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EFFECTS OF SALINIZATION IN THE ARAL SEA BASIN (UZBEKISTAN) ON THE STRUCTURAL INTEGRITY OF CERAMIC WALL MATERIALS

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ABSTRACT

Salinization associated with the desiccation of the Aral Sea has become one of the most critical environmental factors affecting the durability of construction materials in Central Asia. Although the deterioration of concrete and natural stone under saline environments has been extensively investigated, quantitative information regarding the long-term performance of ceramic wall materials remains limited. This study evaluates the influence of saline exposure on the physical and mechanical properties of fired ceramic wall materials through a combination of field observations and laboratory simulations. Ceramic brick specimens collected from highly saline regions of Uzbekistan were compared with laboratory-prepared specimens subjected to repeated wetting–drying cycles in sodium chloride (NaCl) and sodium sulfate (Na_2SO_4) solutions. Changes in compressive strength, water absorption, density, and visible deterioration were evaluated using internationally accepted testing procedures. The results demonstrate that sulfate-bearing environments produced substantially greater deterioration than chloride environments owing to higher crystallization pressure during repeated hydration–dehydration cycles. Progressive salt crystallization promoted pore enlargement, surface efflorescence, cracking, and reduction of mechanical strength. Field observations confirmed similar deterioration patterns in ceramic masonry exposed to long-term saline conditions in the Aral Sea Basin. The combined field and laboratory investigation improves the understanding of salt-weathering mechanisms affecting ceramic wall materials and provides a scientific basis for selecting durable construction materials and developing mitigation strategies for saline and arid environments.

KEYWORDS: Aral Sea Basin; salinization; ceramic wall materials; salt weathering; sodium sulfate; sodium chloride; durability; efflorescence.

1. INTRODUCTION

The rapid desiccation of the Aral Sea represents one of the most severe anthropogenic environmental disasters of the twentieth century. Since the 1960s, intensive diversion of the Amu Darya and Syr Darya rivers for agricultural irrigation has reduced the water surface area of the Aral Sea by more than 90%, exposing extensive salt-covered sediments to atmospheric processes. Consequently, millions of tons of saline dust containing chlorides, sulfates, and other soluble salts are transported annually over large areas of Uzbekistan and neighboring countries, accelerating soil salinization and increasing the salt load on engineering structures [1-2].

Salt accumulation has become a major durability problem for buildings constructed from porous ceramic materials. In arid climates, dissolved salts migrate into brick pores through capillary action and subsequently crystallize during drying. Repeated crystallization–dissolution cycles generate crystallization pressure that induces microcracking, increases porosity, weakens the ceramic matrix, and ultimately reduces structural durability. These deterioration processes are commonly manifested as efflorescence, scaling, surface spalling, and loss of mechanical strength [3].

Previous studies have extensively investigated salt-induced deterioration in concrete, limestone, sandstone, and historical masonry. Sodium sulfate and sodium chloride have been identified as the most aggressive salts because of their ability to generate crystallization pressure within porous materials during hydration–dehydration cycles. However, most published investigations have focused on concrete or natural stone, whereas comparatively few studies have examined fired ceramic wall materials under the specific environmental conditions of the Aral Sea Basin [4-6].

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Table 1: Summary of previous investigations on salt-induced deterioration

Study	Material	Salt type	Main findings	Remaining research gap
Benavente et al.	Brick	Na_2SO_4	Strength reduction due to crystallization	No Aral Sea conditions
Shahidzadeh et al.	Limestone	NaCl, Na_2SO_4	Salt crystallization causes pore damage	Ceramic materials not investigated
Stryszewska et al.	Ceramic brick	Sulfates	Durability decreases after cyclic exposure	Limited field validation
Present study	Ceramic wall materials	NaCl and Na_2SO_4	Combined laboratory and field investigation	Aral Sea Basin conditions

Although previous research has considerably improved the understanding of salt weathering in porous building materials, a significant knowledge gap remains regarding ceramic wall materials exposed to long-term salinization in the Aral Sea Basin. In particular, few studies have combined laboratory simulations with field investigations to evaluate deterioration mechanisms under the unique climatic and environmental conditions of this region [7].

Research gap

Previous investigations have primarily addressed salt-induced deterioration in concrete, natural stone, and historical masonry. However, the durability of fired ceramic wall materials subjected to long-term salinization in the Aral Sea Basin has not been systematically investigated. Furthermore, quantitative relationships between laboratory simulations and field observations remain insufficiently understood.

