

Mechanical Properties and Frost Resistance of Cement-Modified Soil Treated with Sucrose-NaCl Composite for Subgrades in Cold-Region Metallurgical Plants

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Abstract: Subgrade infrastructure in metallurgical plants located in cold regions is highly susceptible to deterioration from freeze-thaw (F-T) cycles and performance loss due to delays between mixing and compaction. This study investigates a composite chemical admixture of sucrose and sodium chloride (NaCl) to enhance cement-stabilized soils for subgrade applications. Laboratory testing included standard Proctor compaction to determine density configurations, unconfined compressive strength (UCS) testing under simulated operational delay periods (0–3) h, and strict freeze-thaw (F-T) cyclic evaluations for durability profiling. Results identified an optimal dosage of 0.08 % sucrose and 1.0 % NaCl (by cement mass). This composite mix achieved a maximum dry density of 2.136 g·cm⁻³ (97.96 % of the non-admixed control), increased 28-day UCS by 12.88 % to 3.33 MPa, and exhibited minimal strength loss after five freeze-thaw cycles. Sucrose effectively preserved workability to mitigate delay effects, while NaCl concurrently enhanced strength and frost resistance. The proposed admixture system provides a practical solution for constructing durable subgrades in cold-climate metallurgical facilities.

Keywords: cement-stabilized soil; metallurgical plant infrastructure; freeze-thaw durability; chemical admixture; delayed compaction

1. Introduction

The construction and maintenance of robust infrastructure within metallurgical plants situated in cold climatic zones present distinct engineering challenges. In this context, "robust infrastructure" specifically refers to the heavy-duty pavement subgrades and foundation beds that support critical plant operations. Plant road subgrades, essential for the continuous transport of heavy equipment—such as multi-axle slag pot carriers and raw material haulers—must withstand dynamic and vibrational loading effects far exceeding those of conventional municipal road networks [1]. Furthermore, these subgrades are perennially exposed to process-related chemical run-offs, localized temperature gradients, and detrimental freeze-thaw (F-T) cycles, which can cause significant structural deterioration [2]. Concurrently, the large-scale nature of plant earthworks often introduces unavoidable delays between the mixing of stabilizing agents and the final compaction of the soil layer, leading to suboptimal compaction and compromised long-term performance [3].

Conventionally, cement stabilization is a preferred method for subgrade improvement due to its ability to form a rigid, load-bearing matrix rapidly. Typical cement-stabilized soils exhibit significant improvements in

shear strength and stiffness [4]. However, application in cold-region metallurgical facilities exposes critical material vulnerabilities. The time-sensitive nature of cement hydration causes early stiffening (workability loss) during construction delays. Furthermore, existing conventional cement-treated bases exhibit poor performance in cold environments: moisture ingress combined with sub-zero temperatures initiates frost heave and micro-cracking, leading to severe strength degradation when repeated F-T cycles disrupt the rigid but brittle cementitious bonds [5, 6].

To individually address workability loss and frost damage, chemical admixtures such as retarders (e.g., sucrose) and accelerators/anti-freeze agents (e.g., sodium chloride, NaCl) are commonly used [7, 8]. However, single-purpose admixtures often introduce trade-offs; a retarder may unduly delay strength gain, while an accelerator like NaCl can exacerbate early stiffening, worsening the challenges of delayed compaction [9]. Furthermore, the drive towards sustainable construction encourages the use of industrial by-products in stabilized layers [10, 11], highlighting a broader need for innovative, multi-functional solutions that holistically address complex field conditions [12].

This study proposes an innovative composite admixture strategy combining sucrose and NaCl to synergistically enhance cement-stabilized soils for subgrade applications in cold-region metallurgical plants. The fundamental hypothesis is that sucrose will function as a retarder to preserve compactability during potential construction delays [13], while NaCl will serve a dual purpose: (i) acting as an accelerator to ensure robust early strength development despite the retarding effect of sucrose [14], and (ii) providing potent anti-freeze properties to ensure long-term durability against F-T action [15]. This research systematically investigates the individual and combined effects of these admixtures on the compaction characteristics, strength development under simulated delayed compaction scenarios, and the frost resistance of the treated soil.

