

Experimental Measurement of the Stress and Strains of the Clay with consideration of NaCl content and Temperature

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Research Article

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Abstract

This study experimentally investigates the stress–strain behavior and desiccation cracking of clay under varying sodium chloride (NaCl) concentrations and temperature conditions, addressing a critical gap in understanding marine clay performance in saline environments. Laboratory tests assessed the effects of water content, salinity, and temperature on crack geometry (length, width, depth), while unconfined compression tests quantified mechanical responses. The results reveal that higher NaCl levels and elevated temperatures significantly alter clay strength and promote distinctive crack patterns, highlighting the coupled influence of salinity and thermal conditions on deformation and failure. These findings provide a robust framework for predicting the mechanical behavior and cracking potential of marine clay, with direct implications for coastal infrastructure design and geotechnical management in salt-affected soils.

Keywords: Cracks, Stress, Strains, Sodium Chloride ‘NaCl’, temperature.

1. Introduction

In recent decades, studies on crack formation in clay samples under various conditions have been conducted worldwide using a wide range of methods. Laboratory experiments, numerical simulations, and field measurements have provided detailed and accurate insights into soil deformation and crack development. These findings have been applied to predict soil behavior under the load of various engineering structures, including roads, buildings, bridges, coastal and river embankments, basements, and slopes. However, the assessment and quantification of cracks in clay samples under varying temperature and salt content have not yet been specifically addressed.

However, the previous studies show that the relative humidity (RH) increases, the cracking water content of the tested soil also increases. When RH rises from 15.0% to 93.7%, the corresponding cracking water content increases markedly from approximately 41% to 80%. This result demonstrates a clear positive relationship between ambient humidity and the moisture level required for crack initiation, indicating that higher RH conditions enable the soil to retain more water before cracking occurs (H. Zeng et al., 20221). However, there is no measurement for the stress and strain with temperatures.

Additionally, this study quantifies the volumetric changes and crack development of recompacted clay exposed to saline solutions during wetting–drying cycles using X-ray computed tomography (XCT). Specimens treated with 4 M NaCl exhibit significantly greater crack volume than those exposed to distilled water (DW) and 0.4 M NaCl. Cracks do not reappear at the same locations in DW-treated samples, indicating self-healing behavior, whereas repeated cracking at identical locations in 4 M NaCl-treated samples confirms the loss of self-healing capacity. As a result, specimens exposed to 4 M NaCl show markedly higher hydraulic conductivity after repeated cycles (M. Julina and T. Thyagaraj, 2020). However, there is no measurement for the Cracks.

On the other hand, Clay collected from the Berrechid Plain in central Morocco was subjected to saturated NaCl solutions at a relative humidity of 75.8%. After 24 hours, the samples exhibited an approximate 40% increase in swelling, accompanied by a 38% reduction in crack aperture (M. Zaidi et al., 2021). However, there is no measurement for the Cracks. Moreover, the behavior of kaolin and bentonite in saline environments was examined in terms of consistency limits, particle sedimentation, and cracking patterns. Kaolin's consistency limits are unaffected by salinity, whereas bentonite's liquid limit decreases significantly with increasing salt concentration. Kaolin flocculates in both distilled water and NaCl solutions, while bentonite disperses in distilled water but aggregates in saline water. With increasing salinity, bentonite shows reduced total crack

area and increased crack length, whereas kaolin remains largely unchanged. These differences are attributed to variations in interparticle interaction forces and initial platelet aggregation (T. Zhang et al., 2019). However, there is no measurement for the stress and strain with temperatures.

Therefore, subsurface cracks in initially dry soil were examined using video microscopy and time-lapse imaging during irrigation events. Soil volume, moisture, drainage, electrical conductivity, and bromide transport were measured. Results demonstrate that cracks persist as preferential flow pathways despite surface sealing, with irrigation type controlling crack behavior: ponded water promotes reformation at previous locations, while simulated rainfall shifts crack positions (A. Greve et al., 2010). However, there is no measurement for the Cracks. In addition, during drying, crack development alters the soil's physical response by modifying its strength, stiffness, and overall permeability. To elucidate crack initiation and propagation mechanisms, a series of controlled laboratory experiments were conducted on drying clayey silt samples under varying initial and boundary conditions. The results indicate that cracks can initiate at any existing defect and propagate laterally below the soil surface. At the surface, cracks tend to intersect perpendicularly, suggesting that tensile stresses predominantly govern their formation (R.N. Tollenaara et al., 2017). However, there is no measurement for the stress and strain with temperatures.

On the contrary, drying experiments on silt samples with varying interface roughness and layer thickness were conducted at 30 °C to study desiccation crack behavior. Water content changes and crack development were monitored using digital imaging and quantified via image analysis. Cracks initiated at high water contents (10–40%), with maximum propagation rate decreasing linearly with layer thickness, while crack intensity increased with higher surface roughness or thinner layers (Hao Zeng et al., 2019). However, there is no measurement for the Cracks with temperature. On the other hand, this study presents a discrete element method (DEM) approach to model desiccation cracking in thin clay layers, accounting for variations in material properties. In the DEM framework, bond strength and contact stiffness evolve during drying, with their changes calibrated against experimental data. The DEM simulations successfully capture crack initiation and propagation mechanisms, surface cracking in thin clay layers, and three-dimensional desiccation cracking in liners or other clay materials whose properties vary with water content or temperature, demonstrating the method's capability to reproduce realistic drying-induced fracture behavior (Jun Sima et al., 2014). However, there is no measurement for the stress and strain.

Moreover, the shrinkage cracking is a common form of distress in cement-stabilized layers (CSL) of pavements. Shrinkage can induce surface cracking due to bonding between the surface layer and the CSL, and includes natural shrinkage from hydration, drying shrinkage from moisture loss, and thermal shrinkage at low temperatures. This study employs dimensional analysis to develop a shrinkage cracking model that predicts crack spacing and width in CSL for both fine- and coarse-grained soils. Laboratory experiments indicate that the developed model effectively predicts the spacing and width of shrinkage-induced cracks (Jingan Wang et al., 2020). However, there is no measurement for the Cracks with sodium chloride and temperatures. This study presents a temperature-dependent model for the tensile strength characteristic curve (TSCC) of unsaturated soils. The model employs the suction stress characteristic curve (SSCC) to represent the uniaxial tensile strength of unsaturated soils at varying water contents and temperatures. Temperature effects are incorporated into both the adsorptive and capillary components of suction stress. The proposed TSCC model shows excellent agreement with laboratory-measured tensile strength data for two clay soils tested over a temperature range of 20–60 °C (Kwestan Salimi et al., 2021). However, there is no measurement for the Cracks.

From the above analyzing, in this study based on the above analyses, the crack behavior of clay under a wide temperature range (from 20°C, 40°C, 60°C, 105°C, 120°C, 150°C, 180°C, to 200°C) was investigated through controlled laboratory experiments. The results provided detailed and accurate observations regarding the initiation and evolution of cracks in terms of length, width, and depth along the clay samples. As the temperature gradually increased, soil particles began to move in a disordered manner, the pores within the soil structure expanded, and water molecules migrated upwards. At this stage, the vapor pressure exerted by the water disrupted the bonds between soil particles, leading to the formation of a heterogeneous mass within the sample. With further temperature increase, water molecules moved more vigorously, and the pores expanded further. This promoted faster evaporation from the soil particle surfaces and upward migration of water, causing the soil structure to rearrange. Consequently, particle bonding progressively weakened, and complete loss of cohesion occurred, resulting in the appearance of cracks at high temperatures, notably starting around 1050 °C. As the temperature continued to rise, the cracks became increasingly pronounced, with greater length, width, and depth. These observations demonstrate that temperature is a critical factor controlling the development and expansion of cracks in clay samples. The measurement of defects (cracks) in clay samples mixed with sodium

chloride (NaCl) was conducted in the laboratory under controlled temperature variations. In this study, the NaCl content varied with temperatures ranging from 20°C to 200°C. The results clearly demonstrated the presence and evolution of cracks along the clay samples, including detailed measurements of crack length, width, and depth under different thermal conditions. Furthermore, Unconfined Compressive Test (UCT) revealed the relationships between stress–strain curves, displacement, and load-bearing capacity of the clay samples with varying NaCl contents at each temperature level. The maximum loads were compared to the minimum loads, corresponding to the highest and lowest resistance values of the clay–NaCl mixtures.

In conclusion, the findings provide valuable and practical insights for the fields of geotechnical engineering, civil construction, and soil mechanics. Researchers, engineers, academics, and students can utilize these results to reduce labor, time, and costs in site investigation, design, and construction of foundations, particularly in regions where the subsoil is exposed to high salinity and elevated temperatures, such as coastal reclamation areas or urban sites near the sea. The study offers a scientific basis for predicting and mitigating crack formation in clay foundations of future high- and low-rise structures.

2. Materials and Methods

2.1. Soils

The collected soil samples were first air-dried under laboratory conditions and subsequently sieved to remove coarse particles and visible impurities. Following the initial preparation, the samples were oven-dried at **105 °C for 24 h** to ensure the complete removal of moisture and pore water within the soil structure. This drying procedure was conducted to obtain fully dried soil and to establish consistent initial conditions for all experimental specimens. After oven drying, the soil was further processed through a fine sieve to obtain a more homogeneous material. During this stage, impurities such as organic debris, coarse sand, gravel particles, and other foreign materials were carefully removed. This preparation procedure improved the cleanliness of the clay soil and ensured a more uniform grain-size distribution, which is essential for minimizing experimental variability. To investigate the influence of salinity on soil behavior, sodium chloride (NaCl) was introduced into the soil samples at different dosages. The NaCl contents were designed at 5 g, 7 g, 11 g, 13 g, 18 g, 21 g, 25 g, 27 g, 31 g, 33 g, 37 g, 39 g, 43 g, 45 g, 49 g, and 51 g, respectively. These varying salt contents allowed the systematic evaluation of salt-induced changes in soil properties.

2.2 ImageJ software

For the microstructural characterization of soil particles, ImageJ software was employed to perform digital image processing and quantitative analysis. The software was used to extract statistical information on soil particle morphology, including particle size distribution and geometric parameters such as particle area, length, and equivalent diameter. This approach enabled a detailed assessment of the microstructural features of the soil under different experimental conditions.

2.3. Methodology

Methodology of the crack's measurement and Unconfined Compression Test (UCT) is shown in figure 1.

*For example: at 20⁰C of the sample C1, C2, C3, C4, and C5.

he sample identification code **C1 (C100251273)** was used to describe the experimental conditions associated with the specimen. In this notation, **C1** represents the sample placed in **Cup 1** during the experimental preparation. The numerical sequence “**0025**” denotes the molar concentration of the Sodium Chloride (NaCl) solution, corresponding to **x₁ = 0.0025 mol**. Meanwhile, the sequence “**1273**” indicates the percentage concentration of Sodium Chloride in the solution, equivalent to **P_{NaCl} = 12.73%**. This coding system was adopted to systematically record both the sample position and the NaCl concentration parameters used in the experiment.

The sample coding system was designed to represent both the molar concentration and the percentage concentration of the Sodium Chloride (NaCl) solution used in the experiment. The sample **C1 (C100251273)** corresponds to a NaCl molar concentration of **M_{1NaCl} = 0.0025 mol** and a percentage concentration of **P_{NaCl} = 12.73%**. Similarly, sample **C2 (C200231186)** represents **M_{1NaCl} = 0.0023 mol** with **P_{NaCl} = 11.86%**, while **C3 (C300211111)** corresponds to **M_{1NaCl} = 0.0021 mol** and **P_{NaCl} = 11.11%**. In addition, **C4 (C400201045)** indicates **M_{1NaCl} = 0.0020 mol** with **P_{NaCl} = 10.45%**, whereas **C5 (C50019986)** corresponds to **M_{1NaCl} = 0.0019 mol** and **P_{NaCl} = 9.86%**. These coded identifiers were used to systematically distinguish the NaCl concentration conditions applied to each soil sample during the experimental program.

a) Water contents

$$W_1 \% = \left[\left(\frac{M_{1wet} - M_{1dry}}{M_{1dry} - M_{1cup}} \right) \right] \times 100\% \quad (1)$$

Whereas, **M_{1wet}** = Initial mass of the sample, gram (g).