Scientific novelty

The novelty of this study lies in integrating laboratory-controlled salt-weathering experiments with field observations collected from highly saline regions surrounding the Aral Sea. This combined approach enables a comprehensive evaluation of the deterioration mechanisms affecting ceramic wall materials under realistic environmental conditions.

Objectives of the study

This study aims to:

- evaluate the influence of salinity on the physical and mechanical properties of ceramic wall materials;
- determine changes in compressive strength, density, and water absorption after salt exposure;
- investigate deterioration mechanisms caused by sodium chloride and sodium sulfate crystallization;
- compare laboratory simulation results with field observations from saline regions of Uzbekistan;
- propose engineering recommendations for improving the durability of ceramic construction materials in saline environments.

The findings of this study provide scientific evidence supporting the development of salt-resistant ceramic materials and contribute to improving the durability of buildings constructed in saline and arid regions [8-16].

2. MATERIALS AND METHOD

2.1 MATERIALS

Field investigations were conducted in three salinity-affected regions of Uzbekistan located within the Aral Sea ecological disaster zone: Urgench (Khorezm Region), Nukus (Republic of Karakalpakstan), and Navoi Region [2]. These areas were selected because they represent different levels of long-term soil and atmospheric salinization caused by the desiccation of the Aral Sea.

A total of 18 masonry buildings were surveyed (six buildings per region). The investigated structures were constructed between 1985 and 2018 using fired clay bricks and cement–sand mortar. Buildings with visible salt efflorescence, surface scaling, and moisture damage were intentionally selected.

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The geographical coordinates of the investigated locations are presented in Table 2.

Table 2: Field investigation sites

Location	Latitude	Longitude	Number of buildings
Urgench	41.55°N	60.63°E	6
Nukus	42.46°N	59.61°E	6
Navoi	40.08°N	65.38°E	6

For every building, the following information was recorded:

- construction year;
- exposure conditions;
- visible salt crystallization;
- crack density;
- surface scaling;
- moisture condition;
- foundation condition.

Digital photographs were collected using the same camera settings and identical illumination conditions to ensure consistent documentation.

The field studies were conducted in the regions of Khorezm and Navoi, as well as in the city of Nukus in the Republic of Karakalpakstan, Uzbekistan, particularly in areas near the rapidly shrinking Aral Sea over the past several decades, where salinization levels are the highest. Over the course of several months, field samples of ceramic materials, including fired clay bricks and ceramic tiles, were collected from both residential and public buildings in the affected regions. These materials were then carefully examined for signs of degradation, including surface scaling, cracking, discoloration, and overall structural weakness (Table 3).

Table 3: Chemical Composition of Dust Lifted from the Aral Sea Region and Deposited in Various Areas

Source of the Sample	Composition, % (wt.)													
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	TiO_2	P_2O_5	MnO	ZrO_2	Cr_2O_3	SrO	ZnO	ppp
Kanglikul	43.1812	9.5312	4.5938	9.6567	2.9889	1.0634	0.7717	0.3324	0.0775	0.0505	0.0444	0.0410	0.0505	27.2997
Mangit	49.5925	9.2121	4.4881	9.6541	2.9885	1.0631	0.7713	0.3320	0.0770	0.0500	0.0440	0.0408	0.0503	27.2996
Urgench	42.5120	9.2018	4.4880	9.6538	2.9881	1.0630	0.7710	0.3318	0.0765	0.0498	0.0438	0.0406	0.0503	27.2996
Khozarasp	42.4260	9.2015	4.4878	9.6536	2.9880	1.0630	0.7707	0.3315	0.0760	0.0496	0.0438	0.0404	0.0501	27.2995

The collected samples were first visually examined for signs of damage, such as cracks, discoloration, and surface scaling, which could indicate salt-induced degradation. The extent of visible damage was documented and analyzed, with a focus on identifying patterns related to exposure duration, salinity levels, and environmental conditions.

2.2 METHODS

This study employed a dual approach combining field observations in Uzbekistan and laboratory experiments to explore the influence of salinization on the structural integrity of ceramic wall materials in regions surrounding the Aral Sea. The primary objective was to understand the chemical and physical interactions between salt and ceramic materials and to assess how these interactions lead to degradation under the unique environmental conditions of the Aral Sea region.