2. Materials and Methods

2.1. Materials

The soil used in this investigation was sourced from a borrow pit associated with an infrastructure project in a metallurgical industrial park in Northeast China. It is classified as a well-graded gravelly sand with fines. The particle size distribution (PSD) of the raw soil is detailed in Table 1. To comply with the dimensional constraints of the laboratory compaction mold and test specimens, particles larger than 20 mm were replaced using the method of equal mass substitution with material from the immediate finer fraction. The PSD curve of the resulting soil blend is presented in Figure 1. The processed soil exhibited a **coefficient of uniformity (CU)** of 74.94 and a coefficient of curvature (C_c) of 2.46, confirming its well-graded nature, which is conducive to achieving high compaction density.

Table 1. Particle size distribution of the raw soil

Particle Size/mm	60	40	20	10	5	2	1	0.5	0.25	0.075
Percentage passing/%	100	93.26	85.12	73.00	54.75	34.78	29.62	21.46	14.08	9.89

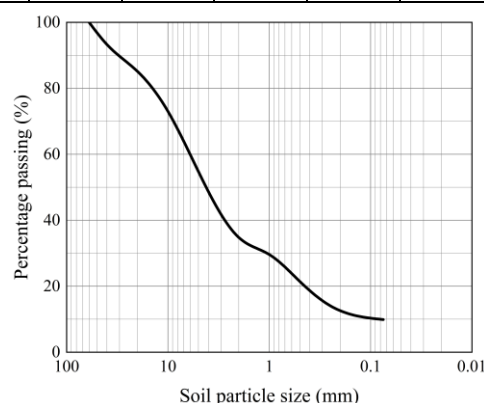


Figure 1. Particle size distribution curve of the soil after equal substitution

The stabilizing agent was Ordinary Portland Cement (P.O 42.5 grade). The chemical admixtures were analytical reagent (AR) grade sucrose ($C_{12}H_{22}O_{11}$), used as the retarder, and AR grade sodium chloride (NaCl), used as the accelerator/anti-freeze agent. Potable tap water was used for all mixtures.

2.2. Specimen Preparation and Testing Protocols

The cement content was fixed at 5 % by the dry mass of the soil, a typical dosage for subgrade stabilization projects. The dosages of sucrose and NaCl were expressed as a percentage of the cement mass. A predetermined amount of water was sprayed onto the soil sample surface while mixing it. 5 % cement was added by mass ratio and mixed thoroughly until uniform (for soil samples with added sucrose and NaCl, first mix sucrose and NaCl into the cement). The soil sample was placed in five layers into the compaction mold, compacting each layer immediately after placement. After compaction, weigh the total mass of the compaction mold and the specimen, then demold the specimen using a demolding apparatus and weigh the compaction mold.

2.2.1. Compaction Test

Standard Proctor compaction tests (ASTM D698) were conducted to determine the maximum dry density (MDD) and the corresponding optimum moisture content (OMC) for various mixture compositions. Tests were performed on: (a) the control mix (soil + 5 % cement), (b) mixes with sucrose only (0, 0.02, 0.05, 0.08, 0.11) %, (c) mixes with NaCl only (0, 0.5, 1.0, 2.0) %, and (d) mixes with a fixed sucrose content of 0.08 % combined with varying NaCl contents (0, 0.5, 1.0, 2.0) %. The soil was compacted in three layers using a standard 2.5 kg rammer, applying 25 blows per layer. Compaction test program, as shown in Table 2, where "Z" denotes sucrose and "N" denotes NaCl.