216 $M_{I\text{dry}}$ = Dry mass of the sample after 24 hours at 105⁰C temperature, gram(g)

217 $M_{I\text{cup}}$ = Cup mass of cups, gram(g)

218 b) The maximum Crack's depths

219 + Total of solute Mol mass of Sodium Chloride" NaCl":

220
$$M_{I\text{NaCl}} = M_{I\text{Na}} + M_{I\text{Cl}} \quad (2)$$

221 + The number of Mol solute Sodium Chloride "NaCl":

222
$$M_{I\text{NM}} = M_{I\text{salt}} / M_{I\text{NaCl}} \quad (3)$$

223 + The number of solutes in water or Concentration "Mol" of Sodium Chloride solution in water:

224
$$x_1 = M_{I\text{NM}} / M_{I\text{water}} \quad (4)$$

225 + The maximum Crack's depths:

226
$$D_{I\text{maxcr}} = f_1(x_1) = e^{x_1} \quad (5)$$

227 Whereas, $M_{I\text{Na}}$ is the molar mass of sodium solute "Na"; expressed in gram per mole (g/mol).

228 $M_{I\text{Cl}}$ is the molar mass of chloride solute "Cl"; expressed in gram per mole (g/mol).

229 $M_{I\text{NaCl}}$ is the total solute molar mass of sodium chloride" NaCl"; expressed in gram per mole
230 (g/mol).

231 $M_{I\text{NM}}$ is the number of molar of solute sodium chloride "NaCl; expressed in mole 'mol'.

232 $M_{I\text{salt}}$ is the mass of sodium chloride used actually; expressed in gram (g).

233 x_1 is the mole concentration of the solution "NaCl"; expressed in mole 'mol'.

234 $D_{I\text{maxcr}}$ is the maximum Crack's depth; expressed in millimeter (mm).

235 e_1 represents the base of the natural logarithm (natural exponential constant). This constant is
236 dimensionless, and its value may be approximated by rounding to the nearest integer when
237 required.

238 $f_1(x_1)$ represents the antiderivative (primitive function) of the considered function, and its value
239 is expressed in millimeters (mm).

240

241 c) The maximum Crack's lengths

242 The maximum cracks' length was calculated for the total solute Mol mass of Sodium Chloride"
243 NaCl".

244 + The number of molar solute sodium chloride "NaCl" was shown below:

$$245 \quad \Psi_1 = M_{1\text{salt}} / M_{1\text{NaCl}} \quad (6)$$

246 + Molar concentration of Sodium Chloride (NaCl) solution in water (mol):

$$247 \quad \Delta_1 = \Psi_1 * x_1 \quad (7)$$

248 + The maximum Crack's length:

$$249 \quad L_{1\text{maxcr}} = C_1 + e^{\Delta_1} = f_1(\Delta_1) = e^{\Delta_1} \quad (8)$$

250

251 Whereas, Ψ_1 is the number of molar of solute sodium chloride "NaCl"; expressed in mole (mol).

252 $M_{1\text{salt}}$ is the sodium chloride mass was done actually; expressed in gram (g).

253 Δ_1 is the molar concentration of Sodium Chloride (NaCl) solution in water (mol).

254 C_1 is the experiment value, "constant"; $C_1 = 155$; millimeter (mm).

255 $f_1(\Delta_1)$ denotes the primitive (antiderivative) of the function and is dimensionless.

256 e_1 denotes the base of the natural logarithm (natural exponential constant). It is a dimensionless

257 constant, whose value may be approximated by rounding to the nearest integer when required.

258 $L_{1\text{maxcr}}$ is the maximum crack's length; expressed in millimeter (mm).

259

260

261

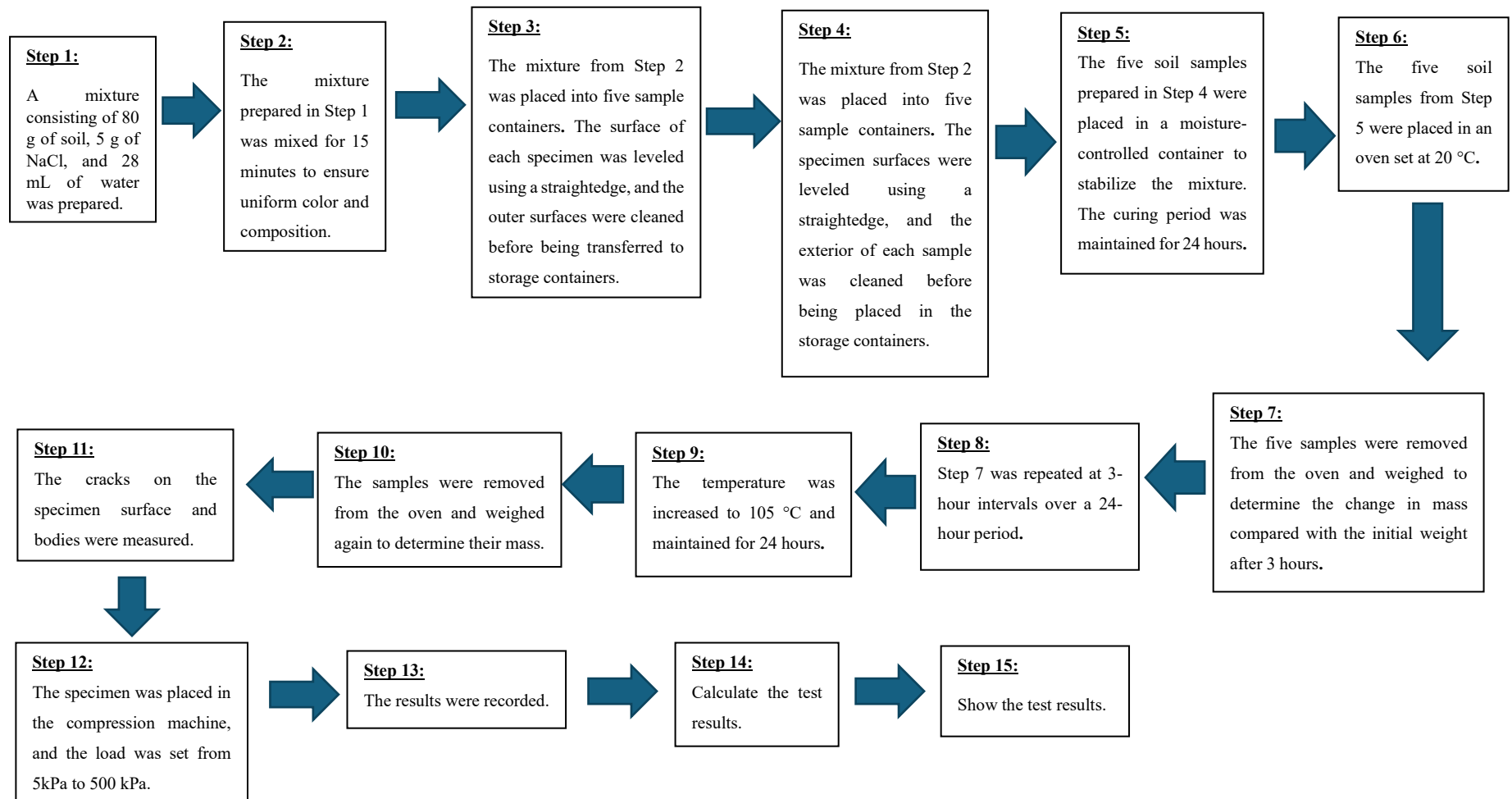


Figure 1. The Crack measurement procedure (from step 1 to step 15; exclude step 12), and Unconfined Compression Test (UCT) (from step 12 to step 15) Prepare clay samples with different salt contents, then gradually increase the temperature under controlled conditions. Observe and record crack formation, while measuring displacement and strength. Finally, compare results across temperature and salinity levels to determine their effects.

3. Results

3.1 Results of the cracks on the bodies with temperatures

3.1.1 Crack formation mechanism

From a micro-mechanical perspective, the increase in stiffness and reduction in crack formation at high NaCl content can be explained by physicochemical interactions within the clay matrix. As temperature rises, water evaporation intensifies, leading to pore expansion and the breakdown of interparticle bonds, which promotes crack initiation and propagation. However, the presence of NaCl alters the soil structure through ionic interactions and crystallization effects. At elevated temperatures, dissolved NaCl can recrystallize within the pore spaces, forming salt bridges between clay particles. These salt precipitates fill voids and reduce pore connectivity, thereby enhancing interparticle bonding and increasing internal friction. This process contributes to a denser and more compact microstructure, which restricts crack propagation despite thermal stresses. Furthermore, the increase in ionic concentration compresses the diffuse double layer surrounding clay particles, reducing repulsive forces and promoting particle aggregation. As a result, the clay matrix becomes more rigid and exhibits higher resistance to deformation and fracture. Therefore, while increasing temperature alone tends to accelerate crack formation due to moisture loss and structural rearrangement, the simultaneous increase in NaCl content counteracts this effect by reinforcing the soil skeleton. This dual mechanism explains the observed reduction in crack occurrence and the enhancement of load-bearing capacity at high temperature and salinity conditions.

3.1.2 Cracks on the sample's bodies



Sample **C5 at 180°C**: S42.86; Water content 55.65%; %NaCl: 42.86%;



Sample **C2 at 120°C**: S38.82; Water content 51.04%; %NaCl: 38.82%;



Sample **C2 at 90°C**: S24.71; Water content 78.81%; %NaCl: 41.28%;

Crack length: 60mm; Crack depth: 11mm; Crack width: 6mm.



Sample **C2 at 180°C**: S46.39; Water content 43.20%; %NaCl: 46.39%; Crack length: 156.3mm; Crack depth: 5mm; Crack width: 3mm.

Crack length: 156.3mm; Crack depth: 6mm; Crack width: 1mm.



Sample **C1 at 105°C**: S36.00 Water content 46.67%; %NaCl: 36.00%; Crack length: 156.3mm; Crack depth: 5mm; Crack width: 1mm.

Crack length: 40mm; Crack depth: 20mm; Crack width: 1mm.



Sample **C1 at 150°C**: S39.39; Water content 49.23%; %NaCl: 39.39%; Crack length: 78.15mm; Crack depth: 11mm; Crack width: 1mm.

Figure 2. Cracks shapes with water content, %NaCl. The shape of cracks depends on the water content, %NaCl. As the water content increases, the soil becomes wetter, and the NaCl salt content reacts more strongly. Cracks also become more pronounced as the temperature rises.

However, a 3D hydro–mechanical model was used to simulate desiccation cracking in clay, with image analysis applied for quantitative crack characterization. The simulations showed good agreement with laboratory results. The influences of shrinkage parameters, evaporation rate, and layer thickness on cracking behavior were systematically evaluated (Chengzeng Yan et al., 2021). This study experimentally investigated soil cracking under natural atmospheric conditions using a large-scale specimen ($3 \times 3 \times 0.5$ m) monitored over one year. Internal soil variables and surface climatic factors were continuously recorded. The findings show that solar radiation and wind speed primarily control evaporation and, consequently, soil cracking development (Josbel A. Cordero et al., 2021).

