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Consolidation Properties of Soil/Modified Bentonite Backfill in Salt Solution

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Abstract: The consolidation properties of soil-bentonite (SB) backfills containing 20% of the weight of sodium-hexametaphosphate-modified calcium bentonite (SHMP-20CaB) and prepared with 0 mM to 1000 mM calcium chloride ($CaCl_2$) solution were evaluated. The results indicated that both consolidation stress and $CaCl_2$ concentration had significant effects on the consolidation behaviors of the SHMP-20CaB backfill. In general, an increase in consolidation stress resulted in a decrease in the void ratio (e) and in the coefficient of volume change (m_v), alongside an increase in the coefficient of consolidation (c_v). The increased $CaCl_2$ concentration yielded a dropped void ratio, and a nonlinear decreased compression index (C_c) and rebound index (C_s), respectively, from 0.18 to 0.13 and from 0.022 to 0.010, and a nonlinear increase c_v. A threshold $CaCl_2$ concentration of 100 mM was observed at the inflection points of the C_c, C_s, and c_v. In contrast, the m_v was insensitive to the $CaCl_2$ solutions. The deterioration in e, C_c, and C_s and the increase in c_v were the result of a compressed diffuse double layer of the bentonite by the $CaCl_2$ solution, which thus exerted certain negative effects on the consolidation behaviors of the SHMP-20CaB backfill.

Keywords: backfill; modified bentonite; consolidation; salt solution; slurry wall

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1. Introduction

Soil–bentonite (SB) slurry walls are widely used in North America to control the lateral migration of contaminated groundwater in geoenvironmental applications [1]. This type of engineering barrier is constructed by the slurry trench method. First, a trench is excavated in highly permeable soils and is simultaneously backfilled by a bentonite slurry that is composed of water and from 4% to 6% by weight of sodium bentonite to support the stability of the trench walls. The excavated trench soils are then mixed with the slurry and additional dry sodium bentonite (if needed), placed back into the trench, and displaced by the in-trench slurry to create a slurry wall with hydraulic conductivity lower than 10^{-9} m/s [2,3].

Sodium bentonite is the key functional material which endows the SB slurry walls with a low hydraulic conductivity through its excellent swelling capability in water. However, in China, India and other countries where high-quality sodium bentonite is scarce and calcium bentonite (Ca-bentonite) is relatively abundant; the latter can be used as an alternative material in SB slurry wall construction after proper modification. Recently, some novel modified Ca-bentonites, such as polymer-modified bentonite [4,5], sodium-hexamatephosphate (SHMP)-modified bentonite [6] have been developed as alternative barrier materials in contaminant control. Especially, a sand-modified Ca-bentonite backfill with an optimum SHMP-modified Ca-bentonite content of 20% by weight was manifested to exhibit comparable hydraulic performance to the typical sand–sodium-bentonite backfill commonly with a bentonite content of 1% to 5% by weight [7,8].

Alongside hydraulic conductivity, the compressibility and strength of the backfill are equally important considerations for the design and construction of the SB slurry wall as well as other engineering applications [3,9–16]. The consolidation behavior of the SB backfill is important for several reasons: (1) The hydraulic conductivity is strongly dependent on consolidation pressure [17]. (2) The chemical resistance and hydraulic conductivity compatibility of the bentonite materials in polluted solution are closely related to its pressure status [18]. (3) The consolidation of the SB backfill in the trench due to the lateral squeezing mechanism has a significant influence on the deformation of the ground adjacent to the SB slurry walls [19]. (4) Increasing the amount of fine in the SB backfill not only decreases its hydraulic conductivity but also increases its compressibility [3,20]. On the basis of these considerations, understanding the basic consolidation properties of the SB backfills is necessary to further clarify the state of stress within and adjacent to the SB slurry walls, especially when the fine content of backfill is high.

Although the consolidation performance for some SB backfills have been reported [3,13,17,19,20], they are mainly concerned on SB backfill with sodium bentonite content ranged from 1% to 7.1%, and the test liquid is commonly clean water or tap water. However, there are limited numbers of systematic assessments conducted on the consolidation of SB backfills with bentonite content higher than 10% or attacked by solutions with a wide range of chemical concentration [21]. As a result, this study aims to evaluate the consolidation properties of SB backfill with 20% by weight of SHMP-modified Ca-bentonite. Moreover, the influences of calcium chloride ($CaCl_2$) solution with a concentration of 0 mM to 1000 mM on the consolidation behaviors of the backfill are explored. The concentration window of $CaCl_2$ adopted in this study is based on salt concentration ranges reported by previous studies that investigated influences of contaminants on the containment performance of SB backfills [22,23]. The obtained results are useful for the safe design and construction of SB slurry wall containing modified calcium bentonite in geoenvironmental applications.

