Expansion of Soils Containing Sodium Sulfate Caused by Drop in Ambient Temperatures

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•AS EARLY AS 1960 it was recognized that soils containing a high concentration of water-soluble sulfates exhibit an expansive phenomenon resembling that of expansive clays and frost heave. This condition was observed particularly in alluvial deposits in the flat arid areas of southern Nevada and southeastern California. The expansion of these soils occurs during ambient temperature drops from daytime temperatures of approximately 90 F to below 40 F at night. This expansion caused structural damage to lightweight single-story homes in particular and to interior concrete floors, exterior flat work, and asphalt driveways. This phenomenon, herein referred to as "salt heave," predominantly caused vertical expansion without many of the inherent swelling and shrinking characteristics of common clay soil.

The writers began as early as 1962 to isolate individual parameters of this phenomenon to obtain control of the condition. Only by early recognition of the presence of water-soluble sulfate salts in the soil was it possible to control or eliminate heaving and resultant structural damage.

The final test procedure described herein provides a method to evaluate soils containing sodium sulfate salts.

FIELD OBSERVATIONS AND EVALUATION

The swelling phenomenon of some surface soils in arid areas is due primarily to the characteristics of sodium sulfates and possibly other water-soluble salts.

Not all soils, however, that contain sodium sulfates exhibit expansive characteristics. It was noted by the writers that soils containing as little as 0.5 percent sodium sulfates may exhibit expansive qualities in greater proportion than soils containing up to 10 percent or more. Some soils containing high percentages of sodium sulfates show very little expansion.

Two major behavioral characteristics of sodium sulfate soils were noted by the writers:

1. Upon evaporation in warm weather, the moisture in the soils containing sodium sulfate deposits the salt on the ground surface; and
2. When subjected to low ambient temperatures, the moisture in the soils containing sodium sulfate forms crystals and increases the soil volume, causing vertical expansion. This expansion sometimes is incorrectly identified as expanding clay rather than salt heave.

Numerous attempts were made in the laboratory to determine the magnitude of the expansion taking place. Progress in the program did not occur until the natural conditions that cause the phenomenon were recognized and more closely studied. The final procedures were based on the condition that soils for laboratory testing should have a similar moisture content, density, sulfate content, etc., as in situ soils have at the time the heaving or expansion takes place. Prolonged testing indicated that, within a 30-day testing period, measured expansion would fluctuate with day and night variation of laboratory temperatures. As a result, a closer study of natural temperatures and soil moisture conditions was made.

It is believed that the following two characteristics of sodium sulfate cause expansion of the soil:

1. If Na_2SO_4 in solution is cooled below a temperature of 90 F, it tends to bind H_2O. One Na_2SO_4 molecule can bind up to 10 H_2O molecules, building the solid phase $Na_2SO_4 \cdot 10\ H_2O$, also known as Glauber's salt. When the temperature rises during periods of higher humidity, the sodium sulfate solid phase apparently dissolves in its own water of hydration and moves toward the surface in this liquid phase by capillary action.

2. Above 90 F, great quantities of Na_2SO_4 salts are in solution in the moisture of the natural soil. At a temperature of 90 F as much as 52 grams of Na_2SO_4 is soluble in 100 grams of water. As the temperature decreases, the solubility of sodium sulfate decreases rapidly and hydration increases. During this process, the salt crystals expand against the soil structure.

Although the principal laboratory and field test work reported herein pertains to the Glenwood Housing Tract, other similar problem soils were investigated and documented. This phenomenon, however, is found in most soils having certain common characteristics of classification, grain-size distribution, and sodium sulfate content.

Houses damaged by salt heave usually exhibited the following defects:

1. Interior floors, nominally 4 in. thick, cracked and raised in the middle of rooms and under non-load-bearing partitions;
2. Exterior concrete flat work, nominally 4 in. thick, cracked and raised as much as 4 in. or more;
3. Carport roof beams, supported on concrete flat work, raised the roof rafters and ceiling joists above the wall top plate;
4. Exterior walls of lightweight stucco frame construction were subject to damage, while block walls were not generally affected;
5. Six-in. concrete block fences were subject to damage when footings were placed less than 12 in. below finished grade.

From these observations, it was evident that salt heave affected relatively light structures and floors with less than 45-lb/sq ft dead loads.

In the Glenwood Tract, a salt heave or swell was predominantly parallel to and directly under the roof eaves or adjacent to lawns and planting areas.

The salt heave damage, in nearly every instance occurred in the late fall and early spring, and always during ambient temperature drops from daytime temperatures of 90 F to below 40 F at night.

This salt heave was generally confined to soils containing 0.5 percent sodium sulfate and in situ soil densities of 80 to 90 lb/cu ft. Although surface and near-surface sodium sulfate concentrations in pockets of up to 40 percent have been encountered in many areas, they generally do not exceed 1 to 2 percent over wide areas.