3.2 Results of the cracks' lengths, depths, and widths with temperature and Sodium Chloride (NaCl)

At 20°C, the results demonstrate a strong correlation between sample composition and crack characteristics. High water content, as observed in sample C5 (86.09%), generally increases material plasticity, enabling better stress accommodation and resulting in relatively shorter cracks (37 mm). In contrast, elevated NaCl content, such as in sample C1 (12.73%), tends to increase material brittleness, which promotes crack initiation but limits crack propagation, leading to

moderate crack lengths (38 mm) with narrower widths. Sample C2, with intermediate water (78.56%) and NaCl (10.45%) contents, exhibited the longest crack (45 mm) with significant depth and width (10 mm and 1 mm), suggesting that the combined effects of moisture and NaCl content allow for extended crack propagation under stress. Similarly, sample C4, with high water content (83.21%) but moderate NaCl (8.52%), showed substantial crack depth and width, indicating that water-induced ductility interacts with salt-induced stress concentration to influence crack morphology. However, This study examined the effects of maize roots and sodium chloride (NaCl) on crack dynamics and morphology in light shrink–swell clay. Drying tests were performed on soils with root densities of 0–1.5 cm/cm³ and NaCl contents of 0–2.0%. Increasing salinity enlarged total crack area and mean crack width, while reducing total crack length, indicating the formation of fewer but wider dominant cracks (C. Wang et al., 2021).

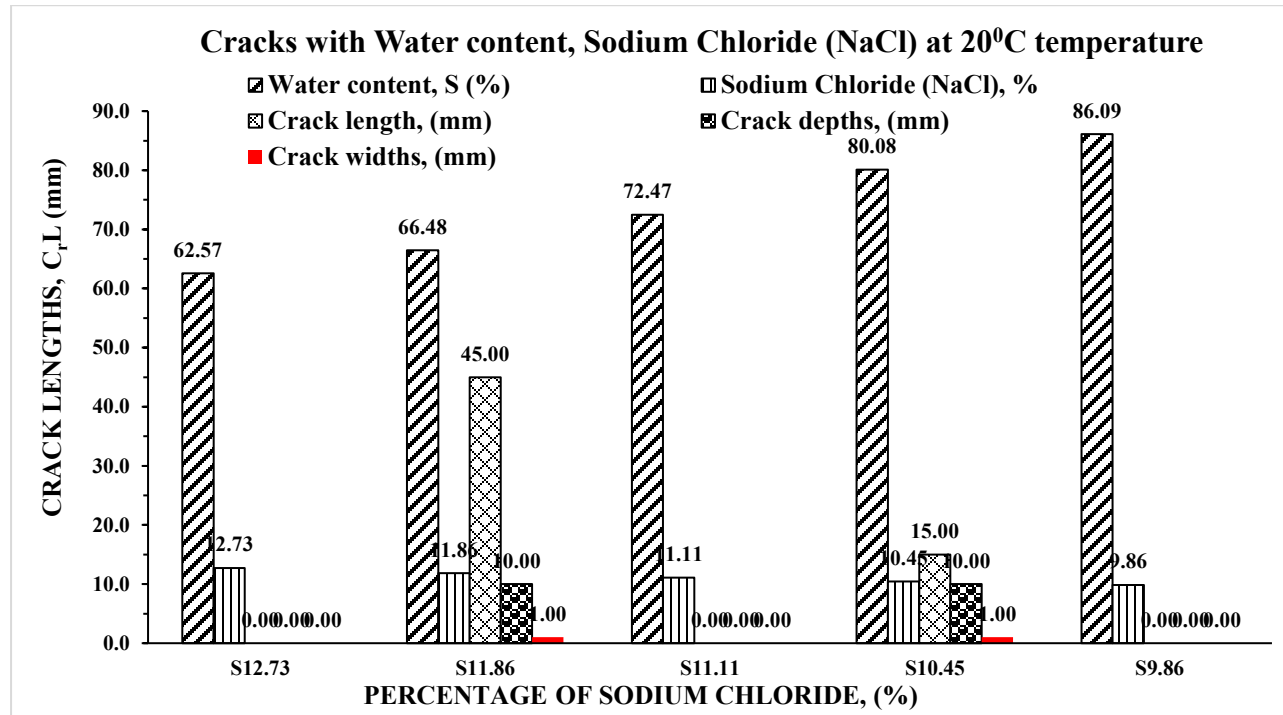


Figure 3. Change of the Cracks with Water content, Sodium Chloride (NaCl) at 20°C temperature. The crack is more pronounced at S11.86, where the NaCl salt content corresponds to a water content of 66.48% and a crack length of 45.00 mm. At S10.45, the NaCl content is 10.45%, corresponding to a water content of 80.08%. Conversely, the remaining samples show very small cracks or no cracks at all.

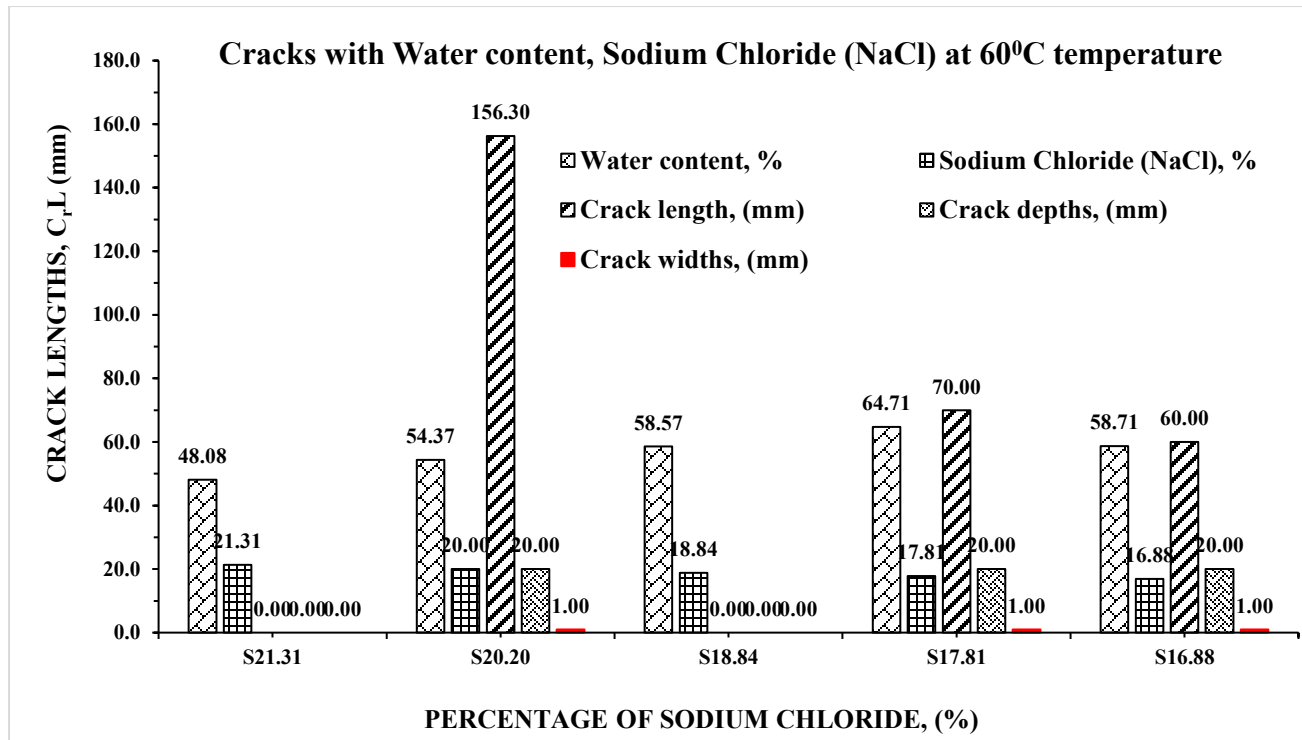


Figure 4. Change of the Cracks with Water content, Sodium Chloride (NaCl) at 60°C temperature. The samples showed more cracks as humidity continued to increase, with salt content increasing correspondingly with increasing temperature. Conversely, samples S21..31 and S18.84 did not show cracks. The sudden increase in water content at 60°C was 156.30%.

At 60°C, the result illustrates the variations in water content, sodium chloride (NaCl) content, and crack characteristics of the tested samples. Sample C4 exhibited the highest water content (64.71%), whereas sample C1 showed the maximum NaCl content (21.31%). The longest crack was observed in sample C2 (156.3 mm). Maximum crack depth and width, both equal to 20 mm and 1 mm, were recorded in samples C2, C4, and C5. Variations in crack length, depth, and width among the remaining samples corresponded to differences in water and NaCl content. Overall, these findings confirm that water content primarily governs material ductility and crack expansion, whereas NaCl content predominantly affects brittleness and crack initiation. Understanding this interplay is critical for controlling crack development in materials with varying moisture and salt compositions. However, The Electrical Resistivity Method (ERM) effectively evaluates soil properties linked to resistivity distribution. This study clarifies the mechanisms of desiccation cracking and highlights ERM's potential for crack monitoring and early detection (Ni An et al., 2019).

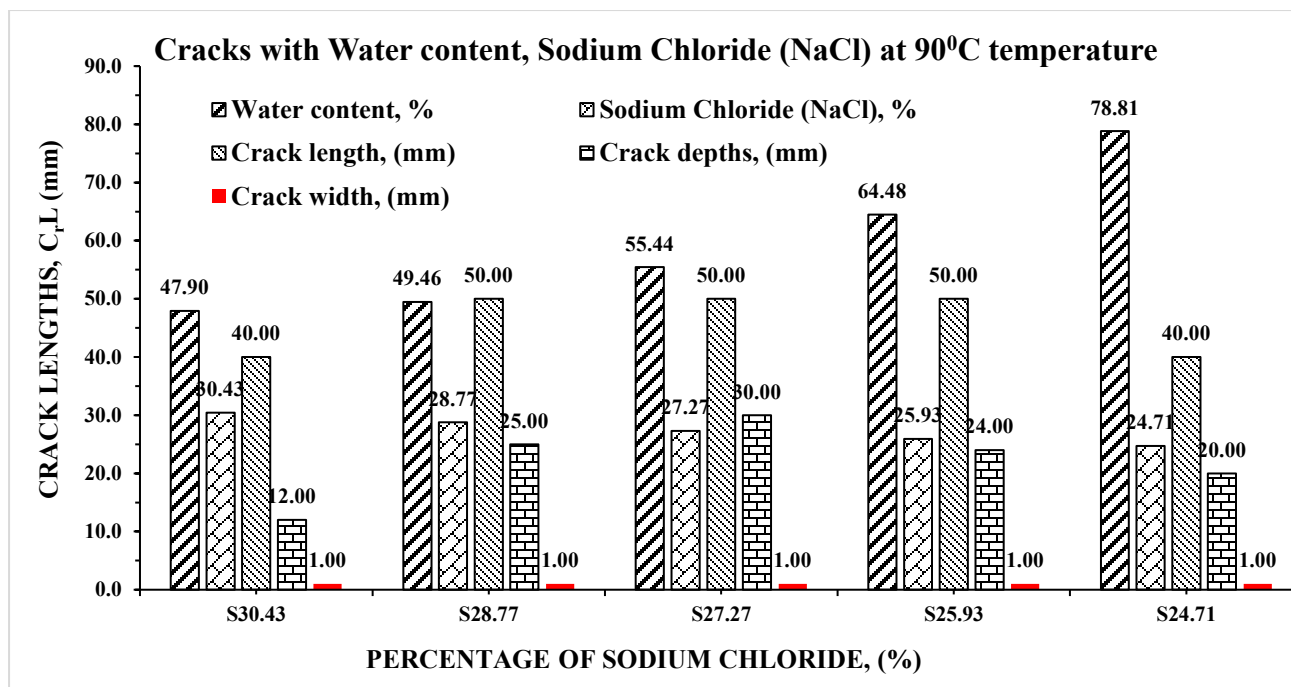


Figure 5. Change of the Cracks with Water content, Sodium Chloride (NaCl) at 90°C temperature. There were no sudden changes in water content, and the NaCl salt content increased relatively uniformly in the samples as the temperature increased. At this temperature of 90°C, the water and salt content did not differ significantly, and the cracks appeared relatively uniform at 1mm.