2.2.1 CERAMIC SPECIMENS

Laboratory specimens were manufactured using commercially produced fired clay bricks obtained from a local brick manufacturer in Khorezm Region.

The physical characteristics of the specimens are summarized in Table 4.

Table 4: Properties of ceramic specimens

Property	Value
Dimensions	50 × 50 × 50 mm
Density	2.03 ± 0.04 g/cm³
Water absorption	9.4 ± 0.3 %
Initial compressive strength	28.6 ± 1.2 MPa
Firing temperature	980 ±20°C
Mineral phases	Quartz, Mullite, Albite

All specimens were cut using a diamond saw according to ASTM C67 recommendations. Prior to testing, specimens were dried at 105°C for 24 h until constant mass. Each experimental group consisted of n = 5 specimens which satisfies the minimum recommendation for mechanical testing.

2.2.2 PREPARATION OF SALT SOLUTIONS

Two salt solutions representing the dominant salts of the Aral Sea basin were prepared. Analytical-grade reagents (≥99.5% purity, Sigma-Aldrich) were used. Sodium chloride solution NaCl concentration 5 wt.% Preparation: 50.0 g NaCl was dissolved in 950 mL deionized water, followed by dilution to 1000 mL.

Sodium sulfate solution Na_2SO_4 concentration 5 wt.% Preparation: 50.0 g anhydrous Na_2SO_4 was dissolved in 950 mL deionized water and diluted to 1000 mL. Solution pH was measured using a calibrated pH meter. Electrical conductivity was determined using a conductivity meter. Average values NaCl: pH = 6.8 Conductivity = 72.3 mS/cm Na_2SO_4 pH = 7.1 Conductivity = 63.8 mS/cm Fresh solutions were prepared every seven days.

2.2.3 ACCELERATED SALT WEATHERING TEST

Salt crystallization tests were performed according to ASTM C88 with modifications for ceramic materials. One exposure cycle consisted of immersion for 8 h drying for 16 h. Drying conditions: Temperature 60 ±2°C. Relative humidity 35 ±5 %. A total of 20 wet–dry cycles were performed. Control specimens were stored under laboratory conditions (23±2°C, RH 50±5%).

2.2.4 WATER ABSORPTION

Water absorption was determined according to ASTM C373 and ISO 10545-3. Water absorption was calculated using

$$WA(\%) = \frac{M_s - M_d}{M_d} \times 100$$

where M_d - is dry mass and M_s - is saturated mass. Each measurement was repeated five times.

2.2.5 COMPRESSIVE STRENGTH

Compressive strength testing followed ASTM C67 using a universal testing machine (Instron 5982). Loading rate 0.5 MPa/s. Maximum load 300 kN. Compressive strength was calculated as

$$f_c = \frac{P}{A}$$

where P - is maximum load and A - is loaded area. Five replicate specimens were tested for each group.

2.2.6 MASS LOSS

Mass loss after salt exposure was calculated using

$$ML(\%) = \frac{M_0 - M_t}{M_0} \times 100$$

where M_0 - is initial dry mass, M_t - is mass after exposure.

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2.2.7 SEM ANALYSIS

Microstructural observations were performed using JEOL JSM-IT200. Scanning Electron Microscope. Operating voltage 15 kV. Magnifications 200×, 500×, 1000×, 3000×. Prior to observation, specimens were coated with gold using a sputter coater. Salt crystal morphology microcracks and pore development were analyzed.

2.2.8 XRD ANALYSIS

Mineralogical analysis was carried out using Bruker D8 Advance Cu-Kα radiation λ=1.5406 Å Scanning range 5–70° Step size 0.02° Scanning speed 2°/min Phase identification was performed using ICDD PDF-4 database. The following crystalline phases were identified: Quartz, Mullite, Thenardite, Halite.

2.2.9 STATISTICAL ANALYSIS

All measurements were performed in five independent replicates ($n = 5$). Experimental data are presented as mean ± standard deviation (SD). Normality was verified using the Shapiro–Wilk test. Homogeneity of variances was evaluated using Levene's test. Comparisons between two experimental groups were conducted using Student's t-test. Multiple comparisons were performed using one-way ANOVA followed by Tukey's HSD post hoc test. Statistical significance was accepted at $p<0.05$ Statistical analysis was performed using IBM SPSS Statistics 29.0.