EARLY TREATMENT

An early method to counteract the effects of salt heave was accomplished by mechanically blending expanding soils with open-grained pit-run gravels in order to increase the void ratio, thereby permitting expansion and minimizing vertical displacement. Other methods of early control included chemical soil treatment by additives to stabilize the saline soils by chemical reaction converting hydrating salts to insoluble non-hydrating salts.

Calcium chloride ($CaCl_2$ as a stabilizing additive) was first used in laboratory research and subsequently in the field at three housing tracts. This produced a satisfactory restraining result when low sodium sulfate concentrations in soils were encountered. The additive was introduced to the mixing water during grading operations.

Phosphoric acid (H_3PO_4) was subsequently used, producing similar results. This procedure was used with good results on several projects where sodium sulfate contents were in the range of up to approximately 1.5 percent and where uniform soil classifications were ML and OL. The additive was also introduced to the mixing water during grading operations.

INITIAL LABORATORY TEST PROCEDURES AND FIELD DETERMINATIONS

Based on the understanding and knowledge of the salt heave phenomenon, laboratory work was initiated to attempt to duplicate natural field conditions. A special test chamber was developed where temperature variations could be induced and controlled between 35 and 120 F (Fig. 1).

The initial testing program, using the temperature-controlled chamber, was conducted with a 2½-in. diameter ring and a 2-in. diameter reaction plate (Fig. 2). Results were erratic because sample-to-ring friction influenced expansion. Using the same soils, it was determined that the expansion in the 2½-in. ring reached a maximum of 11.4 percent whereas in the subsequently adopted ring molds the same soil produced a 17.0 percent expansion (Fig. 3).

The field investigation included two studies of soil conditions. These tests were initiated on the basis of a preliminary outdoor soil temperature measurement during an ambient temperature of 32 F. The results indicated a soil temperature increase to 65 F at a depth of 18 in.

Two field investigations were conducted to obtain information necessary to evaluate the local salt heave problem; they consisted of the following:

1. A study, conducted inside a house, of the effects of simulated ambient temperature changes on in situ soils to depths of 24 in.; and
2. A study, conducted outdoors, of soluble sodium sulfate and soil moisture content vs depth.

The test arrangement for the temperature study included the installation of long-stem dial temperature gages to various depths and periodic readings for a term of 9 days during the heating cycle and various readings for a period of 15 days during the cooling cycle. The temperature measurements were conducted by circulating air at 110 F for a period of 7 days and subsequently cooled air at 50 to 55 F for 15 days. This test was carried out in an unoccupied house with a wood flooring system. The results of the tests are shown in Figure 4, which indicates the initial temperature rise and subsequent drop to approximately 61 F at a depth of 10 to 15 in., decreasing to approximately 51 F near the surface.

The soluble sodium sulfate and soil moisture determinations were made to assist in the evaluation of the evidently important relation between sodium sulfate and moisture, and its effect on foundation depths. Data in Figure 5 indicate that the high sodium sulfate content decreases with depth and diminishes to approximately 0.4 percent below 5ft. The moisture increases to 10 percent at 2.5 ft and up to approximately 20 percent at 5 ft.

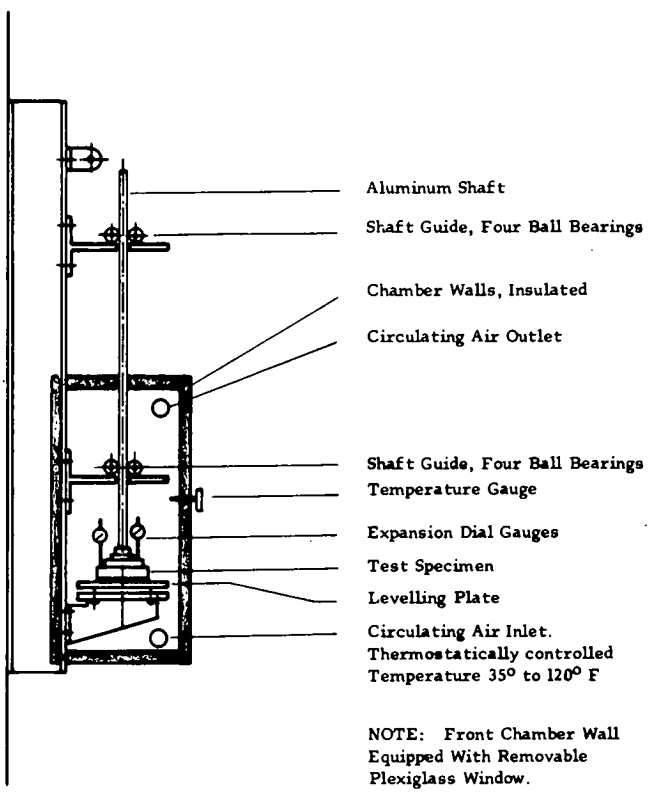
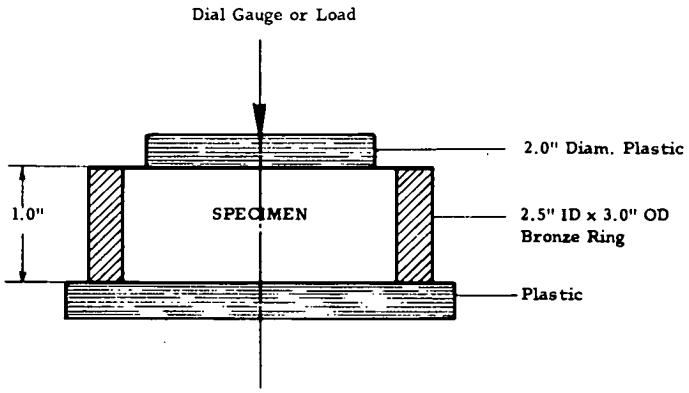
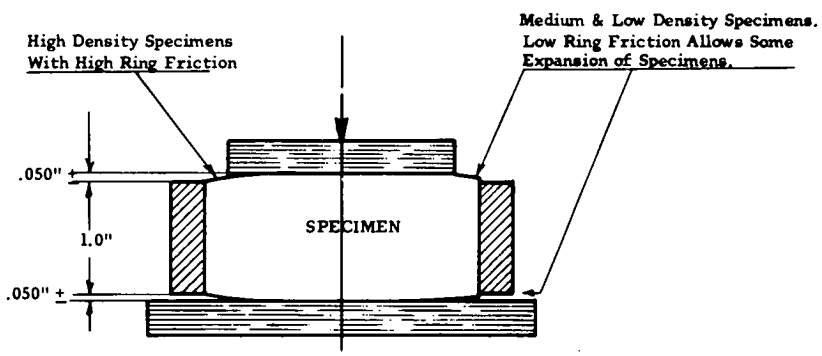


