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Salt rock filling in subgrade: a comprehensive review

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Abstract

Purpose – Salt rock from salt lakes can serve as a cost-effective material for subgrade filling, as demonstrated in projects like the Qarhan Salt Lake section of the Qinghai-Tibet Railway and the Qarhan Salt Lake section of the G215 Highway. This state-of-the-art paper aims to summarize the engineering properties of salt rock filling and present the advances of its utilization.

Design/methodology/approach – This paper collects and analyzes laboratory and field data of salt rock filling from previous studies to present a comprehensive analysis of the engineering properties and utilization of salt rock fillings.

Findings – Salt rock primarily contains minerals such as halite and glauberite, which contribute to its unique phase-changing behavior under varying environmental conditions, impacting its mechanical properties. Salt rock filling shrinks when in contact with vapor or unsaturated brine and expands under cooling or evaporation. Its use is particularly recommended for arid regions, with specific restrictions depending on the structure type. This paper discusses suggested countermeasures to mitigate these issues, as well as key quality acceptance indices for salt rock filling compaction. Moisture content after air-drying is recommended as a crucial parameter for construction quality control.

Originality/value – This review aims to support future research and engineering practices in salt rock subgrade applications.

Keywords Salt rock, Subgrade filling, Engineering properties, Waterproofing, Construction quality control

Paper type General review

1. Introduction

Salt lakes are found in many regions of the world, with prominent examples including Lop Nor and Qarhan Salt Lakes in China (Figure 1 (a)), Burlinskoye Salt Lake in Russia, and the Great Salt Lake in the United States. Salt rocks (Figure 1 (b)) are sedimentary deposits formed through the evaporation of these lakes. Typically, these salt rocks exhibit excellent mechanical properties and are stable in their natural environments (Chen, Chen, & Dou, 1988; Song, Niu, Wang, & Wen, 2021).

In areas where conventional subgrade materials are scarce, such as around salt lakes, salt rock can be utilized locally as an alternative filling material (National Railway Administration of the People’s Republic of China, 2018; Ministry of Transport of the People’s Republic of China, 2022). The Qarhan Salt Lake section of the G215 Highway, completed in 1955, represents the first recorded instance of artificial transportation infrastructure using salt rock

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(a) **(b)**

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Figure 1. Typical photos of a salt lake and salt rock sample: (a) Qarhan Salt Lake; (b) Salt rock

filling in China (Xu & Fang, 2005). Since then, several railway and highway projects have employed salt rock as a subgrade material, as summarized in Table 1.

One distinctive property of salt rock is its capacity for crack healing, which enhances its suitability as a subgrade material. After compaction and air-drying, salt rock particles bond together, significantly increasing the strength of the salt rock layer. Crack healing in salt rocks occurs through three main mechanisms (Houben, Hove, Peach, & Spiers, 2013): mechanical closure by pressure (Chan, Bodner, & Munson, 2001), diffusive crack healing (Cinar, Pusch, & Reitenbach, 2006), and recrystallization (Heege, Bresser, & Spiers, 2005). Mechanical closure involves elastic strain, plastic flow, and pressure dissolution under compression (Chen, Weiss, & Stickler, 1996; Miao, Wang, & Schreyer, 1996). Diffusive crack healing refers to the transfer of pore solution to crack ends driven by chemical potential differences, effectively reducing crack size (Heidug, 1991; Spiers & Schutjens, 1999). Recrystallization drives the transfer of crystal boundaries, diminishing crack connectivity. These processes work in tandem, although their influence varies across different stages of the salt rock structure's evolution. Mechanical closure dominates the initial stages, while diffusive healing and recrystallization gain importance as stress equilibrium is approached.

Salt rocks are highly sensitive to environmental changes, particularly variations in moisture. Improper treatment can lead to serious issues, such as salt karst formation, excessive settlement, and other stability problems that compromise the integrity of the subgrade (Dong, Li, Ge, & Chen, 1997; Li, Chen, Song, Wen, & Wang, 2020; Wang, 1992). This paper aims to provide a comprehensive review of the engineering properties, practical applications, challenges, and countermeasures associated with salt rock filling, with the goal of guiding future design and construction efforts in salt lake regions. To better understand the potential of salt rock as a subgrade material, this review presents a detailed discussion on the material's behavior under different environmental conditions. Additionally, suggested methods for mitigating challenges associated with salt rock use, as well as quality control metrics to ensure long-term stability, are explored. This work aims to bridge knowledge gaps and provide a foundation for engineers seeking to employ salt rock fillings in challenging environments.

2. Engineering properties of salt rock fillings

2.1 Basic physicochemical properties

Salt rock fillings are derived from local natural salt sediment through processes such as air-drying, crushing, or screening. Natural salt sediments typically consist of a mix of highly

Table 1. Reported cases of salt rock subgrades in China

Type	Line section	Year of construction	Line grade	Length of salt rock subgrade (km)	Source
Railway	Qarhan Salt Lake section of Qinghai-Tibet Railway	Line I: 1976~1979 Line II: 2005	I	30.86	Chen *et al.* (1988)
	Hami-Lop Nor Railway	2012	II	85	Xie (2013)
	Luozhong Industrial Siding Railway	2012	II	8.47	Lin, Ren, Yi, and Jiang (2012)
Highway	Qarhan Salt Lake section of G215 Highway	Original line: 1955 Reconstructed line: 2006	II	32	Fang, Liu, and Xu (2005) and Xu and Fang (2005)
	Seketi Gas Field Dedicated Highway	1995~1996	IV	N/A	Li *et al.* (2020)
	Qarhan-Golmud Express way	2012	N/A	0.35	Cai, Gao, and Liu (2015), Dai (2011), Li *et al.*, (2020)
	Qarhan Salt Lake section of G3011 Express way	N/A	N/A	3.3	Li *et al.* (2020)
	Hami-Luozhong section of S235	2003–2005	III	73	Li *et al.* (2020)
	Luozhong-Ruoqiang section of S235	2022–2023	III	N/A	Li *et al.* (2020)

Source(s): Authors' own work

soluble salts, moderately soluble salts, and insoluble components. While many minerals can be classified as salts from a chemical perspective, such as kaolinite and feldspar, in subgrade engineering, "salt rock" usually refers to rocks primarily composed of highly soluble salts, including halite, glauberite, carnallite, and mirabilite.

The formation and evolution of shallow salt sediment are complex processes (Li & Shi, 2021; Licsandru *et al.*, 2019), influenced by historical atmospheric temperatures, groundwater levels, floodwater, precipitation, and evaporation (Bowen, Kipnis, & Pechmann, 2017; Bowen, Kipnis, & Raming, 2018; Christiansen, 1963; Liu & Yang, 1997; Zhao, Xia, Wang, Cao, & Lv, 2005).

As listed in Table 1, all of the reported railways and highways in China with salt rock filling are constructed in Lop Nor Salt Lake and Qarhan Salt Lake by far. There is hardly any other reported literature to be referred out of the two areas. Thus, only salt rock fillings in Lop Nor Salt Lake and Qarhan Salt Lake are discussed in this paper.

