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Full Length Research Paper

Evaluation of geotechnical properties of the salt layers on the Lake Tuz

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In this study, a soil survey of Lake Tuz was performed to determine the equipment to be used to collect salt from the saltpans of Lake Tuz. Moreover, the shearing and bearing strengths of the related salt layer were calculated considering the salt production and the salt quality, and the effects of the soil contamination in the lake were investigated. For this purpose, salt blocks were cut from the Cihanbeyli-Yavşanli and Şereflikoçhisar-Kayacik saltpans and from various parts of the lake and then subjected to several tests in the laboratory. The physical and chemical characteristics of the salt were determined. Additionally, plate loading tests were carried out to determine the maximum wheel-load capacity of the salt layer. Following the results of this research, the Turkish Tekel Salt Industry Institute purchased a modified cold milling machine 2000 DC from Australia Wirtgen Group to be used in Lake Tuz.

Key words: Lake Tuz, Kayacık saltpan, salt production, brine, evaporation.

INTRODUCTİON

Lake Tuz basin is a 15000 km^2 closed basin in the centre of Turkey, which includes Lake Tuz in the middle. The provinces surrounding Lake Tuz are Ankara to the northwest, Konya to the south, and Aksaray to the west. It is the second largest lake in Turkey with its 1665 km^2 surface area (Figure 1) and is under protection according to the Ramsar Agreement, which covers the international protection of watery areas. The natural regime of the lake presents itself as an increase in the water level due to surface water and underground water flows in winter and spring and a decrease in the water level due to evaporation in autumn. The lake, which is fed by surface rainfall, surface water, and underground water flows, loses its water only by evaporation. Depending on this hydraulic balance, the lake's surface area expands and shrinks with the rise and fall in the water level, and the salt rises up to the surface of the lake after dissolving from the salt layers at the lake's bed and remains at the surface as a result of evaporation. With the assistance of the shallow structure of the lake (the average water depth is 1.0 m), the salt layers formed during drying and evaporation related to the water regime in the summer months, support salt production in the lake. The annual salt (NaCl) production of the lake is 200 million tons (DSI, 2005) and 63% of the salt consumed in Turkey is produced by the three saltpans existing close to Lake Tuz. Lake Tuz has the same geological properties as the Great Salt Lake (Utah, USA). Many investigations have been carried out into Great Salt Lake and it has the biggest salt production areas (Koday, 1999).

Lake Tuz has been subjected to the risk of contamination due to various reasons. Currently, a series of studies have been carried out in order to determine the reasons and countermeasures of this contamination. The most important reason of the contamination was indicated to be the 185 km long main drainage channel that was built to drain the irrigation water of Konya Plain and connected to Lake Tuz with a channel including industrial and municipal waste water (Beker, 1989).

Another factor that leads to an increase contamination is the accidentally excavated soil or the soil surrounding the saltpans, which mixed with the saltwater during the salt processes at the lake and the saltpans. Therefore, the quality and the colour of the salt are affected