2. Materials and Methods

2.1. Backfill Constituents and Test Liquids

The sand–bentonite backfill tested in this study composed of sand and SHMP-modified Ca-bentonite. The sand used was obtained from a quarry in Beloit, WI, USA, and had a coefficient of uniformity (c_u) of 2.44, a coefficient of curvature (c_c) of 1.00, and was classified as poorly graded sand (SP) as per ASTM D2487 [24]. The SHMP-modified Ca-bentonite was prepared by procedures provided in [7,8,25]. In brief, the procedures included creating a slurry with a SHMP-to-bentonite ratio of 2%, curing the slurry in room temperature for 24 h, oven drying for 24 h, grinding the dried soil, and passing it through a No. 200 sieve.

Two types of test liquids, tap water and $CaCl_2$ solutions with a solute concentration of 5 mM to 1000 mM, were used to prepare the consolidation specimen. The $CaCl_2$ solutions were prepared by dissolving the precalculated amount of $CaCl_2$ into distilled water to create a stock solution with a solute concentration of 1000 mM. The stock solution was then diluted to a target solute concentration of 5 mM to 500 mM, as shown in Table 1.

Table 1. Program and initial specimen state for one-dimensional consolidation tests.

Test Solution	Target Moisture Content/%	Actual Moisture Content/%	Initial Void Ratio	$CaCl_2$ Concentration/mM
Tap water	30.0	33.1	0.88	0
		29.9	0.84	5
		29.6	0.81	10
		29.7	0.79	20
$CaCl_2$ solution	30.0	30.3	0.80	50
		31.2	0.77	100
		30.4	0.77	500
		30.0	0.73	1000

2.2. Consolidation Tests

The sand and SHMP-modified Ca-bentonite backfills (denoted as SHMP-20CaB) prepared with either tap water or 5 mM to 1000 mM $CaCl_2$ solutions were subjected to one-dimensional consolidation tests. These backfills were created by mixing 80% by weight of sand, 20% by weight of SHMP-modified Ca-bentonite, and one of the test liquids to achieve a desired moisture content of 30% that corresponded to the target slump of 125 mm as suggested by [8,26]. The moist backfills were then sealed in plastic bags and cured at 20 °C room temperature for approximately 15 days to allow chemical equilibrium [27]. The total mass of each backfill and the plastic bag was monitored at the beginning and end of the curing period, and the appropriate amount of distilled water was added to the backfill to compensate for evaporation loss.

The consolidation tests were performed in accordance with ASTM D2435 [28]. The stepwise loading sequence began at 24 kPa and was doubled after each stage (24 h), until it achieved a maximum vertical effective stress of 1532 kPa, as recommended by [29]. Subsequently, each specimen was successively unloaded by reducing the applied load with a factor of four relative to the previous load. The initial properties of the prepared specimens are shown in Table 1.

3. Results and Analysis

3.1. Void Ratio–Stress Relationships

Figure 1 shows the relationship between the void ratio (e) and the logarithm of effective consolidation stress [log(σ')] of the backfill specimens prepared with a $CaCl_2$ concentration of 0 mM to 1000 mM. For all the specimens, noticeable inverse S-shape compression curve can be observed at the loading segment of each e-log(σ') curve. In contrast, a straight rebound line occurs at the unloading segment of each consolidation curve. This finding is consistent with those reported by previous studies conducted on remolded natural clayey soils [30], sodium bentonite slurry [31], and clayey SB backfills [21,23,32]. Considering that there is an approximately equal initial moisture content and liquid limit in the SHMP-20CaB backfill, e.g., with an initial moisture content of 30% to 33% as shown in Table 1 versus a liquid limit of 30% as reported by [8], the presence of the inverse S-shape compression curve can be attributed to the existence of the shear strength of the backfill provides sufficient resistance to low external compression stress [21,30].