Table 2. Compaction test program

NO.	Soil: Cement	Cement: Sucrose: NaCl
Z0+N0	95.24: 4.76	1: 0: 0
Z0.02	95.24: 4.76	1: 0.02 %: 0
Z0.05	95.24: 4.76	1: 0.05 %: 0
Z0.08	95.24: 4.76	1: 0.08 %: 0
Z0.11	95.24: 4.76	1:0.11 %: 0
N0.5	95.24: 4.76	1: 0.5 %
N1	95.24: 4.76	1: 1.0 %
N2	95.24: 4.76	1: 2.0 %
Z0.08+N0.5	95.24: 4.76	1: 0.08 %: 0.5 %
Z0.08+N1.0	95.24: 4.76	1: 0.08 %: 1.0 %
Z0.08+N2.0	95.24: 4.76	1: 0.08 %: 2.0 %

2.2.2. Unconfined Compressive Strength (UCS) Test

Cylindrical specimens (100 mm in diameter and 100 mm in height) were prepared for UCS testing. The moist mixture was statically compacted into a split mold in three layers to achieve the target dry density corresponding to its predetermined MDD and OMC. To realistically simulate field delayed compaction, three distinct delay periods were enforced between the completion of mixing and the commencement of compaction: 0 hours (immediate, representing ideal conditions), 1 hour, and 3 hours (representing a significant but plausible delay) under sealed ambient conditions to prevent early moisture evaporation. After molding, specimens were sealed and cured in a humidity chamber ($(20 \pm 2) ^\circ\text{C}$, relative humidity $>95\%$) for 28 days. Prior to testing, specimens were saturated by immersion for 24 hours. UCS tests were performed using a displacement-controlled loading frame at a constant strain rate of 1.0 mm/min. The unconfined compressive strength test program is shown in Table 3.

Table 3. Test scheme of unconfined compressive strength

NO.	Time (h)	Cement: Sucrose: NaCl
Y0+Z0+N0	0	1: 0: 0
Y1+Z0+N0	1	1: 0: 0
Y3+Z0+N0	3	1: 0: 0
Y3+Z0.02+N0	3	1: 0.02 %: 0
Y3+Z0.05+N0	3	1: 0.05 %: 0
Y3+Z0.08+N0	3	1: 0.08 %: 0
Y3+Z0.11+N0	3	1: 0.11 %: 0
Y0+Z0+N0.5	0	1: 0: 0.5 %
Y0+Z0+N1.0	0	1: 0: 1.0 %
Y0+Z0+N2.0	0	1: 0: 2.0 %
Y3+Z0.08+N0.5	3	1: 0.08 %: 0.5 %
Y3+Z0.08+N1.0	3	1: 0.08 %: 1.0 %
Y3+Z0.08+N2.0	3	1: 0.08 %: 2.0 %

2.2.3. Freeze-Thaw (F-T) Cycle Test

For the durability assessment, specimens (with selected admixture combinations) were prepared, cured, and saturated as described above. A single F-T cycle consisted of placing the saturated specimen in a low-temperature cabinet at $(-30 \pm 1)^\circ\text{C}$ for 12 hours, followed by thawing in a water bath at $(20 \pm 1)^\circ\text{C}$ for 12 hours. The freeze-thaw cycle test program is shown in Table 4. The freeze-thaw process is illustrated in Figure 2. Specimen sets were subjected to 0, 5, and 10 such cycles. After completing the designated number of cycles, the specimens were tested for their residual UCS. The resistance to F-T damage was quantified using the Strength Loss Rate (BDR, %), calculated as follows:

$$BDR_n = \frac{q_{uo} - q_{un}}{q_{uo}} \times 100 \quad (1)$$

where BDR_n is the strength loss rate after n F-T cycles, q_{uo} is the average UCS of companion specimens before any F-T cycling (0 cycles), and q_{un} is the average UCS after n cycles.