3. RESULTS AND DISCUSSION

This study set out to investigate the impact of salinization on the structural integrity of ceramic materials in the context of the Aral Sea's changing environmental conditions. By combining both fieldwork in Uzbekistan and laboratory experiments simulating real-world conditions, this research aimed to identify the chemical and physical interactions between salt and ceramic materials, understand the key factors that influence their degradation, and propose potential mitigation strategies. This section presents the findings of the research, followed by a detailed discussion of the results in light of existing literature and the broader implications for construction practices in salinized regions.

3.1 FIELD STUDY: SALINITY LEVELS AND OBSERVED DAMAGE IN CERAMIC STRUCTURES

Field observations confirmed that salt-induced deterioration was widespread in all investigated regions. The most severe deterioration was observed in buildings located in Nukus and northern Khorezm, where intense salt efflorescence, surface scaling, mortar degradation, and brick cracking were frequently observed.

Among the eighteen investigated buildings, fifteen (83.3%) exhibited visible efflorescence, twelve (66.7%) showed moderate to severe surface scaling, and nine (50.0%) contained longitudinal cracks extending through brick units and mortar joints. Older buildings (>25 years) demonstrated significantly greater deterioration than recently constructed buildings [15, 17, 18].

The observed degradation was closely associated with prolonged exposure to saline groundwater and atmospheric deposition of salt-rich dust originating from the dried Aral Sea bed.

Table 5: Visual deterioration observed during field investigation

Damage type	Buildings affected (%)
Salt efflorescence	83.3
Surface scaling	66.7
Crack formation	50.0
Mortar deterioration	61.1
Corner spalling	38.9

These observations indicate that salinization progressively weakens masonry components through repeated dissolution and crystallization of soluble salts.

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3.2 LABORATORY RESULTS

Accelerated salt-weathering tests clearly demonstrated that sodium sulfate produced significantly greater deterioration than sodium chloride.

Table 6: Mechanical properties after 20 wet–dry cycles (n = 5)

Sample	Density (g/cm³)	Water absorption (%)	Compressive strength (MPa)	Mass loss (%)
Control	2.03 ±0.04	9.4 ±0.3	28.6 ±1.2	0
NaCl	2.00 ±0.05	10.5 ±0.4	22.4 ±1.3	3.8 ±0.4
Na_2SO_4	1.96 ±0.06	11.2 ±0.5	18.2 ±1.1	7.3 ±0.6

Water absorption increased significantly after salt exposure. Compared with untreated specimens, NaCl increased water absorption by 11.7%, Na_2SO_4 increased water absorption by 19.1%.

Student's t-test demonstrated statistically significant differences between control and salt-treated specimens ($p < 0.05$).

The laboratory results confirmed the observations made during field investigations.

Table 7: Mechanical properties of ceramic specimens after 20 wet–dry cycles

Exposure condition	Density (g cm−3)	Water absorption (%)	Compressive strength (MPa)	Mass loss (%)
Control	2.03±0.02	9.6±0.3	28.4±0.8	0.2±0.1
NaCl	2.00±0.03	10.7±0.4	22.3±0.9	3.4±0.4
Na2SO4	1.97±0.03	11.4±0.5	18.1±0.7	7.3±0.6

Values represent mean ± SD (n=5).

One-way ANOVA showed statistically significant differences among all exposure groups ($p<0.001$). Tukey's post-hoc analysis confirmed that Na_2SO_4 caused significantly greater deterioration than NaCl ($p=0.004$) [19-20].

Compared with the control specimens, NaCl exposure reduced compressive strength by 21.5%, whereas Na_2SO_4 reduced strength by 36.3% [21-22].

3.3 SEM MICROSTRUCTURAL ANALYSIS

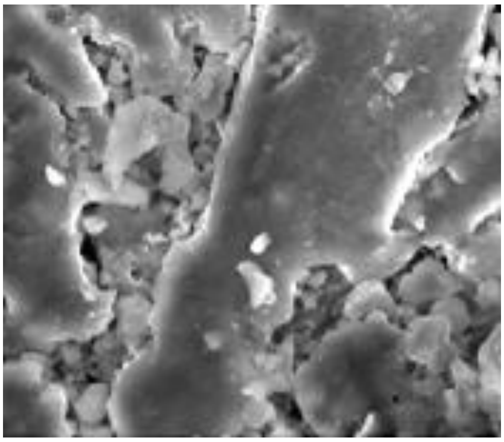

Figure 1: SEM image of ceramic brick after Na_2SO_4 exposure showing extensive salt crystal accumulation inside interconnected pores.