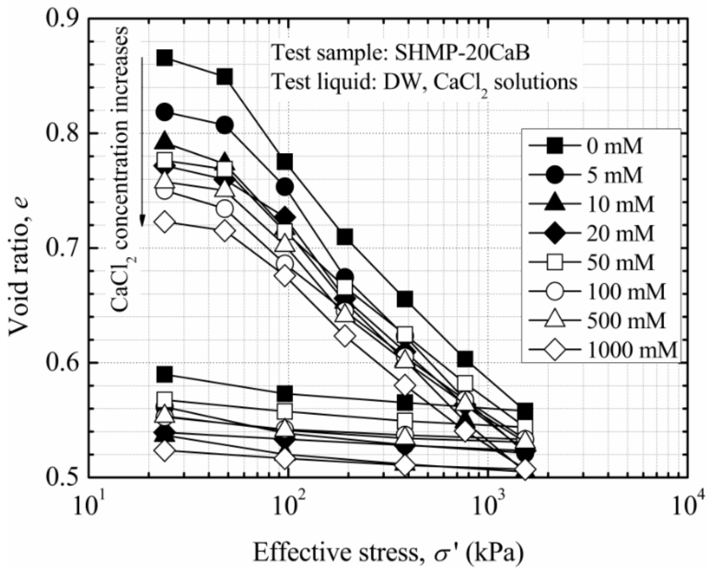

Figure 1. Effective consolidation stress versus void ratio for the SHMP-20CaB backfill prepared with 0 mM to 1000 mM $CaCl_2$ solution.

The void ratios of the SHMP-20CaB backfill are found varied from 0.9 to 0.5 and decreased with an increase in $CaCl_2$ concentration throughout the whole-loading and unloading stages. The sequential order of these void ratios is consistent with that of initial void ratios as shown in Table 1. For example, the lower the $CaCl_2$ concentration in solutions used to prepare the SHMP-20CaB backfill, the higher the initial void ratio that is measured. This phenomenon is the result of the shrinkage in the diffuse double layer of the bentonite induced by the $CaCl_2$ solution, and can be described by the Gouy–Chapman theory model expressed as Equation (1) [33]:

$$\frac{1}{\kappa} = \left(\frac{\varepsilon_0 D k_B T}{2 n_0 E^2 v^2}\right)^{1/2} \tag{1}$$

where the $1/\kappa$ is the thickness of the diffuse double layer; ε_0 is the permittivity of vacuum; D is the dielectric constant of the medium; k_B is the Boltzmann constant; T is absolute temperature; n_0 is the cation concentration; E is the electronic charge; and v is the cation valence.

It is shown in Equation (1) that the thickness of the diffuse double layer varies inversely with the square root of the pore cation concentration. An increase in cation concentration results in a thinner diffuse double layer on the bentonite, and decreased interparticle repulsive forces among the clay particles as a consequence [33]. One practical consequence of this is deteriorated swelling of the bentonite, which directly generates a decrease in the void ratio of the sand–bentonite backfill specimen.

In addition, the void ratios of the SHMP-20CaB backfill prepared with tap water (i.e., a 0 mM $CaCl_2$ solution) in this study are significantly lower than those of typical SB backfills containing sodium bentonite, as reported by previous studies [13,20]. This may be the result of two reasons: (1) a lower swelling capacity of the SHMP-modified Ca-bentonite as compared to the high-quality sodium bentonite, and the former occupying less void space within the backfill than the latter; (2) the SHMP-20CaB possesses higher bentonite content relative to its sodium bentonite backfill counterpart, i.e., 20% in the former versus 2% to 5% in the latter.

3.2. The Influence of $CaCl_2$ Concentration on C_c and C_s

Figure 2 presents variations of two characteristic parameters, compression index, C_c, and rebound index, C_s, with $CaCl_2$ concentration in a solution used to prepare the SHMP-20CaB backfill. The values of C_c and C_s are, respectively, calculated from the slopes of the linear loading and unloading portion of the e-log(σ') curves. The C_c of the backfill first sharply decreases from 0.18 to 0.13 and then maintains stability as the $CaCl_2$ concentration increases from 0 mM to 1000 mM. A C_c inflection point is obtained at the threshold $CaCl_2$ concentration of 100 mM. The same change trend is also found in the C_s value of the backfill. For example, the C_s of the backfill first decreases dramatically from 0.022 to 0.010 and then maintains stability as the $CaCl_2$ concentration rises up from 0 mM to 1000 mM. The C_s inflection point is also observed at the threshold $CaCl_2$ concentration of 100 mM. Such a variation in C_c and C_s with solute concentration is not unprecedented. For instance, [21] investigated compression behaviors of the clayey SB backfill containing 5% to 15% by weight of bentonite in lead solution. They indicated that the C_c of the backfill changes significantly at low lead concentration, while it tends to be stable at a relatively high lead concentration. The C_c inflection point occurs at a solute concentration of 120 mM in their experiments, which is slightly higher than that showed in this study (i.e., 100 mM $CaCl_2$).