At 90°C, the water content, sodium chloride (NaCl) content, and crack characteristics of the tested samples showed notable variations. Sample C1 exhibited the highest water content (78.81%), corresponding to the maximum NaCl content (30.43%). The longest cracks, measuring 50 mm, were observed in samples C2, C3, and C4, while the maximum crack depth (30 mm) was recorded in sample C3. Crack width was uniform across all five samples, measuring 1 mm. Overall, these findings demonstrate that water content primarily governs material ductility and crack accommodation, whereas NaCl content predominantly influences brittleness and crack initiation. Understanding this interplay is essential for controlling crack development in materials exposed to high-temperature conditions. However, Natural flax fibers (0–0.6% by mass, lengths 12–50 mm) were added to clay concrete to study early-age plastic shrinkage and cracking. Digital Image Correlation tracked strain and crack width in the first 24 hours. Fibers reduced early plastic shrinkage and mitigated stress concentrations and cracking (Nathalie Kouta et al., 2020).

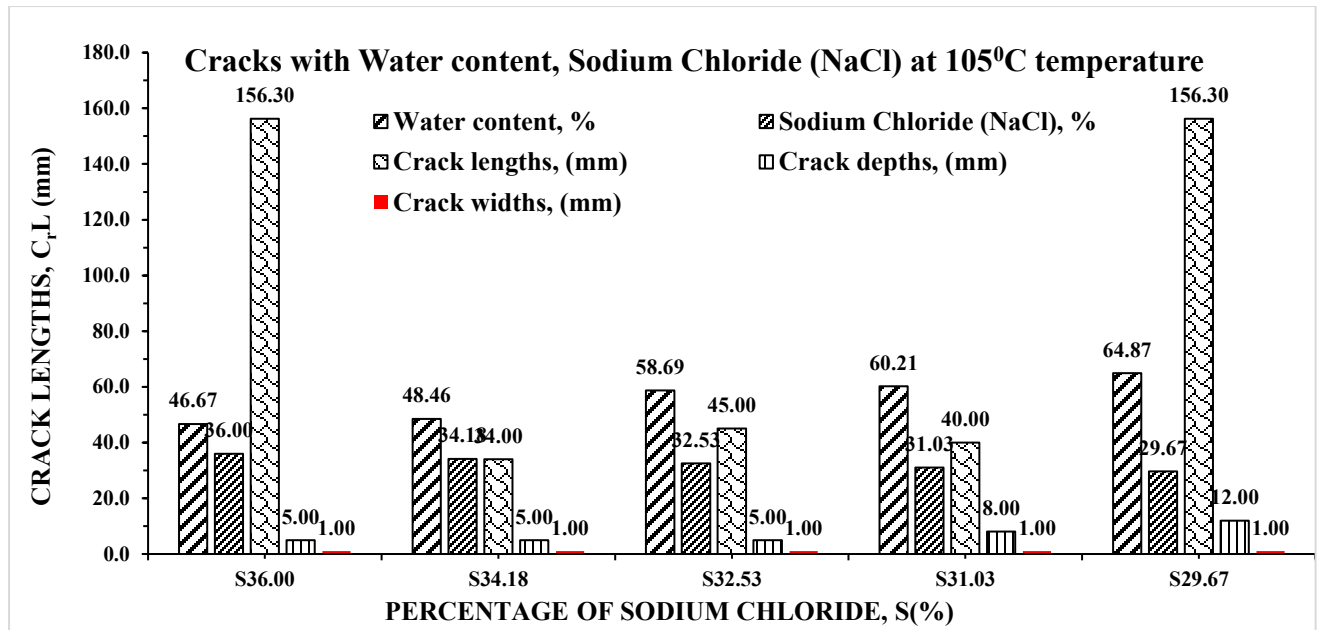


Figure 6. Change of the Cracks with Water content, Sodium Chloride (NaCl) at 105°C temperature. The increase in crack length was 156.3mm, while the water content and NaCl salt content did not differ significantly between samples S36.00 and S29.67, which had NaCl salt content of 36% and 29.67%, respectively. Conversely, the remaining samples showed a gradual decrease in crack length and a uniform width of 1mm.

At 105°C, the highest water content was observed in sample C5 (64.87%), while the maximum NaCl content was recorded in sample C1 (36%). The longest cracks, measuring 156.1 mm, were observed in samples C1 and C3. The maximum crack depth (12 mm) was recorded in sample C5. Crack width was consistent across all five samples, measuring 1 mm. However, Five soils compacted at varying water contents (12.5–20.5%) were dried after saturation, with pore structure and surface cracking monitored. Lower water contents increased crack ratio and density nearly linearly, while more dispersed soils showed pronounced primary and secondary cracks with two-stage growth during drying (Qing Cheng et al., 2019).

At 120°C, the maximum water content was observed in sample C5 (65.17%), corresponding to the highest NaCl content in sample C1 (40.74%). Crack lengths were identical across samples C1, C2, C3, and C4, measuring 156.30 mm. The maximum crack width (6.0 mm) was recorded in sample C2, whereas the crack width was uniform across all five samples at 1 mm. However, This study shows that ultrafine slag (US) with lime or cement significantly reduces durable cracking in marine clay (MS). CSIF measurements indicate up to 50% reduction for MS + 12%US + 3%L, with other US–L/C combinations also effectively mitigating cracks (Ram Wanare et al., 2022).

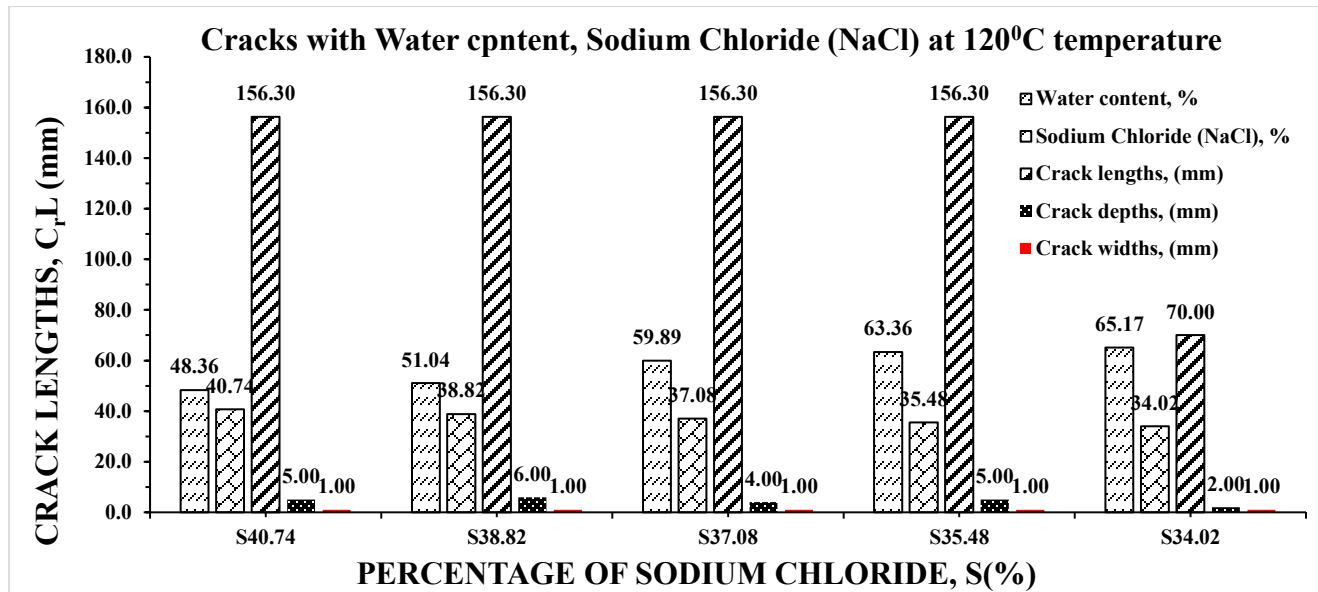


Figure 7. Change of the Cracks with Water content, Sodium Chloride (NaCl) at 120°C temperature. There was a similarity in crack length (156.3mm) among samples S40.74, S38.82, S37.08, and S35.48, corresponding to NaCl salt content of 40.74%, 38.82%, 37.08%, and 35.48%, respectively. There was no significant difference between salt content and moisture content. Sample S34.02 had a salt content of 34.02% with the largest crack depth of 2mm.

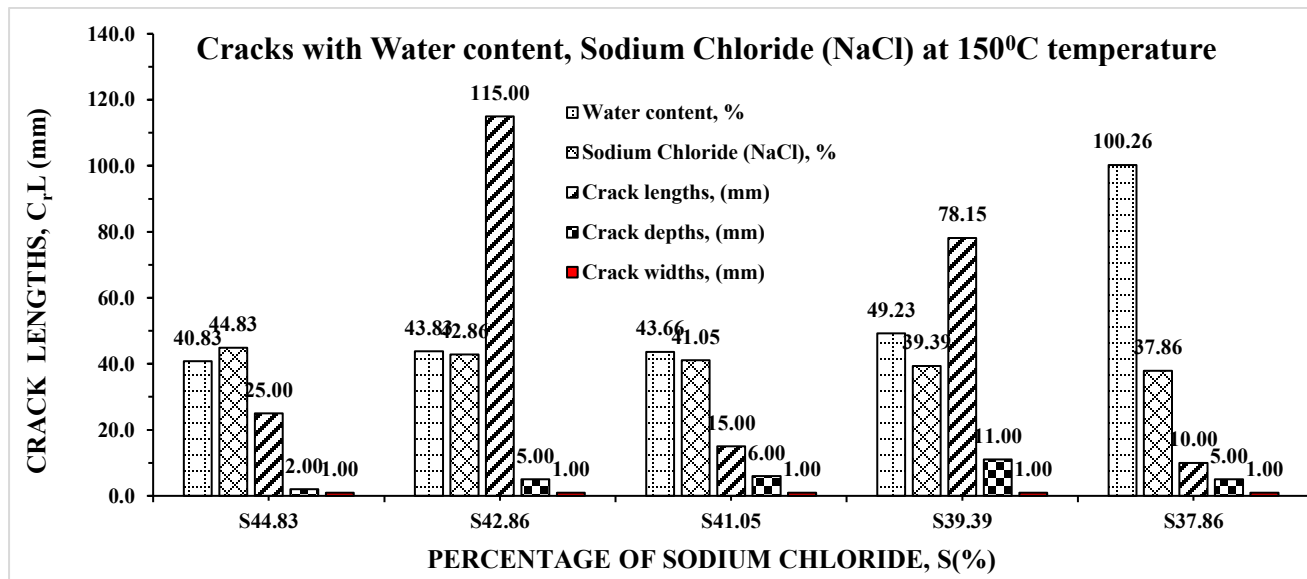


Figure 8. Change of the Cracks with Water content, Sodium Chloride (NaCl) at 150°C temperature. The variation in crack length was 115mm, 78.15mm, and 100.26mm in samples S42.86, S39.39, and S37.86, representing 42.86% and 37.86%, respectively. Conversely, there were no significant differences in moisture content and NaCl salt content.