Figure 1. Test chamber arrangement.



a) SPECIMEN BEFORE TEST



b) SPECIMEN AFTER EXPANSION TEST

Figure 2. Test specimen arrangement, initial program.

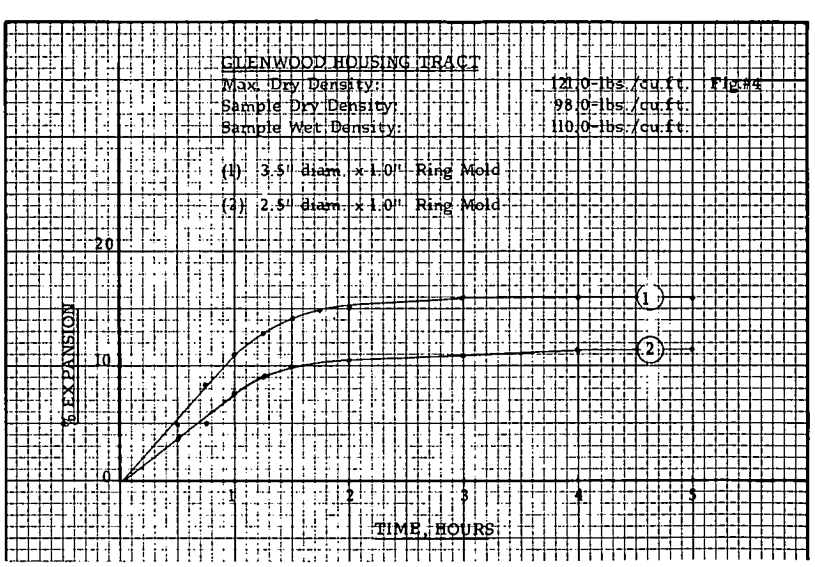


Figure 3. Comparison of final procedure (1) and initial procedure (2) results.