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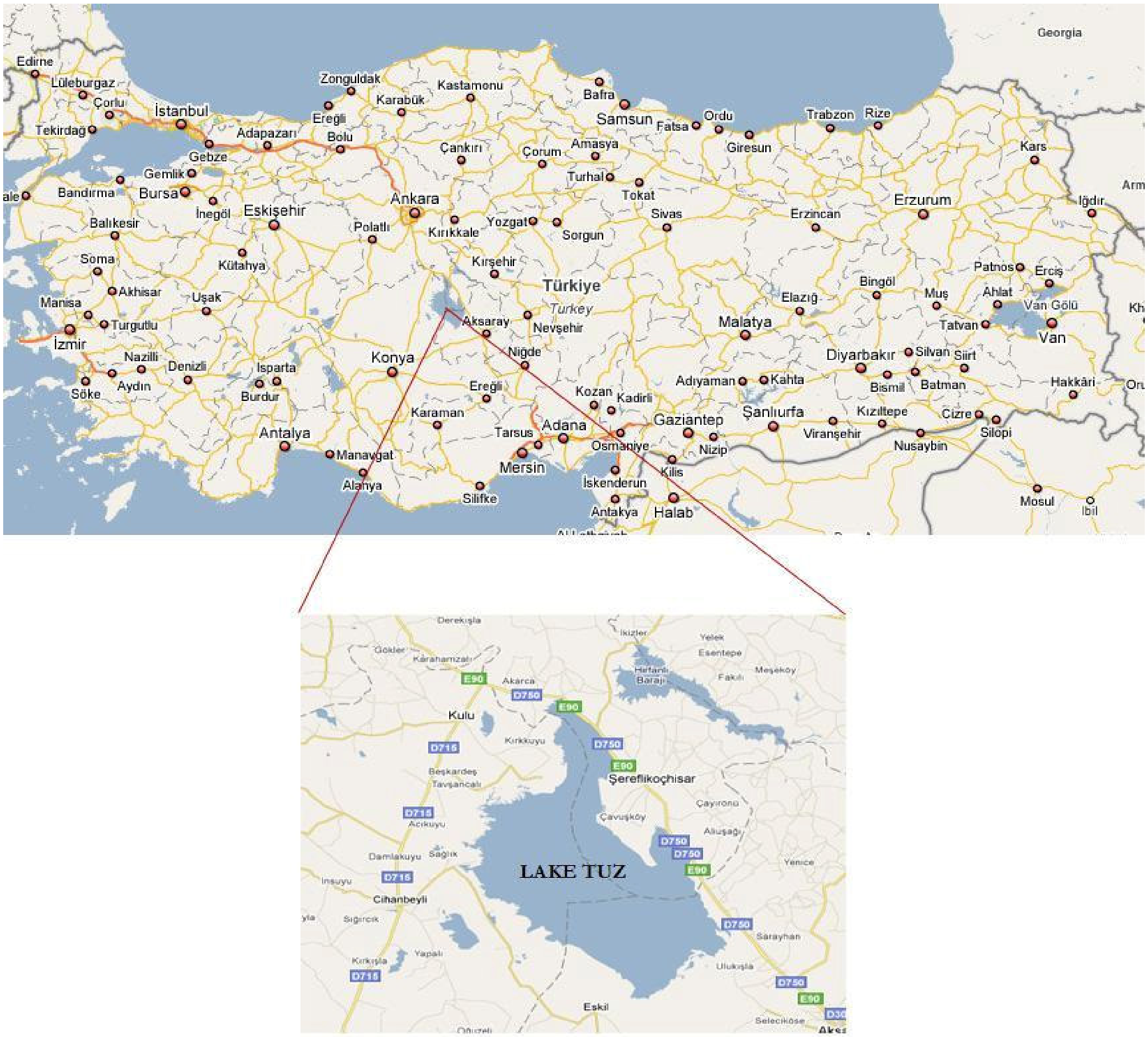

Figure 1. The map of Turkey and Lake Tuz.

negatively.

Salt production from salt lakes depends on evaporation of brine by solar effect and crystallization of salt. Salt production becomes easy because of the high density of salt in Lake Tuz and salt form in the summer; a large portion of Lake Tuz that has 1 - 1.5 m variation in level is shallow. These shallow portions of the lake become dry in the summer season due to severe evaporation and a 5 - 30 cm thick salt layer forms (MTA, 1982). Salt production begins in August and continues until December. There are three saltpans in Lake Tuz. These are Konya-Cihanbeyli-Yavşan saltpan, Ankara Ş. Koçhisar-Kaldırım saltpan, and Kayacık saltpan (Koday, 1999). The quantity and quality of salt produced from these saltpans are listed in Tables 1 and 2 (Ertem ve Engin, 2001).

Lake Tuz's water evaporates and forms a 5 - 30 cm thick salt layer at the top of the older salt layers including nearly 4 - 5 salt layers formed in the previous periods. The layers that have been formed graduate from hard (at the bottom) to soft (at the top); the layer at the bottom, which is the hardest salt layer, is called the "wooden layer". The layers are separated from each other with interfaces such that the connections are weaker between the top layers and stronger between the bottom layers.