(1) Physical properties

Reported data on the soluble mass fraction of natural salt rock in Lop Nor Salt Lake and Qarhan Salt Lake are summarized in Table 2. Most salt rock samples from Qarhan Salt Lake have a total soluble salt content exceeding 70%, with sodium chloride being the predominant component. In contrast, salt rock from Lop Nor Salt Lake generally has a lower total soluble salt content but higher concentrations of calcium ions Ca^{2+} and sulfate ions ($SO_4{}^{2-}$).

Halite's specific gravity is notably lower than that of other common salt rock minerals, while the values for other minerals are relatively close. Consequently, the halite content in a salt rock sample can be roughly estimated based on its specific gravity. (Table 3)

Table 2. Reported soluble mass fraction of salt rock in Lop Nor Salt Lake and Qarhan Salt Lake

			Soluble mass fraction in salt rock sample (%)									
Salt lake	Source	Sample No.	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Na^{+} & K^{+}	Cl^{-}	SO_4^{2-}	CO_3^{2-}	HCO_3^{-}	Total soluble salt
Lop nor	Cheng, Liu, Wang, and Song (2023)	1	0.75	1.53	N/A	N/A	12.54	18.54	8.91	N/A	0.03	42.65
		2	0.27	1.25	N/A	N/A	18.82	29.69	4.68	N/A	0.02	54.25
		3	0.88	0.23	N/A	N/A	23.86	35.69	5.55	N/A	0.02	65.18
	Xi *et al.* (2022)	1	0.93	0.07	N/A	N/A	N/A	48.65	2.64	N/A	N/A	83.87
	Han, He, and Cui (2021)	Average	1.05	1.18	23.63	1.24	N/A	26.95	7.59	0.12	N/A	62.55
	Maimaitiaili (2020)	1	1.22	0.28	33.94	0.08	34.02	50.04	5.50	1.07	N/A	N/A
		2	1.24	0.25	31.72	0.07	31.79	52.88	5.89	1.05	N/A	N/A
	Sun (2020)	1	1.25	1.48	23.63	1.40	25.03	26.95	7.73	0.32	N/A	68.73
		2	8.69	2.12	21.04	0.89	21.93	27.60	27.17	0.27	N/A	63.32
		3	5.96	1.51	24.46	0.91	25.37	26.10	11.96	0.44	N/A	75.59
	Xi (2020)	1	1.80	0.00	N/A	N/A	4.44	7.45	3.48	0.01	0.02	19.10
		2	1.39	0.07	N/A	N/A	9.36	14.02	4.20	0.01	0.01	30.09
		3	1.65	0.22	N/A	N/A	4.58	8.06	3.48	0.00	0.01	19.85
		4	0.75	0.01	N/A	N/A	2.58	4.08	1.70	0.00	0.02	10.03
		5	1.17	0.10	N/A	N/A	9.04	14.31	2.70	0.00	0.02	27.62
		6	1.32	0.12	N/A	N/A	13.91	22.02	2.88	0.00	0.01	42.69
		7	1.57	0.14	N/A	N/A	6.92	11.55	3.12	0.00	0.02	25.07
		8	1.15	0.04	N/A	N/A	9.95	15.65	2.52	0.00	0.01	29.72
	Zhou (2017)	N/A	0.709	0.213	N/A	N/A	14.701	26.75	0.32	0.001	0.012	16.33
			~1.832	~2.053			~34.223	~50.81	~5.52	~0.013	~0.024	~90.30
	Zhou (2007)	1	0.87	1.41	N/A	N/A	14.70	26.75	2.23	N/A	0.02	51.83
		2	0.83	0.29	N/A	N/A	24.59	38.25	2.76	N/A	0.01	62.38
		3	0.99	2.05	N/A	N/A	15.71	29.89	2.94	N/A	0.02	53.77
		4	0.71	0.21	N/A	N/A	28.81	44.94	1.92	N/A	0.01	72.86

(*continued*)

Table 2. Continued

			Soluble mass fraction in salt rock sample (%)									
Salt lake	Source	Sample No.	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Na^{+} & K^{+}	Cl^{-}	SO_4^{2-}	CO_3^{2-}	HCO_3^{-}	Total soluble salt
Qarhan	Wang, Xu, and Fang (2022)	1	0.35	2.70	18.28	1.88	20.16	37.75	0.75	0.03	0.03	61.77
	Sun (2020)	1	0.56	0.36	33.62	0.33	33.94	54.09	0.86	0.09	N/A	83.98
		2	0.39	0.55	35.97	0.11	36.08	57.08	0.54	0.10	N/A	94.35
		3	0.44	0.52	36.21	0.12	36.33	55.36	0.99	0.10	N/A	93.71
		4	0.52	0.60	34.51	0.07	34.58	57.42	0.45	0.10	N/A	93.58
	Wu *et al.* (2014)	1	0.89	2.90	10.00	1.50	11.50	26.00	2.10	0.04	0.00	N/A
	Liu, Zhang, and Wang (2013)	1	0.29	1.10	23.10	1.34	24.44	42.28	1.95	0.00	0.03	72.60
		2	0.27	1.21	23.85	1.39	25.24	41.87	1.98	0.00	0.03	71.80
		3	0.26	1.63	21.12	1.72	22.84	41.06	1.56	0.00	0.02	72.90
		4	0.51	1.67	21.63	1.10	22.73	40.42	1.15	0.02	0.02	70.90

Source(s): Authors' own work

Table 3. Specific gravity of some common minerals in salt rock

Mineral	Halite	Glauberite	Silt	Sand
Specific gravity	2.165	2.75~2.85	2.65~2.69	2.65

Source(s): Authors' own work

The specific gravity of salt rock typically ranges from 2.1 to 2.5., listing the specific gravity of some common minerals. The specific gravity of halite is notably lower than that of other common salt rock minerals, while the values for other minerals are relatively close. Consequently, the halite content in a salt rock sample can be roughly estimated based on its specific gravity (Cheng & Liu, 2012).

The structure of natural salt sediment can range from granular, weakly cemented, and cemented to strongly cemented (Xu & Fang, 2005). This variation depends on the historical environmental conditions the salt rock experienced during its formation. The physical and mechanical properties of natural salt rock in these various structures are summarized in Chen *et al.* (1988) (see Table 4). The structural characteristics of natural salt rock significantly influence the treatment process required before using it as fill material. For instance, granular salt sediment typically needs to be air-dried before paving because its natural moisture content is usually higher than the optimum moisture content. In contrast, strongly cemented salt sediment should be crushed before paving, as it is often too large to use directly as filling.

The composition and structure of salt rock are complex and highly variable, with significant differences at different locations and depths. These variations result in considerable differences in the physical and chemical properties of the salt rock filling, which in turn increases the difficulty of engineering design and construction. The specific impact of the composition and structure of salt rock on engineering properties is discussed in detail in Section 2.5.

