EFFECT OF SALINITY ON COMPRESSIVE STRENGTH OF BRICK AGGREGATE CONCRETE

Md. Minhaz Uddin[1], Md. Khasro Miah[2], Robiul Islam*[3] and Sk Azharul Haque[4]

[1]*Graduate Student, Department of Civil Engineering, DUET, Gazipur, Bangladesh*
e-mail: minhaz.duet.ce28@gmail.com
[2] *Professor, Department of Civil Engineering, DUET, Gazipur, Bangladesh*
e-mail: mkhasro@duet.ac.bd
[3]*Graduate Student, Department of Civil Engineering, DUET, Gazipur, Bangladesh*
e-mail: robiulimlammd986@gmail.com
[4]*Graduate Student, Department of Civil Engineering, DUET, Gazipur, Bangladesh*
e-mail: azharul.duet@gmail.com

***Corresponding Author**

ABSTRACT

This study investigates the effect of salinity on the compressive strength development of brick aggregate concrete (BAC). Standard cylindrical specimens (Ø100 mm × 200 mm) were prepared with a constant mix ratio of 1:1.5:3 and a water-cement ratio of 0.50. Sodium chloride (NaCl) and magnesium sulfate ($MgSO_4$) were introduced into the mixing and curing water at concentrations of 15, 25, 25, 35, and 45 g/L, and 0.5, 1.0, 1.5, and 2.0 g/L, respectively, to simulate coastal exposure. A total of 255 specimens were cast and tested at 7, 28, 56, 90, and 180 curing days. Results revealed that moderate NaCl concentrations enhanced early-age strength due to accelerated hydration, showing up to a 22.7% increase at 7 days and 19.5% at 28 days compared to the control mix. The highest 56-day strength (30.4 MPa) was recorded at 45 g/L NaCl, about 14.8% higher than the control. However, prolonged exposure led to a decline, with 22.4% strength reduction at 180 days relative to the control concrete. In addition, $MgSO_4$ exposure consistently caused strength reduction, ranging from 9% at 28 days to 25-35% at 180 days depending on concentration. The findings highlight that chloride ions may enhance early hydration and strength, but long-term saline exposure particularly to sulfates significantly compromises the compressive strength of brick aggregate concrete. These results provide essential insights for sustainable concrete construction in saline-prone regions of Bangladesh.

Keywords: *Salinity, Compressive strength, Sodium chloride (NaCl), Magnesium sulfate ($MgSO_4$), Durability*

1. INTRODUCTION

Concrete is a popular construction material in civil engineering because of its high compressive strength, durability, flexibility, and adaptability in application (Islam et al. 2017). The mechanical properties of concrete, particularly its compressive strength, is critical in structural design because they affect a structure's resilience and ability to withstand loads. Nevertheless, the presence of salt compounds can have a substantial impact on the mechanical characteristics of concrete, resulting in a reduction in strength and durability (Alrowaih & Sulaiman, 2018). Furthermore, brick chips are commonly used as coarse aggregate in Bangladesh and regions like West Bengal because they are easily accessible and affordable (Islam et al., 2017). However, the appropriateness and durability of brick aggregate concrete are threatened by environmental saline attack especially in coastal turbulent and arid environments where both mixing and curing waters possess salts above the allowable limits (Bryant, 1964; Mbadike & Elinwa, 2011). Sodium chloride (NaCl) and magnesium sulfate ($MgSO_4$) are aggressive substances and can infiltrate the concrete during mixing and curing, affecting the hydration kinetics, pore structure, long-term mechanical performance and durability of concrete (Arunakanthi & Rao, 2013; Oladapo & Ekanem, 2014).

Several studies have reported that use of NaCl can enhance the early age compressive strength performance of concrete through an increase in the rate of hydration and refinement of pore (Liu et al., 2023), however, this is perfectly all right due to higher concentration or prolonged exposure by which it might cause reductions in strength through expansive reactions, microcracking and destabilization of hydration products, and thus reflecting on the bizarre behavior between type and content of salt intended with stimuli provided for its performance (Mbadike & Elinwa, 2011; Oladapo & Ekanem, 2014; Umoh 2012). The high-water absorption and porosity of brick aggregates enhance the penetration of sulphate salts in concrete, leading to the formation of ettringite and other expansive hydration products that degrade and weaken the strength of concrete (Arunakanthi & Rao, 2013; Tanvir et al., 2019; Umoh, 2012). At the microstructural level, the weak interface and high porosity of brick aggregates can exacerbate the ingress and effects of saline ions, causing concrete's mechanical properties and durability to deteriorate faster than in conventional stone aggregate mixes (Tanvir et al., 2019). Moreover, the susceptibility of brick aggregate concrete to environmental aggression is further conditioned by factors such as water–cement ratio, cement type, and the mineral composition of the bricks and sands used.

