USING ADDITIVES TO IMPROVE COLD WEATHER COMPACTION

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A laboratory investigation was conducted to determine possible methods of improving cold weather earthwork techniques and extending the construction season. Compaction tests, using standard and modified AASHO compactive effort, were conducted on a silty sand at temperatures of 68 and 19 F (20 and -7 C). The low-temperature tests of soil with 0, 2, and 3 percent calcium chloride were performed to study the influence of an additive on the moisture-density relationship of the test soil. Tests at 68 F (20 C) were used to establish a frame of reference for the low-temperature tests and to determine the normal compaction characteristics of the silty sand. To eliminate the effects of particle size, a single sized particle was prepared in the laboratory and used throughout the low temperature testing. Test results indicate that (a) additives can be effectively used to offset the detrimental effect of low temperature on compaction; (b) soils compacted at 19 F (-7 C) and treated with 2 or 3 percent calcium chloride have essentially the same compaction characteristics as an untreated soil compacted at a temperature of 68 F (20 C); and (c) an untreated soil compacted at 19 F (-7 C) has significantly lower dry densities than a soil compacted at 68 F (20 C). The low densities that occur when a soil is compacted while frozen are due to the formation of ice within the pore spaces. Modeling the pore fluid as a solution of additive and water and using the concept of phase equilibria shows that the amount of additive required to prevent the formation of ice in a compacted soil is related to the freezing point depression characteristics of the additive. A discussion of field problems and application techniques is included to aid the practicing engineer in using the method suggested in the paper.

•MANY innovative techniques and practices have been developed in the area of winter construction, particularly in the placement of concrete masonry. However, most state and federal agencies still prohibit the placing of frozen soils in embankments or fills. Yoakem (15) researched the public and private policy associated with excavation, placement, and compaction of soils for embankments and foundations and reported that "Twenty-five of the forty-five highway departments which replied to the questionaire stated they do not construct embankments using frozen soils during freezing weather and they do not allow footings or pavements to be placed on frozen ground."

The limitations on cold weather earthwork are due primarily to the observed difficulties of obtaining specified densities and the implied problems of large settlement and inadequate strength. For example, Higher, Altschaeffl, and Lovell (3) recognized that low-temperature compaction is approximately equivalent to reducing the effective compactive effort and found that a decrease in compaction temperature results in a decrease in unit weight, degree of saturation, and undrained strength. They noted that cold but unfrozen soil may be successfully field compacted by increasing the level of

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Publication of this paper sponsored by Committee on Compaction.

compactive effort. Other authors (1, 8) also noted higher densities when test temperatures were increased from near freezing to 75 F (24 C). Typically, increases in maximum dry density were from 3 to 5 lb/ft^3 (48 to 80 kg/m^3) for granular soils and as high as 11 lb/ft^3 (175 kg/m^3) for some fine-grained soils. Johnson and Sallberg (6) found that when a sandy soil was compacted a decrease in dry density of 2 to 3 lb/ft^3 (32 to 48 kg/m^3) occurred as a result of lowering the temperature from 75 to 40 F (24 to 4 C). They also cited results that clearly show the large reduction in soil unit weight caused by temperatures below 32 F (0 C).

The results of these investigations catalog the effect of temperature on soil compaction, but no attempt is made to investigate possible methods of offsetting the detrimental influence of low temperature. If soil could be successfully compacted in spite of below-freezing temperatures, it is possible that the construction season could be lengthened or even continued year round. This would spread fixed costs of equipment operation over more work units, reduce or eliminate layoffs of construction labor, and permit earlier use of new facilities.

MATERIALS AND TESTING PROCEDURE

Materials

The soil selected for the laboratory investigation was one of marginal frost susceptibility. It was obtained from a site near the Houghton County Airport in Michigan. The uniformity of the stored material was confirmed by grain size analysis of selected samples. Typical results of these tests are shown in Figure 1. Texturally the soil is classified as a silty sand. The unified engineering classification is SM. According to the Corps of Engineers criteria, the frost susceptibility classification is F2(b), low to medium. The specific gravity of the soil is 2.69.

The additive used in the test program was a high-test flaked calcium chloride. Solubility and freezing point depression characteristics for pure calcium chloride can be obtained from the Handbook of Chemistry and Physics (14).