At 150°C, the maximum water content was observed in sample C5 (100%), corresponding to the highest NaCl content in sample C1 (44.83%). The longest crack (115 mm) was recorded in sample C2, while the maximum crack depth (11 mm) was observed in sample C4. Crack width was uniform across all five samples, measuring 1 mm. The results indicate a strong influence of water and NaCl content on crack morphology. Maximum water content in sample C5 enhances ductility, allowing the material to accommodate stress effectively. In contrast, elevated NaCl content in sample C1 increases brittleness, promoting crack initiation while limiting excessive propagation. Sample C2, with intermediate water and NaCl contents, exhibits the longest crack (115 mm), suggesting that balanced moisture and salt levels facilitate crack propagation. The greatest crack depth (11 mm) observed in sample C4 indicates a synergistic effect of water-induced plasticity and NaCl-induced brittleness. Uniform crack width (1 mm) across all samples suggests that lateral expansion is less sensitive to compositional differences under these conditions. Overall, these observations confirm that water content primarily governs material ductility and crack accommodation, whereas NaCl content predominantly affects brittleness and crack initiation. Managing these parameters is essential for controlling crack formation and propagation. However, Ultrafine slag with activators (lime/cement) more effectively reduces cracking in marine clay than slag alone, with the M1 mix (19.5% slag + 0.5% cement) optimal under both 27 °C and 45 °C drying conditions (Ram Wanare et al., 2020).

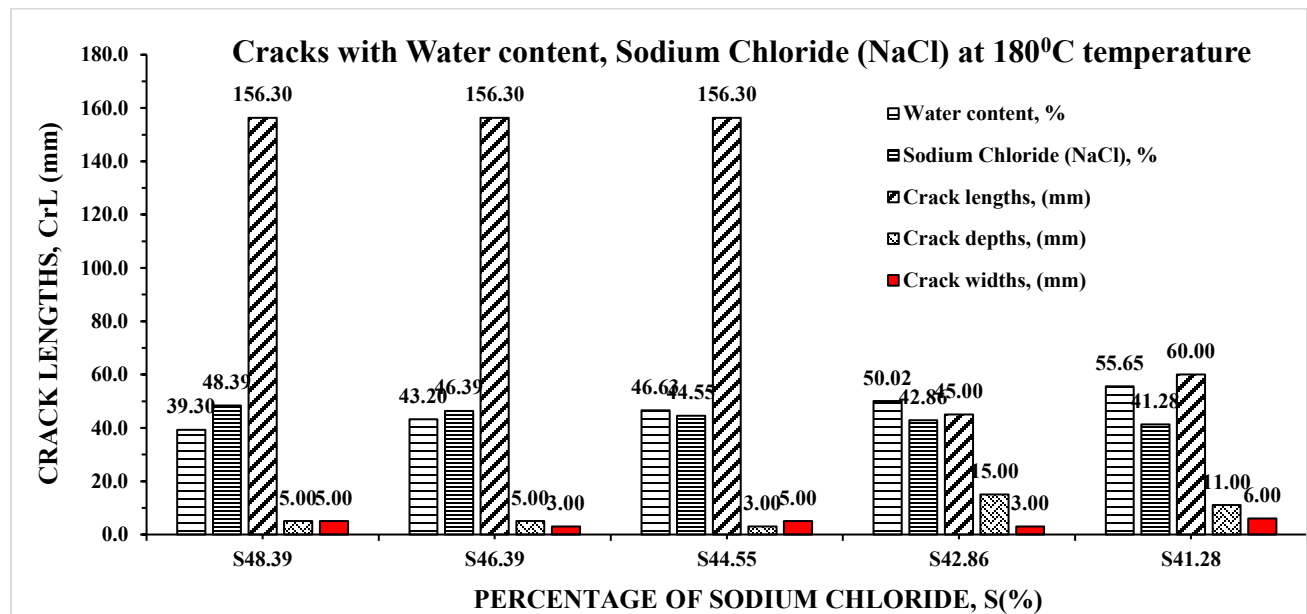


Figure 9. Change of the Cracks with Water content, Sodium Chloride (NaCl) at 180°C temperature. The increase in crack length was 156.3mm in samples S48.39, S46.39, and S44.55 compared to the other two samples which had smaller crack lengths. There were no significant differences in moisture content and NaCl salt content between the samples. The crack width gradually increased by 3mm in all samples.

At 180°C, the maximum water content was observed in sample C5 (55.65%), while the highest NaCl content was recorded in sample C1 (48.39%). The longest crack, measuring 156.3 mm, was observed in sample C2, whereas sample C5 exhibited a crack depth of 6 mm and a crack width of 11 mm. In comparison, at 200 °C, water content decreased to 37.18% in sample C5, while NaCl content increased to 51.52% in sample C1. Crack lengths were uniform across all five samples, measuring 156.3 mm; however, crack width was reduced, with the minimum width of 5 mm observed in sample C5 and 6 mm in samples C3 and C4. These results indicate that increasing temperature leads to a reduction in water content and crack width, while NaCl content rises, affecting crack morphology by promoting narrower cracks despite similar crack lengths. However, This study examines marine clay desiccation using ultrafine slag (2.5–40%) to reduce cracking. CSIF analysis shows up to 38% reduction in cured soils and 57% in uncured soils during drying (Ram Wanare et al., 2022). crack formation was monitored after each cycle, and crack patterns were quantified using image analysis and fractal dimension. Results show that cracks gradually evolve from irregular rectangles to polygonal or near-hexagonal shapes, with water loss—closely related to sample thickness—playing a key role in crack development (Yang Lu et al., 2016).

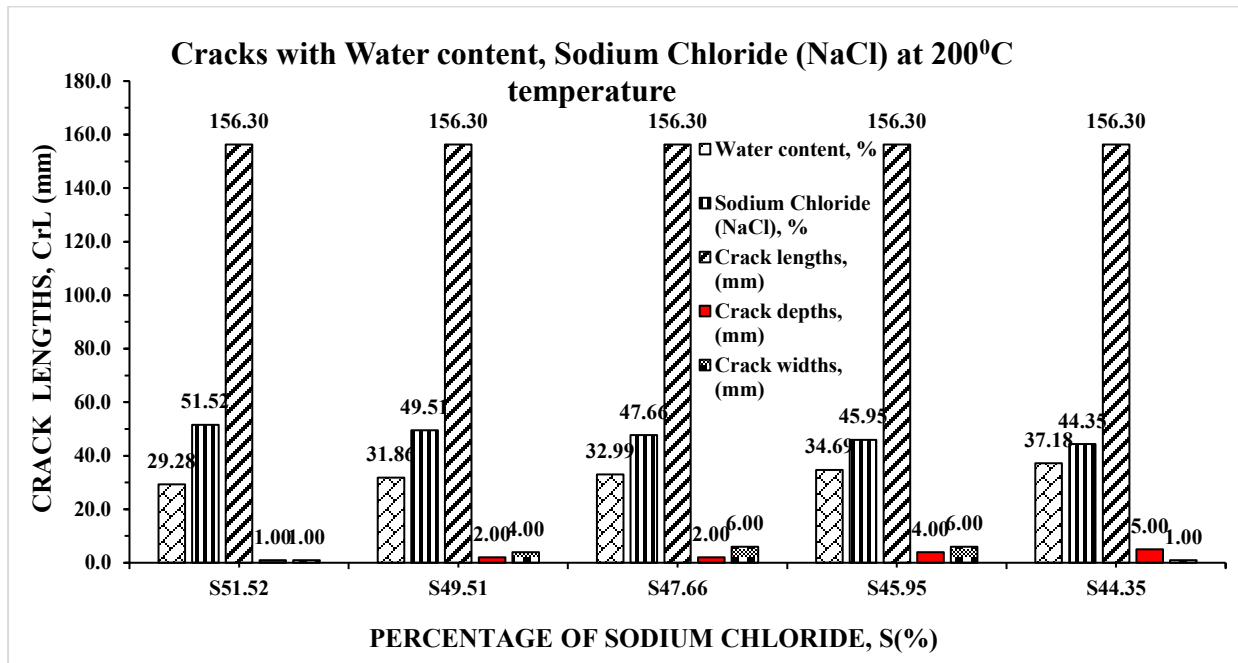


Figure 10. Change of the Cracks with Water content, Sodium Chloride (NaCl) at 200°C temperature. At the maximum temperature, the maximum crack length increased equally among the samples at 156.3 mm. The difference in crack width was more pronounced between samples corresponding to the moisture content and NaCl salt content, which did not differ significantly.

3.3 The results of the Unconfined Compression Test (UCT)

At 20°C, samples exhibited relatively high stress with moderate strains. Sample **C100251273** reached 1.2 N/cm² with a strain exceeding 0.25 mm, indicating high stiffness. Other samples (**C300211111** and **C400201045**) had moderate stress (~0.7 N/cm²) with strains of 0.15–0.2 mm, whereas **C200231186** and **C50019986** showed lower stress (0.4–0.5 N/cm²) and slightly higher strains (0.18–0.22 mm). These results suggest that at ambient temperature, stress dominates the mechanical response. The results of the Unconfined Compression Test (UCT) are used to show the relationship between the Stress and Strain. The samples are measured from 20°C to 200°C. The loadings are done from 0,5 MPa to 50 Mpa or 0,5 N/mm² đến 50 N/mm².

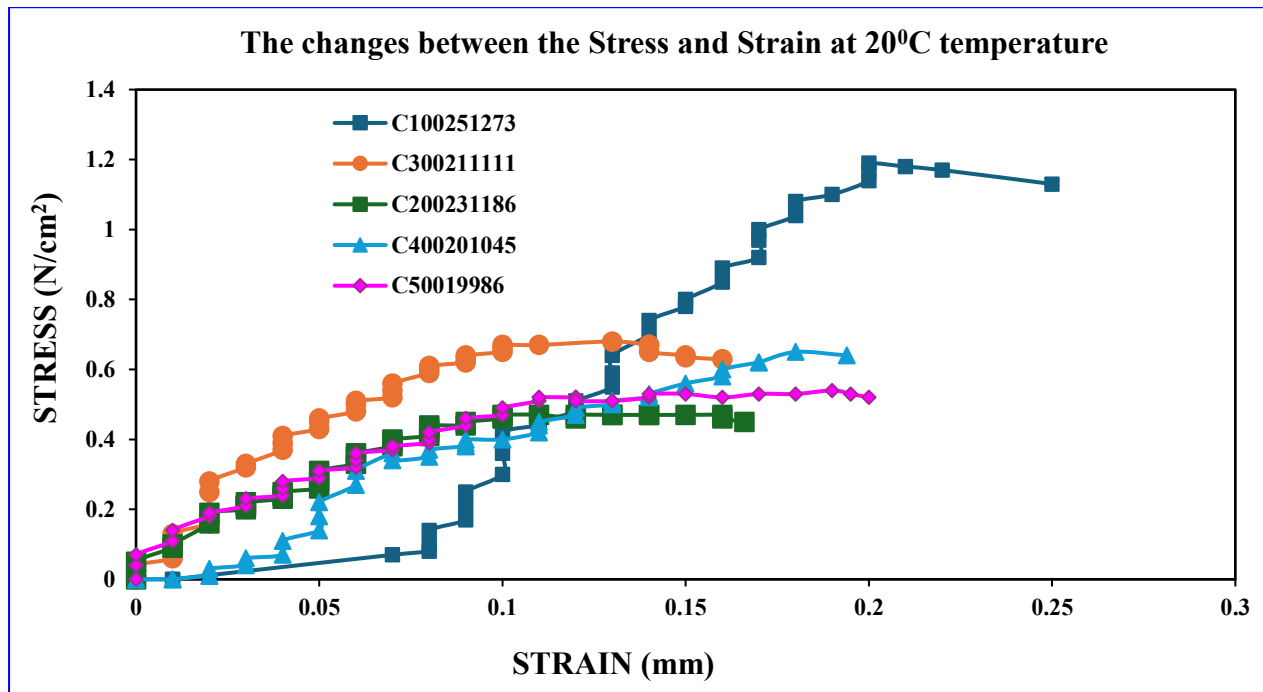


Figure 11. Results of the changes between the Stress and Strain at 20°C temperature. Sample **C200231186** showed the highest increase in stress and strain resistance at a tensile strain of 0.25 mm with a NaCl salt content of 11.86%, while other samples showed little variation between stress and strain values. As stress increased, strain increased under applied load.