Despite ongoing study, a complete understanding of the impacts of salinity is still lacking, especially for brick aggregate concrete subjected concurrently to different salt types, concentrations, and curing methods over extended periods of time. The early-age and long-term (>90 days) performance of concrete under local environmental conditions is often overlooked in prior study (Taylor, 1978; Wang et al., 2025). The combined effects of several salt sources, such as aggregates, mixing water, and curing water, in coastal regions are also unexplored because most research only concentrate on one or two salt sources at a time (Arunakanthi & Rao, 2013). In order to address these issues, the aim of this study is to investigate the effects of salinity on compressive strength of brick aggregate concrete.

2. MATERIALS AND METHODOLOGY

2.1 Collection of Materials

To accurately represent the real construction conditions in Bangladesh, all materials used in this research (shown in Figure 1) were sourced locally. Ordinary Portland cement (Type I) was employed as binder, and the packing density was enhanced by incorporating fine aggregate, specifically Sylhet sand. First class burnt clay brick chips, with a maximum size of 25 mm, were used as coarse aggregates. In order to control the w/c ratio, the brick aggregates were cleaned, sieved, and maintained in a saturated surface-dry (SSD) state before mixing. Potable tap water was used to prepare the control concrete as well as the saline solutions of magnesium sulfate (MgSO4) and sodium chloride (NaCl) for the purpose of mixing as well as curing. To replicate the salinity levels of Bangladesh's coastal areas, controlled saline conditions were prepared using analytical-grade salts.

Figure 1 Photograph of materials (cement, sand, and brick chips).

2.2 Tests on Materials

Laboratory tests were conducted on all constituent materials to determine their fundamental physical properties in accordance with ASTM standards (Table 1). Ordinary Portland Cement (OPC) exhibits normal consistency, with initial and final setting times within the standard range specified for cement. Compressive strength tests on typical mortar cubes revealed favorable results at early ages, validating their applicability for structural concrete applications. Table 1 displays the test results of cement and applicable standards.

Table 1 Properties of Cement

Property		Test Standard	Present Study	ASTM C150
Normal Consistency (%)		ASTM C187 (2016)	25	28-32
Initial Setting Time (min)		ASTM C191(2021)	67	≥ 45
Final Setting Time (min)		ASTM C191(2021)	339	≤ 375
Compressive Strength (MPa)	3 days	ASTM C109 (2016)	17.52	12
	7 days	ASTM C109 (2016)	21.43	19

This study employed two types of fine aggregates. Local sand exhibited a lower fineness modulus, medium specific gravity, and low water absorption, but Sylhet sand had a greater fineness modulus, comparable specific gravity, and somewhat higher water absorption. The two sands were different compacted and loose unit weights, which reflected their gradation and packing characteristics. The physical parameters of fine aggregate are illustrated in Table 2.

Table 2 Physical Properties of Fine Aggregates

Property	Unit	Test Standard	Present Study
Fineness Modulus	-	ASTM C136(2019)	2.76
Specific Gravity (SSD)	-	ASTM C128(2007)	2.69
Water Absorption (%)	*%*	ASTM C128(2007)	2.95
Unit Weight	kg/m^3	ASTM C29(2017)	1590

The coarse aggregate consisted of crushed brick chips that show considerable water absorption, highlighting their porous nature, which affects the effective water-cement ratio and subsequently the strength progression of the concrete. Additionally, the physical properties, including unit weight and specific gravity, also have an impact on concrete performance. Physical properties of coarse aggregate are shown in Table 3.

Table 3 Properties of Coarse Aggregate (Brick Chips)

Property	Unit	Test Standard	Present Study
Fineness Modulus	-	ASTM C136 (2019)	6.59
Specific Gravity (SSD)	-	ASTM C127 (2007)	2.02
Water Absorption	*%*	ASTM C127 (2007)	19.2
Unit Weight	*kg/m³*	ASTM C29 (2017)	944