(2) Phase change of salt rock

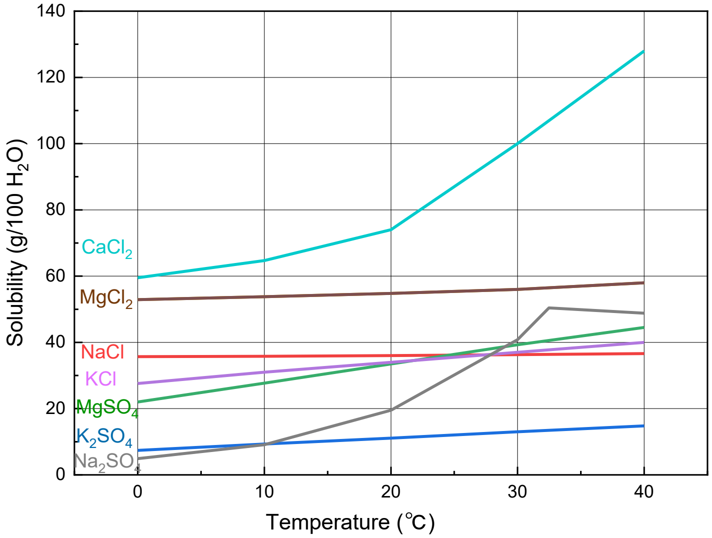
The high solubility of readily soluble salts in salt rock makes it highly susceptible to dissolution when exposed to rainfall, water immersion, humid air, or other moist conditions. Figure 2 illustrates the solubility lines of some common soluble salts found in salt rocks. Additionally, the solubility of certain soluble salts, such as sodium sulfate such (Na_2SO_4) and magnesium chloride ($MgCl_2$), is highly sensitive to temperature changes, leading to volume changes in the matrix.

As shown in Figure 3 (a) (Pronk, 2006), the composition of a single salt-water system can be predicted based on temperature and salt concentration at a given pressure. However, salt rocks typically contain multiple components and possess a porous structure, making their

Table 4. Physical and mechanical properties of natural salt rock

Parameter	Loose	Consolidated	Strongly consolidated
Uniaxial compressive strength (MPa)	<1.0	1~2.5	2.5~5.0
Shear strength (MPa)	<0.02	0.02~0.1	>0.1
Elastic modulus (MPa)	<100	100~200	>200
Longitudinal wave velocity (km/s)	2.0	2.0~3.0	>3.0
Dynamic poison's ratio	0.3	0.2~0.3	0.2
Dry density (g/cm^3)	1.48~1.6	1.6~1.8	1.8~1.95
Porosity	0.36~0.42	0.26~0.36	0.198~0.26

Source(s): Chen *et al.* (1988)



Source(s): Authors' own work

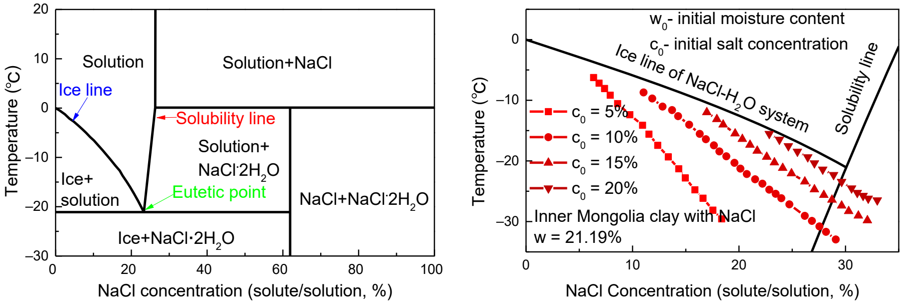
Figure 2. Solubility of some soluble salts

phase changes under environmental variations extremely complex. The conditions and pathways of phase changes in salt rock are influenced by its concentration and the presence of other solutes. The freezing point of pore water can be lowered by the matrix and solute concentration (Figure 3 (b)), and the solubility of a specific salt can be decreased by the presence of other salts with the same cations or anions (Figure 3 (c)) (Zhao, Zhang, Wang, & Wang, 2015).

It is important to note that in the special multi-salt environment of salt rock, the presence of other salts not only affects the solubility of a specific salt but also influences its dissolution process and the formation of precipitation products. For example, glauberite ($Na_2SO_4 \cdot CaSO_4$) forms as a precipitate in a $Na^+ - Ca^{2+} - SO_4{}^{2-} - H_2O$ system. During the dissolution of glauberite, calcium sulfate can reprecipitate on the mineral surface at high temperatures, inhibiting further dissolution (Gao, Xu, Han, Liang, & Zhao, 2012). Given the complex formation and phase transition processes, along with the historical environmental conditions of salt rock, accurately predicting changes in phase composition in practice is challenging. Thermodynamics-based phase diagram calculations can aid in analyzing salt rock composition changes (Jie, 2019). For instance, some models that incorporate Pitzer's equations (Pitzer, 1973) have demonstrated high accuracy in predicting multicomponent phase diagrams for salt rocks (Steiger, Kiekbusch, & Nicolai, 2008).

2.2 Mechanical properties

(1) Compaction properties During the compaction of salt rock filling, saturated brine is used instead of freshwater to prevent erosion of salt rock particles. The data related to this topic are listed in Table 5, and the corresponding components are provided in Table 6. The optimum moisture content and maximum dry density of salt rock filling vary depending on mineral composition and gradation. Generally, the optimum moisture/brine content ranges from 5 to 12%, and the maximum dry density is between 1.61 and 1.94 g/cm^3. As the maximum particle size and mud content decrease, the



Phase diagram of a $NaCl-H_2O$ system

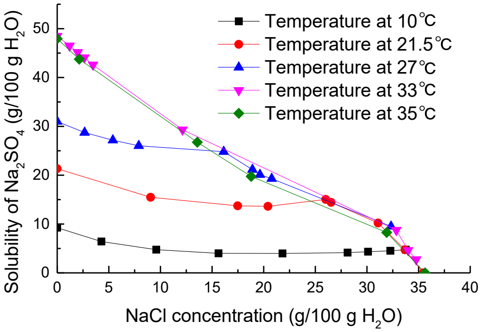
(a)

Source(s): Pronk (2006)

Change of ice line by soil matrix

(b)

Source(s): Wang, Liu, Yu, Wang, and Feng (2021)



Solubility of Na_2SO_4 in $NaCl$ solution

(c)

Source(s): Zhao, Zhang, Wang, and Wang (2015)

Figure 3. Typical phase diagram and impacts from soil matrix and other solutes

optimum moisture/brine content increases, while the maximum dry density decreases (Wang, Chen, Song, Wen, & Chen, 2024; Wang, 2005).

However, conventional compaction tests may not always yield expected results. For salt rock with a relatively high total soluble salt content, dry density tends to increase with increasing moisture content without showing a significant peak (Shi & Zhao, 1989; Xi, Chen, Song, Zhang, & Wang, 2022). It is recommended to consider the moisture content and dry density at the saturation point as the optimum values in compaction tests (Shi & Zhao, 1989). Alternatively, Xi *et al.* (2022) suggested using the moisture content corresponding to the peak unconfined compressive strength of dry samples at a given dry density.