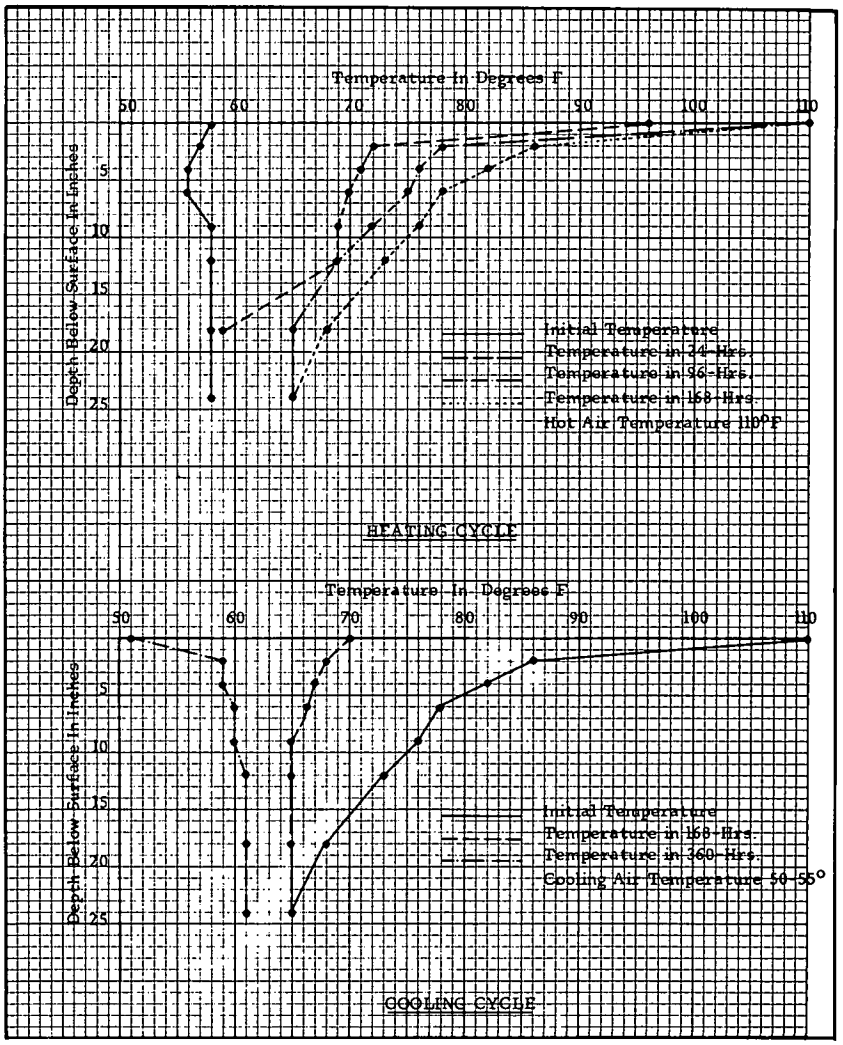


Figure 4. Temperature penetration into foundation soils due to artificial heat and cold cycles.

FINAL LABORATORY TESTING

Consistent test results suitable for correlations could not be obtained with various soils having different characteristics, grain size, Atterberg limits, and sulfate content, so all further testing was performed with a blended soil from the Glenwood Tract. This blending included soils from surface to 24 in. in depth and is hereafter identified as sample No. 3 (Figs. 6 and 7).

The final research was based on the following known factors affecting salt heave:

1. Soils that contain over 0.2 percent Na_2SO_4 in solution and over 15 percent of minus 0.005-mm fractions are subject to salt heave in varying degrees;
2. A change in ambient temperatures to below approximately 55 F causes crystallization of Na_2SO_4 solutions, and this crystallization in turn causes volume change or salt heave;
3. The volume change increases with an increase of the Na_2SO_4 content and an increase in minus 0.005-mm fractions; and

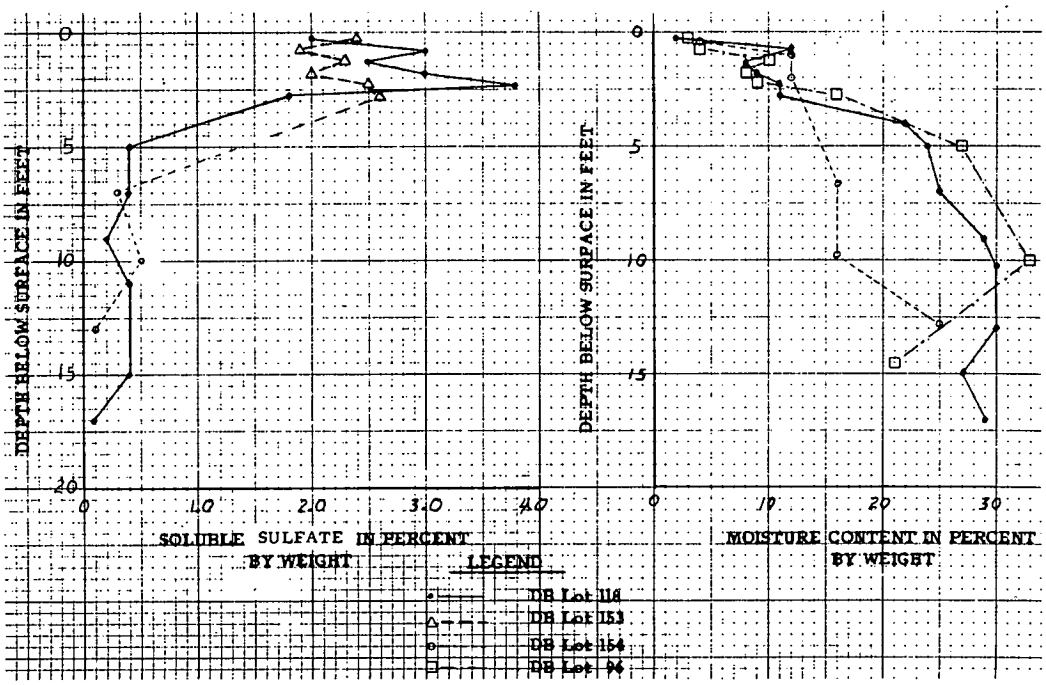


Figure 5. Soluble sulfate and moisture vs depth.