2.3 Mixing of Materials

The concrete mixture was prepared with a consistent water-to-cement ratio of 0.50, using a mix proportion of 1:1.5:3 for cement, sand, and brick aggregate. Fine aggregate mix was produced by combining two varieties of sand, selected according to their fineness modulus. Saline solutions were prepared by dissolving analytical-grade salts in potable water. The concentrations of magnesium sulfate were adjusted to 0.5, 1.0, 1.5, and 2.0 g/L, while the sodium chloride concentrations were maintained at dosage of 15, 25, 35, and 45 g/L respectively. To replicate realistic saline exposure, concrete in the combined-exposure condition was mixed and cured with saline water. Conversely, in the saline-mixing-only condition, concrete was mixed with saline water but cured with fresh water. The mix proportions of different concrete materials are presented in Table 4. Then all materials were measured and mixed for five to six minutes at a speed of 15 to 20 rpm in a tilting-drum mechanical mixer to ensure uniformity. The mixing process of concrete is illustrated in Figure 2.

Table 4 Materials Detail for Preparing 1 m³ of Concrete (w/c = 0.50)

Salt Type	Concentration (g/L)	Cement (kg)	Sand (kg)	Brick Aggregate (kg)	Water (kg)	Salt (Kg)
NaCl	15	393	650	772	196	2.94
	25	393	650	772	196	4.90
	35	393	650	772	196	6.87
	45	393	650	772	196	8.83
$MgSO_4$	0.5	393	650	772	196	0.098
	1.0	393	650	772	196	0.196
	1.5	393	650	772	196	0.294
	2.0	393	650	772	196	0.392

Figure 2 Mechanical mixing of concrete in the laboratory.

2.4 Preparation of Specimens

The concrete was poured into cylindrical molds of 100 mm diameter and 200 mm height. Each mold was filled in three layers, and each layer was compacted with 25 blows of a tamping rod to eliminate air voids. The molds were lightly oiled before the concrete was poured and were removed the next day. For this study, 15 control specimens were prepared using fresh water. Additionally, 120 specimens were mixed with saline solutions (NaCl or $MgSO_4$) but cured with fresh water, while another 120 specimens were both mixed and cured with saline water at the specified salts concentrations. The experimental matrix is presented in Table 5. To evaluate both early-age and long-term strength characteristics, the specimens were cured for 7, 28, 56, 90, and 180 days, respectively. The saline curing water was replaced every seven days to maintain constant salinity and prevent concentration loss due to evaporation or absorption. The casting and curing process of cylindrical specimens is shown in Figure 3.

Table 5 Experimental Matrix

Group	Salt Type	Curing Water	Concentrations (g/L)	No. of Specimens
A	-	Fresh	0	15
B	NaCl	Fresh	15, 25, 35, 45	60
		Saline	15, 25, 35, 45	60
C	$MgSO_4$	Fresh	0.5, 1.0, 1.5, 2.0	60
		Saline	0.5, 1.0, 1.5, 2.0	60

Figure 3 Casting and curing of cylindrical concrete specimens.

2.5 Tests on Specimens

After the specified curing ages, the samples were tested for compressive strength utilizing a 3000 kN Universal Testing Machine (UTM) according to ASTM C39 (2021). A thin layer of 1:3 cement-sand paste (w/c = 0.50) was applied to the ends of the specimens prior to testing to ensure uniform load distribution. The load was applied constantly at a rate of approximately 0.40 MPa/s until failure occurred. The compressive strength was determined by dividing the maximum load by the cross-sectional area of the specimen. The average strength for each condition was computed by taking the mean of the results obtained from three specimens. The testing procedure of cylindrical specimens is illustrated in Figure 4.

Figure 4 Compressive strength testing of concrete specimens.

3. RESULT AND DISCUSSION

This section examines how sulfate (MgSO4) and chloride (NaCl) salts influence the compressive strength of concrete over different curing durations. Figures 5 to 8 illustrate the variations in concrete strength as a function of the concentration of mixing and curing water that contains these salts. The results reveal that low or moderate proportion of NaCl in the mixture can lead to accelerated early-age strength development due to an enhanced rate of hydration, whereas high concentrations or prolonged exposure adversely affect long-term performance. On the contrary, the formation of gypsum and ettringite from MgSO4 is always accompanied by a loss of strength, which is an unfavorable effect on concrete durability.