Testing Procedure

When compaction tests were conducted at 68 F (20 C), the soil was compacted according to the procedure outlined in AASHO T-99 for standard compactive effort or AASHO T-180 for modified compactive effort. If an additive was used, it was added with the water. After mixing, the prepared soil was sealed in plastic bags and stored at room temperature for 20 hours prior to compaction. Compaction of the soil was carried out by using a Soiltest mechanical compactor with a 6-in. (152-mm) mold.

The testing procedure at temperatures below 32 F (0 C) involved a number of deviations from the conventional method of sample preparation and testing. To eliminate the effect of particle size, particles of constant size were prepared in the laboratory by forming individual particles in an ice cube tray. The tray contained 36 tapered cubes with an edge dimension of 0.8 in. (20 mm). Based on water content each particle was subjected to a static load by a soil loading press to achieve a precompaction density of 85 lb/ft^3 (1360 kg/m^3). The prepared samples were exposed to below-freezing temperatures for 20 hours prior to testing. Moisture loss was prevented by sealing the prepared samples in plastic bags.

Compaction in the cold room began by removing the frozen soil cubes from the trays. The cubes were then placed in the compaction mold, and they were compacted to the required energy per layer. When compaction was completed, the soil and mold were weighed. If no additive was used at the time of preparation, trimming of the frozen compacted samples was extremely difficult. In this situation the volume of the compacted sample was determined by using the sand cone method suggested by Campen (2). When 2 or 3 percent calcium chloride was used in preparing the sample, the pore water was

Figure 1. Typical gradation curve for the test soil.

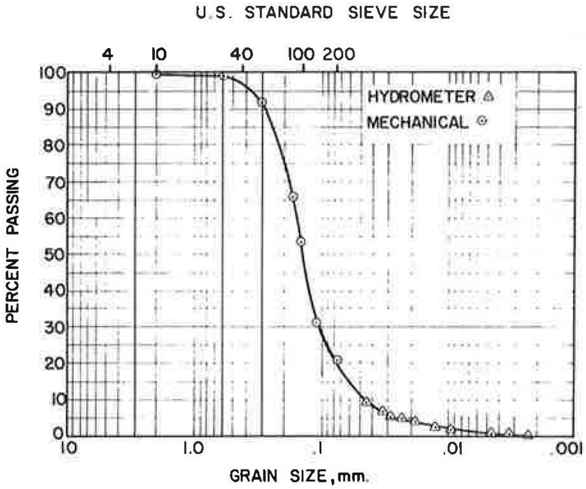


Figure 2. Moisture-density relationship for the test soil with no additive.

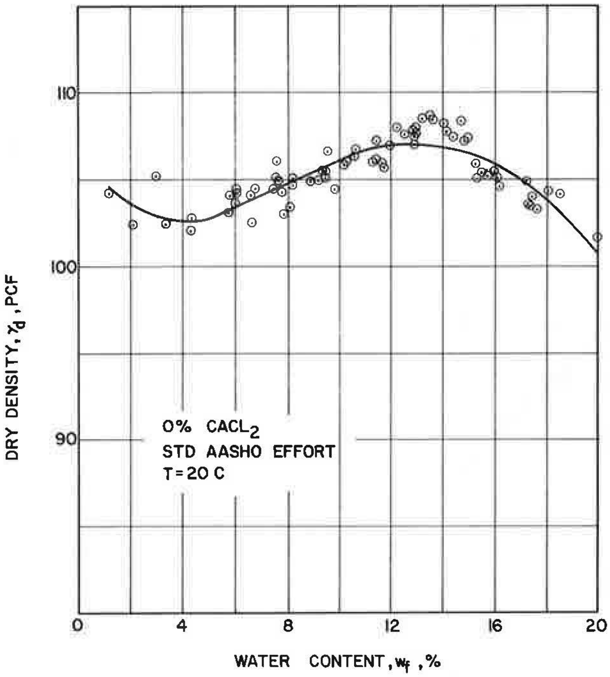


Figure 3. Moisture-density relationship for the test soil with 1 percent calcium chloride.

