

# Density-Compactive Energy-Calcium Chloride Content Relationships for an Iowa Dolomite

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The effects of calcium chloride content and the amount of compactive effort on the density of a crushed limestone were determined by laboratory experiments. The data were analyzed on the basis of energy cost or savings due to the presence of calcium chloride. The results indicate that the expenditure of compactive energy to obtain a given density is dependent on the calcium chloride content. The results also show that for a given density, an optimum calcium chloride content exists which will produce the density with a minimum compactive effort. The optimum calcium chloride content varies with the density.

● PRESENT DAY theory of soil stabilization is based on mechanical principles either alone or in combination with the addition of chemicals or materials whose principal properties are considered to be of a chemical nature. Regardless of whether the method of stabilization is purely mechanical or chemical and mechanical, compaction principles are always used and generally understood. However, the effects of additive chemicals or materials on the compaction characteristics are not well understood.

Well established mechanical principles leading to mechanical stability are gradation, binding properties of the fine material, and the compaction characteristics of the system. The addition of chemicals to the soil material changes all of these. Gradation is changed because the lower limit of particle size now becomes the size of a molecule or a crystal of the chemical used. The binding properties are changed due to ion exchange and other surface chemical phenomena. The compaction characteristics are also changed due to intermolecular forces in the soil and a change in the liquid used from water to a solution. Pure water is seldom used except in the laboratory.

The investigation described herein was undertaken to better understand the mechanism causing changes in the compaction characteristics of a crushed dolomite when calcium chloride is added. The basis of computation used in the analysis was somewhat different than usually used in density studies. Ordinarily the basis is a cubic foot. Here the basis is weight, because the volume of a mold is a constant, whereas the weight of material forced into a mold is variable. All energy values are expressed as energy per pound of compacted crushed rock plus calcium chloride or per pound of compacted crushed rock.

## MATERIALS

The calcium chloride used was a commercial product known as Peladow supplied by the Dow Chemical Company. The material contains a minimum of 94.0 percent calcium chloride and less than one percent water. The magnesium chloride content is less than 0.5 percent and the alkali chloride content (such as sodium chloride) is less than 5.0 percent.

The crushed rock was obtained from Cook's Quarry which is located about 5 mi northeast of Ames, Iowa. The rock is a buff to brown calcitic dolomite of Mississippian age and has physical properties similar to limestone. The material was crushed at the quarry to pass a  $\frac{3}{4}$ -in. screen. A partial particle size analysis is given in Table 1.

TABLE 1  
 SIZE FRACTIONS OF CRUSHED DOLOMITE AND AMOUNTS USED FOR  
 INDIVIDUAL BATCHES

Passing sieve	$\frac{3}{4}$ in.	$\frac{1}{2}$ in.	No. 16	Totals
Air-dry wt, gm	85,737	182,835	51,910	319,482
Moisture content, %	nil	0.1495	0.4762	0.1622
Oven-dry wt, gm	85,737	182,562	51,664	319,963
Fraction, %	26.80	57.05	16.15	100.00
<b>Batch composition:</b>				
Oven-dry wt, gm	536.00	1,141.00	323.00	2,000.00
Wt of moisture, gm	nil	1.71	1.54	3.25
Air-dry wt, gm	536.00	1,142.71	324.54	2,003.25

### EXPERIMENTAL PROCEDURE AND DATA

Moisture-density relations were determined for batches of dolomite containing 0, 1/2, 1, 1 1/2 and 2 percent calcium chloride (based on the oven-dry weight of the rock) by the AASHO standard method, T-99-57. However, the compactive effort used was 20, 25 or 30 blows per layer, the amount being constant for any one study.

Initial studies gave an indication that the crushed rock suffered degradation when used repeatedly in the density determinations. This was reflected by data which gave erratic density correlations. Henceforth each density determination was conducted with fresh material; material was discarded after being compacted once. All data reported in this paper were derived from fresh material as outlined in the following procedure.

About 1,000 lb of dolomite, crushed to pass a  $\frac{3}{4}$ -in. screen, were separated into three size fractions. Each density determination was made with a 2,000-gram sample composed of the appropriate quantities of the size fractions necessary to produce a mixture having the original mechanical analysis. This procedure was followed to reduce errors due to segregation of fine material. The original size fractions and the amounts used in batches are given in Table 1.