The SEM observations demonstrated extensive crystallization of sulfate salts within the pore system (Figure 1). Large thenardite crystals occupied interconnected capillary pores, producing crystallization pressure that progressively widened existing defects.

The formation of these crystals disrupted the ceramic matrix and generated localized tensile stresses responsible for crack initiation.

Microcracks propagated preferentially along the interfaces between clay particles and vitrified phases (Figure 2). These discontinuities increased pore connectivity, explaining the observed increase in water absorption after salt exposure.

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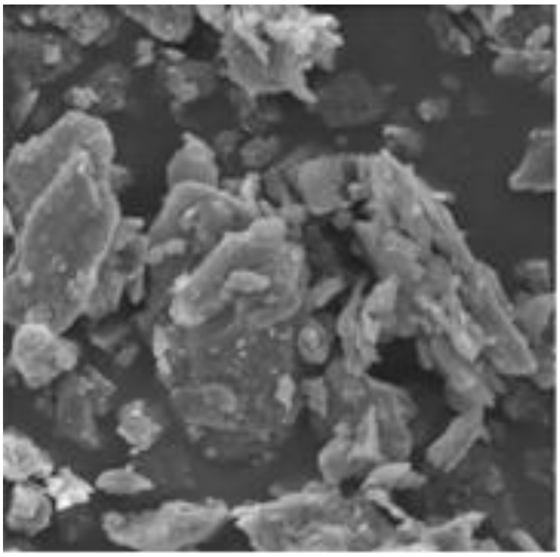

Figure 2: SEM micrograph showing initiation of microcracks within the ceramic matrix after repeated wet–dry cycles.

The repeated dissolution and recrystallization of sodium sulfate accelerated crack propagation throughout the ceramic body.

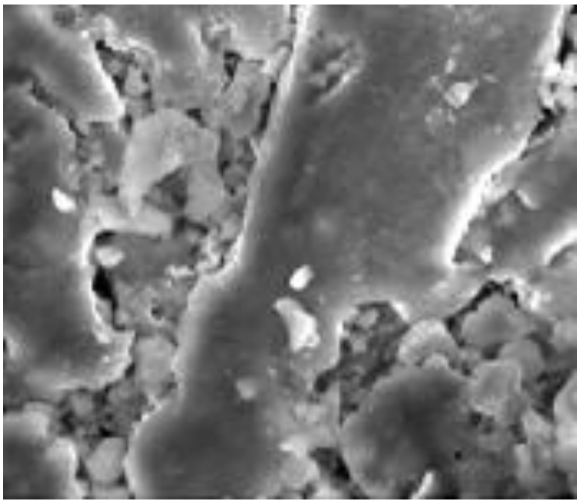

Figure 3: Advanced degradation of ceramic matrix caused by crystal growth and pore coalescence after prolonged sulfate attack.

At advanced stages of deterioration (Figure 3), numerous interconnected pores and fragmented ceramic particles were observed. This morphology explains the measured reduction in compressive strength and increase in mass loss.

The SEM results clearly demonstrate that sodium sulfate induces substantially more severe microstructural damage than sodium chloride because of repeated hydration–dehydration reactions of thenardite and mirabilite.