4. Sufficient free moisture must be present in the soil to sustain crystallization of the sodium sulfate.

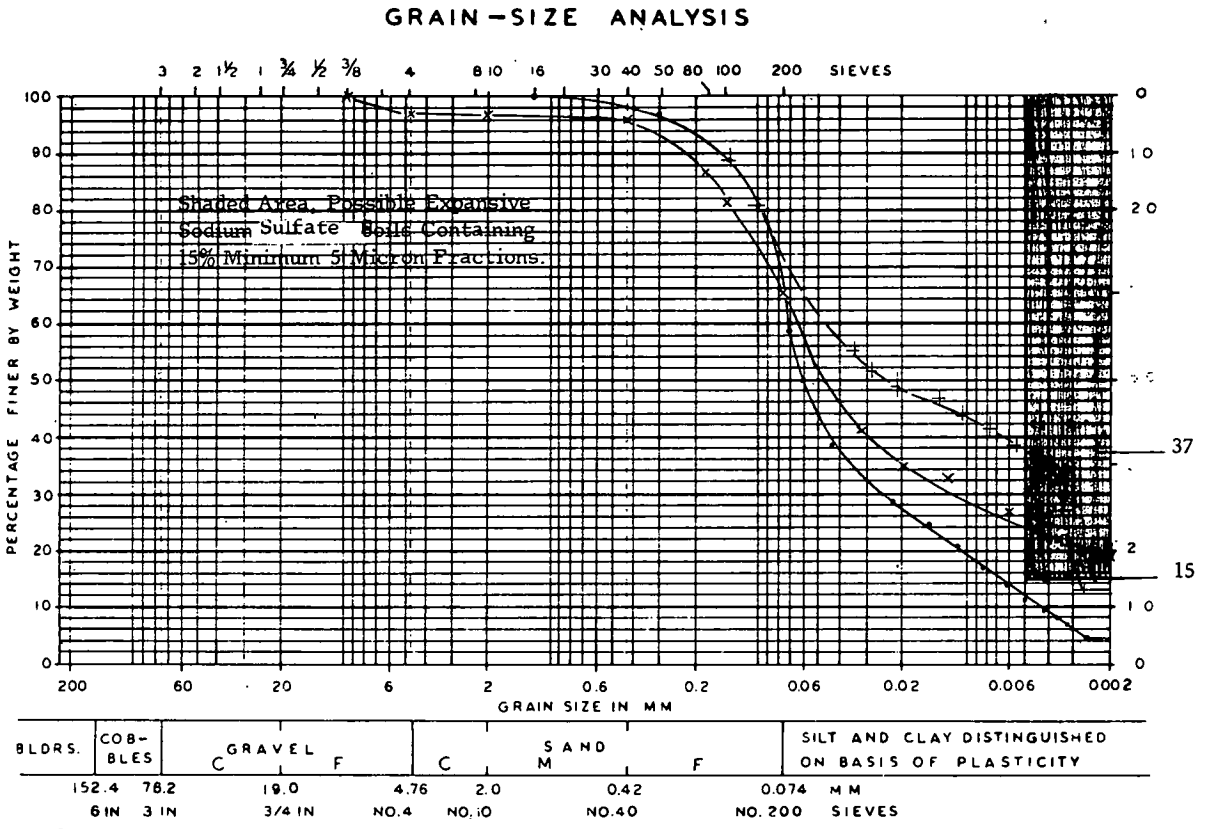
The physical and chemical characteristics of sample No. 3 were as follows:

Soil classification:	Light brown silty clay, some fine to coarse sand CL.	
Grain-size analysis (hydrometer):	25 percent minus 5-micron fractions (Fig. 7)	
Atterberg limits and indices:		
Liquid limit	28.8	(Fig. 8)
Plastic limit	14.8	(Fig. 8)
Plasticity index	14.0	(Fig. 8)
Specific gravity	2.68	
Maximum dry density (ASTM Designation D 1557, Method C)	121.0 lb/cu ft	(Fig. 7)
Maximum wet density	135.0 lb/cu ft	(Fig. 7)
Optimum moisture	12.0 percent	(Fig. 7)
Chemical analysis:		
Total soluble salts	3.8 percent	

The minus 5-micron soils fractions were composed about equally of non-clay and clay minerals. The principal non-clay minerals were calcite, dolomite, quartz, and various hydration forms of gypsum, hemihydrate, and anhydrite. The clay minerals were mica, montmorillonite chlorite, and minor trace amounts of kaolinite, illite, and sepiolite. These determinations were from X-ray diffraction analysis.

Atterberg limits determinations, made in 1965 with various Glenwood soils (Fig. 8), indicated plasticity indices of 9.0 minimum and 18.8 maximum.