(2) Shear behavior

Due to its capacity for crack healing, the shear strength of remolded salt rock samples at an appropriate dry density or compaction ratio is typically higher than 1 MPa, comparable to that of natural cemented salt rock (Dai, 2011). This meets the strength requirements for stabilized soil as fill (Zhou, 2017). The shear strength of salt rock is influenced by factors such as total soluble salt content, particle size distribution, dry density, moisture content, and more. The

Table 5. Reported optimum moisture content and maximum dry density of salt rock filling

Reference	Total soluble salt content (%)	Particle size	Optimum moisture content (%)	Optimum brine content (%)	Maximum dry density (g/cm^3)
Wang *et al.* (2024)	65.18	≤40 mm	N/A	13.2	1.76
		≤20 mm	N/A	16.9	1.71
		≤10 mm	N/A	18.4	1.69
Wang, Xu, and Fang (2022)	61.77	N/A	4.49	N/A	1.91
Maimaitiaili (2020)	90.46~93.48	<2.75 mm	N/A	5.42	1.613
Liu *et al.* (2013)	70.9~72.9	N/A	11	N/A	1.82
Dai (2011)	70~90	N/A	11~12	N/A	1.7
Wang (2005), Xiao *et al.* (2007)	98.38	Natural Salt rock particle (0.5 ~ 20 mm)	12.16	N/A	1.78
	93.58	Natural Salt rock particle (0.5 ~ 20 mm) + 5% mud particle (≤ 0.25 mm)	11.72	N/A	1.86
	88.84	Natural Salt rock particle (0.5 ~ 20 mm) + 10% mud particle (≤ 0.25 mm)	11.53	N/A	1.87
	77.90	Natural Salt rock particle (0.5 ~ 20 mm) + 20% mud particle (≤ 0.25 mm)	10.57	N/A	1.94

Source(s): Authors' own work

uniaxial compressive strength of remolded salt rock samples increases with smaller particle sizes, higher total soluble salt content, and greater dry density (Xiao, Liu, Hou, Fang, & Wang, 2007; Zhou, 2007). Adding mud content from 0 to 20% can also strengthen remolded salt rock samples (Xiao *et al.*, 2007).

The dynamic shear behavior of salt rock filling differs from that of discrete filling in subgrades. The failure mode of salt rock filling is characterized by brittle fracture. The critical cyclic load ratio of salt rock filling is relatively high, while the accumulative strain and failure strain are relatively low (Wang *et al.*, 2022; Wang, 2005; Xiao *et al.*, 2007) proposed different equations to predict the accumulative strain of salt rock subjected to train-induced load, respectively.

Previous studies on the shear behavior of salt rock have mainly focused on the stability and durability of salt cavern storage, with little attention given to salt rock subgrades. The engineering conditions of salt cavern storage differ significantly from those of subgrades. For instance, the total soluble salt content and porosity of salt rock filling from shallow salt sediment are more variable than those from deep salt deposits. Subgrade salt rock filling is subject to variations in atmospheric and hydrogeological conditions, whereas environmental conditions for deep salt deposits are relatively stable. Additionally, the load patterns on salt rock in subgrades and cavern storage are entirely different. In subgrade engineering (Yang *et al.*, 2024; Zhang, Kang, & Zhang, 2024), the confining pressure and train-induced load on subgrade salt rock filling are usually below 100 kPa, with load frequencies often exceeding 1 Hz and load cycles numbering in the millions over a 100-year service life. In contrast, for salt cavern storage (Liu *et al.*, 2024; Ma, Wang, Wang, Xue, & Duan, 2021; Wang, Zhang, *et al.*, 2022), the confining pressure and gas injection-production-induced load on surrounding salt rock typically exceed 5 MPa, with load frequencies lower than once per day and load cycles

Table 6. Reported specific composition of the rock salt filling materials

Reference	Sample No.	Soluble mass fraction in salt rock sample (%)									
		Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Na^{+} & K^{+}	Cl^{-}	SO_4^{2-}	CO_3^{2-}	HCO_3^{-}	Total soluble salt
Wang *et al.* (2024)	1	0.88	0.23	N/A	N/A	23.86	35.69	4.55	N/A	0.02	65.18
Wang, Xu, and Fang (2022)	1	0.35	2.70	18.28	1.88	20.16	37.75	0.75	0.03	0.03	61.77
Maimaitiaili (2020)	1	1.22	0.28	33.94	0.08	34.02	50.04	5.50	1.07	N/A	N/A
	2	1.24	0.25	31.72	0.07	31.79	52.88	5.89	1.05	N/A	N/A
Liu *et al.* (2013)	1	0.29	1.10	23.10	1.34	24.44	42.28	1.95	0.00	0.03	72.60
	2	0.27	1.21	23.85	1.39	25.24	41.87	1.98	0.00	0.03	71.80
	3	0.26	1.63	21.12	1.72	22.84	41.06	1.56	0.00	0.02	72.90
	4	0.51	1.67	21.63	1.10	22.73	40.42	1.15	0.02	0.02	70.90
Dai (2011)	1	0.026	0.002	N/A	N/A	0.151	0.111	0.068	0	0	N/A
	2	0.035	0.002	N/A	N/A	0.164	0.114	0.078	0.003	0.007	N/A
	3	0.710	0.012	N/A	N/A	0.582	1.077	0.214	0.002	0.012	N/A
Wang (2005), Xiao *et al.* (2007)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A		N/A

Source(s): Authors' own work

fewer than 10,000 over a 30-year service life. Consequently, research results from salt cavern storage have limited applicability to salt rock filling studies, necessitating further investigation into the mechanical properties of salt rock filling.

2.3 Salt dissolution

As a porous medium, the water retention curve and permeability of salt rock share some similarities with other common rocks and soils (Schulze, Popp, & Kern, 2001; Song, Chen,Wang,Wen, & Chen, 2023). However, salt dissolution distinguishes salt rocks from other materials in certain hydrological properties. During dissolution, the solution flows through cracks and pores or scours the salt rock surface, dissolving soluble minerals. The dissolution of salt rock is primarily driven by the unsaturation of pore solutions. The dissolution rate is influenced by both internal and external factors (Xiao, Zhao, Zhang, Wang, & Tang, 2017), and generally decreases to zero over time as the solute concentration increases.

Internal factors include salt solubility, soluble mass fraction, other compositions, and structure. Generally, the dissolution rate positively correlates with salt solubility and soluble mass fraction. Other compositions can also play a role; for example, the dissolution rate of halite can be inhibited by the presence of ions like I^-, Br^-, and F^- (Alkattan, Oelkers, Dandurand, & Schott, 1997). Salt rocks with many cracks and pores usually exhibit a high dissolution rate (Liu, 2014).

External factors include dissolution area, concentration, temperature, confining pressure, and flow rate. Dissolution can be accelerated by increasing the dissolution area (Durie & Jessen, 1964a), temperature (Jiang, Wang, Ren, Chen, & Zhang, 2012), and flow rate (Jiang *et al.*, 2012), while decreasing the concentration (Durie & Jessen, 1964b; Jiang *et al.*, 2012) and confining pressure (Wu, Li, & Dong, 2014). Increased confining pressure reduces pore volume and dissolution area, thereby depressing the dissolution rate (Wu *et al.*, 2014). According to Jiang *et al.* (2012), the influence order is temperature > flow rate > concentration.