At 60°C, stress decreased for all samples while strains increased, reflecting material softening. **C100462131** exhibited minimal stress (0.1 N/cm²) but the highest strain (0.33 mm). Other samples showed moderate stress (0.14–0.25 N/cm²) with strains ranging from 0.19 mm to 0.23 mm. These trends indicate that intermediate temperatures reduce compressive strength while allowing greater deformation, demonstrating enhanced ductility.

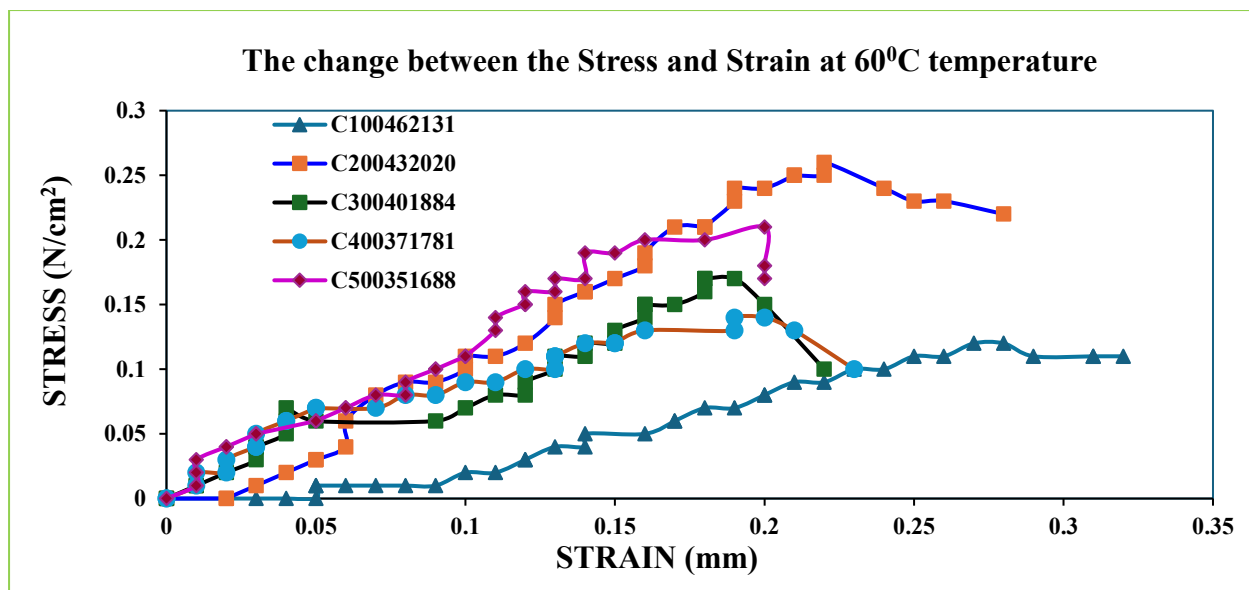


Figure 12. Results of the changes between the Stress and Strain at 60°C temperature. Samples C200432020 and C100462131 showed greater deformation with NaCl content of 20.20% and 21.31%, respectively. The deformation of these two samples was more prolonged compared to the others, and the stress also increased with increasing load.

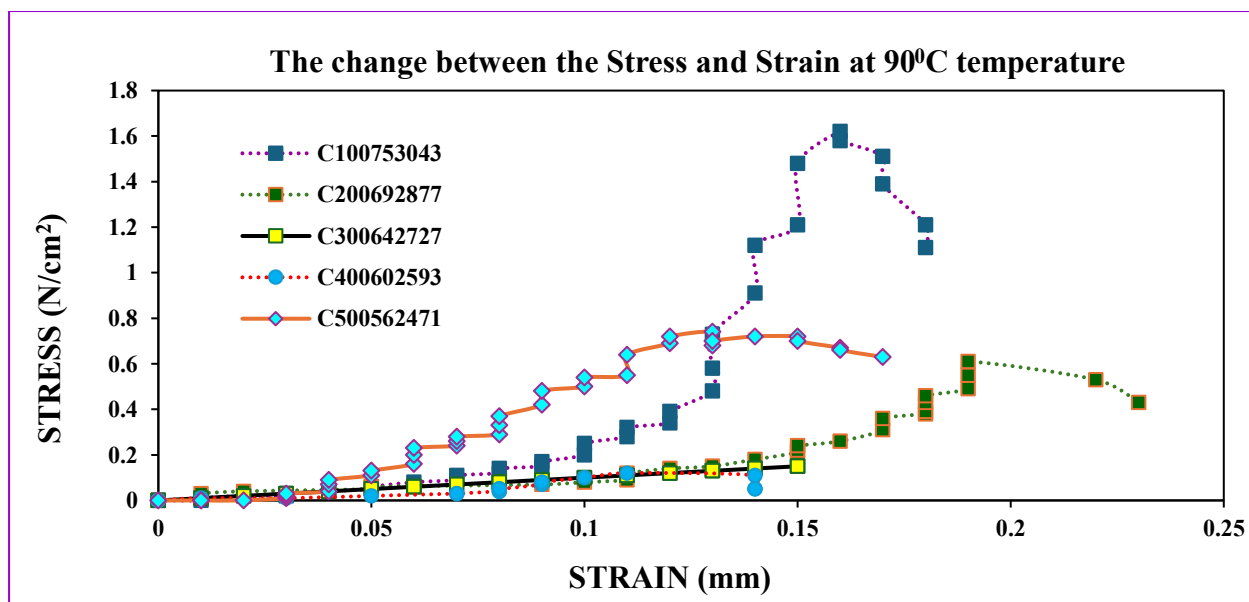


Figure 13. Results of the changes between the Stress and Strain at 90°C temperature. The stress and strain spikes were observed in sample C100753043 with a NaCl content of 30.43%. The strain elongation was greater in sample C200692877 with a NaCl content of 28.77%. Conversely, the other samples showed no significant differences in values as the load increased with increasing temperature.

At 90°C, stress responses became highly variable. Sample **C100753043** retained high stress (1.7 N/cm²) with low strain (0.16 mm), whereas **C200692877** showed minimal stress (0.06 N/cm²) and moderate strain (0.24 mm). **C500562471** exhibited extremely high strain (0.6 mm) under moderate stress (~0.17 N/cm²), indicating substantial softening. The heterogeneity at elevated temperatures likely arises from differences in microstructure or composition. Overall, increasing temperature generally **reduces stress resistance** and **increases strain capacity**, although individual sample responses vary significantly, particularly at high temperatures. These findings underscore the importance of evaluating both stress and strain for thermal-mechanical performance assessments.

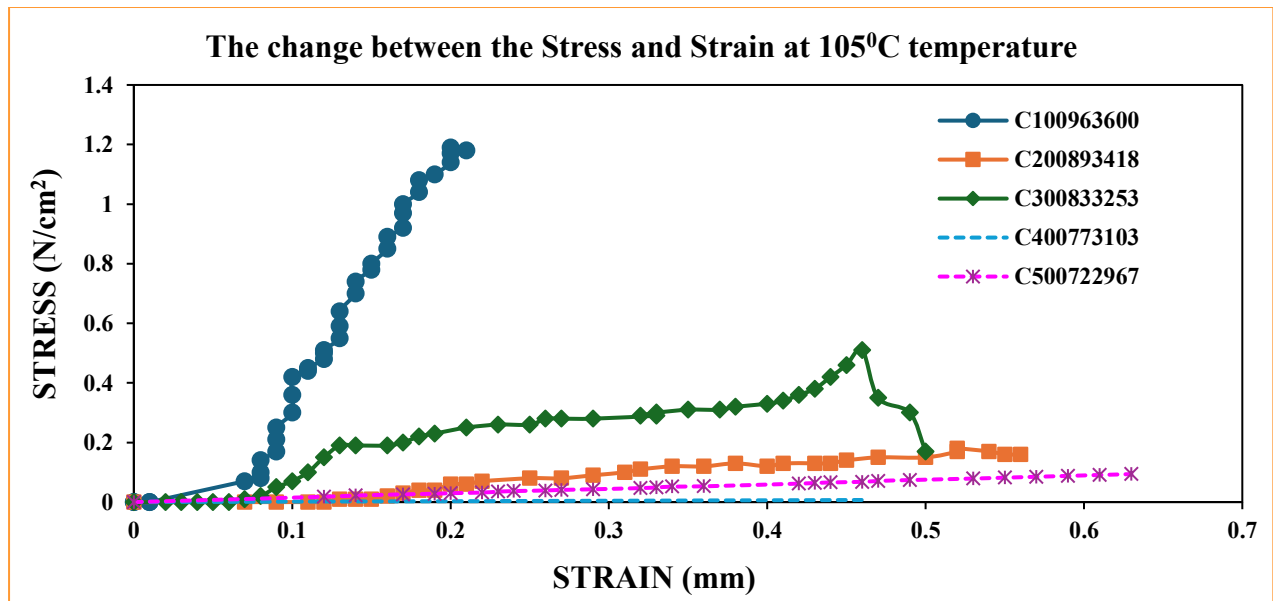


Figure 14. Results of the changes between the Stress and Strain at 105°C temperature. As the temperature increased, the strain of sample C100963600 with %NaCl reached 36.00%. Conversely, the other samples showed relatively stable changes in strain and stress values. The strain value increased steadily with small and stable stress values in sample C500722967 with %NaCl of 29.67%.

At 105°C, the samples exhibited significant variability in stress and strain responses. Sample **C100963600** showed the highest stress (~1.2 N/cm²) with a strain exceeding 0.2 mm, indicating relatively strong resistance to deformation. In contrast, **C200893418** exhibited very low stress (~0.15 N/cm²) but a high strain (>0.55 mm), suggesting pronounced softening. Samples

C300833253 and **C400773103** showed intermediate stress values ($\sim 0.5 \text{ N/cm}^2$ and 0.1 N/cm^2 , respectively) with strains exceeding $0.45\text{--}0.46 \text{ mm}$, while **C500722967** demonstrated low stress ($\sim 0.15 \text{ N/cm}^2$) but the largest strain ($>0.65 \text{ mm}$). Overall, at 105°C , the results are consistent with the general trend of temperature-induced softening: **stress decreases while strain increases**, with pronounced heterogeneity among individual samples. Some samples, such as **C100963600**, retain relatively high stress, whereas others, like **C500722967**, undergo extreme deformation under low stress. This indicates that at elevated temperatures, the mechanical behavior becomes increasingly sample-dependent, likely reflecting variations in composition or microstructure.