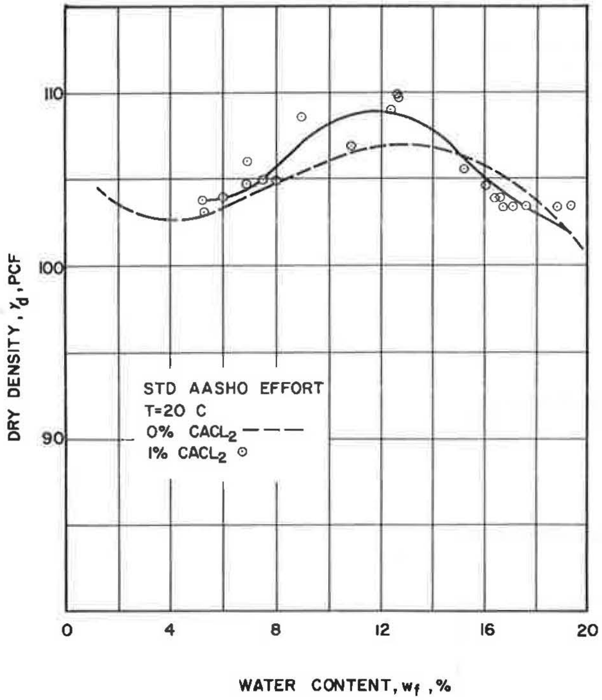
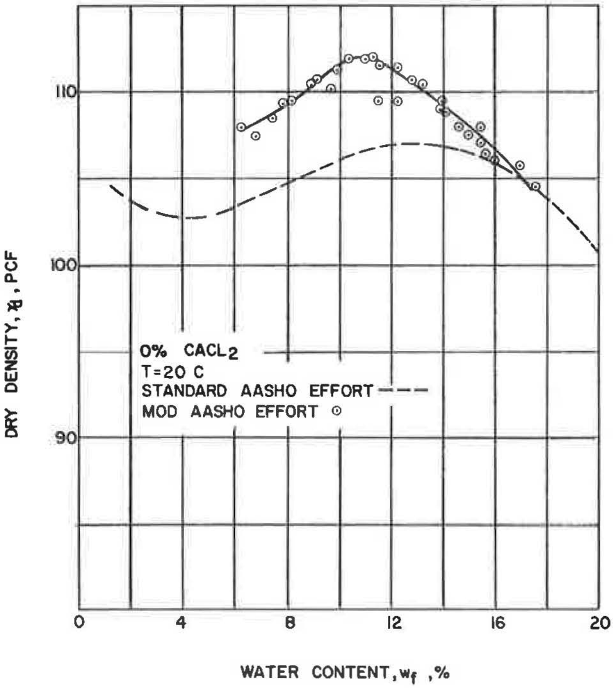


Figure 4. Moisture-density relationship for the test soil using modified AASHO compactive effort.



not completely frozen and the volume of soil was determined by conventional trimming as in the AASHO test method. Three samples from each compacted specimen were taken to determine the average moisture content.

DISCUSSION AND INTERPRETATION OF RESULTS

Compaction at 68 F (20 C)

The initial phase of the testing involved compacting the soil at room temperature to establish a frame of reference for the remaining parts of the test program. The results of standard AASHO testing are shown in Figure 2. The moisture-density curve has the shape expected for a fine silty sand. The maximum dry density is approximately 107 lb/ft^3 (1712 kg/m^3) at a moisture content of 13 percent. The increase in dry density at low water contents is typical of a soil with a large amount of fine sand (bulking) and is related to the interruption of capillary forces and the large effective stresses that go with these forces.

Seed, Mitchell, and Chan (9), in discussing the development of effective stresses in compacted soils, divided pore pressure into two parts, pore air pressure and pore water pressure. On the dry side of optimum at low water contents, the pore air pressure is low and less than the negative pore water pressure. Therefore, the total pore pressure is negative, which causes high effective stresses and resulting low densities. As the water content increases to optimum, the negative pore water pressures become increasingly less negative and the pore air pressure increases. This causes a decrease in effective stress and higher density in the compacted soil. Beyond the optimum water content, the pore air pressure is approximately constant (7), but the pore water pressures become more negative as in an undrained test on a dense, saturated soil. The large negative pore water pressure causes increased effective stress and a decrease in density typical of soils compacted on the wet side of optimum.