Table 4. Freeze-thaw cycle test protocol

NO.	Time (h)	Cement: Sucrose: NaCl
Y0+Z0+N0	0	1: 0: 0
Y0+Z0+N0.5	0	1: 0: 0.5 %
Y0+Z0+N1.0	0	1: 0: 1.0 %
Y0+Z0+N2.0	0	1: 0: 2.0 %
Y3+Z0.08+N0.5	3	1: 0.08 %: 0.5 %
Y3+Z0.08+N1.0	3	1: 0.08 %: 1.0 %
Y3+Z0.08+N2.0	3	1: 0.08 %: 2.0 %

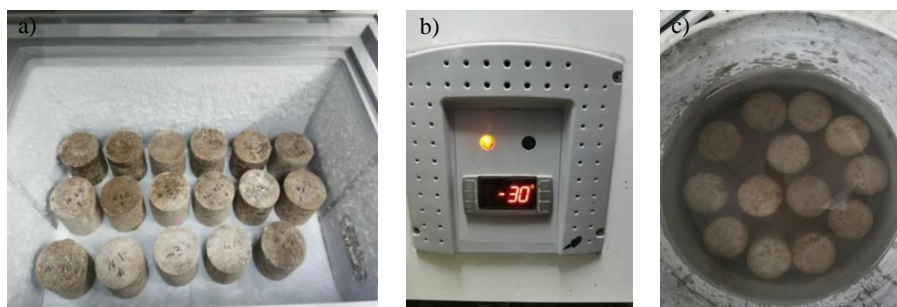


Figure 2. Freeze-thaw process of the specimen: a) ultra-low temperature test chamber controller, b) specimen freezing process, c) specimen water-thawing process

3. Results and Discussion

3.1. Compaction Characteristics

The compaction test results reveal the distinct influences of sucrose and NaCl on the soil's densification. To provide complete transparency, Table 5 presents the absolute compaction parameters evaluated across all test mixtures.

Table 5. Results of compaction test

NO.	MDD/(g·cm ⁻³)	OMC/%
Z0	2.1240	8.3
Z0.02	2.1388	8.4
Z0.05	2.1503	8.3
Z0.08	2.1592	8.3
Z0.11	2.1437	8.3

The addition of sucrose, up to an optimal content of 0.08 %, resulted in a slight but consistent increase in the Maximum Dry Density (MDD). This is attributed to its retarding action, which delays the hydration of cement silicate phases (e.g., C₃S), thereby prolonging the period during which the mixture retains sufficient lubricity for soil particles to rearrange into a denser configuration under compactive effort. In contrast, the incorporation of NaCl caused a clear decrease in MDD. This is a direct consequence of its accelerating effect, which promotes the rapid formation of early hydration products, increasing mixture stiffness and reducing workability, thus hindering optimal particle packing.

The interaction between the two admixtures is crucial. As the data show, the composite with 0.08 % sucrose and 1.0 % NaCl achieved an MDD of 2.136 g·cm⁻³. Although slightly lower than the control mix's MDD of 2.180 g·cm⁻³ (immediate compaction, no admixtures), this represents 97.96 % of that benchmark value. This performance is critical, as it confirms that the retarding effect of sucrose effectively neutralizes the adverse impact of NaCl on workability. Consequently, the composite-admixed material can reliably meet standard field compaction specifications (often requiring ≥95 % of laboratory MDD) even when subjected to practical delays.

3.2. Unconfined Compressive Strength Development

The influence of delayed compaction and admixtures on strength development was pronounced. For the control mix, a 3-hour delay led to a reduction in 28-day UCS from 2.95 MPa to 2.75 MPa, highlighting the practical consequence of missing the optimal compaction window. Figure 3 illustrates the typical failure process of specimens under unconfined compression. Table 6 presents the expanded UCS tracking matrix for 0 h and 3 h delay periods across the mixtures.