2.4 Salt expansion

Upon saturation, solutes precipitate from the pore solution as crystals, releasing heat during cooling or evaporation. This liquid-to-solid phase change is typically accompanied by heat release, observable in temperature-time curve development, with local peaks defining initial precipitation points (Lai, Wan, & Zhang, 2016; Li & Shi, 2021; Nachshon, Weisbrod, Katzir, & Nasser, 2018; Wang *et al.*, 2024; Wang, Liu, Feng, Zhang, & Liu, 2020). The growth of salt crystals within pores drives the expansion of the matrix. Salt expansion in salt rock accumulates during the first few freeze-thaw cycles (Liu, Li, & Li, 2017; Maimaitiaili, 2020; Wang *et al.*, 2024).

According to Wang *et al.* (2024) and Zhang, Dai, Yang, and Chen (2019), salt expansion is affected by overburden pressure, moisture content, maximum particle size, freeze-thaw cycles, and compaction ratio. Salt expansion increases with higher moisture content and maximum particle size and decreases with reduced overburden pressure and compaction ratio. Overburden pressure significantly impacts salt expansion, greatly suppressing its development. After three freeze-thaw cycles, the accumulated salt expansion rate is reported to be 5.38% (Luo, 2013).

It is worth noting that frost heave has a minor impact on the volume change of salt rock compared to salt expansion in most cases. Halite is usually the dominant component in salt rock (Table 2), with content typically exceeding 60% (Table 5). The optimal moisture content for salt rock fillings in previous projects is generally below 12% (Table 5). The freezing point of pore water is significantly lowered by solute and soil matrix effects, potentially dropping below −20°C in such situations (Wang, Liu, Yu, Wang, & Feng, 2021), which is lower than the temperatures typically experienced by subgrade salt rock fillings in salt lake regions (Liu, Li, & Li 2017; Wang *et al.*, 2024).

2.5 Discussion on influences of composition and structure of salt rock filling on its engineering properties

(1) Influence of composition of salt rock

According to the data presented in Table 2 of Section 2.1, the main components of salt rock filler are soluble salts, with small amounts of moderately soluble salts and insoluble substances. The characteristics of soluble salts include: (1) Cementing action: During compaction and air-drying, the higher the content of soluble salts, the better the overall strength and stability; (2) High solubility: Soluble salts have high solubility and fast dissolution rates, which can lead to salt dissolution problems. The higher the content of soluble salts, the more pronounced the salt dissolution effect, which can significantly impact the integrity and bearing capacity of the roadbed structure.

Soluble salts are typically dominated by sodium chloride (NaCl). Sodium chloride has good cementing properties and can effectively bond other particles in the filler. Additionally, temperature has little effect on its solubility. The higher the sodium chloride content in salt rock, the greater the strength and stability of the rock during the liquid-solid phase transition (from liquid to solid). Natural salt rocks predominantly composed of sodium chloride crystals exhibit high strength and hardness (Maimaitiaili, 2020).

Sodium sulfate (Na_2SO_4) is highly sensitive to temperature changes, and its volume and structure undergo significant changes before and after phase transitions. As the temperature decreases, sodium sulfate reaches a supersaturated state and forms Glauber’s salt ($Na_2SO_4 \cdot 10H2O$), with its volume expanding 3.14 times. Its structure also changes from orthorhombic to monoclinic. This transformation further affects the strength and stability of salt rock. Therefore, the higher the sodium sulfate content in salt rock, the more likely it is to experience significant degradation in strength and stability during freeze-thaw cycles.

Moderately soluble salts are characterized by low solubility, dissolving only partially in water at a slow rate, which results in less pronounced salt dissolution problems. As a result, the impact of water on salt rock is relatively minor. Moderately soluble salts are typically gypsum ($CaSO_4$). Gypsum has a stable solubility at room temperature and is not easily affected by temperature fluctuations. When using gypsum-based soil as filler, it is important to first destroy its honeycomb structure. The content of gypsum is generally not strictly limited, but adequate compaction should be ensured. Although gypsum’s salt dissolution problem is less severe than that of soluble salts, prolonged hydration may lead to gradual dissolution, which could affect the overall stability and durability of the filler.

Insoluble substances have extremely low solubility, making them virtually insoluble in water. For example, calcium carbonate is a typical insoluble substance. Calcium carbonate particles are fine and highly plastic, which can enhance the workability and particle gradation of the filler. However, the solid particles may reduce their cementing ability during the solid-liquid phase transitions of easily soluble salts, such as sodium chloride. The higher the content of calcium carbonate in salt rock, the poorer the bonding between particles, leading to a decrease in the overall strength of the salt rock. (2) Influence of the structure of salt rock.

For the structure of rock salt, current research is limited. According to Table 4 in Section 2.1, summarizing the physical and mechanical properties of natural salt rock by Chen *et al.* (1988), rock salt can be classified into three types: loose, consolidated, and strongly consolidated. As introduced in Section 2.1, existing studies have only suggested that the treatment methods for salt rock before filling differ depending on its degree of consolidation. However, they have not indicated which type of salt rock structure is most suitable for use as roadbed filling. Therefore, further research is needed to explore the influence of the structure of salt rock on its engineering properties.

3. Use of salt rock fillings in subgrade

3.1 Application requirements

(1) Environmental conditions

Salt rocks are highly sensitive to moisture. When exposed to humid air or liquid water, they can soften or even dissolve rapidly. This sensitivity is why salt rocks with a soluble salt content greater than 1% are often not permitted in earthworks in certain regions (CEN/TC 396, 2018). Therefore, it is crucial to avoid exposing salt rock fillings in subgrades to humid air and liquid water. According to (2018), saline soil fillings are not restricted in regions with an aridity index greater than 50, mean annual precipitation less than 60 mm, relative humidity below 40%, and no surface water immersion. This suggests that in such regions, there are no specific conditions concerning the solubility of salt-containing fillings.

(2) Material conditions and structure conditions

It is recommended that salt rock fillings have a soluble salt content of greater than 40% (Ministry of Transport of the People's Republic of China, 2022). This high level of soluble salt content helps cement and strengthen the structure of salt rock, as soluble salts precipitate and solidify after compaction and air drying. The solubilities of some salts are highly sensitive to temperature changes, which can significantly impact the volume of salt rock fillings. For example, the solubility of sodium sulfate is 4.9 g in 100 g of water at 0 ℃ and 40.8 g at 30 ℃. However, the specific limitations regarding sulfate content or the variation in solubility of salt rock fillings remain unclear.

As illustrated in Table 7, the use of salt rock fillings in railway construction is generally limited to lower-grade lines or subgrade layers of lesser importance, primarily due to cost considerations (2018). In highway construction, salt rock fillings can be used in Grade III and IV lines, extending from the pavement to the subgrade with appropriate design. Highways with salt rock pavements are referred to as salt cap highways (Ministry of Transport of the People's Republic of China, 2022).