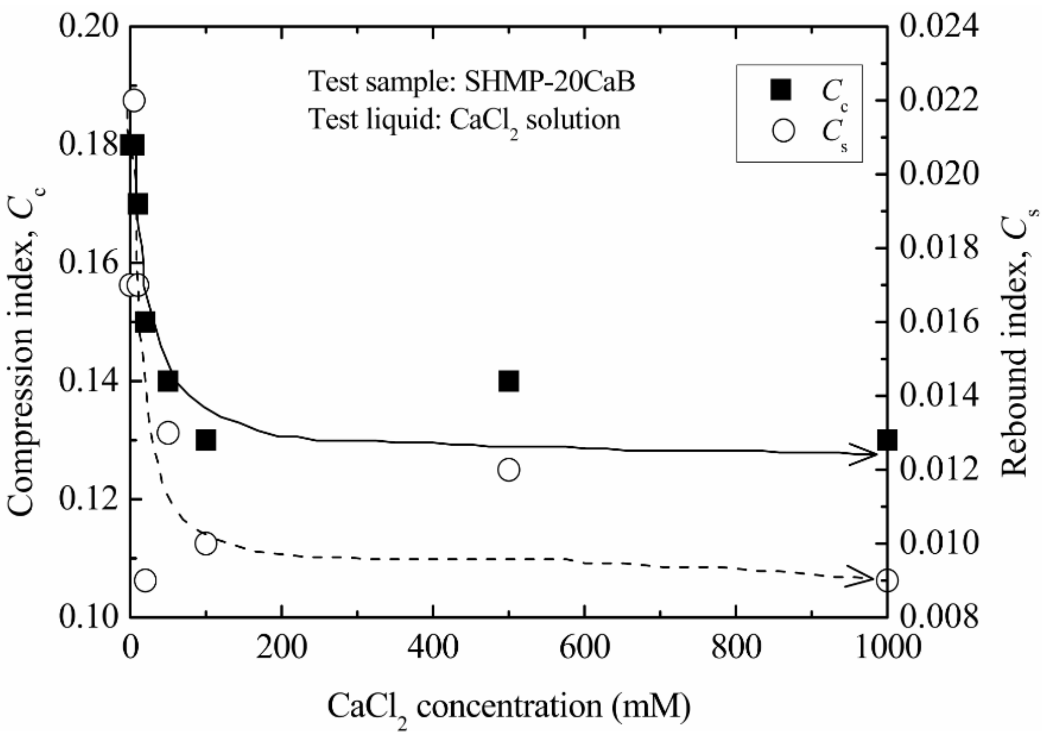

Figure 2. Compression index and rebound index of the SHMP-20CaB backfill versus $CaCl_2$ concentration of solution used to prepare the backfill.

The relatively low C_c value in a high level of $CaCl_2$ concentration reflects a relatively incompressible SHMP-20CaB backfill in salt solution. This is likely the result of shrinkage in the diffuse double layer of the bentonite induced by the $CaCl_2$ solution [34–36], which endows the backfill a lower initial void ratio and relatively dense skeleton to sustain the compressive stress. Similarly, relatively low C_s value in high levels of $CaCl_2$ concentration indicates less swelling potential for this backfill in salt solution, which is the response of the compressed diffuse double layer of the bentonite. In summary, the decrease in C_c and C_s values with $CaCl_2$ concentration implies an adverse influence of the salt solution on the compression and swelling capacities of the SHMP-20CaB backfill.