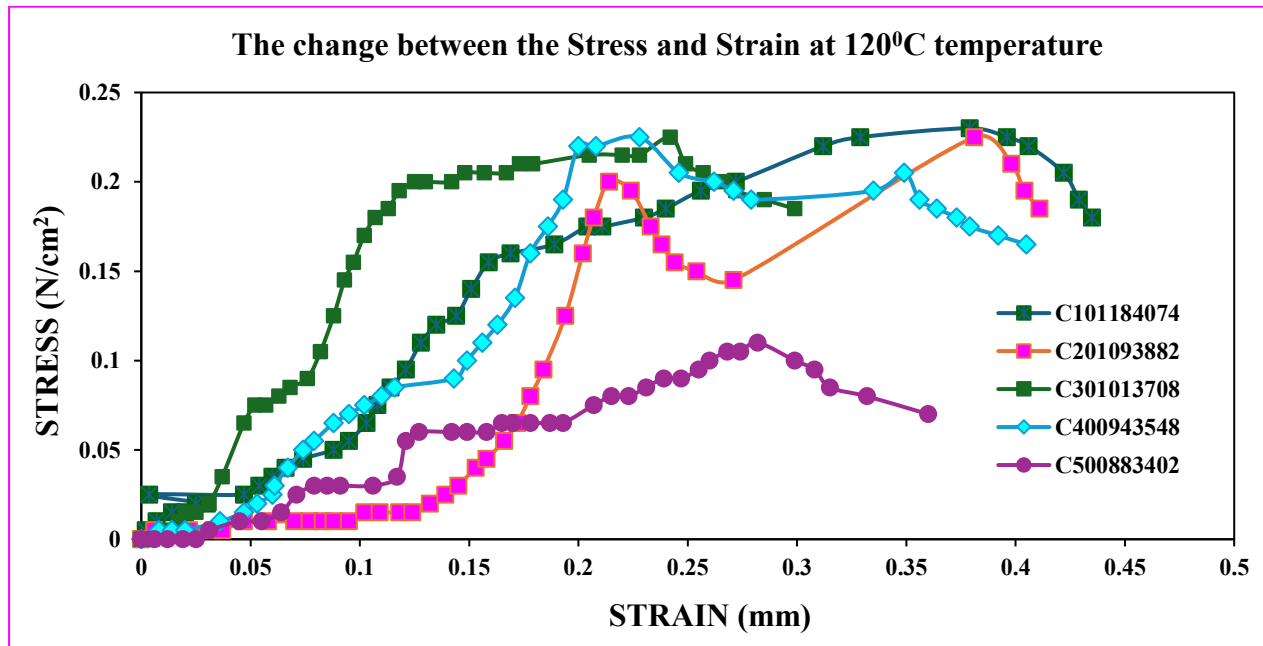


Figure 15. Results of the changes between the Stress and Strain at 120°C temperature. At this temperature, the samples exhibit sudden and chaotic changes in values, with large differences in stress and strain corresponding to different %NaCl concentrations. The samples gradually increase and decrease, reaching a maximum value of 0.35 mm when the load is at its maximum.

At 120°C , the samples (C1–C5) exhibited varying Sodium Chloride (NaCl) contents of 40.74% , 38.82% , 37.08% , 35.48% , and 34.02% , respectively. These compositional differences corresponded to notable variations in mechanical behavior under unconfined compression. Sample **C1** reached a stress of 0.22 N/cm^2 with a strain of 0.38 mm , representing the highest stress among the group. Sample **C2** exhibited a stress of 0.18 N/cm^2 with strains ranging from 0.18 mm to 0.38 mm , indicating a wider deformation range. Sample **C3** achieved a stress of 0.21 N/cm^2 with a strain of 0.22 mm , while **C4** showed a stress of 0.20

N/cm² with strains between 0.23 mm and 0.35 mm. Finally, **C5**, with the lowest NaCl content, displayed the lowest stress of 0.11 N/cm² and a strain of 0.28 mm. These results indicate a clear correlation between NaCl content and stress response: samples with higher NaCl content generally exhibited higher stress under compression, while lower NaCl content resulted in reduced stress. Strain responses, however, were more variable, suggesting that deformation behavior is influenced by both the chemical composition and the internal microstructure of the samples. Overall, the data demonstrate that **NaCl content significantly affects mechanical performance**, particularly at elevated temperatures. Moreover, the influence of NaCl content on the mechanical behavior of samples was investigated at three temperatures: 150°C, 180°C, and 200°C. At all temperatures, the NaCl content decreased progressively from C1 to C5, yet the stress and strain responses exhibited distinct temperature-dependent trends.

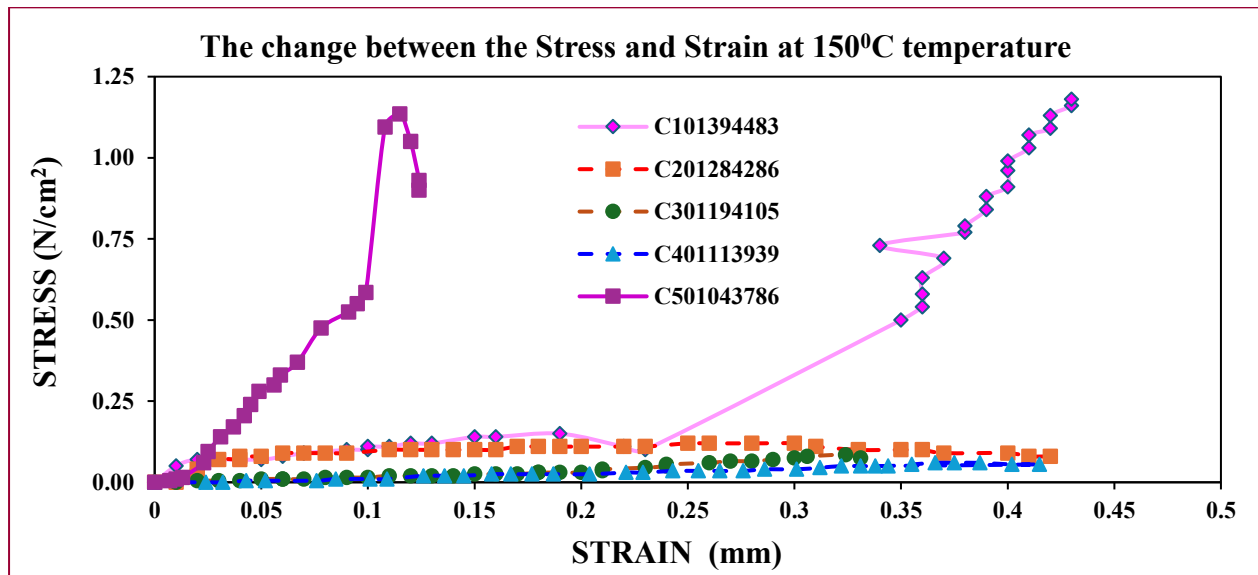


Figure 16. Results of the changes between the Stress and Strain at 150°C temperature. The mutations in samples C101394483 and C501043786 corresponded to %NaCl of 44.83% and 37.86%, respectively. The remaining samples showed little variation in stress and strain values.

At 150 °C, NaCl contents ranged from 44.83% (C1) to 37.86% (C5). Stress values showed a non-linear pattern: C1 exhibited high stress (1.23 N/cm²), which dropped sharply to 0.10 N/cm² in C2. Minor increases were observed in C3 (0.13 N/cm²) and C4 (0.12 N/cm²), followed by a significant rise in C5 (1.20 N/cm²). Strain values also varied irregularly, with C1 and C2 showing 0.44 mm and 0.43 mm, C3 and C4 slightly lower at 0.34 mm and 0.42 mm, and C5 the lowest at 0.11 mm. These non-monotonic trends suggest that, at 150 °C, mechanical behavior is influenced not only by NaCl content but also by microstructural factors such as matrix densification, particle

distribution, and porosity. The high stress coupled with low strain in C5 indicates enhanced stiffness due to matrix consolidation, whereas intermediate samples (C2–C4) may suffer from incomplete densification or heterogeneous microstructure, resulting in lower load-bearing capacity.

At 180 °C, samples contained 48.39% (C1) to 41.28% (C5) NaCl. Stress values displayed a non-linear response: C1 (0.03 N/cm²) and C2 (0.02 N/cm²) were low, while C3 reached a peak of 0.16 N/cm². Stress then decreased in C4 (0.05 N/cm²) and C5 (0.04 N/cm²). Strain values followed a similar irregular trend: C1 and C2 showed 0.22 mm and 0.23 mm, C3 peaked at 0.42 mm, and C4–C5 decreased to 0.15 mm and 0.18 mm. The intermediate NaCl content (C3, 44.55%) appears to provide a balance between structural integrity and deformability at this temperature. The non-monotonic trends suggest that mechanical behavior at 180 °C is governed by microstructural rearrangements, including pore distribution and phase interactions, rather than solely by salt content.

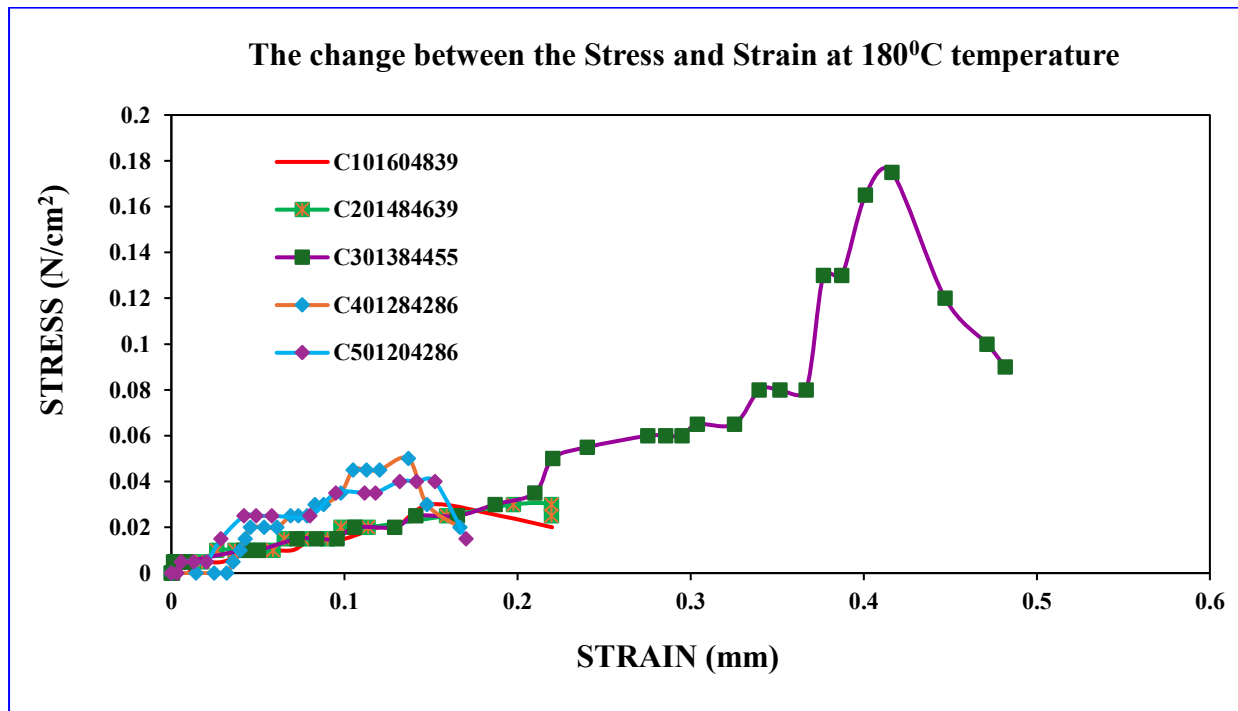
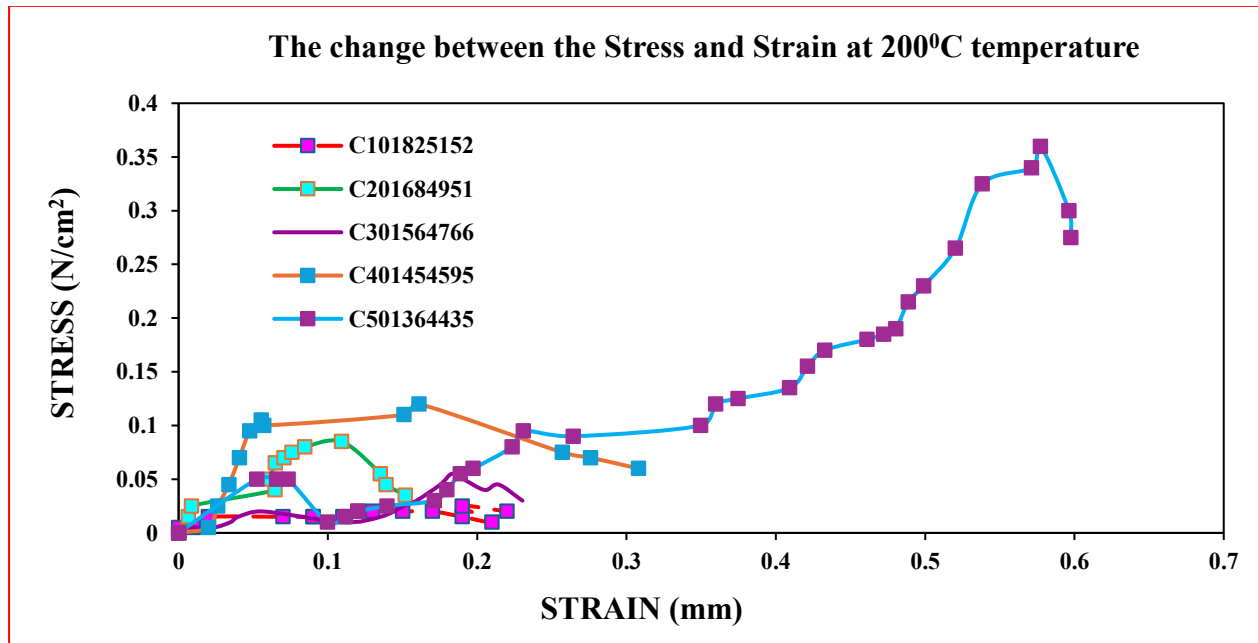