It can be concluded that the use of salt rock filling varies in different applications within railway and highway construction. In railway engineering, depending on the design standards for different track speeds, salt rock is mostly allowed only as the bottom layer of the subgrade. In contrast, in highway engineering, it is even permitted to be used as the surface material for low-grade roads. The reasons for this difference may include the following: (1) Using salt rock in the surface layer of the subgrade in railway tracks could cause adhesion between the salt rock and the track ballast, leading to a reduction in ballast flexibility, which may deteriorate the quality of track. (2) The use of salt rock filling in the surface layer of the subgrade in railway tracks could exacerbate the problem of salt erosion on components such as rails, tie plates, and fasteners. (3) In arid regions, the relatively lower vehicle load on low-grade roads and the less

Table 7. Restriction of salt rock as subgrade filling in railway construction

Subgrade layer	High-speed railway and intercity railway	Heavy haul railway, and ≥160 km/h mixed passenger & freight railway	<160 km/h mixed passenger & freight railway
Upper layer of subgrade bed	Not allowed	Not allowed	Not allowed
Bottom layer of subgrade bed	Not allowed	Not allowed	Allowed
Below the subgrade bed	Not allowed	Allowed	Allowed

Note(s): After National Railway Administration of the People's Republic of China (2018)
Source(s): Authors' own work

stringent durability requirements for the pavement design make the use of salt rock as a surface layer for low-grade roads sufficient to meet the design needs.

3.2 Threats and countermeasures

Salt rock subgrades in arid regions are generally threatened by various water sources, including rainwater, floodwater, confined water, construction water, and others. It is crucial to identify the primary threats and implement appropriate waterproofing or other countermeasures.

Due to the complex nature of the dissolution-precipitation-deformation processes in salt rock, accurately determining the evolution of salt rock subgrades when exposed to water and predicting changes in service performance using numerical simulations or laboratory methods can be challenging. The impacts of water and the selection of waterproofing methods are analyzed and summarized based on engineering practices as follows.

(1) Rainwater

Rainwater, as a form of freshwater, can erode salt rock. Although rainfall in arid regions is typically low, exposed surfaces of salt rock fillings, such as slopes and pavements, are still affected over the long term. Raindrops and runoff can erode salt rock slopes and pavements, making them rough and loose.

Common road surface protection measures include: setting up drainage ditches and intercepting ditches according to the terrain, as well as installing cross slopes and laying high-permeability gravel or crushed stone drainage layers. Common countermeasures for slope protection include pebbles, dry-laid flagstones, road shoulder widening, low slope ratios, and berms at the slope foot (National Railway Administration of the People’s Republic of China, 2018). Although many protective measures are implemented on the road surface and embankment slopes, rainwater can also accumulate in pavement concavities, infiltrating the salt rock layer and creating salt karst holes along the infiltration path, which can compromise the stability of the subgrade (Xi, 2020). To prevent this, a composite geomembrane is recommended to cover the salt rock layer (National Railway Administration of the People’s Republic of China, 2018).

(2) Floodwater

Floodwater poses a significant threat to salt rock subgrades, affecting large areas. Being unsaturated, floodwater is highly erosive to salt rock. For instance, a section of the Qinghai-Tibet Railway along Dabson Lake experienced severe subgrade settlement in 1989 due to floodwater erosion (Cao, 2007).

Common methods to mitigate the impact of floodwater on subgrades include constructing retaining dams, culverts, drainage ditches, widened road shoulders, and berms at the slope foot.

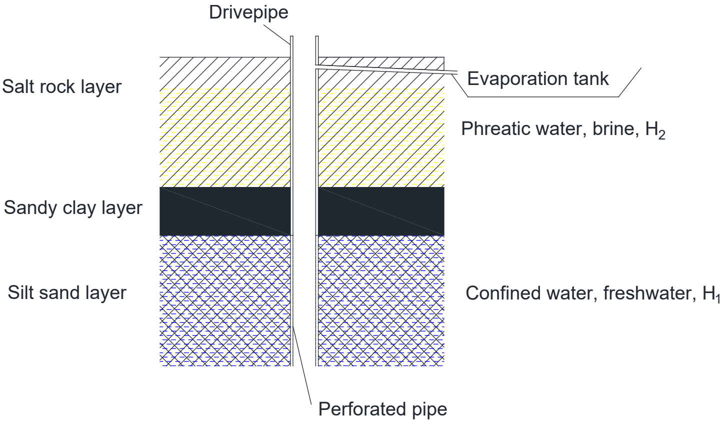
(3) Confined water

Confined water with a low total dissolved solids (TDS) value presents a common risk to salt rock subgrades. As shown in Figure 4, confined water can infiltrate upward through weak aquitards, eroding the salt rock as the water head is above ground level. Without a subgrade cover, water pressure is released after the confined water penetrates the salt crust and wells up. With a subgrade cover, confined water erodes the salt rock filling layer until the water head equalizes, leaving a void along the erosion path.

A free drainage well (Figure 5) is an effective and practical solution for managing confined water (Yu & Wang, 2005). This method involves artificially releasing confined water pressure beside the subgrade rather than allowing natural release beneath it. Once the pressure is released, the confined water pressure H_1 becomes lower than that of the phreatic water H_2, altering the flow direction of the confined water.

Source(s): Authors' own work

Figure 4. A salt karst hole in salt rock deposits of Chaka Salt Lake



Source(s): Authors' own work

Figure 5. Scheme of free drainage well in salt rock foundation

(4) Phreatic water

Phreatic water, which originates from adjacent lower layers or foundations beneath the salt rock layer, typically comprises saturated brine with low dissolution potential for salt rock. However, it can still reduce the elastic modulus and strength of salt rock, potentially causing excessive settlement (Salvati, Guarente, & Douglas, 2015).

For this type of hazard, the following protective measures are recommended: (1) During the embankment design, a raised cross-section is adopted. (2) A composite geomembrane placed under the salt rock filling layer effectively prevents the capillary rise of phreatic water. (3)

Borrow pits are excavated along both sides of the embankment to accelerate the evaporation of groundwater and the accumulation and crystallization of salts, thereby lowering the underground brine level. (4) Drainage ditches and other measures are implemented to prevent surface water infiltration, which could cause the underground brine level to rise. In areas with drainage difficulties, evaporation ponds can be installed. (5) In areas with well-developed salt dissolution, materials such as sand, gravel, or aeolian sand can be used for replacement (Ministry of Transport of the People's Republic of China, 2015).

(5) Construction water

Construction water includes saturated brine used for compacting salt rock fillings and freshwater for compacting upper layer fillings. It is essential to prevent freshwater from the upper layers from infiltrating the salt rock filling layer during construction. Before compaction, saturated brine is added to crushed salt rock fillings to achieve optimal moisture content. After compaction, the salt rock filling layer is air-dried to remove liquid water and cement the grains. For salt rock fillings with relatively high sulfate content, removing liquid water content can also reduce salt expansion. It is crucial to avoid using unsaturated brine and freshwater for compacting salt rock fillings, as they can erode the salt rock grains (Bai & Long, 2010).

(6) Vapor

Vapor can originate from the atmosphere or adjacent layers of the salt rock. As some local workers have noted (Long & Lu, 1975), salt rock roads are as hard as iron on sunny days but as soft as mud on cloudy days. The hygroscopic nature of salt rock means its strength significantly decreases upon moisture absorption. In arid regions, the impact of vapor is usually minimal since most days are sunny, and relative humidity is extremely low. However, the water-vapor transport path changes due to the covering effect of the salt rock subgrade on the natural foundation. It may take a long time to reach a new equilibrium, and the mechanisms and effects on subgrade stability remain unclear.