The salt collection process in Lake Tuz is performed as follows: First of all, the newly formed 5 - 10 cm thick salt layer at the top is scraped with working machines of various types, from wheeled to crawler, according to the difficulty of the salt layer scraping process. Sometimes liper is used to scrape the top salt layer. During the scraping processes, especially when the layers are tightly

Table 1. Salt production capacity in Turkey (ton).

Place	Production capacity	Rate
Kayacık	500.000	25
Kaldırım	400.000	19
Yavşan	400.000	19

Table 2. Salt qualities in Turkey (saltpans).

Analyze	Kayacık	Kaldırım	Yavşan
Humidity	5.4950	16710	1.1320
Melting material m water	0.0780	0.1100	0.2840
$CaSO_4$	0.6807	0.4766	0.6870
$CaCl_2$	-	-	-
K_2SO_4	0,2467	0.4629	0.4371
MgSO	0.0430	0.3481	0.0348
MgCl	-	-	-
NaCl (Humid)	93.2566	96.7314	97.2314
NaCl (dry)	98.7516	98.4024	98.3634

connected to each other, sometimes much more force is required to separate the layers from each other such that the salt layer becomes completely broken. The broken layers reveal multi-directional problems, one of which is that the salt mixes with the soil water due to the liquid consistency state of the soil under the salt layer, and the colour and quality of the salt change. The second problem is the loss of manpower due to load trucks and working machines moving on the layer and sinking into the soil because of the insufficient bearing capacity of the layer. Another important factor is the long time period necessary for the renovation of the broken salt layer leading to continuity of the contamination for years.

A machine to prevent the disadvantages as aforementioned and to collect salt more economically was planned and developed. With this aim, a study was executed to determine the vertical and horizontal bearing strengths of the salt layers and the characteristics of the soil lying under the salt layers. Furthermore, the effects of the contamination due to the broken salt layers and the clay-silt seawalls surrounding the lake on the quality of the salt produced and the production saltpans were investigated.

THE GEOLOGY OF THE REGION

Lake Tuz basin covers an area of 15,000 km^2 with the rocks of Kırşehir Massif in the east, Boz mountains and Karapınar's volcanic formations in the south, and Karacadağ and a wide Neogene Plain in the west. An important fault zone known as the Koçhisar-Aksaray Fault along the NW–SE direction lies along the eastern Lake Tuz. Similarly, the western side of the lake has faults of limited lengths in which a system is formed with large and small faults lying parallel to each other instead of a single fault developing. According to many geological investigations performed in the region for various purposes, a marine stack made up of marine and terrestrial clastics and alga limestone began to settle continuously from the Cretaceous to the Eocene at the basin and ended after the Middle Eocene. Moreover, red coloured clastic units containing gypsum and lignite reserves were formed in the Upper Eocene and Oligocene, and then the formation of marine deposits occurred in the Miocene period following the Oligocene.

The terrestrial units began to settle completely after the early Miocene, and the clays including gypsum were formed in the late Pliocene. The plains around the lake consist of extensive alluvial areas of Pleistocene formations, which include gravels, sand, and clay-sized materials from the surrounding rocks (Uygun, 1981).

LAKE TUZ AND SALT FORMATION MECHANISMS

The region between the faults extending in the NW–SE directions at the east and west sides of the present lake area began to subside with the late Mesozoic period. This subsided basin has gradually taken the graben shape and formed the Lake Tuz, which is believed to have existed since the Pleistocene period according to researches performed up to now. Salt formation by evaporation has occurred continuously for centuries in the lake covering an approximate area of 1665 km^2.

Many different opinions have been put forward so far about the salt formation mechanism of the lake. However, in the light of the obtained data, the most consistent formation mechanism is thought to be related to the salt minerals existing at the base of the basin and around the lake. The salty sediments dissolved from these units and transported to the lake basin by the underground waters have settled under evaporable conditions (Ergun, 1988; Görür and Derman, 1978).

In this basin, salt domes of different sizes were detected during the geophysical measurements of the petroleum explorations. The underground waters flowing through the salty parts of this basin have drawn a certain amount of dissolved salt from the domes (Abdusselamoğlu, 1982; Uğurtaş, 1975).