When an additive such as an inorganic salt is added to the soil, the basic mechanism of compaction will be the same. However, the addition of the salt may have other effects that cause the compaction characteristics of a treated soil to be different from those of an untreated soil (5, 10, 16). Johnson and Sallberg (6) concluded, "There is general agreement on the effect of calcium chloride on soils that are essentially granular. These soils have shown a consistent increase in dry unit weight due to the use of calcium chloride." In their study of the use of calcium chloride, the increases due to the additive were quite small (less than a 2 percent increase in dry density). Several test series were conducted to verify the results of work done by others and to note the effect of the additive on the soil type used in this program. Room temperature tests using standard AASHO compactive effort were conducted by adding 1.0 percent calcium chloride. The effects of the calcium chloride on the compaction characteristics are shown in Figure 3. In comparison with the untreated soil tested at the same temperature, the maximum density of the treated soil is 2 lb/ft^3 (32 kg/m^3) higher and the optimum moisture content is 2.0 percent lower.

Increasing compactive effort will result in an increase in dry density and a decrease in optimum water content for most soils. Figure 4 shows a plot of dry density versus water content for a series of tests on specimens compacted by using modified AASHO compactive effort. The resulting maximum dry unit weight is 112 lb/ft^3 (1792 kg/m^3) at a water content of 11.0 percent. Compared to the standard effort curve, the increase in dry density is modest but does follow the usual pattern of moving up and to the left.

Compaction at 19.4 F (-7 C) Without an Additive

For a soil with no additives and a temperature low enough to ensure complete freezing of all pore moisture, the shear strength of the soil is dependent not only on the frictional resistance of the soil but also on the shear resistance provided by the pore ice. It is well known that the strength of ice is highly time dependent (13), but for the short loading time involved in compaction procedures it is reasonable to assume that the resistance to compaction provided by the ice is constant. If this observation is valid, then densities obtained from compacting frozen soils will be less than those obtained from unfrozen soil by an amount proportional to the energy required to overcome the additional resistance to rearrangement provided by the ice in the pore spaces.

Several researchers (12, 17) have demonstrated that the shear strength of soil-ice materials is dependent on the amount of ice in the void spaces. By extension, it may be possible to say that the density of a compacted frozen soil should also be related to the amount of ice in the pore spaces. This implies that the density of a compacted soil-ice system will decrease as the water content increases, as has been noted by Johnson and Sallberg (6). The validity of this observation can be checked by compacting a soil frozen at various water contents, calculating the amount of ice in the sample, and plotting the results.

The results of a series of standard AASHO tests on an untreated soil frozen prior to compaction are shown in Figure 5. In this figure the temperature at which the soil was prepared and compacted was 19 F (-7 C). This temperature was low enough to ensure complete freezing of all pore fluid since the absorbed layer of water is minimal in a silty sand. The resulting curve of dry density versus water content is bilinear with the intercept at a water content of approximately 3 percent.

The behavior of the untreated soil at low temperatures can be explained by considering the amount of ice present in the void spaces at a particular water content. For example, at zero water content the particles are in contact over a very small area and no ice is present; the resistance to rearrangement is due to the frictional resistance at the soil particle contacts. The resulting dry density is nearly the same as that for a soil compacted at temperatures above 32 F (0 C). As the water content increases from zero, individual particles begin to accumulate water in the region of the intergranular contacts, and as the temperature is decreased the water changes to ice. The ice between adjacent particles increases the resistance to rearrangement by an amount proportional to the area of the ice. This causes large decreases in dry density until all particles are joined by a continuous layer of ice. This condition occurs at approximately 3 percent water content for the silty sand. Above this point, the interparticle void spaces begin to fill with ice, and the net increase in area of resistance along a potential plane of sliding is increased by only a small amount. The result is a smaller decrease in dry density as shown in the second part of the curve in Figure 5. The decrease in dry density in this region is continuous until all void spaces are filled with ice. Any further increase in the amount of ice beyond that required to fill all void spaces will result in soil particles being forced apart, which completely eliminates the frictional resistance of the soil. Compaction of the material in this state would be dependent only on the ability of the ice matrix to resist the applied energy.

