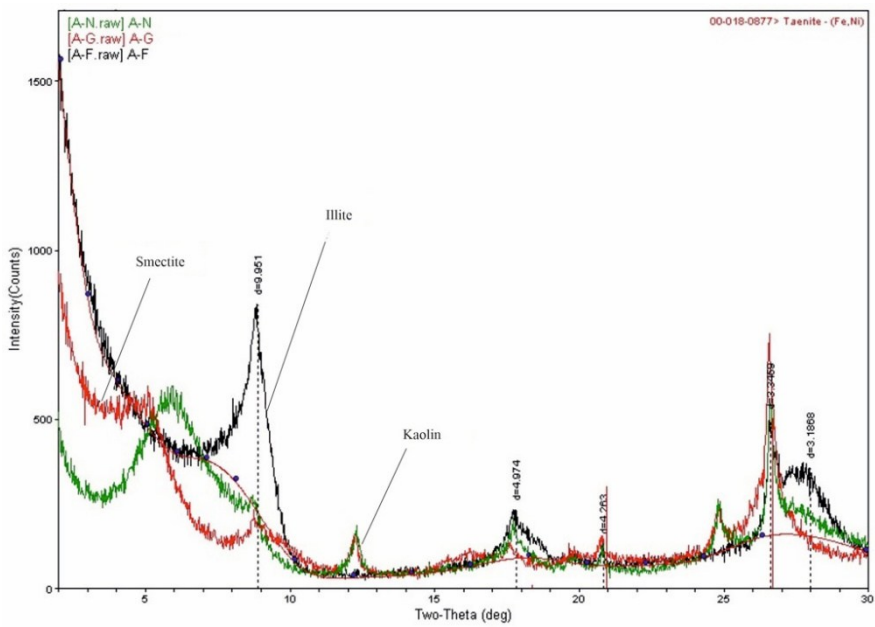


Fig. 3. Typical X-ray diffractograms of a soil sample showing clay minerals

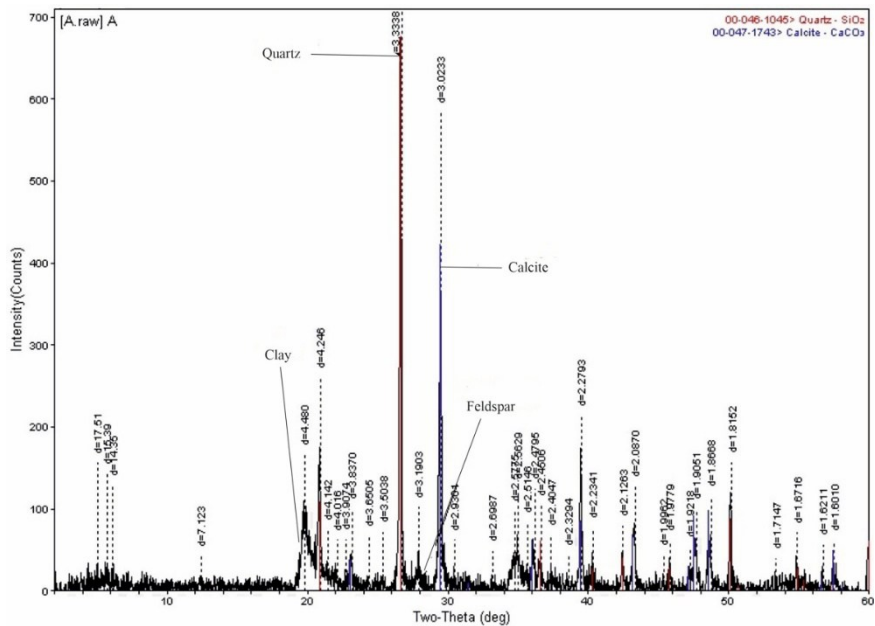


Fig. 4. Typical X-ray diffractogram of the soil sample showing the identified non-clay minerals and their relative quantitative distribution

3.2. COMPACTION CHARACTERISTICS

Standard proctor compaction tests (ASTM D698) were performed to assess the influence of stabilizers on the compaction behaviour of expansive Ankara Clay. Representative compaction curves are presented in Fig. 5, while the corresponding maximum dry density (MDD) and optimum moisture content (OMC) values are summarised in Table 3.