All tests referred to above were performed under dead load surcharge conditions varying between 0 and 75 lb/sq ft. Maximum expansion for sample No. 3, shown in



TEST PIT/BORING NO.	DESCRIPTION AND CLASSIFICATION		
#1 . Desert Hills	0.0 to 0.6-ft. depth;	Natural Moisture = 9.0%;	Na_2SO_4 = 0.6%
#2 + Glenwood Lot 153	1.5 to 2.0-ft. depth;	Natural Moisture = 16.0%;	Na_2SO_4 = 3.2%
#3 x Glenwood - Blended Sample;	0.0 to 2.0-ft. depth;	Natural Moisture = 14.0%;	Na_2SO_4 = 3.8%

Figure 6. Description of soil samples 1, 2, and 3.

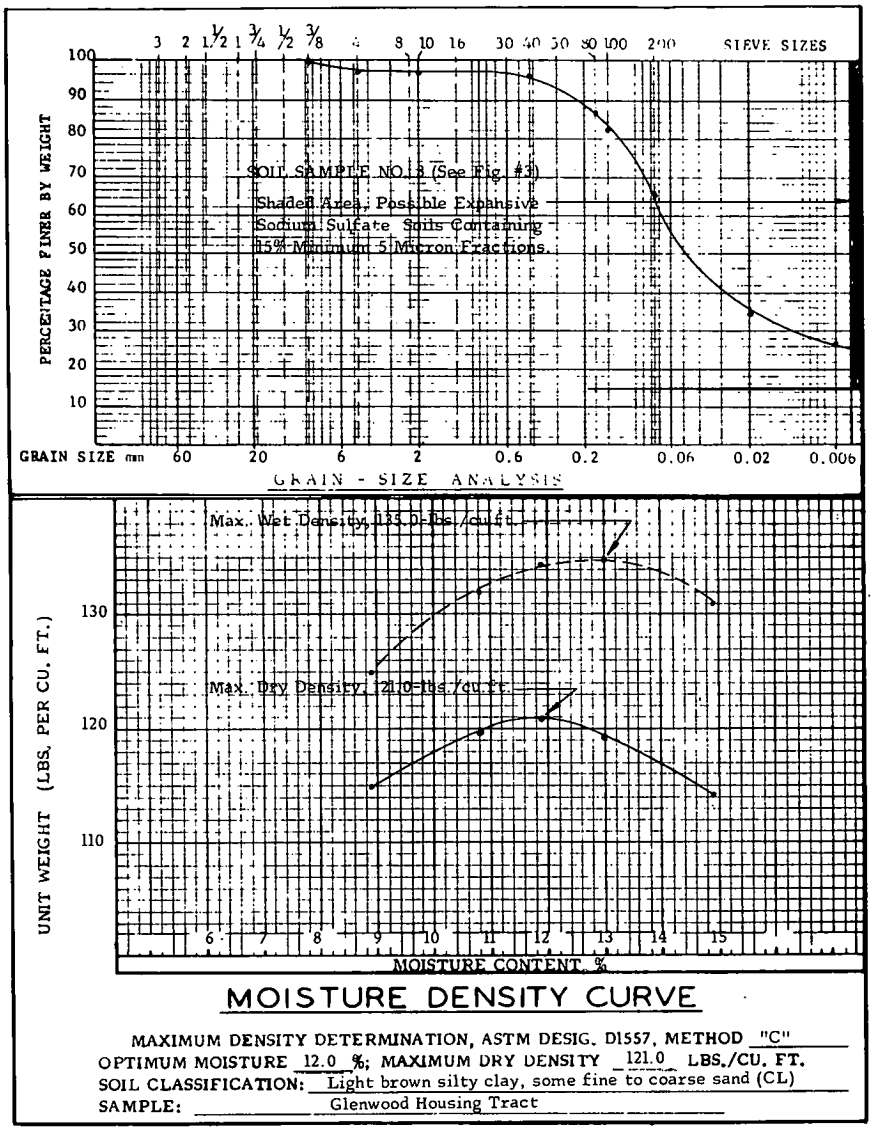


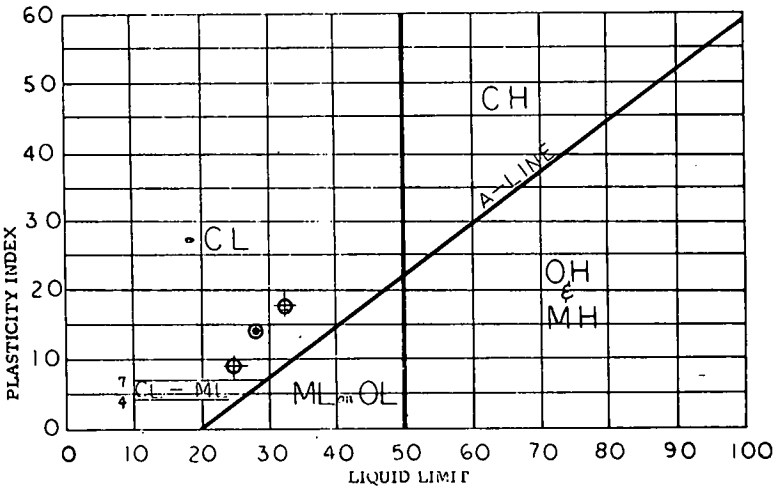
Figure 7. Analysis of blended soil sample No. 3.