In contrast, the strength deterioration of brick aggregate concrete exposed to $MgSO_4$ is primarily caused by sulfate reactions with cement hydration products, leading to the formation of gypsum and ettringite (Benkabouche et al., 2023). Sulfate ions react with calcium hydroxide to form gypsum, an expansive compound that increases porosity and weakens the cement matrix (Penttala, 2009). Magnesium ions further decalcify the C–S–H gel, producing non-cementitious magnesium silicate hydrate (M–S–H), which significantly reduces strength and cohesion. Moreover, sulfate ions react with tricalcium aluminate phases to form secondary ettringite after hardening. This delayed ettringite formation generates internal expansive stresses, causing microcracking and degradation at the aggregate–paste interface (Jebli et al., 2021). These effects are intensified in brick aggregate concrete due to its higher porosity and permeability, facilitating deeper sulfate ingress. Consequently, prolonged $MgSO_4$ exposure results in progressive strength loss, consistent with the significant reductions observed at 90 and 180 days, highlighting the detrimental effect of sulfates on concrete durability.

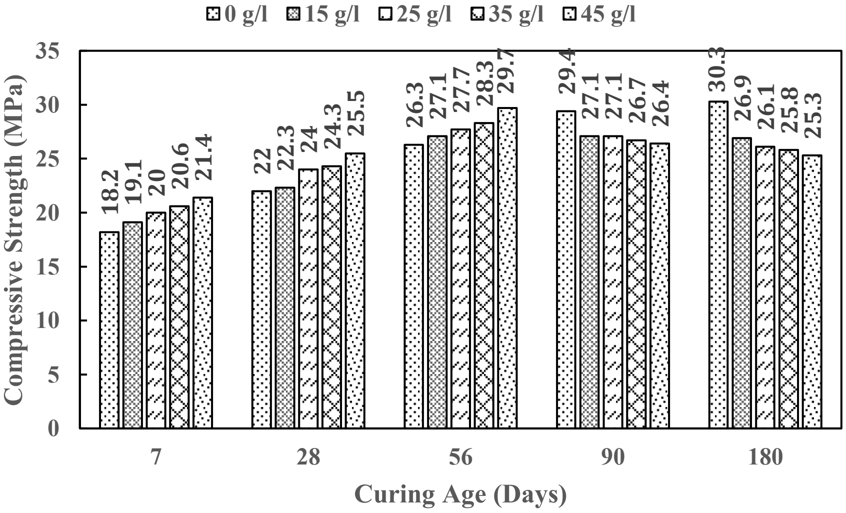

Figure 5 Compressive strength versus curing age (days) for different NaCl dosages in curing water

Figure 5 illustrates the variation in compressive strength at different curing ages under various concentrations of NaCl in the curing water. The x-axis represents the curing age (7, 28, 56, 90, and 180 days), while the y-axis indicates the corresponding compressive strength in MPa. Each set of bars compares the effect of NaCl concentrations of 0, 15, 25, 35, and 45 g/L at each curing age.

The Compressive strength increased markedly with the increasing of NaCl concentration in the first seven days curing period. For 45 g/L NaCl, the mix reached 21.4 MPa, which was an increase of 17.7% in strength over control specimen (0 g/L) strength of 18.2 MPa. A comparable trend was also shown at 28 curing days where the mixture of 45 g/L reached a strength of 25.5 MPa, compared to 22.0 MPa for the control specimen, representing an increase of 15.9% over the control sample. This early age improvement can be attributed due to the accelerating impact of chloride ions, which promote rapid hydration and the formation of additional calcium silicate hydrate (C-S-H) gel (Liu et al., 2023). The mixture containing 45 g/L achieved the highest compressive strength of 29.7 MPa at 56 days, which was approximately 13.2% higher than the control. However, over time, this trend shifted. By 90 days, the 45 g/L sample experienced a 12% drop to 26.4 MPa, while the control mix increased to 30.0 MPa. The disparity became even more pronounced at 180 days, when the control reached 30.3 MPa, whereas the 45 g/L mix only measured 25.3 MPa, reflecting a 16.4% decline in strength. The decrease in strength after 56 days may be attributed to prolonged exposure leading to salt crystallization in the capillary pores, with NaCl potentially being the cause (Zheng et al., 2021). This generates internal stresses, induces microcracking, increases porosity, and consequently leads to a gradual decline in compressive strength at later ages (Kang et al., 2025).

Overall, compressive strength increased with curing duration for all mixes, reflecting continued hydration. However, prolonged exposure to high chloride concentrations negatively influenced long-term strength, likely due to salt crystallization and pore disruption. Moderate saline levels enhanced early-age strength, while excessive chloride exposure led to gradual deterioration in mechanical performance and durability.