SALT PRODUCTION WITH THE SOLAR EVAPORATION METHOD

Solar evaporation is the oldest method of salt production. It has been used since salt crystals appearing in trapped saltpans of sea water were noticed by man. Its use is practical only in areas with warm climates, in which the evaporation rate exceeds the precipitation rate, either annually or for extended periods, and ideally where there are steady prevailing winds (Calvonico, 1990).

Solar salt production is the capturing of sea water in shallow ponds, in which the heat of the sun evaporates most of the water. The concentrated brine containing impurities is then discarded by mechanical harvesting machines.

Two types of ponds are used: First, the concentrating pond, in which the salt water from the ocean or salt lake is settled and concentrated, and second, the crystallizing pond, in which the salt is actually produced.

Crystallizing ponds range from 60,000 - 360,000 m^2 with a foot-thick floor of salt that has been deposited over the years. During the salt-making season of four to five months, a saturated brine solution flows continuously through these ponds. There are much salts in the water as it can hold and therefore, most of the pure salt crystallizes out of the solution as the water evaporates.

The ponds are then completely drained. Mechanical harvesting machines gather the loose salt and carried it into piles (Calvinaco, 1990).

Solar evaporation depends on certain factors:

1. Large areas with small slope
2. Low salt water permeability
3. Low rainfall rate
4. High evaporation
5. Dry wind
6. Long summer season for evaporation

STUDIES PERFORMED IN THE LAKE AND SALTPANS

At present, salt collection processes continue in a 5% section of Lake Tuz, and production saltpans were formed by surrounding some sections of the lake with seawalls. In some dry years, as a result of evaporation, waters ebb at the open region of the lake from where the saltwater is taken to the production saltpans, and much less salt formation occurs in the open lake region. Therefore, the required water level should be provided before the evaporation period at the start of saltpan production (the first days of May). For this purpose, saltwater is pumped from the open lake region to the production saltpans before the evaporation period starts. However, the excessive water occurring in some years retards the evaporation and the salt production. Then, the excess water of the saltpans is pumped to the lake to provide rapid evaporation and early salt production.

Boreholes were drilled at various points to determine the characteristics of the soil beneath the salt layer of the saltpans and the lake from which salt was collected. Disturbed and undisturbed soil specimens were taken from the boreholes to be used in the consolidation tests and to identify the index and strength characteristics of the soil (Yıldız, 2000).

In some places under the salt layer, the soil continues with a black coloured clay layer of liquid consistency or with a green coloured soft clay layer, both of which are classified as the CL-CH group in the USCS. The water contents of the clay layers varied between 37 and 42%, which was closer to the liquid limit, especially for the black clay layer. The soil layer below the salt layer has potential high compressibility. Additionally, the soil including abundant gypsum crystal that is subjected to the Field Veyn Test, presented similar characteristics both in the lake and in the saltpans, which was also determined similarly during the investigations into the salts of Cihanbeyli Yavşanlı.

Another study was carried out by applying the loading tests on various salt layers of the lake and the saltpans using plates in order to determine the vertical load-bearing capacity of the salt layer. For this purpose, a hydraulic jack with a 100 kN indicator was mounted on the dozer and the working machine, and various loading tests were performed on the lake and the saltpans in a $0.15 \times 0.15 = 0.0225$ m^2 area. A load of 90 kN did not cause any failure on either the loading plate or the salt layers in each loading case, which means that the salt layers safely carried the compression of 4000 kN/m^2 in the vertical direction. The same 90 kN loading was also applied to the section where the upper salt layer had been removed, and no failure occurred on the tested salt layers either.

The compression applied on the salt layers by means of the wheels of the trucks transferring salt across the lake and the saltpans was determined to be 500 - 700 kN/m^2. When the thread area of the working machines and dozers in contact with the salt layer were considered, the pressure acting on the unit area of the salt layer varied between 1000 and 1200 kN/m^2. Although these compression values could exhibit a small increase under moving or braking conditions of the machines, the salt layers were found to be capable of carrying these extra pressure values safely according to the field investigations.