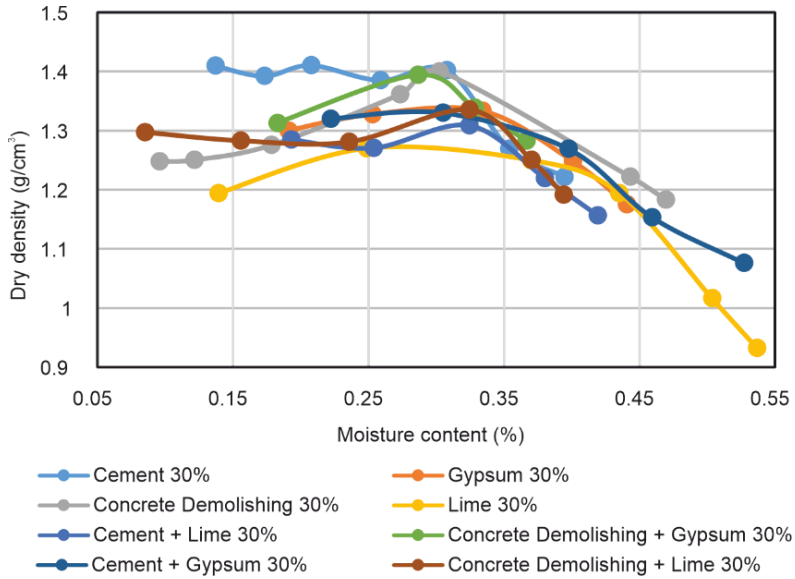


Fig. 5. Standard proctor compaction curves (ASTM D698) for expansive Ankara Clay stabilized with various additives at 30 wt % dosage

Table 3

Maximum dry density and optimum moisture content of the Ankara Clay stabilized with different additives

Stabilizer (30 wt %)	MDD [g/cm ³]	OMC [%]
Cement	1.42	21
Gypsum	1.36	24
Concrete demolition waste (CDW)	1.40	30
Lime	1.28	28
Cement + lime	1.33	31
Cement + gypsum	1.34	30
CDW + gypsum	1.40	26
CDW + lime	1.36	31

MDD – maximum dry density, OMC – optimum moisture content.

In two-component mixtures, the total additive dosage was fixed at 30 wt % of dry soil. Each component contributed equally (15 wt % + 15 wt %) unless otherwise noted. For example, the mixture of cement + lime contained 15 wt % of cement and 15 wt % of lime, while the mixture of demolition + gypsum contained 15 wt % concrete demolishing waste and 15 wt % gypsum.

The results reveal distinct differences among the stabilizer systems. Cement produced the highest MDD (1.42 g/cm^3) with the lowest OMC (21%), indicating improved packing efficiency. Gypsum produced a lower MDD (1.36 g/cm^3) and a higher OMC (24%), reflecting weaker densification. CDW showed intermediate behaviour (MDD = 1.40 g/cm^3 , OMC = 30%), while lime resulted in the lowest density (1.28 g/cm^3) and an elevated moisture demand (28%). The mixed systems generally showed moderate improvements, with CDW + gypsum achieving a balanced profile (MDD = 1.40 g/cm^3 , OMC = 26%).

In general, cement proved to be the most effective in improving compaction efficiency, while lime and gypsum increased the demand for moisture. The blends demonstrated synergistic effects, particularly CDW + gypsum, which combined relatively high density with moderate moisture requirements.