Compaction at 19 F (-7 C) With an Additive

When the temperature of the soil is lowered, the pore fluid becomes more viscous and dry densities decrease slightly until the temperature of the pore fluid is lowered to the freezing point. With a further decrease in temperature, the pore fluid begins to change to ice, causing a substantial decrease in dry unit weight. However, using an appropriate amount of additive will lower the freezing point of the pore fluid, and the soil will remain unfrozen even at very low temperatures.

When calcium chloride is dissolved in water, the freezing point of the resulting solution (a function of the composition of the solution) can be determined directly from the Handbook of Chemistry and Physics. To apply freezing point depression characteristics to a compacted soil requires that the composition of the pore fluid be calculated for various levels of treatment with the additive. From the definition, the composition of a solution, A, is the weight of anhydrous compound per 100 g of solution. For a compacted soil this can be expressed as the weight of additive divided by the

Figure 5. Low-temperature dry density versus water content for soil without additive.

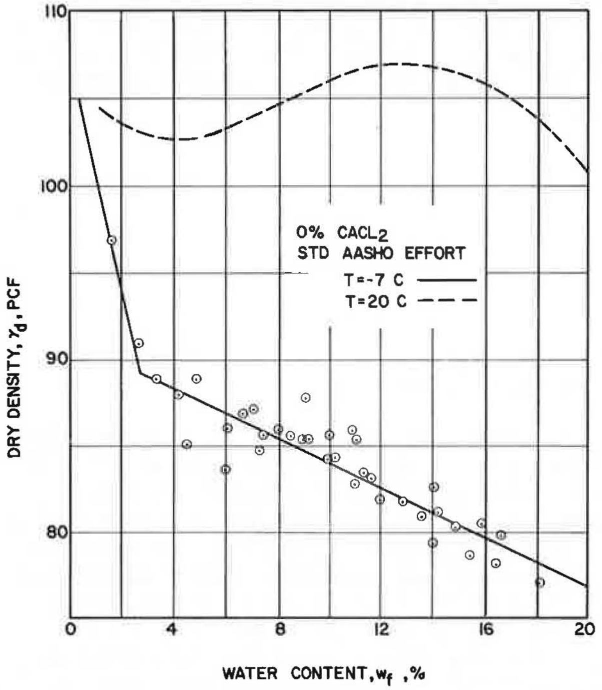
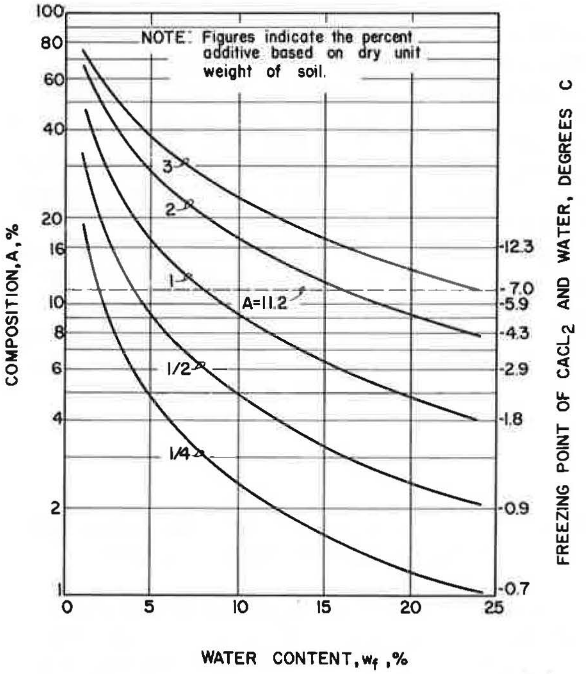


Figure 6. Composition of the soil pore fluid for various percentages of additive.



weight of pore fluid multiplied by 100. Because the amount of additive used for the compaction test series is based on the dry unit weight per cubic foot, the weight of additive is the dry unit weight of the soil multiplied by the percentage of additive divided by 100. If complete solubility of the additive is assumed, the weight of the solution is equal to the weight of water (water content times dry unit weight) per cubic foot (cubic meter) plus the weight of the additive. These observations can be substituted into the definition of A with the following result:

$$A = \frac{P_a}{w_f + P_a} \times 100 \tag{1}$$

where

P_a = percentage of additive by weight of dry soil and
w_f = final water content of the compacted soil in percent.