The boreholes drilled on the lake and the saltpans proved that the salt layer formed by 4 - 5 layers had a thickness of 20 - 25 cm (Figure 2). The stratification was clearly visible in the contaminated parts, but not visible with stronger connections between the layers in the uncontaminated parts. According to the investigations, the lower salt layer was harder than the upper, and the last two layers at the bottom were observed to be extremely strong.

LABORATORY TESTS

Determination of the physical and chemical characteristics of the salt

The physical and chemical characteristics of Lake Tuz

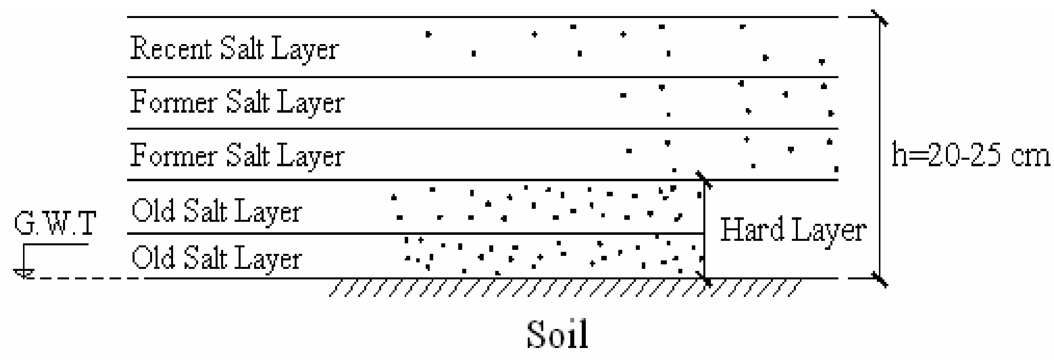

Figure 2. The formation of the salt layer.

Table 3. Physical and chemical characteristics of the salt (NaCl).

NaCl ratio	98%
Na	40%
Cl	60%
Hardness	2 - 2.5
Specific gravity	21-25.5 kN/m^3
Melting point	800℃
Boiling point	1412℃
Color	Colorless – White

salt were determined in the chemical laboratory and tabulated in Table 3.

Determination of the soil characteristics

In order to classify the soil, sieve analysis and Atterberg limit tests were performed on the disturbed samples in the laboratory. A series of tests, namely: The moist unit weight test on the undisturbed soil specimens; the shear and unconfined compressive tests for the load-bearing parameters of the soil; and the triaxial compression test for the cohesion and angle of friction of the soil were carried out during the study. Additionally, the consolidation test was applied to determine the settlements at the soil due to various loads. When a general evaluation was made according to the results given in Table 4, the soil was found to be soft and very soft in various different sections and was placed in the CL-CH group. On the other hand, the strength characteristics of the soil including gypsum were rather weak and had a large compressibility capacity. According to the tests performed in this study, the cohesion of the soil was in the range of c_u = 15 - 30 kN/m^2 and the unconfined compression strength of the soil was in the range of q_u = 30 - 60 kN/m^2. Although the angle of friction of the soil was φ = 0, a small amount of the angle of friction occurred due to the gypsum crystals existing in the soil. Additionally, a burning test was applied to determine the amount of organic matter in the soil, and an average value of 20 -27% organic matter in the soil was obtained.

Shear strength determination of the salt layer

In order to determine the required shear force that will be used to remove a salt layer of a desired thickness by using a machine during salt production in the lake and the saltpans, salt block specimens of thicknesses varying between 20 and 25 cm were taken from the lake and the saltpans with a marble cutting machine was subjected to a series of cutting tests. A 20 × 20 cm shear box was developed to determine the shear strength of the salt layers. Then, salt block specimens of 20 × 20 cm and different heights were obtained by cutting the salt blocks brought to the laboratory. Placing the specimens into the shear box, the shear forces, introduced as the forces breaking the specimens by sliding, were applied to certain layers and heights of the salt blocks and the shear strength of the salt was calculated by dividing the obtained shear force by the shear area. This varied between the values of 400 and 700 kN/m^2 with respect to the old and recent stratification of the salt. The results, depending on the layer and height variables, are given in Table 5.