Batches were prepared from the indicated quantities of crushed rock. Appropriate amounts of calcium chloride solutions were mixed with the dolomite in a Hobart C-100 kitchen mixer until the material appeared to be uniform. A density test was then conducted according to AASHO designation T-99-57.

Moisture samples were taken from the molds and dried for 24 hr at  $105 \pm 2$  C and were redried for an additional 24 hr to check the initial determination. All checks showed 24 hr drying time to be sufficient.

Data resulting from the experimental work are plotted in Figures 1 and 2 with iso-optimum moistures and iso-density curves plotted as a function of the compactive energy and the calcium chloride content. The compactive energy values are expressed as foot-pounds of potential energy per pound of dry material (rock +  $\text{CaCl}_2$ ) and the densities are expressed as pounds of dry material (rock +  $\text{CaCl}_2$ ) per cubic foot. The data in Figure 2B are based on a pound of rock only and exclude the  $\text{CaCl}_2$  content. The optimum moisture values and calcium chloride contents are expressed as a percentage of the dry weight of the soil.

### ANALYSIS OF DATA

The study of any process must include an exact accounting of all material and energy that enters or leaves the system. Such an accounting must be accomplished by computing all quantities to some arbitrary basis. The quantities may be added or

subtracted provided the basis establish equivalent amounts of material or energy. The use of mass as the basis for computation has been used in this study inasmuch as compactive energy is absorbed by the mass rather than the volume. The energy is expended in the rearrangement of particles, as a heat loss due to friction and as a force causing fluid flow.

The use of mass as a basis for computations also allows an easier and more readily apparent comparison of values. For instance, using 30 blows per layer and 3 layers in  $\frac{1}{30}$  of a cubic foot may produce a density of 120 pcf for one percentage of calcium chloride and 125 pcf for another. Using the cubic foot basis, these two densities result from the same compactive effort, whereas on a pound basis one received 123 foot-pounds per pound of material and the other 118 foot-pounds per pound. This then represents a difference of 5 foot-pounds of energy less per pound of material to attain a higher density, rather than the same compactive effort to attain a higher density.

The introduction of calcium chloride to the dolomite-water system affects the density that results from any given compactive effort. The variations in density are caused by the physical presence of the calcium chloride and by the chemical influence of the calcium chloride on the system. The amount of energy involved in the chemical influence can be indirectly found because the magnitude of the total effect on energy requirements is known from Figure 2A and the magnitude of the physical effect can be calculated for any amount of calcium chloride added. The difference between these two, therefore, represents the magnitude of the chemical influence.

Consider a cubic foot of dry compacted crushed rock (specific gravity 2.70) weighing 126 pcf. The volume of solid material is 0.750 cu ft and the volume of voids is 0.250 cu ft. The weight of such a cubic foot of material can be increased through partially filling the voids by allowing a solution of calcium chloride to seep into the material and then evaporating the water. Theoretically the void space could be completely filled by hexahydrate calcium chloride thereby increasing the density to 152.2 pcf, the increase in density being accomplished by the physical presence of the calcium chloride. A plot of density versus calcium chloride content for this case is a linear function. The maximum calcium chloride content theoretically possible is limited by the void space available which is dictated by the initial density. In this case the top limit is 20.8 percent hexahydrate calcium chloride or 10.5 percent anhydrous calcium chloride.

Figure 2C shows a series of iso-density lines plotted from the energy value required to produce arbitrarily chosen densities for zero percent calcium chloride. Assuming that the presence of calcium chloride causes only a physical effect (any increase in density is due to added weight of calcium chloride in the voids) and shows no chemical influence, the lines should represent the densities attainable with the same compactive effort that was required to achieve the initial density (0 percent  $\text{CaCl}_2$ ).