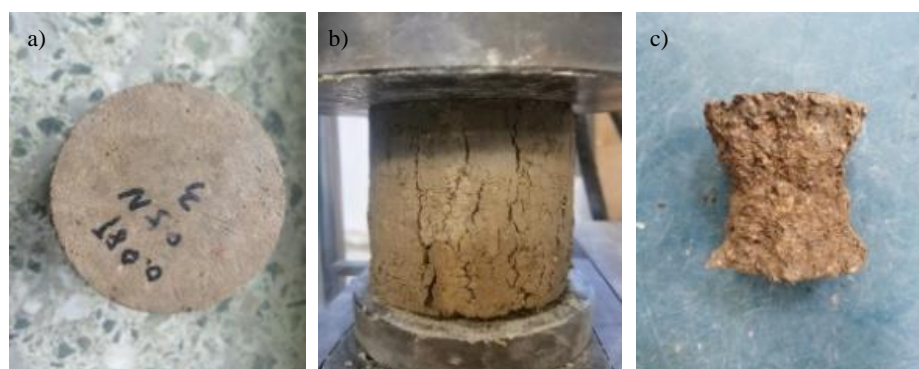


Figure 3. Specimen destruction process under unconfined compression: a) before test, b) during loading, c) after failure

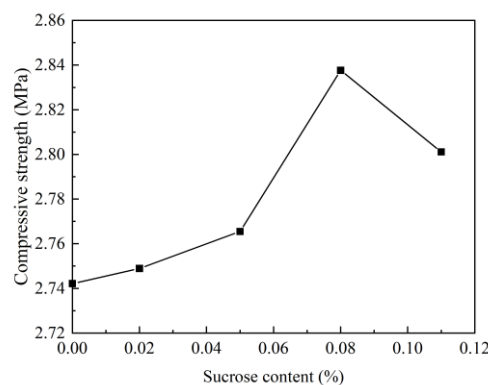
Table 6. Results of UCS test

NO.	Time/h	UCS/MPa
Y0+Z0+N0	0	2.95
Y1+Z0+N0	1	2.84
Y3+Z0+N0	3	2.74
Y3+Z0.02+N0	3	2.75
Y3+Z0.05+N0	3	2.77
Y3+Z0.08+N0	3	2.84
Y3+Z0.11+N0	3	2.80
Y0+Z0+N0.5	0	3.20
Y0+Z0+N1.0	0	3.33
Y0+Z0+N2.0	0	3.07
Y3+Z0.08+N0.5	3	3.13
Y3+Z0.08+N1.0	3	3.31
Y3+Z0.08+N2.0	3	3.05

Effect of Sucrose on Delayed Compaction: When 0.08 % sucrose was added, the UCS of the 3-hour delayed specimen recovered to 2.92 MPa, nearly matching the strength of the immediately compacted control. This confirms that sucrose preserves the mixture's ability to be densely compacted after a delay, which is the primary factor governing subsequent strength. Comparing this to other typical organic retarders reported in literature [16], sucrose exhibits superior stabilization of unhydrated cement particles without permanently poisoning the setting process.

Effect of NaCl on Strength: Under immediate compaction, the inclusion of 1.0 % NaCl increased the 28-day UCS to 3.33 MPa, a significant 12.88 % improvement over the control. This enhancement stems from the accelerating effect of NaCl, which promotes early and potentially more complete hydration. However, isolated NaCl usage proved catastrophic under delayed compaction (dropping to 2.50 MPa), demonstrating the severe penalty of unmanaged premature setting [17].

Synergistic Effect of the Composite: The most significant finding pertains to the composite admixture's performance under delayed conditions. The mix containing 0.08 % sucrose and 1.0 % NaCl achieved a UCS of 3.33 MPa even after a 3-hour compaction delay. This value is not only substantially higher than that of the delayed control (2.75 MPa) but is also identical to the strength achieved by the NaCl-only mix under ideal (immediate) compaction conditions. This demonstrates a powerful synergy: sucrose ensures the creation of a dense matrix despite the delay, while NaCl actively drives the development of high strength within that matrix. The result is a material whose final mechanical performance becomes robust against typical construction timeline variability. The relationship between admixture content and compressive strength is detailed in Figure 4 (sucrose) and Figure 5 (NaCl).