This equation is independent of type of additive and can be solved for various water contents and percentages of additive. The solution to equation 1 for several different amounts of additive is shown in Figure 6. It is apparent from this graph that for a given percentage of additive the composition of the resulting solution decreases rapidly with an increase in final water content. Also shown in this figure is the composition (A = 11.2) of the solution of water and calcium chloride required to reduce the freezing point of the solution to the test temperature of 19 F (-7 C). For any combination of water content and percentage of calcium chloride that falls above this line, all pore fluid will remain unfrozen, and the compaction characteristics of the soil should remain essentially the same as an untreated soil compacted at temperatures above 32 F (0 C). For example, a soil treated with 2 percent calcium chloride that has a water content less than 16 percent will have unfrozen pore fluid.

To verify the hypothesis stated above, standard AASHO tests at 19 F (-7 C) were conducted on the silty sand after it was treated with 2 and 3 percent calcium chloride. The results of these tests are shown in Figure 7. For the tests with 2 and 3 percent calcium chloride, the maximum dry densities are essentially the same at approximately 105 lb/ft^3 (1680 kg/m^3). Also, this value is very close to the maximum dry density of the untreated soil tested at a temperature of 68 F (20 C) as was originally assumed. Additional results from modified AASHO compaction tests conducted at 19 F (-7 C) with 2.0 and 3.0 percent calcium chloride are shown in Figure 8. Compared to the standard AASHO test at the same temperature there are significantly more scatter in the dry densities and an apparent slight increase in dry density for the soil treated with 3 percent calcium chloride. The maximum dry density for the soil treated with 2 percent calcium chloride is 101 lb/ft^3 (1616 kg/m^3). This value is less than the maximum dry density obtained from the standard AASHO tests at the same temperature and is not consistent with the observation that increased compactive effort causes increased maximum dry densities. However, the maximum dry density is substantially greater than would be obtained for an untreated soil, which indicates the beneficial effect of the calcium chloride treatment.

FIELD APPLICATIONS

In the field, the process of compacting soils at below-freezing temperatures is dependent on implementation of special application, mixing, and treatment sequences in order to prevent freezing of the soil.

Depending on the moisture content of the soil, calcium chloride can be applied as either a liquid solution or dry flakes. Below optimum moisture content, a calcium chloride solution of the correct composition is the most efficient method of applying the additive. If the soil possesses sufficient moisture, application of the additive in

Figure 7. Effect of calcium chloride on the test soil compacted at 19 F (-7 C).

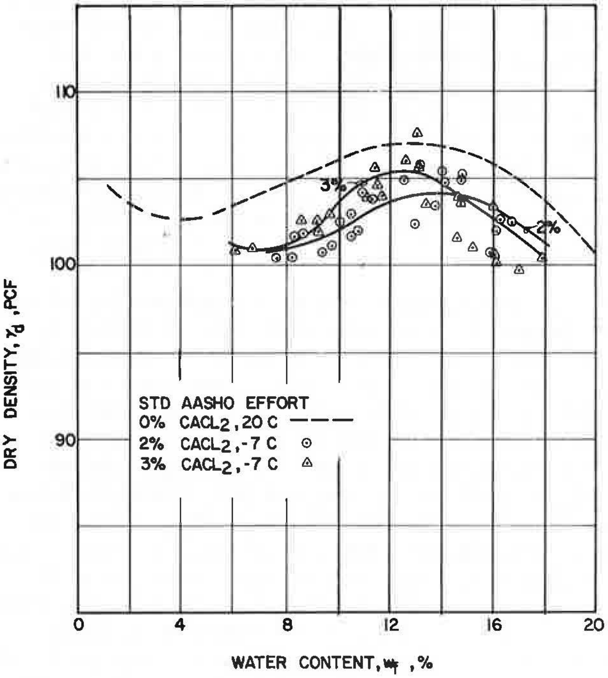
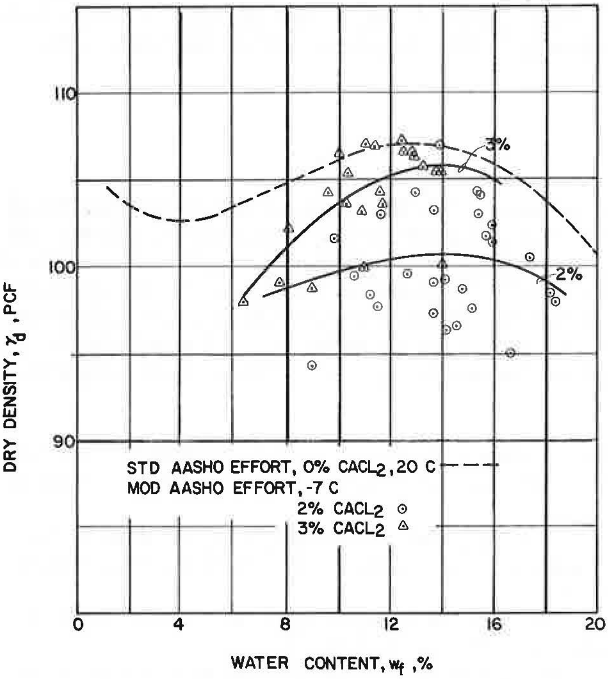