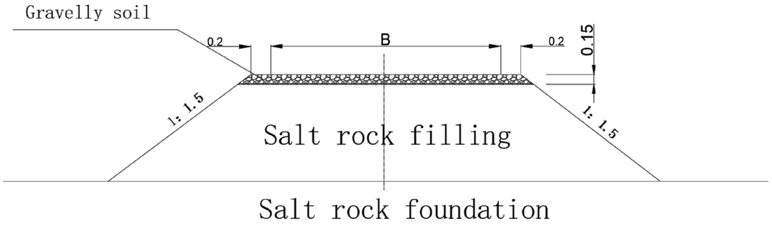
3.3 Salt rock subgrade structure

(1) Railway subgrade

Decades ago, the structure was relatively simple. The Qarhan Salt Lake section of the Qinghai-Tibet Railway Line I, constructed in 1978, exemplifies this simplicity. As depicted in Figure 6 (Long & Chu, 2005), the road shoulder was widened by 0.2 m on both sides. The main body of the subgrade consisted of salt rock, topped with a 0.15 m thick layer of gravelly soil.

The Qarhan Salt Lake section of the Qinghai-Tibet Railway Line II was constructed in 2005. Its subgrade structure, shown in Figure 7 (Li, 2009), features a core filled with salt rock. The top of the subgrade comprises 0.25 m of gravelly sand, a geomembrane, and an additional 0.1 m of gravelly sand. The left and right sides of the subgrade are composed of 0.5 m of salt rock, 0.5 m of gravelly sand, a geomembrane, and another 0.5 m of gravelly sand. The road shoulder was broadened by 1.5 m on both sides.

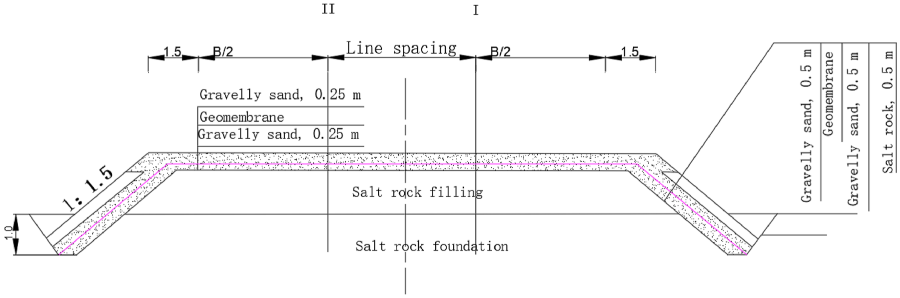
The Lop Nor Salt Lake section of the Hami-Lop Nor Railway, constructed in 2012, features a more complex structure. As depicted in Figure 8 (Xie, 2013), the top layer of the subgrade bed is filled with A/B group fillings, while the bottom layer and the layer below it are filled with salt rock. The top and bottom layers are separated by a barrier consisting of 0.1 m of medium coarse sand, a composite geomembrane, and another 0.1 m of medium coarse sand. The shoulders and slopes of the top layer are covered with 0.15 m of pebble, and both sides of the bottom layer's shoulder are widened by 0.5 m. Berms are laid at the slope foot on both sides.



Note(s): Unit: m; B denotes designed basic width

Source(s): Authors' own work

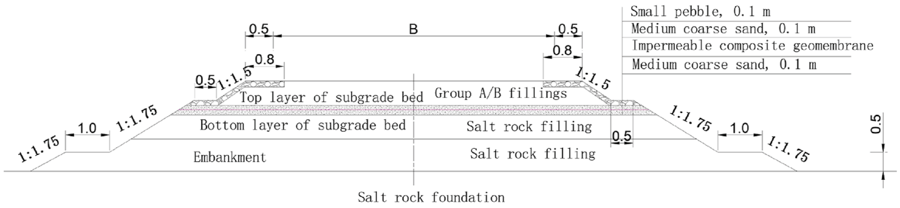
Figure 6. Salt rock subgrade structure of Qarhan Salt Lake section of Qinghai-Tibet Railway Line I



Note(s): Unit: m; B denotes designed basic width

Source(s): Authors' own work

Figure 7. Salt rock subgrade structure of Qarhan Salt Lake section of Qinghai-Tibet Railway Line II



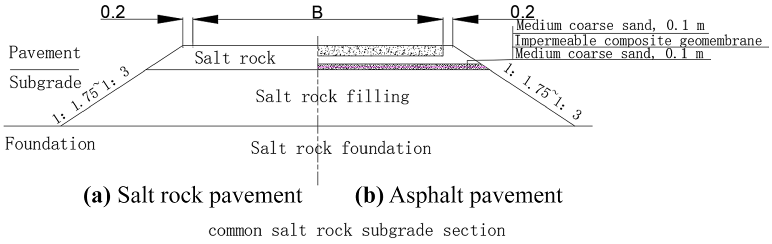
Note(s): Unit: m; B denotes designed basic width

Source(s): Authors' own work

Figure 8. Salt rock subgrade structure of the Lop Nor Salt Lake section of Hami-Lop Nor Railway

(2) Highway subgrade

Based on previous engineering practices, some recommended designs for salt rock subgrade structures are shown in Figures 9 and 10 (2022). For highways with salt rock pavement, both the pavement and subgrade are constructed with salt rock, as seen in the Qarhan Salt Lake section of the Qinghai-Tibet Highway. For highways with asphalt pavement, the pavement and subgrade are separated by an impermeable composite geomembrane layer, as demonstrated in the Lop Nor Salt Lake section of the S235 Highway. In cases where shallow groundwater is present, a ditch should be constructed 2 m outside the foot of the slope.

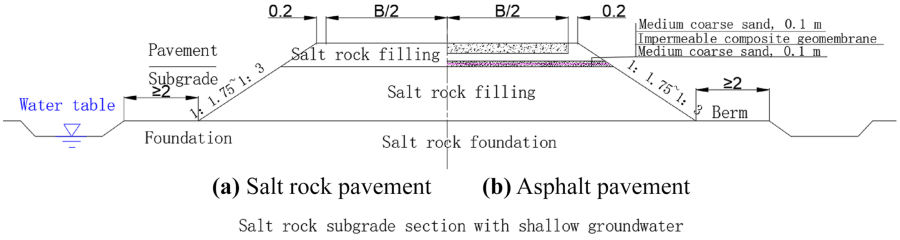


(a) Salt rock pavement **(b)** Asphalt pavement

Note(s): Unit: m; B denotes designed basic width

Source(s): Authors' own work

Figure 9. Recommended salt rock subgrade structure design for highway without shallow groundwater



(a) Salt rock pavement **(b)** Asphalt pavement

Source(s): Authors' own work

Figure 10. Recommended salt rock subgrade structure design for highway with shallow groundwater

3.4 Salt rock fills construction quality control

There are notable differences between the construction of salt rock fillings and conventional fillings. As previously mentioned, saturated brine with a TDS concentration of ≥300 g/L, rather than freshwater, is mixed with salt rock grains during compaction (Liu *et al.*, 2013; Xi *et al.*, 2022). After compaction, the salt rock filling layer is air-dried. During the curing process, it is recommended to repeatedly sprinkle saturated brine on the surface of the salt rock layer and allow it to air-dry (Liu *et al.*, 2013; Pang, 2014).