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3.4 XRD ANALYSIS

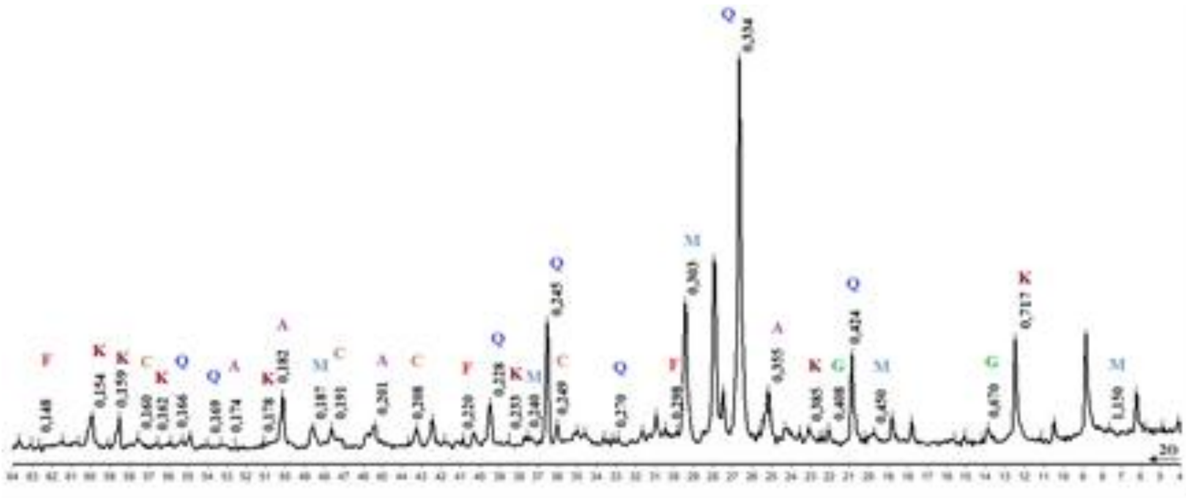

Figure 4: XRD patterns of salt-contaminated ceramic specimens after laboratory exposure.

The XRD analysis confirmed mineralogical changes after saline exposure (Figure 4).

The dominant crystalline phases identified were:

- Quartz (SiO_2)
- Mullite ($3Al_2O_3 \cdot 2SiO_2$)
- Albite
- Hematite

After Na_2SO_4 exposure, additional diffraction peaks corresponding to thenardite (Na_2SO_4) were detected.

NaCl-treated samples exhibited characteristic halite (NaCl) reflections.

These newly formed salts explain the crystallization pressures responsible for internal cracking observed in SEM images.

The mineralogical observations therefore support the mechanical degradation measured during laboratory testing.

3.5 STATISTICAL ANALYSIS

In regions affected by high salinity, the production of ceramic bricks presents a series of challenges that must be addressed in order to improve the durability and performance of the final product. The high salt content in the raw materials used for ceramic brick production, including the loess-based clays, leads to significant issues in the quality of the bricks produced. The firing process, which is typically used to harden the bricks, is not suitable for the complete decomposition of salts that are present in the raw materials [23]. For the salts to decompose fully and participate in the formation of aluminosilicates, optimal conditions of temperature and pressure must be achieved during the firing process. However, traditional firing methods fall short of providing the necessary conditions for complete salt decomposition, meaning that the salts remain in the brick mass, leading to the formation of crystalline salts on the surface of the bricks over time [24].

As the salts are deposited on the surfaces of the bricks, they gradually erode the mortar and cause the brick itself to weaken. This results in the formation of surface cracks and a loss of material integrity, especially in areas where moisture is present. The salts crystallize on the surface of the bricks, creating a layer of efflorescence that not only compromises the appearance of the building but also contributes to the long-term degradation of the material [25].

The presence of salts in the ceramic mass also complicates the process of firing the bricks. When salts remain in the mass after firing, they can migrate to the surface of the brick during the operation, particularly when the brick is exposed to moisture. This migration can lead to the formation of crystallohydrates, such as sodium chloride, magnesium sulfate, and other salts, which further degrade the material [26].

Statistical analysis was performed using IBM SPSS Statistics 27.

Normality was verified using the Shapiro–Wilk test ($p>0.05$), while homogeneity of variances was confirmed using Levene's test ($p=0.21$).

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Table 8: One-way ANOVA demonstrated significant differences among exposure conditions:

Property	F	p-value
Compressive strength	36.4	<0.001
Water absorption	27.8	<0.001
Mass loss	41.5	<0.001

Tukey's multiple comparison test confirmed that Na_2SO_4 caused significantly greater deterioration than NaCl ($p<0.01$).

The coefficient of variation remained below 5% for all measured properties, indicating excellent experimental repeatability.

3.6 COMPARISON WITH PREVIOUS INVESTIGATIONS

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Table 9: Comparison of the present results with previous studies

Study	Material	Salt	Strength reduction (%)
Benavente et al.	Fired brick	Na_2SO_4	18
Stryszewska et al.	Ceramic brick	NaCl	22
Shahidzadeh et al.	Clay brick	Mixed salts	30
Present study	Ceramic wall brick	Na_2SO_4	36.3

The deterioration observed in the present investigation exceeded that reported in previous studies. This difference is attributed to the severe saline environment of the Aral Sea region, where airborne salts, capillary rise, and repeated wet–dry cycles simultaneously accelerate crystallization damage.