Figure 8. Effect of calcium chloride and compactive effort on the test soil compacted at 19 F (-7 C).



its dry form would be required to keep the soil moisture at optimum.

To obtain results comparable to those obtained in the laboratory requires that the additive and soil be thoroughly mixed. Common stabilization equipment, such as single- and multiple-rotor and traveling mixer units, can be effectively used. Less efficient mixing can be achieved by blading the soil and additive back and forth with a motor grader until the chemical is completely mixed and dissolved into the soil pore fluid. Agriculture equipment, such as the disk harrow, could prove useful as a mixing tool, and effective mixing of lime has been achieved (11) by spreading the lime over a surface that has been ripped by a crawler tractor and mixed with a plow. The degree of mixing that can be achieved in the field is not known, but Ingles and Metcalf (4) have concluded that a coefficient of variation of 30 percent in additive content can be expected for normal field mixing techniques. This compares with 10 percent for average laboratory work.

If good field results are to be obtained, the treatment sequence must be planned to provide calcium chloride to the soil at the proper time and in the correct amount to prevent freezing of the soil pore water. This requirement may force treatment at both the project site and the borrow area. At the borrow area it may be necessary to apply calcium chloride just prior to stopping the day's operations to prevent nighttime freezing of the borrow material. Overnight salt treatment may also be needed at the project site in the areas disturbed by the day's construction activities. Normally, calcium chloride treatment is required during daily earthwork operations only if temperatures are low enough to cause freezing prior to final placement and compaction of the soil. Surface treatments during the day can be minimized by keeping the work areas as small as possible and working in the vertical direction of the embankment or borrow area.

Various problems other than those listed above are associated with field compaction of soils at below-freezing temperatures. Large temperature fluctuations can make it difficult for the field engineer to make a decision on whether treatment is required and how much. Precipitation in the form of snow presents a maneuverability problem for the mixing equipment and reduces the effectiveness of treating the soil with calcium chloride. However, these problems do not diminish the fact that a soil properly treated with calcium chloride can be prevented from freezing and can be successfully compacted. Careful cost analysis is required for each project to determine whether the costs of calcium chloride, including mixing with the soil, would be offset by improved equipment utilization, reduction in seasonal layoffs of labor, and earlier use of the new facility.

CONCLUSIONS

The experimental program conducted as part of this study required a large number of compaction tests on a single soil at various temperatures and compactive efforts. Of primary interest were the compaction tests at 19 F (-7 C), but a substantial number of tests were conducted at 68 F (20 C) to establish a frame of reference for the tests at lower temperatures. An additive was used to investigate possible methods of improving compaction of soils at low temperatures. Based on the results of the experimental program the following conclusions concerning the compaction of soil at low temperature were made.