3.3. The Coefficients of Volume Change and Consolidation

Figure 3 illustrates the relationship between the coefficient of volume change, m_v, and average effective stress, σ', where the average effective stress represents as the average value of initial and final effective stress of each loading increment. The m_v of all the backfills tested in this study has a similar variation trend and exhibits two segments of change as the average effective stress increases. For instance, the value of m_v increases with increasing average effective stress before the average effective stress is over 100 kPa. Then, as the average effective stress further increases to 1532 kPa, the value of m_v shows a linear decrease trend in the log(m_v)-log(σ') plot. In general, the SHMP-20CaB backfills prepared with 0 mM to 1000 mM $CaCl_2$ possess a similar m_v value, and the variation in $CaCl_2$ concentration did not yield an obvious discrepancy in the m_v of the SHMP-20CaB backfill. Therefore, the $CaCl_2$ solution is concluded to have a negligible effect on the volume change of the backfill tested in this study.

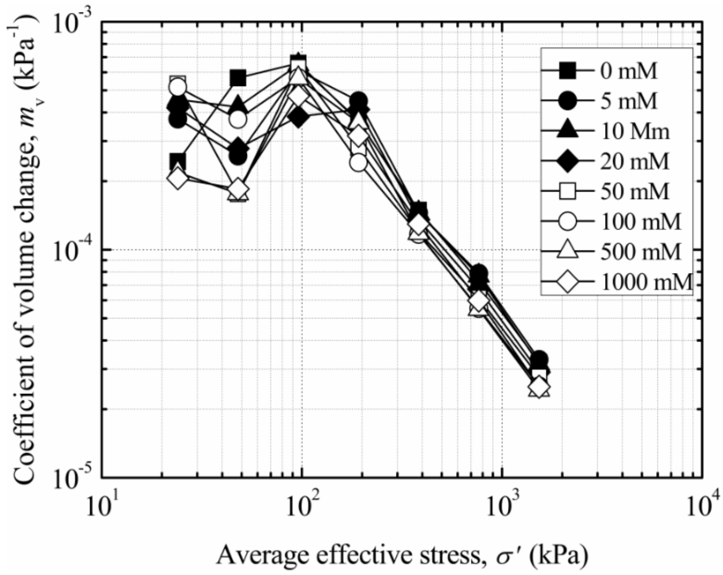

Figure 3. Coefficient of volume change as a function of average effective stress during loading of the SHMP-20CaB backfills prepared with 0 mM to 1000 mM $CaCl_2$ solution.

The coefficients of consolidation, c_v, were determined using the square-root-of time (Taylor) method in loading segments of the consolidation tests. The c_v values are plotted against average effective stress on the dual-logarithmic scale, as shown in Figure 4. In general, the c_v of the all the tested specimens increases across the range of 10^{-7} to 10^{-4} m^2/s as it increases in the average effective stress. This agrees well with the c_v trends reported for typical SB backfills and clayey SB backfills [13,20,21]. Figure 5 shows variation of c_v with increasing $CaCl_2$ concentration in solutions used to prepare the SHMP-20CaB backfill. It can be seen from Figure 5 that the higher the $CaCl_2$ concentration in solution used to prepare the backfill, the higher the c_v value that is obtained. As compared to the specimen prepared with 0 mM $CaCl_2$, a maximum c_v increase of two orders of magnitude is obtained on specimens prepared with 1000 mM $CaCl_2$.

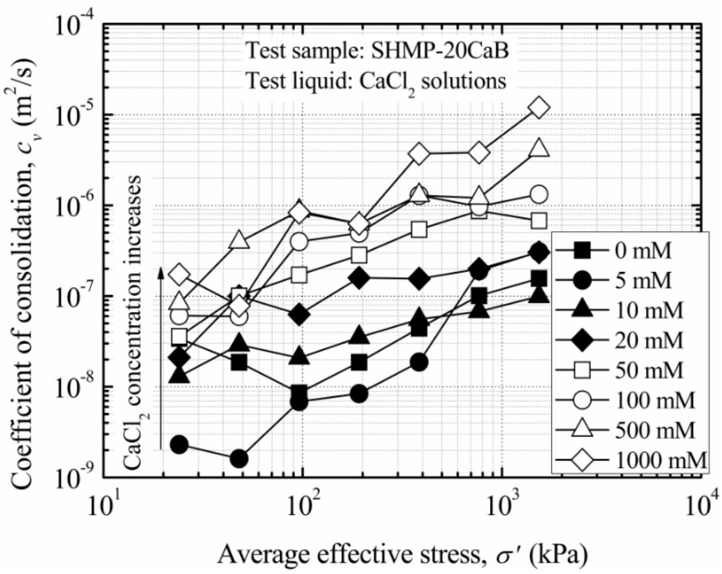

Figure 4. Coefficient of consolidation as a function of average effective stress during loading of the SHMP-20CaB backfills prepared with 0 mM to 1000 mM $CaCl_2$ solution.