**Figure 4.** Sucrose addition and compressive strength curve

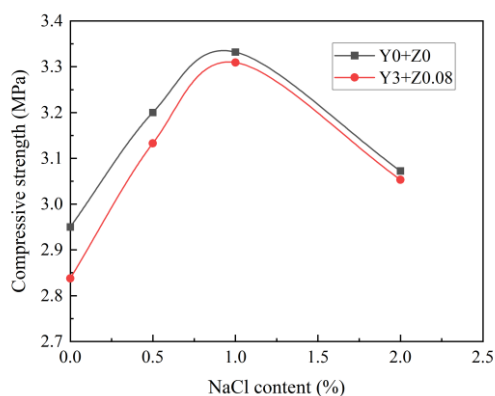


Figure 5. NaCl addition and compressive strength curve

3.3. Resistance to Freeze-Thaw Cycling

The durability of the stabilized soil under cyclic freezing and thawing is paramount for cold-region applications. The incorporation of NaCl markedly improved frost resistance. A functional evaluation criteria threshold dictates that a subgrade material should retain a strength loss rate (BDR) below 30 % after 5 F-T cycles to be deemed acceptable [18]. Table 7 outlines the F-T capability of all tested configurations, providing empirical confirmation across variables.

Table 7. Results of F-T Cycle Test

NO.	Number of freeze-thaw cycles	UCS/MPa	BDR/%
Y0+Z0+N0+0	0	2.95	—
Y0+Z0+N0+5	5	1.04	35.25
Y0+Z0+N0+10	10	0.80	27.12
Y0+Z0+N0.5+0	0	3.20	—
Y0+Z0+N0.5+5	5	1.56	48.75
Y0+Z0+N0.5+10	10	1.21	37.81
Y0+Z0+N1.0+0	0	3.33	—
Y0+Z0+N1.0+5	5	1.70	51.05
Y0+Z0+N1.0+10	10	1.44	43.24
Y0+Z0+N2.0+0	0	3.07	—
Y0+Z0+N2.0+5	5	1.60	52.12
Y0+Z0+N2.0+10	10	1.38	44.95
Y3+Z0.08+N0.5+0	0	3.13	—
Y3+Z0.08+N0.5+5	5	1.53	48.88
Y3+Z0.08+N0.5+10	10	1.13	36.10
Y3+Z0.08+N1.0+0	0	3.31	—
Y3+Z0.08+N1.0+5	5	1.67	50.45
Y3+Z0.08+N1.0+10	10	1.43	43.20
Y3+Z0.08+N2.0+0	0	3.05	—
Y3+Z0.08+N2.0+5	5	1.56	51.15
Y3+Z0.08+N2.0+10	10	1.35	44.26

Specimens without NaCl suffered the greatest strength loss after F-T cycling.

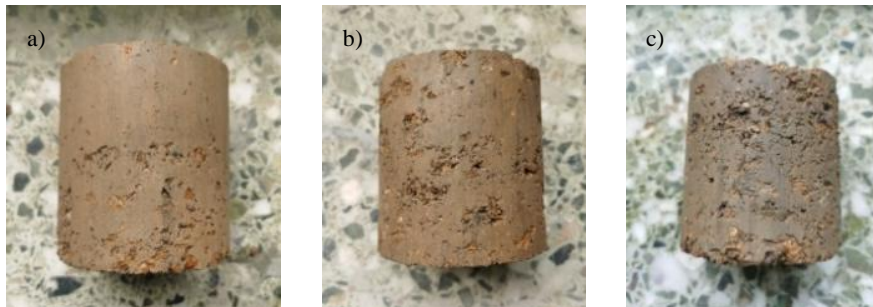


Figure 6. Comparison of specimen condition before and after freeze-thaw cycles: a) after 1 cycle, b) after 5 cycles, c) after 10 cycles

Figure 7 presents the relationship between compressive strength and the number of freeze-thaw cycles for different NaCl contents, showing that NaCl-modified specimens maintain higher residual strength with increasing cycles.