Determination of the effects of soil contamination on crystallization and efficiency of the salt

The effects of the contamination resulted from the soil-water and the soil under the salt layer, which mixed with the salt due to the breaks in the salt layer during the processes of cutting and collecting the salt from the lake and saltpans (Baryakh et al., 1992). Moreover, considering the crystallization and efficiency of the salt, the effects of the soil mixing with the salt from the seawalls formed with the clay-silt soils to separate the saltpans from the lake were investigated.

For this purpose, in the laboratory, a series of

Table 4. The characteristics and the consolidation test results of the soil 1 m beneath the salt layer.

Soil characteristics	Production saltpans	Lake
Moist unit weight , γ_n (kN/m^3)	18.5 - 19.0	18.5 - 19.0
Dry unit weight, γ_s (kN/m^3)	25.5 - 26.0	25.2 - 26.2
Angle of friction, φ_u (◦)	0 - 5	0 - 5
Cohesion (UU), c_u (kN/m^2)	1.5 - 3.0	1.5 - 3.0
Unconfined compression strength, , qu (kN/ m^2)	3 - 6	3 - 6
Moisture content, ω_n (%)	37 - 42	38 - 42
Liquid limit, ω_L (%)	47 - 54	45 - 52
Plasticity index, I_p	27 - 32	22 - 32
Soil category	CL – CH	CL – CH
Consistency Index, $I_ç$	0 - 0.25, 0.25 - 0.50	0 – 0.25, 0.25 - 0.50
Organic material amount, (%)	22 - 30	25 - 32
Consolidation Test	**Production saltpans**	**Lake**
Compression level, (kN/ m^2)	**Coefficient of volume compressibility , m_v (m^2/kN)**	
0	0	0
25	0.00195	0.00185
50	0.00062	0.00112
100	0.00053	0.00048
200	0.00027	0.00031
400	0.00018	0.00017

Table 5. Shear box test results of the salt blocks.

Cutting height from top to bottom (cm)	Height of the sample (cm)	Sample Cross-Section Height 20 × 20 cm^2	Shear force (kN)	Shear strength (kN/m^2)
4	22	400	20	500
10	25	400	18	450
10	25	400	26.5	660
10	20	400	20	500
12	25	400	30	750
14	20	400	23	575

experiments were performed on a certain amount of salty water taken from the lake and saltpans. Before now, the effect of evaporation at different temperatures on the formation of the salt was investigated by placing the salty water samples in different containers and evaporating them at the lake surface temperatures of 35 and 40℃ with the drying ovens, and the remaining salt amounts and halogenation (crystallized NaCl) ratios were determined (Table 6). The evaporation at different temperatures did not cause any discrepancy in the crystallization and halogenation (crystallized NaCl) ratio of the salt as seen in Table 6.

Quantifying the production of salt can be accomplished through experimentation or by numerical simulation. Experimentation is often advantageous and controlling the variables is easy, but this task is time consuming. It may take weeks to obtain salt by solar evaporation. It takes less time by numerical simulation. For any batch evaporation, the amount of salt produced can be determined by (Akridge, 2007):

$$m_s = m_w(1.52\times10^{-4}S^2 + 9.50\times10^{-3}S) \qquad (1)$$

where m_s is the mass (kg) of salt crystallized, m_w is the mass (kg) of water evaporated, and S is the initial salt concentration of the brine in wt% NaCl. For ease of calculation, the dissolved salt is assumed to be pure sodium chloride.

If Formula (1) is used in this experimental study, in Table 6. S = 98% (0.98) and m_w = 1 kg is taken; the amount of salt produced is:

Table 6. The effect of evaporation on halogenations (Crystallized NaCl) at different temperatures.

Evaporation temperature (℃)	Halogenation ratio (Crystallized NaCl) (%)			Average halogenation ratio (Crystallized NaCl) (%) Σ (%)
35	10.33	11.39	10.49	10.73
40	11.49	10.63	9.71	10.61

Table 7. The effect of soil contamination on halogenations (NaCl Crystallized).