3.3. SWELLING BEHAVIOUR

The response to swelling of untreated and stabilized expansive Ankara Clay was evaluated through one-dimensional oedometer tests. Figure 6 presents the overall percentage for all stabilizer systems at 30% dose, while the time-dependent swelling behaviour is illustrated in Figs. 7 and 8.

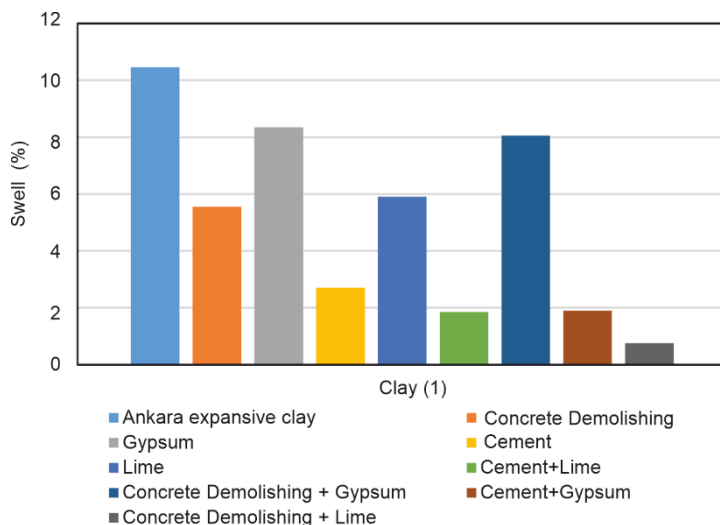


Fig. 6. Swell percentage of untreated and stabilized expansive Ankara Clay with various additives

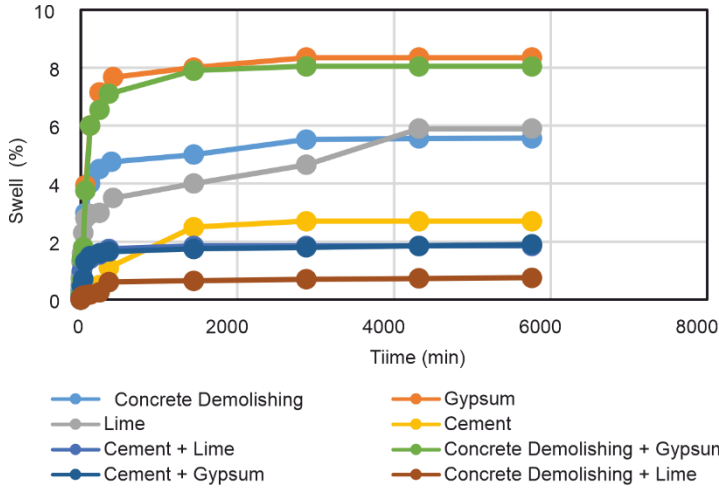


Fig. 7. Swell percentage versus time for expansive Ankara Clay samples stabilized with various additives at an initial dry density of 1.25 g/cm^3 and initial water content of 35%

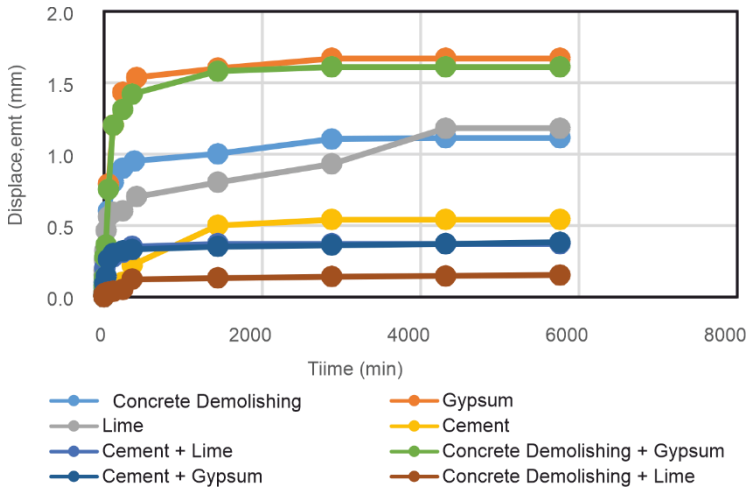


Fig. 8. Vertical displacement versus time for expansive Ankara Clay samples stabilized with various additives at an initial dry density of 1.25 g/cm^3 and initial water content of 35%