Figure 9, was obtained with a dead load of 5.0 lb/sq ft. The total volume change did not materially change although the specimen height varied from 0.25 to 1.0 in.

Although various soil densities were used for the research work, the data given here are based on 98 lb/cu ft dry density or approximately 81 percent of maximum dry density.

TEST PROCEDURES

Soils for ring molds 0.25 to 1.0 in. high were weighed for each ring mold volume to produce the 98 lb/cu ft dry density and were compacted to substantially uniform conditions. A special mold compaction unit that produced uniform soil densities was developed and subsequently used. Soils were compacted to 81 percent of maximum dry density in 0.25, 0.50, 0.75 and 1.0-in. high rings 3½ in. in diameter. The weighed soil



GLENWOOD HOUSING TRACT

Soil Classification: Light brown silty clay; some fine to coarse sand

Maximum Density Determination, ASTM Desig. D 1557, Method "C"

Maximum Dry Density:	121.0-lbs./cu.ft.
Optimum Moisture:	12.0%

◎ Atterberg Limits Determination

Liquid Limit:	28.8
Plastic Limit:	14.8
Plasticity Index:	14

Φ 1965 Determinations - Maximun & Minimum

Figure 8. Plasticity chart, unified soil classification system.

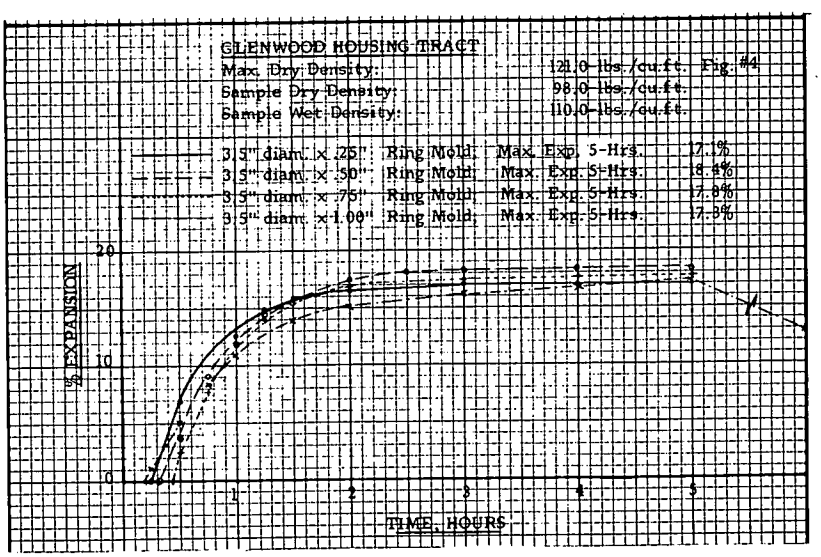


Figure 9. Results of final laboratory tests, sample No. 3.

sample was placed in layers and compacted manually with a ½-in. diameter brass rod or in a special apparatus with a static hydraulic pressure.

The sample was then placed in the test chamber (Fig. 1) at laboratory temperatures of 75 F. A plate (¼ x 2-in. diameter) was placed in the center of the test specimen.

When tests were conducted without surcharge loads, the dial gage stem was placed directly on the 2-in. diameter plate. When tests were conducted with surcharge loads from 0 to 30 lb/sq ft, weights were placed directly on the 2-in. diameter plate and the dial gage stem on either the plate or surcharge weight. The shaft with various additional weights was placed directly on the 2-in. plate to obtain surcharge loads from 30 to 75 lb/sq ft.

The sample remained in the test chamber for a period of 1 hour at laboratory temperature to allow for possible expansion due to overcompaction. If no measurable change occurred within this time period, as determined by the dial gage, the chamber was closed and the cooling cycle started.

Within 30 minutes (or as soon as the chamber temperature reached 54 to 55 F) the volume change was initiated and was continued to nearly peak expansion, which was reached within approximately 2 hours. Figure 9 shows the expansion in percent of the