Figure 6 presents the variation in compressive strength of concrete cured in magnesium sulfate ($MgSO_4$) solution with concentrations of 0, 0.5, 1.0, 1.5, and 2.0 g/L at curing ages of 7, 28, 56, 90, and 180 days. The results reveal a distinct influence of $MgSO_4$ concentration and curing duration on the strength development of concrete. At 7 days, the control mix (0 g/L) achieved a strength of 18.2 MPa, while specimens with 0.5, 1.0, 1.5, and 2.0 g/L showed 17.8, 16.8, 16.2, and 15.4 MPa, indicating reductions of 2.1%, 7.8%, 10.9%, and 15.3%, respectively. As curing progressed, all samples exhibited strength gain due to continued hydration; however, mixes exposed to higher $MgSO_4$ concentrations consistently showed lower values. At 28 days, the control achieved 22.0 MPa, while 0.5 and 2.0 g/L specimens recorded 21.9 and 21.4 MPa, respectively, showing minimal deviation. Beyond 56 days, the negative effect of $MgSO_4$ became more evident. The control mix achieved 26.3 and 29.4 MPa at 56 and 90 days, respectively, while the 2.0 g/L sample dropped to 24.1 MPa (−8.6%) and 22.1 MPa (−25%) for same curing ages.

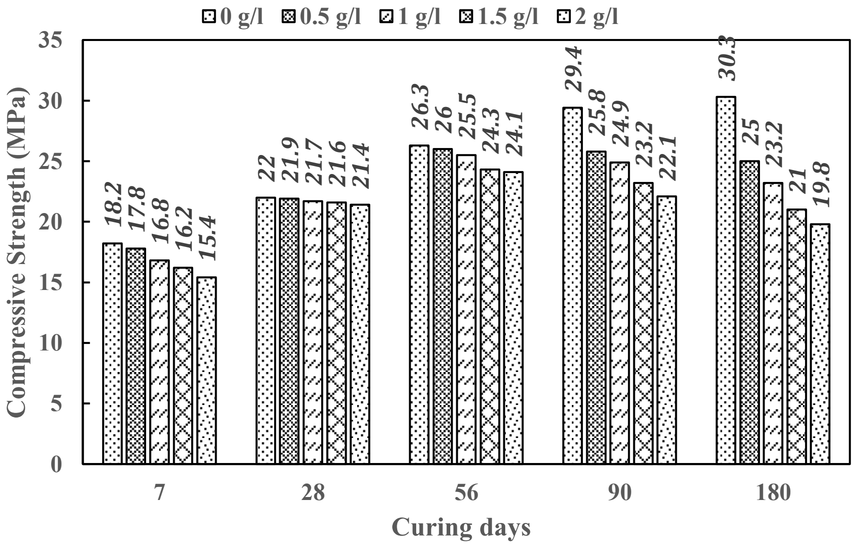

Figure 6 Compressive strength versus curing age (Days) for different $MgSO_4$ dosages in curing water

At 180 days, the control attained 30.3 MPa, whereas the 0.5–2.0 g/L mixes ranged between 25.0 and 19.8 MPa, corresponding to 17–35% strength losses over control specimen. Prolonged exposure to higher sulfate concentrations accelerates the formation of expansive compounds such as gypsum and ettringite, leading to microcracking, loss of cohesion, and substantial strength deterioration (Wu et al., 2021).

Figure 7 presents the variation of compressive strength with curing age for concrete specimens prepared and cured using water with different NaCl concentrations (0, 15, 25, 35, and 45 g/L). The horizontal axis represents curing ages, and the vertical axis shows compressive strength in MPa, with each series corresponding to a specific NaCl dosage.

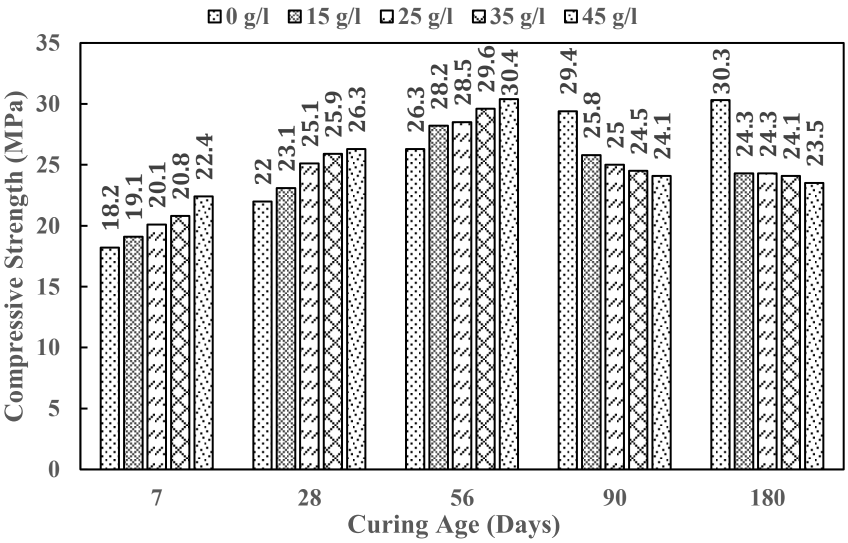

Figure 7 Compressive strength versus curing age (Days) for different NaCl dosages in both mixing and curing water