The results show that the untreated clay exhibited the highest swell percentage, confirming its high expansivity. Among the stabilizers, lime and cement produced the most pronounced reduction in swelling, lowering the values by more than half compared to the untreated specimen. CDW also contributed to swell reduction, although its effect was moderate relative to chemical stabilizers. Gypsum showed limited improvement, with swell percentages remaining relatively high.

The time-dependent curves (Fig. 7) reveal that untreated clay undergoes rapid initial swelling followed by gradual stabilization, while stabilized specimens display lower swelling rates and equilibrium values. The lime-treated samples reached equilibrium quickly, reflecting chemical binding and reduced water affinity. On the contrary, CDW treated samples exhibited a delayed but steady reduction in swelling, consistent with mechanical densification effects.

Vertical displacement trends (Fig. 8) further highlight differences in stabilizer performance. Untreated clay showed the largest upward displacement, while lime and cement treatments significantly suppressed vertical expansion. The mixed systems (e.g., CDW + gypsum, CDW + lime) demonstrated intermediate behaviour, suggesting partial synergy between chemical and mechanical stabilization mechanisms.

In general, stage 1 results confirm that chemical stabilizers (lime, cement) are more effective in controlling swelling, while CDW provides moderate improvement and gypsum alone is less effective. These findings guided the selection of lime and CDW for a detailed stage 2 evaluation.

3.4. RELATIONSHIP BETWEEN SWELL PERCENTAGE AND PLASTICITY INDEX

A clear positive correlation is observed between the plasticity index (PI) and the percentage for expansive Ankara Clay stabilized with different additives (Fig. 9).

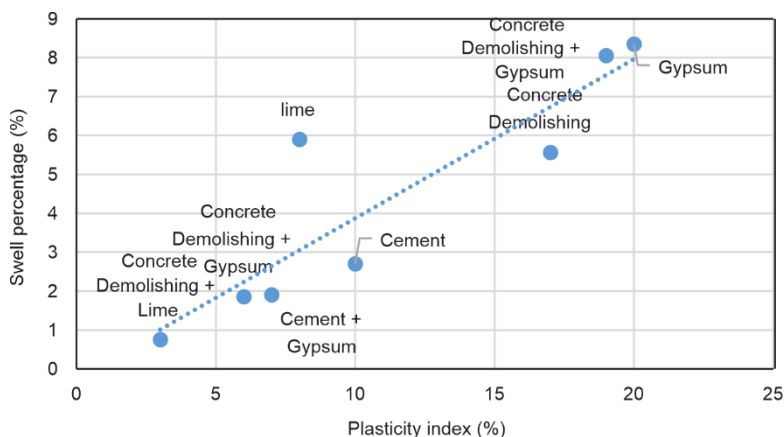


Fig. 9. Relationship between swell percentage and the plasticity index for expansive Ankara Clay stabilized with various additives

Treatments that produced lower PI values consistently resulted in reduced swelling, indicating improved soil workability and volumetric stability. Composite systems, particularly concrete demolition waste (CDW) + lime, CDW + gypsum, and cement + gypsum, achieved the lowest swell percentages of swelling (1.9%) and correspondingly low plasticity indices, demonstrating superior stabilization efficiency.

In contrast, gypsum alone and selected cement–gypsum mixtures retained relatively high PI values and exhibited the highest percentages of swelling, indicating limited effectiveness. The lime and CDW used individually showed moderate reductions in swelling, confirming that their performance is significantly enhanced when combined with complementary additives. Overall, Fig. 9 confirms that the reduction in the plasticity index is a reliable indicator of swelling suppression and stabilization efficiency.