Figure 17. Results of the changes between the Stress and Strain at 180°C temperature. The C301384455 sample showed a significant change in stress and strain values, with elongation reaching 0.5mm corresponding to a NaCl content of 44.55%, while other samples showed little change, with small strain values and low stress.

560

561 Moreover, Strain measurements also reflected this irregular pattern. C1 and C2 displayed
562 similar deformation (0.22 mm and 0.23 mm, respectively), whereas C3 exhibited the highest strain
563 of 0.42 mm, suggesting enhanced deformation capacity at intermediate NaCl content. In contrast,
564 C4 and C5 showed lower strain values (0.15 mm and 0.18 mm), indicating reduced flexibility under
565 load. The non-monotonic trends in stress and strain suggest that at 180 °C, the mechanical behavior
566 is not solely governed by NaCl content. Microstructural factors such as pore distribution, phase
567 interactions, and thermal-induced rearrangements are likely influencing load transfer and
568 deformation mechanisms. Notably, sample C3, with an intermediate NaCl fraction, appears to
569 achieve a balance between structural integrity and deformability, highlighting the importance of
570 optimizing salt content for mechanical performance at sub-elevated temperatures. These
571 observations provide valuable insights into the temperature-dependent influence of NaCl on
572 material behavior, indicating that optimal mechanical properties may not necessarily correspond to
573 the lowest salt content, in contrast with trends observed at higher temperatures.



574

575 **Figure 18.** Results of the changes between the Stress and Strain at 200°C temperature. The extreme
576 value of elongation strain of sample C501364435 is 0.6mm, corresponding to the maximum
577 increase in %NaCl with the maximum increase in load. Other values for stress are 0.1 N/cm² and
578 strain concentration are around 0.2mm.

At 200°C, a systematic variation in mechanical behavior was observed as a function of NaCl content. The NaCl fraction decreased progressively from 51.52% (C1) to 44.35% (C5), leading to a pronounced modification in both stress and strain responses. Sample C1, containing the highest NaCl content (51.52%), exhibited the lowest stress value (0.02 N/cm²) and a moderate strain of 0.22 mm. When the NaCl content decreased to 49.51% (C2), the stress increased to 0.08 N/cm², although the strain slightly decreased to 0.18 mm. In C3 (47.66% NaCl), a minor reduction in stress (0.06 N/cm²) was accompanied by an increase in strain (0.25 mm), suggesting transitional deformation behavior. A more pronounced improvement in mechanical performance was observed for C4 (45.95% NaCl), where the stress reached 0.13 N/cm², and the strain increased to 0.32 mm. Notably, C5, which had the lowest NaCl content (44.35%), demonstrated a substantial enhancement in both parameters, exhibiting the highest stress (0.35 N/cm²) and strain (0.55 mm). The sharp increase in stress between C4 and C5 indicates a potential threshold effect in structural consolidation. Overall, the results reveal an inverse correlation between NaCl content and mechanical strength at elevated temperature. The reduction in salt fraction appears to significantly enhance load-bearing capacity and deformation tolerance.

On the other hand, comparison across temperatures reveals that the influence of NaCl content on mechanical properties is strongly temperature-dependent. At lower temperatures (150 °C), mechanical response is dominated by matrix consolidation and localized stiffness effects, leading to non-linear stress-strain behavior. At intermediate temperatures (180 °C), microstructural rearrangements and pore distribution govern performance, resulting in irregular trends. At higher temperature (200 °C), reduced NaCl content consistently enhances stress and strain, indicating improved matrix cohesion and structural integrity. The results highlight the complex interplay between NaCl content, microstructure, and temperature. Optimizing salt content is crucial for achieving desired mechanical performance, with intermediate compositions favored at moderate temperatures and lower NaCl fractions beneficial at elevated temperatures.

4. Discussions

However, some the other stuties present the different results for the soil's cracts such as: a numerical model is developed to predict crack initiation and propagation in soils during electro-osmotic dewatering under unsaturated conditions. The model integrates the constitutive behavior of unsaturated soils with the Mohr–Coulomb failure criterion and accounts for nonlinear variations in soil properties, degree of saturation, and crack evolution. The results enable assessment of crack

development and identification of key factors governing crack formation (Qianli Zheng et al., 2025). Soil desiccation cracking is a common geotechnical issue, typically initiating at surface defects where stress concentrates. Laboratory tests on sludge samples with varying defect conditions were conducted to investigate crack behavior. Digital Image Correlation (DIC) effectively captures surface deformation and predicts crack initiation and propagation. Cracks initially form in Y-shaped patterns, followed by T-shaped and linear forms as the stress field evolves, governed by tensile stress redistribution (Tao Wang et al., 2026). Desiccation tests were conducted on soil samples and panels with varying heights, widths, and aspect ratios to investigate cracking behavior, evaporation rates, and shrinkage characteristics. The results show that specimen size significantly influences desiccation cracking by controlling evaporation and stress development. Airflow velocity affects shrinkage behavior, while size differences lead to differential resistance at the base or ground surface, contributing to crack formation patterns (Tao Wang et al., 2026).

Moreover, a machine learning-based framework is developed to predict the surface crack ratio of soil desiccation. Using 1040 experimental datasets, RF, XGBoost, and ANN models are applied for prediction. SHAP analysis is employed to interpret feature influence, showing that cracking behavior is mainly governed by initial water content, plasticity index, final water content, liquid limit, sand and clay contents, and soil thickness (Ting Wang et al., 2025). The study integrates laboratory experiments and DEM simulations to investigate desiccation cracking under non-uniform temperature conditions. DIC is used to monitor deformation, while the DEM model incorporates temperature-dependent evaporation. Results show that cracks initiate in high-temperature zones and propagate toward cooler areas in a “fish-scale” pattern due to differential evaporation and shrinkage (Tao Wang et al., 2026). The study investigates water seepage in cracked soils with varying initial crack sizes. Photometry and PIV were used to non-destructively track soil deformation and crack evolution during wetting. Results show three stages of soil response: (1) swelling—crack width decreases while depth remains unchanged, (2) collapse—soil particles fill the crack, and (3) stabilization—crack shape becomes stable. Soil failure is strongly influenced by initial crack geometry, with deeper cracks showing an inverted bell pattern due to water softening the underlying soil (Zhai X-W et al., 2025).

In additions, a thermomechanical FEM model with continuous masonry and tensile softening is used to simulate the facade–foundation–soil system, with damage quantified via a crack-based index Ψ . A parametric study of 1,200 simulations considered two facade types, three

soil layers, 33 geometries, and various slope shapes. Results show slope shape strongly influences damage: widespread vertical slopes cause visible damage ($\Psi \geq 1$) at $\sim \Delta T = 20^\circ\text{C}$ (heating) and $\sim 25^\circ\text{C}$ (cooling), about half the gradient needed for localized slopes. Soil stiffness affects severity: stiffer soils increase cracking, while softer soils accommodate thermal movements. Geometric discontinuities, such as openings and low vertical masonry ratios, promote earlier cracks, whereas overall size is less critical. Fragility curves provide practical thresholds for assessment and mitigation (Paul A. Korswagen et al., 2025). Indoor tests of five consecutive wet–dry cycles evaluated soil treated with fly ash and biochar. Image processing and fractal analysis showed that combining 10% fly ash with 4% biochar best reduced crack formation, crack density, and fractal dimension, while improving water retention (residual moisture +105.6%, fractal dimension –28.4%, crack ratio –41.8% after the first cycle). These effects result from biochar adsorption and fly ash hydration, which enhance aggregate stability, slow water loss, and limit structural degradation during wet–dry cycles (Binbin Yang et al., 2025). Digital Image Correlation (DIC) was used to study the dynamic tensile behavior and damage evolution of the mixture at varying stress levels and loading rates. Results show that tensile strength of the MOC composite increases with loading rate, and higher rates produce more complex crack networks, indicating more intricate crack propagation under dynamic conditions (Jian Gong et al., 2025).

Finally, the study investigated the effect of cement solution concentration on soil water retention and microstructure using enzyme-induced calcium carbonate precipitation (EICP), shrinkage tests under wet–dry cycles, and microscopic analysis. Results show that EICP treatment significantly reduces drying shrinkage and sensitivity to wet–dry changes. Volume shrinkage progresses in three stages, and microscopic analysis reveals a bimodal pore structure in treated soils, explaining the mechanism of reduced desiccation cracking (Jianwei Zhang et al., 2025). The study uses indoor wet–dry cycle tests to investigate crack growth, swelling–shrinkage behavior, and lateral swelling pressure of expansive soils, along with the reinforcing mechanism of EICP. Lateral swelling pressure was measured during humidification. Results show that EICP solution rapidly infiltrates cracks, forming a CaCO_3 network. Crack evolution in repaired soils occurs in three stages: formation, shrinkage, and stabilization (Bantayehu Uba Uge et al., 2025).

5. Conclusion

The investigation of stress, strain, and crack development in clay with varying sodium chloride (NaCl) contents under temperature changes ranging from 20°C to 200°C was conducted

through controlled laboratory experiments. The results indicate that both stress and strain increased progressively with rising temperature and NaCl content. Crack formation became more pronounced as the temperature increased, with a greater number of cracks observed along the sample surface at elevated temperatures. However, when the NaCl content increased to its maximum level at 2000 °C, crack occurrence was reduced. This observation suggests that higher NaCl content may inhibit crack propagation and enhance the load-bearing capacity of the clay. Consequently, the soil exhibited increased stiffness and mechanical resistance under combined high-temperature and high-salinity conditions. These findings highlight the significant role of NaCl content in modifying the thermo-mechanical behavior of clay, particularly in limiting crack development and improving structural integrity at extreme temperatures.

***Declaration of interest statement**

The authors report there are no competing interests to declare.

*** Consent for publication**

The author agrees to comply with the journal's regulations upon publication and no any more ideas.

*** Availability of data and material**

The research data and material are shown fully in this research manuscript. The authors received permission to use research data and share it with readers worldwide for reference. If the readers need to use the study's data for reference worldwide, please email the author. We will provide it in full after the journal is published. Please send to email: dtthy@vnkgu.edu.vn or doantructhy@gmail.com.

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