Compaction quality control is a critical aspect of construction quality assurance. For railway construction, there are no specific codes specifying the compaction quality acceptance index for salt rock fillings. As summarized in Table 8, various indices have been proposed based on engineering practices. In the Qarhan Salt Lake section of the Qinghai-Tibet Railway Line I (Shi & Zhao, 1989), the compaction ratio was used as an acceptance criterion for salt rock fill compaction quality. For the Qarhan Salt Lake section of the Qinghai-Tibet Railway Line II (Xie, 2013) and the Lop Nor Salt Lake section of the Hami-Lop Nor Railway (Luo, 2012), porosity and foundation coefficient K_{30} were used as quality control indices.

For highway construction, the compaction quality acceptance index for salt rock fillings is specified in relevant codes (Ministry of Transport of the People's Republic of China, 2015, 2022). As summarized in Table 9, both the compaction ratio and deflection are used as acceptance criteria for highways with asphalt pavement. In contrast, only the compaction ratio is used for salt cap highways.

In the field of railway construction, there is currently a lack of specific standards that clearly define the construction quality criteria for salt rock filling materials. Engineering practice indicates that multiple indicators must be simultaneously controlled during on-site construction, including porosity, K_{30} value, and compaction degree. In contrast, highway

Table 8. Salt rock fill compaction quality acceptance indices for railway

Structure of subgrade	Index	Qarhan salt lake section of Qinghai-Tibet railway line I	Qarhan salt lake section of Qinghai-Tibet railway line II	Lop nor salt lake section of Hami-Lop nor railway
Bottom layer of subgrade bed	Porosity	N/A	≤23%	≤31%
	Foundation coefficient K30 (MPa)	N/A	≥160	≥120
	Compaction ratio	≥0.85	N/A	N/A
Embankment	Porosity	N/A	≤25%	≤32%
	Foundation coefficient K30 (MPa)	N/A	≥140	≥110
	Compaction ratio	≥0.85	N/A	N/A

Source(s): Authors' own work

Table 9. Salt rock fill compaction quality acceptance indices for Grade III and IV highways

Structure of subgrade	Asphalt pavement Compaction ratio	Deflection (0.01 mm)	Salt rock pavement Compaction ratio
Subgrade surface	N/A	≤ Acceptance value	N/A
Top layer of roadbed	≥0.95	N/A	≥0.94
Bottom layer of roadbed	≥0.95	N/A	≥0.94
Top layer of embankment	≥0.94	N/A	≥0.93
Bottom layer of embankment	≥0.93	N/A	≥0.90

Source(s): Authors' own work

construction, particularly for low-grade roads, already has established quality control indicators specified in relevant standards, primarily managed through compaction degree and surface deflection. This suggests that railway projects impose more stringent requirements on salt rock filling, possibly due to differences in load-bearing capacities between railways and highways. Therefore, the railway sector urgently needs to further refine the standards related to salt rock subgrades, explicitly establishing design and construction criteria for salt rock in railway engineering.

The physical properties of filling materials can be evaluated using compaction ratio and porosity, which are strongly correlated for a given filling. However, for two different fillings with varying compositions or grain size distributions, their porosities may not be identical under the same compaction energy. This discrepancy explains why the porosity thresholds for salt rock fillings in the Qarhan Salt Lake section of the Qinghai-Tibet Railway Line II and the Lop Nor Salt Lake section of the Hami-Lop Nor Railway are not the same. Therefore, the compaction ratio is recommended as a more reliable measure for evaluating the physical properties of salt rock fillings.

Moisture content after air-drying is a critical physical index for salt rock fillings. As previously mentioned, the shear strength of salt rock significantly increases with reduced moisture content after air-drying, while salt expansion is also mitigated.

To date, the duration for air-drying salt rock filling layers has been determined based on engineering experience. The dissipation of construction water through natural evaporation can take a considerable amount of time, especially if the salt rock filling layer is not thoroughly air-dried before being covered by the next layer, due to the high hygroscopicity of salt rock. It is more scientific and reasonable to determine the air-drying duration based on a specific moisture content threshold value rather than relying solely on engineering experience.

4. Conclusions

Salt rock fillings have demonstrated their practicality as a subgrade construction material in arid regions, offering cost-effective and stable solutions. With proper design and construction techniques, salt rock fillings exhibit favorable mechanical properties, ensuring long-term stability of subgrades. The following conclusions and recommendations are drawn from this review:

1. *Stability and mechanical properties:* The primary component of salt rock fillings, halite, has proven effective in previous engineering practices. Salt rock fillings with low moisture content are relatively stable, possessing strong mechanical properties. Therefore, waterproofing remains a crucial aspect of salt rock subgrade construction to prevent deterioration due to moisture.

2. *Engineering definitions and material specifications:* The engineering definitions and requirements for salt rock are currently insufficiently detailed. Clear distinctions between salt rock and saline soil are essential, as these materials exhibit different behaviors in subgrade applications. The lack of well-defined boundaries between saline soil and salt rock, along with unclear specifications for composition content and grain size distribution, highlights the need for standardized guidelines to optimize salt rock utilization.

3. *Composition requirements:* It is recommended that salt rock fillings have a soluble salt content of greater than 40%. The salt rock with a high content of easily soluble salts, mainly composed of sodium chloride (NaCl), is suitable for use as roadbed filler due to its higher stability and strength. In contrast, salt rock with a higher content of sodium sulfate (Na_2SO_4) and clayey materials, due to its lower strength and susceptibility to environmental influences, is not suitable for direct use as roadbed filler. However, there is a lack of in-depth research on the specific limits for soluble salts, moderately soluble salts, and insoluble components in salt rock, as well as on how to treat salt rocks with poorer compositions. More investigation and research are needed.

4. *Phase composition analysis:* Predicting the phase composition of salt rock remains a significant challenge due to its inherent complexity. Current phase calculations based on thermodynamic theories require further refinement and simplification to be practically applicable. Developing reliable and simplified methods for predicting phase changes in salt rock is crucial for better understanding its behavior under various environmental conditions.

5. *Long-term stability and environmental influences:* To ensure the long-term stability of salt rock subgrades, effective methods for predicting moisture and solute transport are necessary, particularly in response to environmental variations and covering effects. The development of practical tools to assess these factors would enhance the reliability of salt rock subgrades in diverse environments.

6. *Threats and countermeasures:* Rainwater and confined water pose the most significant threats to the stability of salt rock subgrades. Cost-effective countermeasures, such as covering the salt rock layer with geomembranes and installing free drainage wells alongside the subgrade, are recommended to mitigate these risks and enhance durability.

7. *Quality control indices for construction:* The unique behavior of salt rock fillings—transitioning from discrete particles during compaction to a cohesive mass after air drying—raises questions about appropriate quality control indices. It is essential to determine whether conventional indices for common soils or stabilized soils are suitable for salt rock fillings. Moisture content after compaction and air drying is proposed as a quality control measure to prevent potential salt expansion and ensure the integrity of the subgrade.

In summary, salt rock fillings offer a promising and sustainable solution for subgrade construction in arid regions, provided that their unique properties are well understood and managed. Continued research is needed to refine material definitions, enhance predictive models, and establish effective construction practices. By addressing these challenges, salt rock can be harnessed more effectively, contributing to the advancement of subgrade engineering in salt lake regions.

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