Relationship between swell percentage and liquid limit. The relationship between liquid limit (LL) and swelling percentage also exhibits a strong positive correlation (Fig. 10), where higher LL values are associated with increased swelling potential. Lime-based systems, particularly Lime alone and CDW + lime, produced the lowest liquid limits (50–51%) and the most pronounced reduction in swelling, reflecting effective physicochemical stabilization.

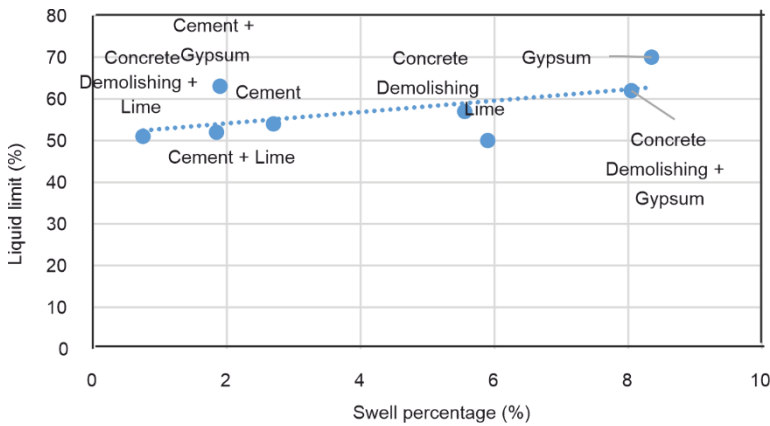


Fig. 10. Relationship between swell percentage and liquid limit for expansive Ankara Clay samples stabilized with various additives

Additives such as cement and CDW resulted in intermediate LL values and moderate swelling reduction, while gypsum-based systems retained higher liquid limits and exhibited poor swelling control. Gypsum alone showed the highest LL and the maximum percentage of swelling, confirming its limited ability to reduce soil expansiveness when applied independently. These results demonstrate that an effective reduction in the liquid limit plays a critical role in improving the volumetric stability of expansive clays.

Relationship between swelling percentage and shrinkage limit. An inverse relationship is observed between the shrinkage limit (SL) and the swell percentage (Fig. 11), indicating that additives that increase the shrinkage limit effectively suppress swelling. Composite stabilizers such as cement + gypsum and CDW + lime yielded the highest shrinkage limits and correspondingly minimal swelling, confirming their strong volumetric stabilization capacity.

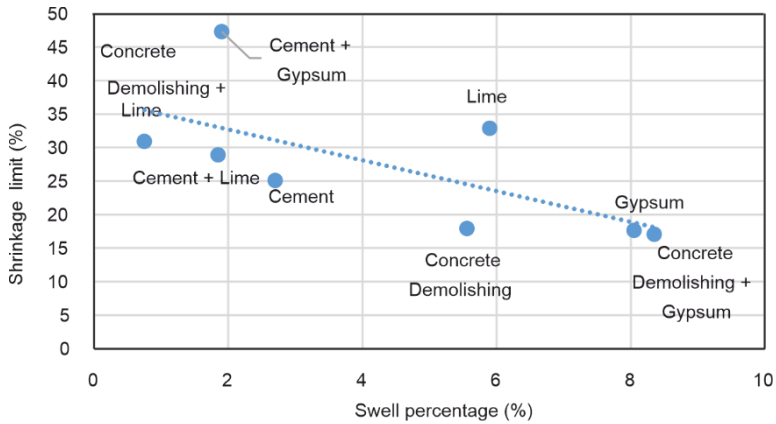


Fig. 11. Relationship between swell percentage and shrinkage limit for expansive Ankara Clay samples stabilized with various additives

Lime and cement + lime produced moderately high shrinkage limits and achieved partial reduction in swelling, while gypsum-based systems, particularly gypsum alone and CDW + gypsum, resulted in low shrinkage limits and a higher swelling potential. These findings highlight the importance of shrinkage limit enhancement to mitigate cyclic shrink–swell behaviour in expansive soils.