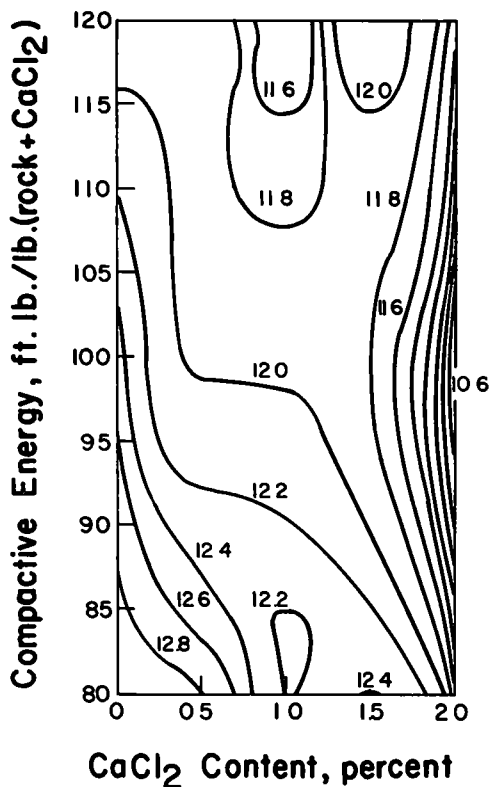


Figure 1. Optimum moisture requirements for the various combinations of compactive energy and calcium chloride content.

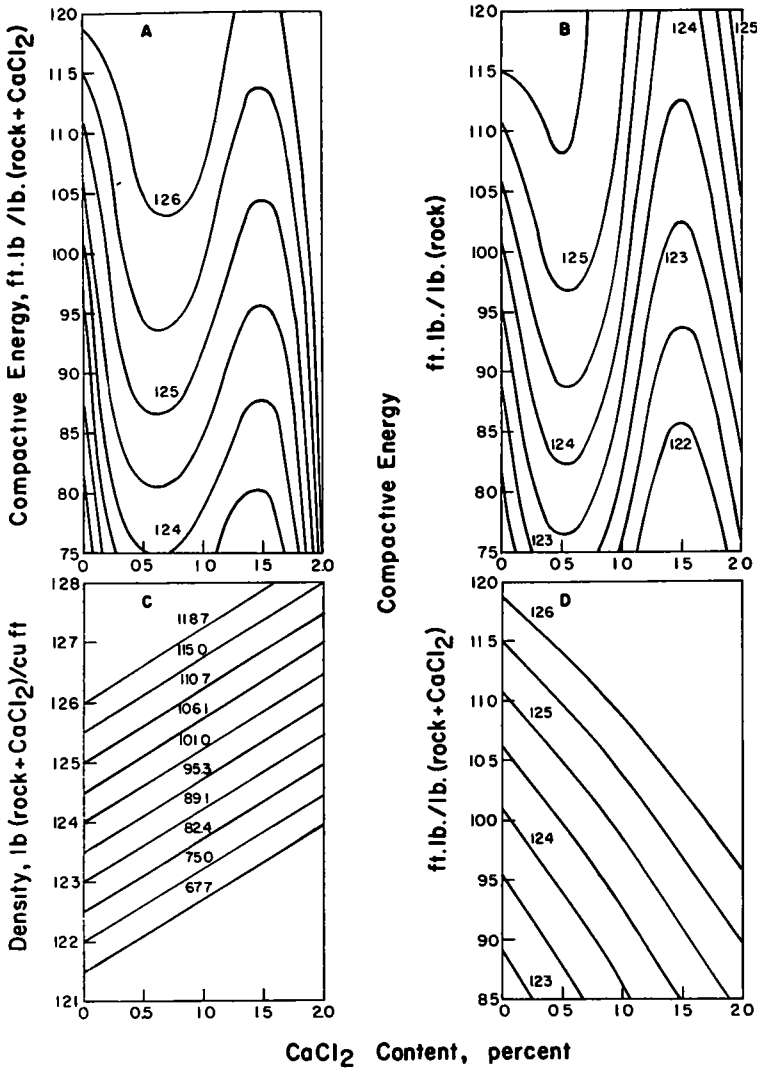


Figure 2. A—Iso-density curves as a function of compactive energy and calcium chloride content. Energy and density values are based on pounds of crushed rock plus calcium chloride. B—Data from Figure 2A plotted with energy and density values based on pounds of crushed rock plus calcium chloride. C—Theoretical iso-energy curves showing the increase in density due to the physical presence of calcium chloride. D—Curves from Figure 2C replotted.

The required compactive efforts for initial density may be obtained from Figure 2A and are shown in Figure 2C for each line. Values from Figure 2C can be replotted as an iso-density chart with the same coordinates as used for Figure 2A. This chart is shown in Figure 2D and represents the combinations of compactive energy and calcium chloride content theoretically necessary to achieve a given density if, and only if, the effect due to calcium chloride is purely physical. The differences in the amounts of energy, necessary to produce a given density with a given calcium chloride content, between Figure 2A and Figure 2D then represent the amount of energy saved or the extra energy requirements due to the chemical effects of the calcium chloride. These energy cost-saving curves are shown in Figure 3. The iso-energy cost-saving chart shown at the bottom of Figure 3 was drawn from the upper six graphs of Figure 3.