At 7 days of curing, compressive strength increased with NaCl content. The control mix (0 g/L) reached to 18.2 MPa, while the concrete mix containing 45 g/L NaCl achieved 22.4 MPa, indicating a 22.7% increase over control specimen. The specimens containing 15, 25, and 35 g/L NaCl, exhibited compressive strengths of 19.1, 20.1, and 20.8 MPa respectively, corresponding to increases of 4.6%, 10.3%, and 14.4% over the control specimen. This early enhancement is attributed to chloride ions accelerating hydration and promoting additional C–S–H gel formation (Liu et al., 2023). By 28 curing days, all mixes continued to gain strength. The 45 g/L specimen reached 26.3 MPa, 19.5% higher than the control mix (22.0 MPa), while 15, 25, and 35 g/L mixes showed increases of 4.7%, 13.8%, and 17.7%, respectively. At 56 days, the 45 g/L mix achieved the highest strength of 30.4 MPa, about 14.8% higher than the control (26.3 MPa).

Beyond 56 days of curing, prolonged exposure to high NaCl concentrations caused strength deterioration. At 90 days, the control reached mix obtained 29.4 MPa, whereas the 45 g/L mix dropped to 24.1 MPa, a 17.9% reduction compared to control concrete. The 35 g/L specimen also decreased slightly to 24.5 MPa (16.6% lower than control). At 180 days, the control attained 30.3 MPa, while the 45 g/L mix further declined to 23.5 MPa, representing a 22.4% loss. Lower NaCl concentrations (15–35 g/L) experienced minor reductions but remained stronger than the highest concentration.

These results demonstrate a dual effect of NaCl: moderate concentrations enhance early-age strength via accelerated hydration (Liu et al., 2023), whereas excessive chloride content adversely affects long-term mechanical performance due to deterioration of the pore structure and durability (Wang et al., 2025).

Figure 8 depicts the development of compressive strength for concrete specimens prepared and cured in magnesium sulfate ($MgSO_4$) solutions of varying concentrations (0, 0.5, 1.0, 1.5, and 2.0 g/L) over curing ages of 7, 28, 56, 90, and 180 days. The results indicate that strength gain with age is evident across all mixes; however, higher $MgSO_4$ concentrations consistently resulted in strength deterioration compared to the control. At 7 days of curing, the control mix recorded 18.2 MPa, whereas the 0.5, 1.0, 1.5, and 2.0 g/L $MgSO_4$ mixed specimens achieved 18.1, 18.0, 17.2, and 16.9 MPa, respectively. With continued curing, the control mix reached 22.0 MPa at 28 days, while the 2.0 g/L specimen dropped to 20.1 MPa, showing about 9% strength reduction. Beyond 56 days of curing, the adverse effect of $MgSO_4$ became more prominent.

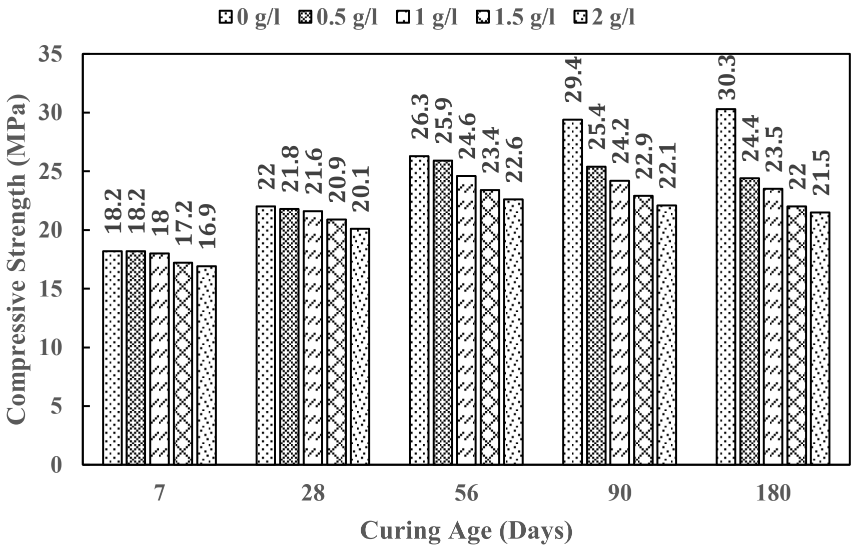

Figure 8 Compressive strength versus curing age (Days) for different $MgSO_4$ dosages in both mixing and curing water