Comparative evaluation and classification of stabilizing additives. A comparative ranking of the eight stabilizing systems was developed based on key geotechnical indicators, including the swell percentage, the plasticity index, the liquid limit, and the shrinkage limit. Based on overall performance, additives were classified into strong, moderate, and weak stabilizers (Table 4).

Table 4

Summary of stabilizer performance

Rank	Additive	Swell [%]	Liquid limit [%]	Plasticity	Shrinkage limit [%]	Effectiveness
1	concrete demolishing + lime	0.75	51	low	30.91	strong
2	concrete demolishing + gypsum	1.85	62	low	17.09	strong
3	cement + gypsum	1.9	63	low	33.33	strong
4	cement + lime	2.91	52	moderate	28.91	moderate
5	cement	2.7	54	moderate	25.12	moderate
6	lime	5.9	50	moderate	32.9	moderate
7	concrete demolishing	5.56	57	moderate	17.93	moderate
8	gypsum	8.35	70	high	17.67	weak

Composite systems incorporating CDW with lime or gypsum, as well as cement + gypsum were ranked as strong stabilizers, achieving the greatest improvements in volumetric stability. Cement, lime, CDW, and cement + lime exhibited moderate effectiveness, while gypsum alone was identified as a weak stabilizer due to limited reductions in plasticity and swelling.

4. RESULTS AND DISCUSSION OF STAGE 2

4.1. SELECTION OF LIME AND CONCRETE DEMOLITION WASTE (CDW) FOR DETAILED EVALUATION

Based on the comparative screening results, lime and concrete demolition waste (CDW) were selected for a detailed evaluation in stage 2 due to their distinct stabilization mechanisms and representative performance in a uniform dosage.

Lime was adopted as a reference chemical stabilizer because of its consistent improvement in swelling control and the reduction in plasticity observed during stage 1 testing. Its well-established reactivity with expansive clays makes it suitable for comparative assessment of chemical stabilization efficiency.

CDW, on the other hand, was chosen as a representative waste-derived stabilizer, demonstrating promising mechanical improvement through particle replacement and densification. Its inclusion enables the evaluation of sustainable and resource-efficient alternatives to conventional binders.

To examine both moderate and intensive stabilization effects, lime and CDW were incorporated at 10 and 20% by dry weight of the soil. This staged approach facilitates direct comparison between chemically dominated and mechanically driven stabilization mechanisms, providing insight into their relative effectiveness and practical applicability.

Testing at two additive contents allowed for the assessment of dose-dependent behaviour and facilitated direct comparison between lime-induced chemical stabilization and CDW-driven mechanical enhancement.

4.2. INDEX PROPERTIES AND COMPACTION CHARACTERISTICS

Table 5 summarises the Atterberg limits, shrinkage limit, and the compaction characteristics of expansive Ankara Clay treated with lime and CDW at 10% and 20% contents. Both stabilizers induce a systematic reduction in the liquid limit and the plasticity index with increasing dosage, indicating a progressive decrease in soil plasticity and clay activity. The lime treatment resulted in a moderate reduction in plasticity accompanied by a slight increase in optimum moisture content, reflecting the increased water demand associated with physicochemical reactions and the formation of a flocculated soil structure. On the contrary, CDW produced a more pronounced reduction in the plasticity index together with a significant increase in the maximum dry density. This behaviour is attributed

to granular replacement, improved particle packing, and the angularity of CDW particles, which improve densification efficiency. The observed reduction in shrinkage limit for both stabilizers further confirms improved volumetric stability, particularly at higher treatment levels.