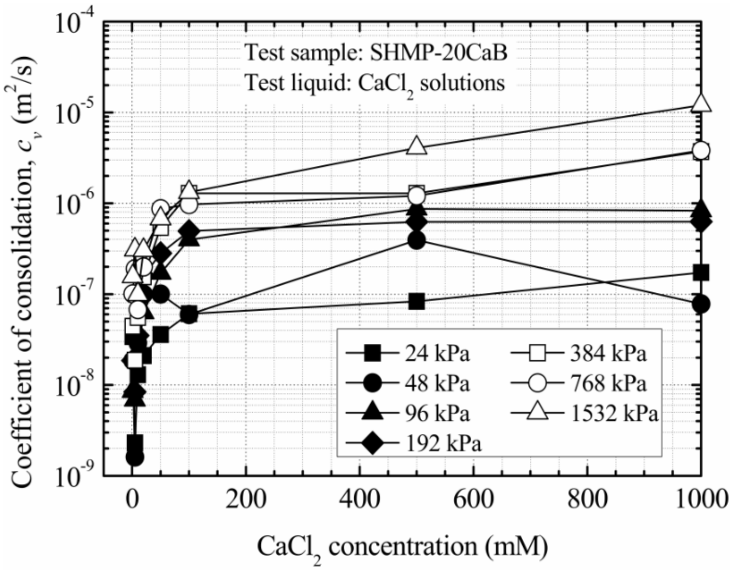

Figure 5. Coefficient of consolidation as a function of $CaCl_2$ concentration in solution used to prepare the SHMP-20CaB backfill.

The increased c_v with increasing average effective stress is attributed to a greater decrease rate in m_v relative to the decrease rate in the hydraulic conductivity of the backfill as the average effective stress increases [20]. In addition, the c_v value depends on the dissipation rate of excess pore pressure. A relatively lower c_v is the result of the slower dissipation of the excessive pore water [21], which corresponds to a more swollen diffuse double layer of the bentonite. The variation trend again manifests the adverse influence of the salt solution on consolidation behaviors of the tested backfill.

4. Conclusions

Sodium hexametaphosphate (SHMP)-modified Ca-bentonite is an acceptable alternative material to the soil–bentonite slurry walls when used based on the availability of local materials. This study investigated consolidation properties of sand/SHMP-modified Ca-bentonite backfill containing 20% by weight of bentonite (SHMP-20CaB) when exposed to groundwater with different salt concentrations. Based on the obtained results, the following conclusions can be drawn.

The void ratio–logarithm of effective consolidation stress, i.e., e-log(σ'), relationship of the SHMP-20CaB backfill displayed an inverse S-shape compression curve, which is a result of the existence shear strength, provided sufficient support to low compression stress. The solution with an increase in $CaCl_2$ concentration from 0 mM to 1000 mM yielded a decrease in the void ratio of the backfill due to shrinkage in the diffuse double layer of the bentonite.

The values of the compression index C_c and the rebound index C_s of the backfill varied from 0.18 to 0.13 and from 0.022 to 0.010, respectively, and exhibited a nonlinear decrease with an increase in $CaCl_2$ concentration due to deterioration in the diffuse double layer of the bentonite when exposed to salt solution. The inflection points of both the C_c and C_s occurred at the threshold of the $CaCl_2$ concentration of 100 mM.

The values of the coefficient of volume change m_v first increased and then decreased, with an increase in average effective stress, and were unresponsive to the $CaCl_2$ concentration. In contrast, the coefficients of consolidation c_v possessed an approximately linear increase from 10^{-7} to 10^{-4} m^2/s with an increasing average effective stress and exhibited a nonlinear increase as $CaCl_2$ concentration rose from 0 mM to 1000 mM. A maximum c_v increase of two orders of magnitude occurred at the backfill prepared with 1000 mM $CaCl_2$ solution.

Overall, the $CaCl_2$ solution yielded an adverse influence on the consolidation behaviors of the SHMP-20CaB backfill. This influence should be carefully considered during the design and construction of the soil–bentonite slurry walls.

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