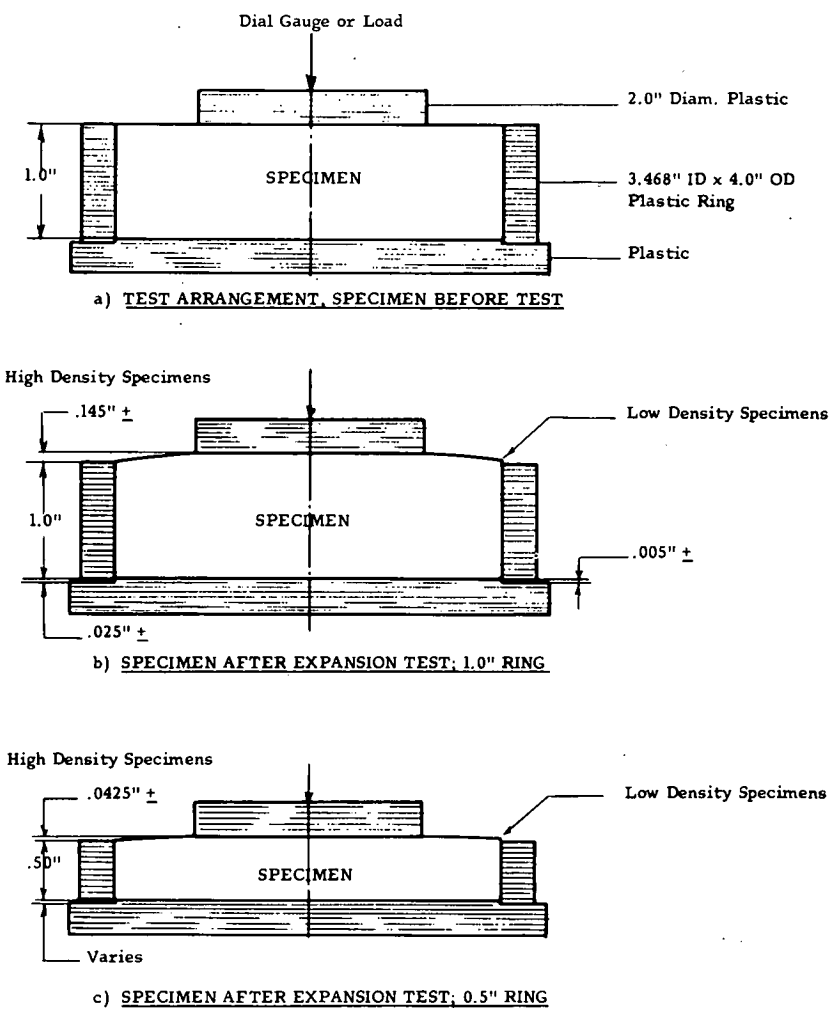


Figure 10. Test specimen arrangement, final laboratory procedure.

initial sample height. No appreciable volume change occurred after the initial 2-hour expansion period.

TEST RESULTS

Figure 2 shows the specimen reaction to the lowered temperature in the 2.5-in. ID ring. High vs lower soil density is illustrated by the final specimen height at the ring, a height which results from variable friction values.

Figure 10 illustrates similar specimen expansion at the ring, but due to the greater distance between pressure plate and ring, friction does not affect specimen expansion. This observation is based on the test data in Figure 9. No appreciable discrepancies in total expansion were noted, provided that the height of the sample and the distance between pressure plate and ring approximated a 1-to-1 ratio.

All specimens exhibited expansion by forming an arc on top and occasionally an arc on the bottom. Because it is not attached to the bottom plate, the ring has free vertical movement also.

During the expansion test no sodium sulfate, such as is deposited by evaporation, is visible on the specimen surface except small sodium sulfate crystals that form in the cooling process.

CONCLUSIONS

1. The salt heave phenomenon as it occurs in the southern Nevada area is due to temperature variations, which usually occur in the fall, late winter, or early spring.
2. Soils that contain over 0.2 percent of Na_2SO_4 in solution and 15 percent or more of minus 0.005-mm fractions should always be investigated for salt heave if ambient daily temperature variations range from 35 to 100 F and if ample soil moisture is available.
3. Although proven successful to date, calcium chloride or phosphoric acid treatment of soils that contain soluble sulfate do not completely eliminate the possibility that sulfates in the underlying soil may rise to the surface, ultimately creating the salt heave problem again. This condition would, however, be limited to areas exposed to hot climatic conditions, but could also be encountered in areas covered by concrete floors or asphalt pavement where adequate moisture is available.
4. Blending sulfate-laden soils with open-grained material would be a solution. As an alternative, finished structural pads should be built with imported salt-free open-grained fill material in order to eliminate cold temperature penetration into lower sulfate-laden soil. It should be noted that the streets in the Glenwood Housing Tract were not subject to damage. The principal reason for this is the fact that the high-sulfate-content soils were removed and replaced with the usually open-grained Type I or II base course material for a total thickness of 12 in. or more. The addition of 2½-in. asphalt pavement placed the soils subject to salt heave beyond the influence of changing ambient temperatures and moisture source.
5. This phenomenon of expansion due to sulfate salts can occur separately or concurrently with other expansive characteristics of clay soils.
6. The expansion, which is due to high sulfate soils and which causes damage to lightweight structures and principally to concrete slabs, can be reduced with adequate surcharge loading. Laboratory testing showed swell reductions from 17 percent to 2 percent under 75 lb/sq ft loading.