Evaporation temperature	Salty water with1 % clay-silt concentration			Salty water with0.5 % clay-silt concentration		
	Halogenation ratio (Crystallized NaCl) (%)			Halogenation ratio (Crystallized NaCl) (%)		
40℃	9.18	7.36	8.39	8.38	9.12	9.62
	(%) Σ 8.83			(%) Σ 9.04		

$M_s = 1(1{,}52\times10^{-4}(0{,}98)^2 + 9{,}50\times10^{-3}\times0{,}98) = 9{,}45.10^{-3}$ kg = 9.45 g

The result (9.45 g) is very close to the experimental result.

In order to investigate the effect of the soil contamination on the crystallization and efficiency of salt, 0.5 and 1% category CL clay-silt soil were added to the salt specimens and mixed together very well before the product was placed in a 40°C oven. The results are given in Table 7.

Comparison of Tables 6 and 7 reveals a 20% approximate decrease in the halogenation (crystallized NaCl) ratio due to the occurrence of soil contamination in the salty water. Additionally, the soil contamination changes the colour and quality of the salt.

SALT PRODUCTION IN LAKE TUZ WITH 2000 DC

For many years, salt production was carried out by dozers and ripping machines. With these machines, it was impossible to separate the salt from the dirt band and the outcome was a very poor salt quality. In 1999 Wirtgen and its Turkish dealer Mor Teknik carried out a machine demonstration with a standard cold milling machine 2000 DC on Lake Tuz. The demonstration was very successful and the Turkish Tekel Salt Industry Institute purchased a modified cold milling machine 2000 DC (Figure 3) (Wirtgen Group Report, 2005).

The following modifications of the standard 2000 DC milling machine have been made:

1. Tool spacing of 30 mm was used.
2. The crawler width was widened by 90 mm to reduce ground pressure, give better traction, and avoid cracking of thin salt layers.
3. The machine was painted with epoxy paint.
4. The electric systems were given extra protection compared to the standard version.

Higher production rates and perfect salt quality without pollution have been gained with 2000 DC by the Turkish Tekel Salt Industry Institute.

Conclusions

Turkey has the potential to become one of the world's leaders in salt production and export by increasing the quality and efficiency of the salt production. Salt has strategic importance in industry and the chemical sector. Modernization studies are being carried out and efforts to increase capacity are being made by the Turkish Tekel Salt Industry Institute in order to produce better quality and cheaper salt. Environmental pollution surrounding salt lakes should be stopped immediately in order to produce clearer and better quality salt,

This study was performed with consideration of the subjects requested by the Directorate of Tekel Kayacık Salt Company. The results of this investigation were used to select a salt-collecting vehicle that would provide the most efficient collection of salt from the production saltpans and the lake.

A plate loading test was performed on the lake and saltpan surfaces to determine whether the wheel loads of the salt collecting, loading, and transporting vehicles can be safely carried by the salt layer or not, and it was seen that the salt layer was able to carry a load of 4000 kN/m^2 safely by distributing the subjected load over a wider area of the flexible foundations lying on the soft soils.

Shear box tests were carried out to calculate the shear force required for cutting and removing the seasonal salt at the top of the salt layer of the production saltpans and lake, and the shear resistance of the salt was found to

Figure 3. Modified cold milling machine 2000 DC developed in Turkey for salt production.

vary between 400 and 700 kN/m2 according to the former and recent layering conditions.

Today, Lake Tuz, a natural miracle, is under the risk of contamination due to various causes. In this study, the main reason for the contamination was stated as the flow of the main drainage channel into Lake Tuz, which includes the waste water of Province Konya, and the problem was investigated in detail. However, the effects of environmental factors, dust formation, and soil contamination were not taken into consideration before these studies. In this study, this subject was investigated.

A soft CL-CH clayey soil including a large amount of gypsum crystals lies under the salt layer, and a possible break at the salt layer causes dirty water to mix with the salt. Moreover, the clay-silt seawalls separating the production saltpans from the lake erode and fall to pieces, resulting in contamination of the salty water. The effects of the soil contamination on crystallization and the efficiency of the salt were investigated, and a reduction in salt production of approximately 20% was determined with respect to the contamination ratios of 0.5 and 1%.

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