At 90 days of curing, the control reached 29.4 MPa, while the 2.0 g/L sample decreased to 22.1 MPa, approximately 25% lower over control specimen. After 180 days, the control specimen achieved 30.3 MPa, whereas 0.5, 1.0, 1.5, and 2.0 g/L mixes showed 24.4, 23.5, 22.0, and 21.5 MPa, indicating 19 to 29% strength losses. However, higher $MgSO_4$ concentrations promoted the formation of expansive phases such as gypsum and ettringite, leading to internal stresses, cracking, and overall degradation of the cement matrix (Benkabouche et al., 2023). These findings confirm the progressively harmful influence of $MgSO_4$ on the long-term durability and strength of concrete.

4. LIMITATIONS AND FUTURE STUDIES

Despite offering helpful insights into the effect of salinity on the compressive strength of brick aggregate concrete, this study has some shortcomings that should be addressed in future research.

i. This study only looked at compressive strength; other key mechanical and durability properties including tensile and flexural strength, modulus of elasticity, permeability, and shrinkage were not evaluated. Future research may be included these factors to better assess the long-term performance of brick aggregate concrete in saline conditions;
ii. Secondly, the effects of NaCl and $MgSO_4$ were examined separately, although real coastal exposure generally involves combined salt actions. Further research should look into mixed-salt scenarios to better simulate field conditions and understand mutual degradation mechanisms;
iii. A single mix proportion (1:1.5:3) with a constant water-cement ratio of 0.50 was employed in this study. Future research could investigate into different mix designs, and water-cement ratio.

5. CONCLUSIONS

Based on the above limited experimental results and discussions, the following key conclusions can be drawn:

i. Compressive strength improved with increasing NaCl content up to 56 days of curing, reaching early-age strength gains of up to 20% due to accelerated hydration and enhanced C–S–H formation. However, beyond 56 days, increases in NaCl resulted in a gradual strength reduction;

ii. Exposure to $MgSO_4$ progressively reduced compressive strength with increasing $MgSO_4$ concentration, with up to 35% loss observed at 2.0 g/L concentration after 180 days, mainly due to gypsum and ettringite formation. However, for same dosage of $MgSO_4$, strength still increased with curing age;

iii. When the salt was present in both mixing and curing water, NaCl produced a slight increase in compressive strength up to 56 days of curing; however, beyond 56 days of curing, strength reduction was more pronounced compared to specimens where NaCl was added only to mixing water. In contrast, $MgSO_4$ caused a continuous reduction in strength throughout the entire curing period, with the rate of loss being higher when the salt was in both mixing and curing water than when added solely to curing water.

ACKNOWLEDGEMENTS

The authors sincerely acknowledge the Department of Civil Engineering, Dhaka University of Engineering & Technology, Gazipur, for their support in providing laboratory facilities and funding to carry out this research.

DECLARATION OF USE OF AI

The authors used artificial intelligence (AI) only to improve the language, grammar, clarity, and structure of the written content. The research concepts, methodology, data analysis, result interpretation, and technology findings were developed independently and without the use of AI technologies. The authors meticulously reviewed and confirmed every aspect of the work to ensure accuracy, originality, and compliance with academic and ethical standards.

REFERENCES

Alrowaih, A., & Sulaiman, A. A. (2018). Effects of Sulphate in Sea Water on Mechanical Strength of Concrete under Various Environmental Conditions. International Journal of Scientific Engineering and Research (IJSER), 6(4), 108-113. https://www.ijser.in/abstract.php?paperid=IJSER172498 https://www.doi.org/10.70729/IJSER172498

Arunakanthi, E., & Rao, N. C. (2013). Effects of magnesium sulfate in mixing and curing water on strength of high-performance metakaolin concrete. International Journal of Engineering Research & Technology, 2(12), 268–274.

ASTM C109 (2016a). Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2 in. or [50-mm] Cube Specimens). ASTM International, West Conshohocken, PA, USA.

ASTM C127 (2007). Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate. ASTM International, West Conshohocken, PA, USA.