1. The dry unit weight of compacted frozen soil is less than the dry unit weight of a soil compacted with the same effort but at a temperature above the freezing point of the pore fluid.
2. The dry unit weight of compacted frozen soils is inversely proportional to the amount of ice in the pore space. For the soil tested, the relationship between frozen dry weight and water content is bilinear.
3. Additives can be effectively used to alter the compaction characteristics of a soil prepared and compacted at temperatures below 32 F (0 C).
4. If enough additive to depress the freezing point of the pore fluid below the test temperature is used, the compaction characteristics of a soil tested at a temperature

below 32 F (0 C) will be the same as those of a soil without an additive compacted at temperatures above 32 F (0 C). For soils compacted in this state the optimum water content of the treated soil is close to the optimum obtained for an untreated soil tested at temperatures above 32 F.

5. The amount of additive required to prevent freezing of the pore fluid can be obtained from the freezing point depression characteristics of the additive. For calcium chloride the values are shown in Figure 6.

ACKNOWLEDGMENT

The work described in this paper was sponsored by a grant from the U.S. Army Cold Regions Research and Engineering Laboratory. Assistance in the laboratory was provided by James Botz and John Zygaj. Equipment modifications and installation were accomplished with the aid of Ernest W. Raisanen. The figures were prepared by Robert Manninen. Their assistance in completing this research is gratefully acknowledged.

REFERENCES

1. D. M. Burmister. Environmental Factors in Soil Compaction. Symposium on Compaction of Soils, ASTM, STP 377, 1964, pp. 47-66.
2. W. H. Campen. Discussion of paper by E. J. Zeigler, Effect of Material Retained on the Number 4 Sieve on the Compaction Test of Soil. HRB Proc., Vol. 28, 1948, p. 414.
3. W. H. Highter, A. G. Altschaeffl, and C. W. Lovell, Jr. Low-Temperature Effects on the Compaction and Strength of Sandy Clay. Highway Research Record 304, 1970, pp. 45-51.
4. O. G. Ingles and J. B. Metcalf. Methods and Machinery. In Soil Stabilization Principles and Practice, John Wiley and Sons, 1973, pp. 189-223.
5. A. M. Johnson. The Role of Calcium Chloride in Compaction of Some Granular Soils. HRB Proc., Vol. 26, 1946, pp. 594-601.
6. A. W. Johnson and J. R. Sallberg. Factors Influencing Compaction Test Results. HRB Bulletin 319, 1962.
7. L. J. Langfelder and V. R. Nivargikas. Some Factors Influencing Shear Strength and Compressibility of Compacted Soils. Highway Research Record 177, 1967, pp. 4-21.
8. P. Y. Lee and D. C. Hsu. Temperature Effect on Irregularly Shaped Compaction Curves of Soils. Highway Research Record 438, 1973, pp. 16-20.
9. H. B. Seed, J. K. Mitchell, and C. K. Chan. The Strength of Compacted Cohesive Soils. Proc., ASCE Research Conference on Shear Strength of Cohesive Soils, 1960, pp. 877-964.
10. F. O. Slate and A. S. Yalcin. Stabilization of Bank-Run Gravel by Calcium Chloride. HRB Bulletin 98, 1954, pp. 21-31.
11. M. R. Thompson. Deep Plow Lime Stabilization for Pavement Construction. Transportation Engineering Journal, ASCE, Vol. 98, No. TE2, May 1972, pp. 311-323.
12. N. A. Tsytovich. Bases and Foundations on Frozen Soil. HRB Special Rept. 58, 1960.
13. S. S. Vialov, ed. The Strength and Creep of Frozen Soils and the Calculations for Ice-Soil Retaining Structures. U.S. Army CRREL, Translation 76, Sept. 1965.
14. R. C. West and S. Selby, eds. Handbook of Chemistry and Physics. The Chemical Rubber Company, Cleveland, 1967.
15. D. Yoakem. A Survey of Winter Construction Practices Earthwork, Concrete and Asphalt. U.S. Army CRREL, Special Rept. 76, July 1966.

16. E. J. Yoder. Freezing-and-Thawing Tests on Mixtures of Soil and Calcium Chloride. HRB Bulletin 100, 1954, pp. 1-11.
17. R. N. Yong. Soil Freezing Considerations in Frozen Soil Strength. Proc., Permafrost International Conference, National Academy of Sciences—National Research Council, Publication 1287, 1963, pp. 315-319.