Abridgment

Physicochemical Considerations in Thermal Susceptibility of a Base-Course Material

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Thermal susceptibility in a granular base-course material indicates that the material will experience a volumetric contraction on freezing in a condition of constant moisture content. The measure of thermal susceptibility is the freeze coefficient of the material (1), which is the linear coefficient of thermal contraction for temperature changes below freezing (strain per degree centigrade).

Earlier data for six tested materials (2) show that a particle reorientation is the most probable mechanism to account for the noted change in the measured properties of suction and volume. Each freeze induces a volume contraction, and each freeze-thaw cycle produces a permanent volume change. The results of a scanning electron microscope study of particle structure with and without a freeze-thaw-cycle history are presented to verify the hypothesis of particle reorientation. Physicochemical measurements are shown to substantiate the clay-moisture interaction that causes the particle reorientation.

SCANNING ELECTRON MICROSCOPE STUDY

A material of intermediate activity was chosen for investigation. A set of samples were compacted at a single moisture content, slightly dry of optimum; this moisture condition would assure a volumetric contraction in all samples. The samples were then sealed for a time to allow moisture equilibrium. Half of the samples were run through a series of six freeze-thaw cycles; all of the samples were then prepared for the scanning electron microscope study.

Original Structure

The electron micrographs in Figure 1 show the compacted clay structure that had not undergone freeze-thaw cycling. These micrographs show that the clay minerals attapulgite and montmorillonite combine to form a clay skin that surrounds the larger silt particles. The attapulgite fibers further show a clay structure interconnecting the silt particles. The orientation of the attapulgite fibers is random, both in covering the silt particles and in interconnecting them.

Structure After Freeze-Thaw Cycling

The electron micrographs in Figure 2 show the compacted clay structure following freeze-thaw cycling. There is no longer a continuous clay skin interconnecting the silt-sized particles, particularly the attapulgite fibers. These fibers are much more oriented around the particles. The montmorillonite film is no longer continuous between the particles and appears as a torn, crumpled film where it lacks the support provided by the attapulgite fibers.

Reorientation

The clay particles maintain an intimate relation with the moisture that surrounds them. The strength with which this moisture is held by the clay particles depends on the size of the clay particle and the ions in the moisture and on the surface of the clay mineral.

When the temperature of the material drops below freezing, the water in the larger voids will freeze first. Further lowering of the temperature draws moisture away from the clay particles, primarily because of the temperature-energy gradient between the ice and the water. This drying process forces the clay particles to reduce their spacing and reorient themselves to use the remaining surface moisture more effectively. With the continuous clay skin shown in Figure 1, this clay particle reorientation will force the enmeshed silt particles to reorient also, producing the volume change noted. This is supported by the reorientation of the attapulgite fibers after freeze-thaw cycling. The more orderly parallel arrangement indicates that the fibers have been drawn together by the freezing process.

This behavior has been postulated for the structural realignment in gels under the effects of freeze drying, which shows a decrease in particle spacing. These phenomena are for rapid freezing in a saturated environment where the ice crystals that form are considered the primary force that pushes the clay particles closer together as the ice crystals grow. The particle reorientation validated in this study cannot use the force of ice crystals on the structure to produce an overall decrease in volume. The clay structure is actually dried by a freezing process that is limited to the larger void spaces in which there is a large amount of air space to absorb the expansion of any ice that forms. The reorientation in this study depends on the clay-moisture interaction.

PHYSICOCHEMICAL CONSIDERATIONS

The volume change for all samples is activated by a uniform decrease in temperature; thus a similar amount of work is done, externally, on all the samples and materials tested. The difference in the amount of volume change is the result of the difference in the interparticle forces in the structure of the sample. Structure differences result from different compaction methods, moisture contents, particle sizes, and ion concentrations in the tested materials.

Repulsive and Attractive Potential

Previous researchers have established theoretical relations for interparticle forces. These forces, which are related to the physicochemical properties of the clay particles, are represented by an attractive or repulsive potential that is controlled by the particle spacing.

Figure 3 shows the relation established for the repul-

sive potential and the influence of ion concentration. In the granular materials investigated in this study, the major ion present remains the same for all materials because the basic material is limestone. The ion concentration changes if the materials have different durability or solubility levels. A material that is more soluble and more easily broken during the compaction process produces a higher ion concentration.