ASTM C128 (2015). Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate. ASTM International, West Conshohocken, PA, USA. ASTM C136 (2019). Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates. ASTM International, West Conshohocken, PA, USA.

ASTM C136 (2019). Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates. ASTM International, West Conshohocken, PA, USA

ASTM C150, Standard Specification for Portland Cement, Annual Book of ASTM Standards, ASTM International, West Conshohocken, PA, USA, 2022. https://store.astm.org/c0150_c0150m-21.html

ASTM C187 (2016). Standard Test Method for Normal Consistency of Hydraulic Cement. ASTM International, West Conshohocken, PA, USA.

ASTM C191 (2021). Standard Test Method for Time of Setting of Hydraulic Cement by Vicat Needle. ASTM International, West Conshohocken, PA, USA. ASTM C29 (2017a). Standard Test Method for Bulk Density (Unit Weight) and Voids in Aggregate. ASTM International, West Conshohocken, PA, USA.

ASTM C39 (2021). Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. ASTM International, West Conshohocken, PA, USA.

Benkabouche, A., Amar, M., Benzerzour, M., Abriak, N.-E., T'kint, M., & Mouli, M. (2023). The Influence of External Sulfate Attack on the Durability of Reinforced Mortars in the Presence of Calcined River Sediments. *Materials*, *16*(20), 6684. https://doi.org/10.3390/ma16206684

Bryant, M. (1964). Effects of ocean salts on the compressive strength of concrete. Defense Technical Information Center. https://apps.dtic.mil/sti/citations/AD0739563

Islam, M. N., Uddin, M. K., & Rahman, M. M. (2017). Compressive strength of brick aggregate concrete using saline water. Journal of Engineering Science, 8(2), 45–53.

Jebli, M., Jamin, F., Pelissou, C., Lhopital, E., & Youssoufi, M. S. E. (2021). Characterization of the expansion due to the delayed ettringite formation at the cement paste-aggregate interface. *Construction and Building Materials*, *289*, 122979. https://doi.org/10.1016/J.CONBUILDMAT.2021.122979

Kang, W., Liu, S., Chen, Y., Yang, S., Liu, Z., Wang, Y., & Sun, H. (2025). Methods for Accelerating Physical Salt Attack on Cement-Based Materials in Laboratory Testing: Effects of Curing Age and Water-to-Cement Ratio. *Buildings*, *15*(16). https://doi.org/10.3390/buildings15162836

Liu, W., Du, H., Li, Y., Yi, P., Luo, Y., Tang, L., & Xing, F. (1500). *Effects of chloride content on early hydration performance of 2 cement pastes*. https://ssrn.com/abstract=4386973

Mbadike, E. M., & Elinwa, A. U. (2011). Effect of salt water in concrete. Nigerian Journal of Technology, 30(2), 63–68.

Oladapo, O., & Ekanem, S. (2014). Effect of sodium chloride on concrete compressive strength. International Journal of Engineering Research and Technology, 3(3), 1560–1564.

Penttala, V. (2009). Causes and mechanisms of deterioration in reinforced concrete. *Failure, Distress and Repair of Concrete Structures*, 3–31. https://doi.org/10.1533/9781845697037.1.3

Taylor, H. F. W. (1978). Cement Chemistry (1st ed.). Academic Press.

Umoh, A. A. (2012). Effect of different sulphate types and contents on compressive strength of periwinkle shell ash blended cement concrete. Journal of Engineering Science and Technology Review, 5(1), 70–76.

Wang, T., Liu, C., Liu, H., Wu, Y., Zhu, C., Yun, J., & Shi, H. (2025). Performance evolution of concrete modified with high-concentration saline effluent: From mechanical properties to freeze-thaw durability enhancement. *Construction and Building Materials*, *471*, 140703. https://doi.org/10.1016/J.CONBUILDMAT.2025.140703

Wang, Y., Wu, Z., Zheng, X., Li, K., & Liu, C. (2025). A review of concrete exposed to low-temperature environments at early ages: mechanical properties and durability. *Journal of Building Engineering*, *111*, 113122. https://doi.org/10.1016/J.JOBE.2025.113122

Wu, Q., Ma, Q., & Huang, X. (2021). Mechanical properties and damage evolution of concrete materials considering sulfate attack. *Materials*, *14*(9). https://doi.org/10.3390/ma14092343

Zheng, X., Liu, F., Luo, T., Duan, Y., Yi, Y., & Hua, C. (2021). Study on Durability and Pore Characteristics of Concrete under Salt Freezing Environment. Materials, 14(23), 7228. https://doi.org/10.3390/ma14237228