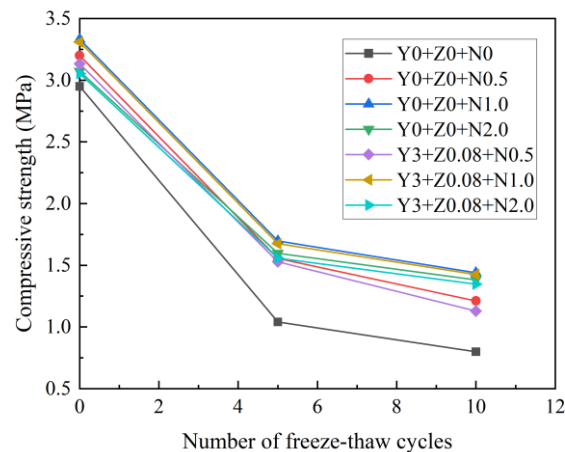


Figure 7. Relationship between compressive strength and number of freeze-thaw cycles for different NaCl contents

As depicted in Figure 8, the strength loss rate (BDR) after 5 cycles was minimized for the mix containing 1.0 % NaCl. Analytically, this optimal 1.0 % dosage outperforms other ratios due to a delicate balance in physical-chemical mechanisms. While a 0.5 % addition provides insufficient solute concentration to successfully depress the pore water freezing point, pushing the dosage to 2.0 % introduces excessive free chloride ions. These excessive ions induce internal expansive crystallization pressure during thermal variations and can inhibit later-stage cementitious bond integrity [19, 20]. Therefore, 1.0 % NaCl represents the optimal kinetic balance between anti-freeze solute depression and structural preservation. The composite mix (0.08 % S + 1.0 % N) inherently benefited from this property, ensuring that the high-strength material was adequately durable.

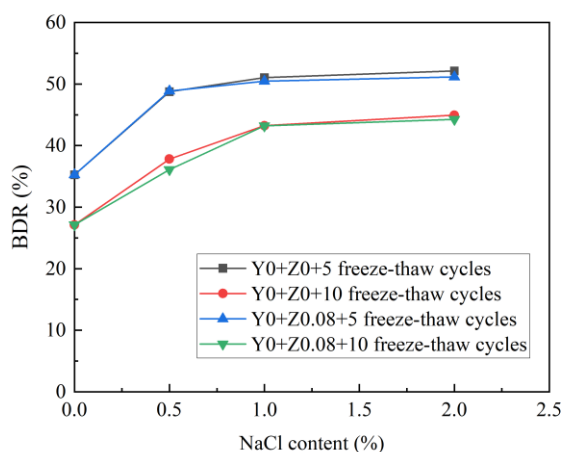


Figure 8. Strength loss rate (BDR) after 5 freeze-thaw cycles versus NaCl content

4. Conclusions

This study demonstrates that the addition of 0.08 % sucrose effectively restores the compactability of cement-stabilized soil subjected to a 3-hour placement delay, enabling the achievement of over 97 % of the laboratory maximum dry density. Meanwhile, the incorporation of 1.0 % sodium chloride notably enhances the 28-day unconfined compressive strength by approximately 12.9 % and imparts enhanced resistance to freeze-thaw damage.

More importantly, a pronounced significant synergistic effect is observed when 0.08 % sucrose and 1.0 % NaCl are used in combination. This optimal composite admixture not only mitigates compaction challenges under delayed placement but also delivers superior final strength (3.33 MPa) and significantly improved long-term freeze-thaw durability. Consequently, the sucrose-NaCl composite system presents a reliable and practical solution for subgrade construction in heavy-duty metallurgical plants spanning seasonal frozen regions. By accounting for the aggressive vibrational loads, chemical exposure, and logistical delays typical of plant operations, it effectively balances constructability with long-term performance, and shows promising potential for industrial subgrade engineering applications.

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