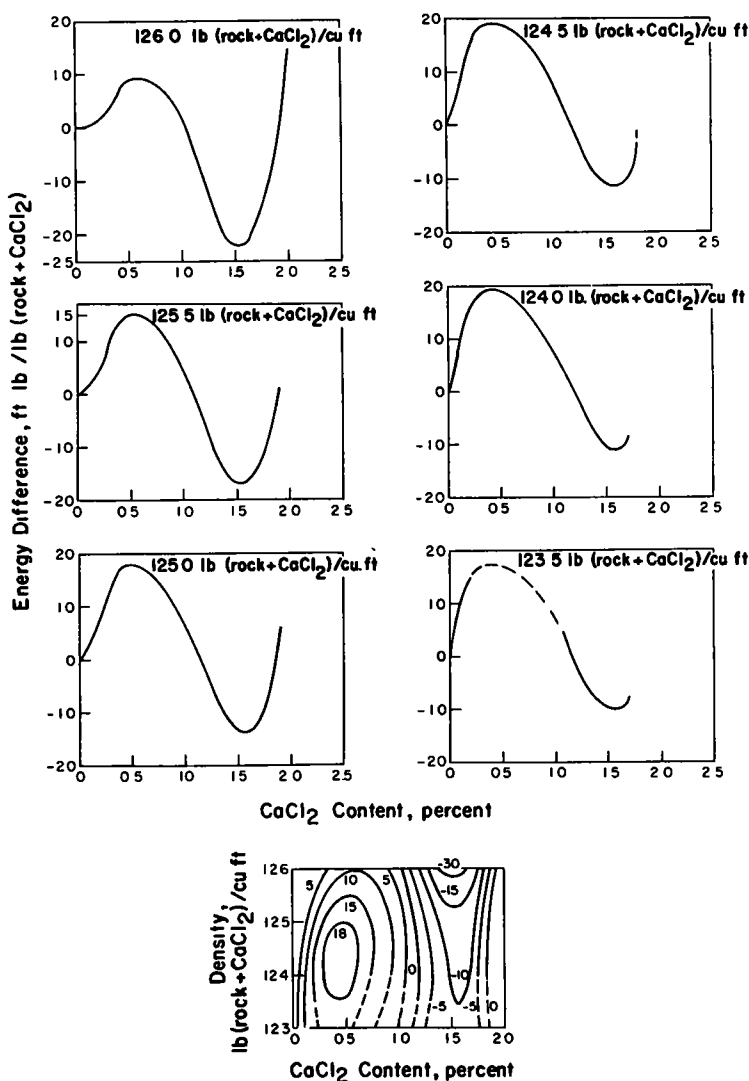


Figure 3. Energy saving or cost due to the chemical influence of calcium chloride. The upper six graphs are for the indicated density and are combined in the lower iso-energy chart. Positive values indicate saving and negative values indicate cost.

The minima occurring near 0.5 percent CaCl<sub>2</sub> in Figure 2A show that in order to achieve a specific density with a minimum expenditure of compactive effort, the amount of CaCl<sub>2</sub> required varies with the specified density. This does not imply that a combination of compactive effort and CaCl<sub>2</sub> content chosen from these minima will be the most economical combination.

Economic analysis of the data is necessarily limited to a relative status by the lack of compaction cost data. Such an analysis can be made from Figure 2D by using a pound of compacted crushed rock for a basis, as follows:

- Let  $E$  = ft-lb per lb rock,
- $C$  = lb CaCl<sub>2</sub> per 100 lb rock,
- $A$  = cost per lb CaCl<sub>2</sub>, and
- $B$  = cost per ft-lb energy.