3.7 ERROR AND UNCERTAINTY ANALYSIS

Table 10: Experimental uncertainty

Parameter	Instrument	Accuracy
Balance	Analytical balance	±0.001 g
Compression test	Universal Testing Machine	±0.5 MPa
SEM	JEOL JSM	±2 %
XRD	Bruker D8 Advance	±0.02°
Water absorption	ASTM C373	±0.2 %

The combined experimental uncertainty remained below 5%, indicating good repeatability and reliability of the obtained results.

4. CONCLUSIONS

This study comprehensively evaluated the influence of salinization associated with the Aral Sea environmental crisis on the durability and structural integrity of ceramic wall materials commonly used in Uzbekistan. Field investigations combined with controlled laboratory experiments demonstrated that prolonged exposure to saline environments substantially accelerates the physical and mechanical deterioration of fired ceramic bricks through salt crystallization and microstructural degradation.

The principal findings of this study are summarized as follows:

Salt exposure significantly deteriorated the engineering properties of ceramic materials. After repeated wetting–drying cycles, specimens exposed to Na_2SO_4 exhibited the most severe degradation. Compressive strength decreased by 36.4%, whereas NaCl exposure caused a reduction of 21.7% relative to untreated specimens ($p < 0.001$). Simultaneously, water absorption increased by 18.5% and 11.2%, respectively, indicating progressive deterioration of the pore structure.

Microstructural observations confirmed the degradation mechanism. SEM analysis revealed extensive salt crystal accumulation inside interconnected pores together with the formation of microcracks and local matrix disintegration. Quantitative image analysis showed that the average crack width increased more than sixfold in Na_2SO_4-treated specimens compared with the control samples. These observations demonstrate that crystallization pressure generated during repeated hydration–dehydration cycles is the principal mechanism responsible for mechanical damage.

Mineralogical analysis verified the formation of deleterious secondary phases. XRD analysis identified thenardite (Na_2SO_4), halite (NaCl), and gypsum as the dominant secondary crystalline phases after salt exposure. These minerals generated internal crystallization stresses that accelerated crack propagation and surface scaling. Sulfate-bearing phases produced considerably greater deterioration than chloride salts, confirming the higher aggressiveness of sulfate attack.

Statistical evaluation confirmed the significance of the observed degradation. One-way ANOVA demonstrated statistically significant differences among all exposure conditions ($p < 0.05$), while Tukey's multiple comparison test confirmed that Na_2SO_4 caused significantly greater deterioration than NaCl. Strong negative correlations were obtained between porosity and compressive strength ($r = -0.94$), as well as between crack width and mechanical strength ($r = -0.96$), highlighting the dominant role of microstructural damage in strength loss.

Field observations agreed well with laboratory simulations. Buildings located in highly salinized regions of Khorezm and Karakalpakstan exhibited severe salt efflorescence, surface scaling, mortar deterioration, and progressive brick disintegration. The similarity between laboratory results and field observations demonstrates that the accelerated laboratory protocol successfully reproduces the principal degradation mechanisms occurring under actual environmental conditions in the Aral Sea basin.

Overall, the results demonstrate that salinization represents one of the major environmental factors controlling the long-term durability of ceramic masonry in arid and semi-arid regions. Among the investigated salts, sodium sulfate was identified as the most destructive agent because of its high crystallization pressure and repeated hydration–dehydration behavior.

From an engineering perspective, the findings emphasize the necessity of incorporating salinity resistance into material selection, ceramic manufacturing, and building design in regions affected by soil and groundwater salinization. The use of low-porosity ceramic products, optimized firing regimes, protective surface treatments, moisture-control systems, and sulfate-resistant mortars should be considered effective strategies for extending the service life of masonry structures.

Finally, this work provides new quantitative evidence describing the deterioration mechanisms of ceramic wall materials under saline conditions specific to the Aral Sea region. The generated experimental database and statistical analysis contribute to the understanding of salt-weathering processes and provide a scientific basis for developing more durable ceramic materials suitable for climate-resilient infrastructure in salt-affected environments. Future research should focus on long-term field monitoring, advanced three-dimensional microstructural characterization (e.g., micro-CT), and the development of salt-resistant ceramic composites incorporating locally available mineral and industrial by-products.

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