In summary, CDW improves compaction and density through mechanical stabilization, whereas lime provides balanced improvements through physicochemical modification.

Table 5

Index properties of expansive Ankara Clay stabilized with lime and CDW

Parameter	Lime		CDW	
Stabilizer content, %	10	20	10	20
Liquid limit, %	74	72	69.9	70
Plastic limit, %	38	43	47.2	41.2
Plasticity index, %	38	29	22.6	28.6
Shrinkage limit, %	12.8	11.5	11.9	10.9
Maximum dry density, g/cm ³	1.28	1.27	1.33	1.38
Optimum moisture content, %	27	27	28	31

4.3. SHEAR STRENGTH BEHAVIOUR AND MOHR–COULOMB PARAMETERS

The peak shear stress–normal stress relationships obtained from direct shear tests are presented in Fig. 12. Untreated expansive Ankara Clay exhibits a shallow failure envelope, reflecting its low shear resistance. The incorporation of lime and CDW results in an upward shift of the failure envelope and an increase in slope, indicating improved shear strength.

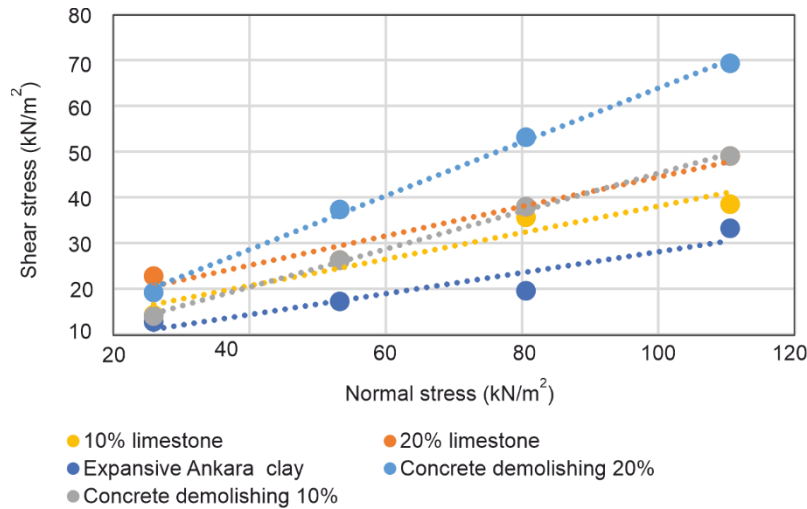


Fig. 12. Peak shear stress–normal stress relationships of expansive Ankara Clay stabilized with limestone powder and concrete demolition waste

The corresponding Mohr–Coulomb shear strength parameters are summarised in Table 6. Lime stabilization led to a substantial increase in cohesion, rising from 5.22 kN/m² in the untreated state to 9.09 kN/m² and 12.2 kN/m² at 10% and 20% contents, respectively. This improvement is attributed to cation exchange, particle flocculation, and pozzolanic bonding, which enhance interparticle bonding and soil structure. A moderate increase in the friction angle was also observed, indicating a combined chemical and frictional contribution to shear resistance.

Table 6

Mohr–Coulomb shear strength parameters
of untreated and stabilized expansive Ankara Clay at peak

Material	Cohesion, c [kN/m ²]	Friction angle, ϕ [deg]
Untreated clay	5.22	12.9
Lim, 10%	9.09	16.16
Lime, 20%	12.2	17.88
CDW, 10%	3.79	22.52
CDW, 20%	4.92	30.53

CDW treated soils exhibit relatively low cohesion values but a marked increase in friction angle, reaching 22.52° and 30.53° at 10 and 20% contents, respectively. Slabs that fail indicate that shear strength improvement is primarily governed primarily by frictional resistance arising from particle replacement, surface roughness, densification, and enhanced interlocking.

In summary, lime provides balanced shear strength enhancement through chemical stabilization, whereas CDW predominantly improves friction-controlled resistance through mechanical modification.