The total cost due to compaction needs and the inclusion of calcium chloride is

$$\text{Cost} = BE + (AC/100) \quad (1)$$

Inasmuch as B is unknown

$$\text{Let } R = A/100B \quad (2)$$

Substitute Eq. 2 in Eq. 1 and the total cost becomes

$$\text{Cost} = B(E + RC) \quad (3)$$

By rearranging Eq. 3 the total costs are expressed as relative costs

$$\text{Relative cost} = \frac{\text{cost}}{B} = E + RC \quad (4)$$

Eq. 4 relates the variables through the relative ratio, R, which may be assigned any arbitrary value for the purpose of study. Values of E and C must be read from Figure 2B to be commensurate. Curves of Eq. 4 using data from Figure 2B are shown in Figure 4 with the arbitrary values of R indicated for each curve.

### DISCUSSION

The iso-density curves of Figure 2A show that the compacted density of the dolomite-calcium chloride system depends on the amount of compactive energy expended and on the amount of calcium chloride in the system. The lowest densities result from the lowest expended energy and the lowest amount of  $\text{CaCl}_2$ ; the highest densities result from the highest values of energy and  $\text{CaCl}_2$  within the ranges studied. Between these limits maxima and minima occur in the family of curves. These maxima and minima are interesting in that they reflect the chemical influence of the  $\text{CaCl}_2$ .

The curves also indicate that the statement "less compactive effort is required to obtain a required density when calcium chloride is incorporated in the mix" does not hold true for all values of  $\text{CaCl}_2$  content. The statement is certainly upheld by the data between 0 and 1.0 percent but the curves for 125.5 and 126.0 pcf near 1.5 percent show that the same or more effort is required than at zero percent. However, 1.5 percent is generally out of the economic range and would therefore seldom be used.

The changes in energy requirements to achieve a given density are caused by the physical presence and the chemical influence of the  $\text{CaCl}_2$ . The degree of change depends on the amount of  $\text{CaCl}_2$  contained in the system. As shown in Figure 2D, the physical presence of  $\text{CaCl}_2$  reduces the energy requirements in a near linear relationship with the amount of  $\text{CaCl}_2$ . The changes in energy requirements due to the chemical influence are of a more complex nature and vary considerably with the amount of  $\text{CaCl}_2$  present and with the density of the system.

The variations in energy requirements due to the chemical influence are shown in Figure 3. Proper analysis of these curves requires a knowledge of the chemical properties of the  $\text{CaCl}_2$  solutions that are present during compaction. These properties vary with the molar concentrations of  $\text{CaCl}_2$ . Molar concentrations may be calculated from the optimum moisture data shown in Figure 1. Viscosity, surface tension, lubrication, zeta potential, streaming potential and crystallization are properties of phenomena that are dependent on molar concentrations.

The molar concentration in the ranges studied is nearly a linear function of the  $\text{CaCl}_2$  content because the molarity is more affected by the amount of  $\text{CaCl}_2$  than by the amount of water. The optimum moisture contents vary only over the limited range of 12.9 to 10.6 percent, whereas the  $\text{CaCl}_2$  content varies from 0 to 2.0 percent.

Inasmuch as the viscosity and the surface tension of the solutions are both linear functions of the molarity, the resistance to compaction should increase linearly with  $\text{CaCl}_2$  content as demonstrated by G. G. Stokes, Osborne Reynolds and many other investigators who have made studies of fluid flow through porous media. The compaction of soil materials is essentially a problem of the forces involved in the flow of fluids through porous media or vice versa because in the process of rearrangement of particles the fluid (water or a solution) must move relative to the solid particles.

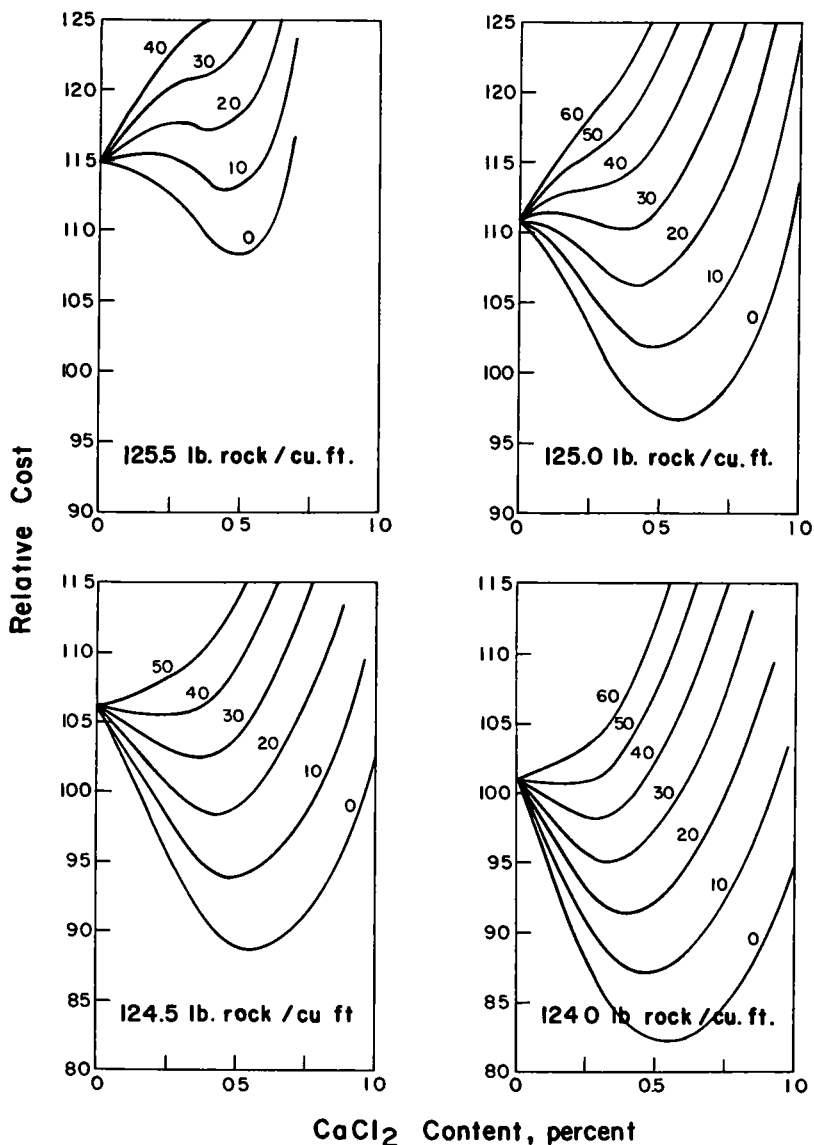


Figure 4. Curves showing relative cost as a function of the calcium chloride content for the density listed. The number identifying each line is the ratio of unit cost per pound of calcium chloride to the unit cost per foot-pound of compactive energy.

Plots of energy versus density, at constant  $\text{CaCl}_2$  content, show that the energy requirements increase with density and that slopes of the energy-density lines also increase as the  $\text{CaCl}_2$  content increases.

The quality or the amount of lubrication is a property that has not been described for any liquid to the author's knowledge. Zeta potential and streaming potentials are probably of little influence in the present system because clay minerals and ion exchange are virtually absent.

Preferential absorption of water by the dolomite, which would increase the concentration of the solution, could cause crystallization to occur before compaction was completed if enough water were absorbed to cause the solution to become supersatu-

rated. The hexahydrate would crystallize and the presence of these crystals would increase the resistance to compaction somewhat.

The foregoing discussion points out various factors that are primarily dependent on the molarity of the  $\text{CaCl}_2$  solutions involved. The total resistance to compaction is in turn a summation of the various contributions of these factors. If all factors were clearly understood, their various contributions could be separated and a summation of these should produce curves such as are shown in Figure 3. This analysis is limited by ignorance of these factors, but it is the author's hope that the discussion will stimulate further investigation of this problem.

A question often posed is whether or not the added cost due to the inclusion of  $\text{CaCl}_2$  is offset by a reduced cost of compaction. The relative cost curves indicate the added cost is allayed, provided the ratio of the unit cost of  $\text{CaCl}_2$  to the unit cost of compactive energy is low. A value of  $R$  exists, for each density, above which the inclusion of  $\text{CaCl}_2$  is not economical. This value of  $R$  may be defined as a permissible cost ratio,  $R_p$ . The value  $R_p$  is then the maximum value of  $R$  that will permit the economical use of  $\text{CaCl}_2$ . The curves show that  $R_p$  decreases with an increase in density from 50 for 124.0 pcf to about 12 for 125.5 pcf. The economical use of  $\text{CaCl}_2$  is therefore dictated by the density desired.

A general statement as to whether or not the cost of  $\text{CaCl}_2$  is offset by reduced compaction costs cannot be made until data for many other materials become available and until a permissible cost ratio is determined. Finally, laboratory data and field data should be correlated to form a realistic basis for conclusions.