4.4. SWELLING BEHAVIOUR OF STABILIZED EXPANSIVE ANKARA CLAY

The swelling behaviour of untreated and stabilized expansive Ankara Clay is illustrated in Fig. 13. The untreated soil exhibits a high swell potential of 10.46%, confirming its strongly expansive behaviour.

At 10% additive content, both lime and CDW significantly reduced swelling, with CDW showing slightly higher efficiency. At 20% content, the swell percentages decreased to 6.4% for lime and 5.9% for CDW. Under maximum stabilization conditions, the swell values reached 4.75% for lime and 4.85% for CDW.

In summary, both stabilizers effectively suppress swelling relative to the untreated soil. Lime exhibits marginally superior performance at higher dosages due to chemically driven stabilization, while CDW achieves comparable efficiency through mechanical restraint and improved soil fabric.

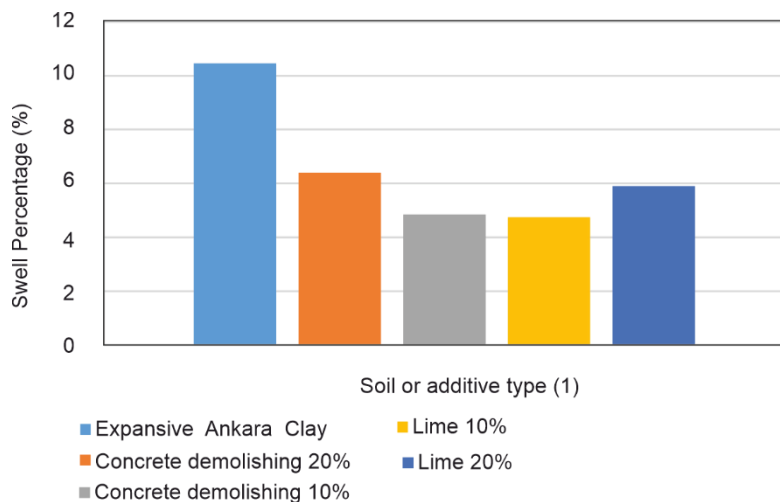


Fig. 13. Swell percentage of expansive Ankara Clay stabilized with concrete demolition waste and lime powder at 10 and 20 wt % contents

5. CONCLUSIONS

A structured two-stage laboratory framework was used to evaluate conventional chemical stabilizers and waste-derived materials for expansive Ankara Clay. Severe volumetric instability, characterised by high swelling potential, plasticity, and shrinkage, can be substantially mitigated by appropriate stabilization strategies.

Stage 1 screening with 30% additive content identified lime and concrete demolition waste (CDW) as the most promising stabilizers due to their different mechanisms and sustainability benefits. Lime acts through physicochemical processes, including cation exchange, clay particle flocculation, and pozzolanic bonding, whereas CDW improves compaction, interparticle interlocking, and mechanical restraint.

Stage 2 testing at 10 and 20% dosages revealed clear dosage-dependent behaviour. At 10%, CDW slightly outperformed lime in reducing swelling, likely due to its mechanical effects, whereas at 20%, lime achieved marginally greater swell suppression owing to more pronounced chemical stabilization. Both stabilizers improved the index properties, swelling behaviour, and shear strength of Ankara Clay, although through different governing mechanisms: lime primarily increased cohesion, with a moderate increase in the internal friction angle, while CDW produced a substantial increase in the friction angle but only a limited increase in cohesion, indicating that its effect on shear strength was governed predominantly by mechanical processes.

Hybrid stabilization combining waste-derived materials with conventional binders provides an effective and sustainable solution for expansive soil treatment, suitable for

geotechnical applications such as pavement subgrades, embankments, and shallow foundations.

The study demonstrates that carefully designed stabilization strategies can deliver complementary chemical and mechanical benefits, thereby optimising both the performance and sustainability of expansive Ankara Clay treatment.

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