The attractive potential is primarily an adsorptive force-field effect resulting from Van der Waal's forces. The condition of low moisture contents, which accentuates these attractive potentials, has previously been shown to exist for base-course material in west Texas. Figure 3 also shows the relation established for the attractive potential and the influence of particle size. Adsorptive properties are influenced primarily by the size, or specific surface area, of a material.

Interpretation

Ion concentration and specific surface area exist together in a material and not as separate quantities as shown in

Figure 1. Compacted clay structure without a freeze-thaw-cycle history.

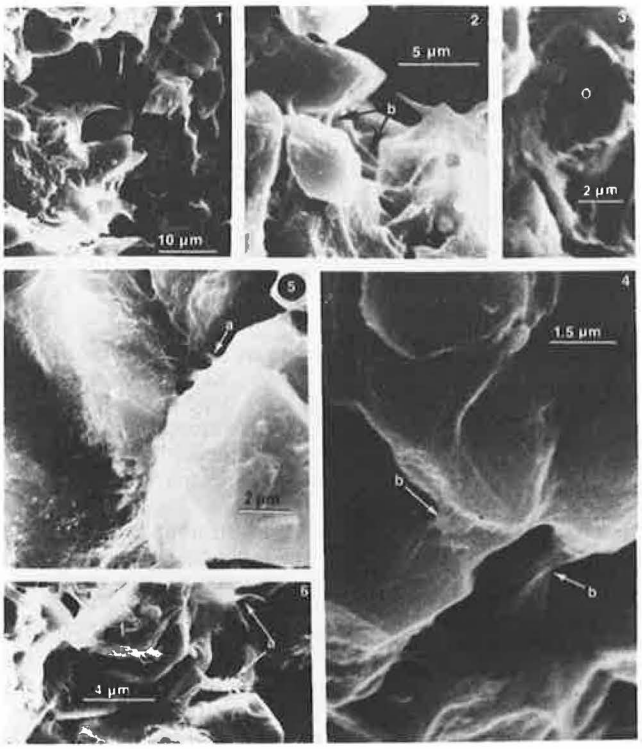

Figure 2. Compacted clay structure after freeze-thaw cycling.

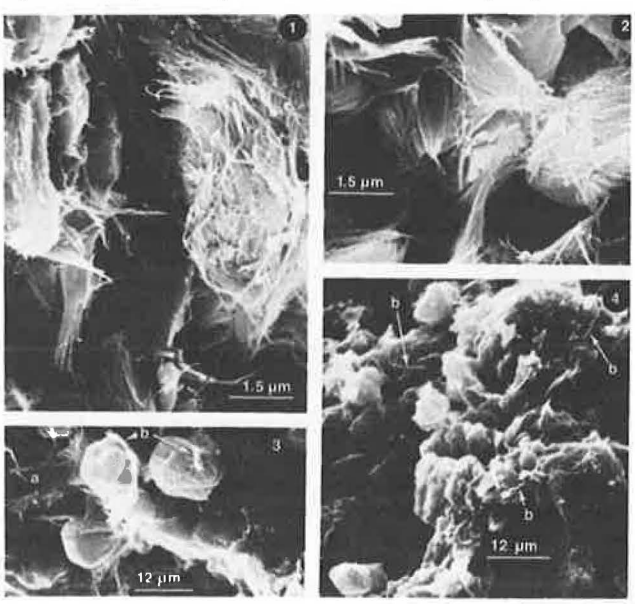

Figure 3. Attractive and repulsive potentials between clay particles as a function of particle spacing.

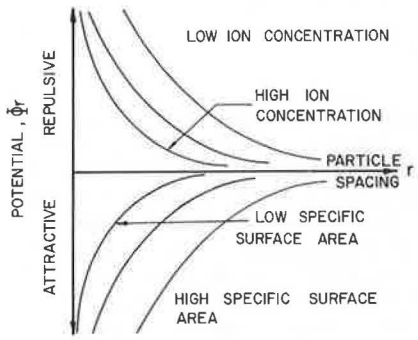

Figure 4. Composite curve formed by combining the effect of attractive and repulsive potentials.

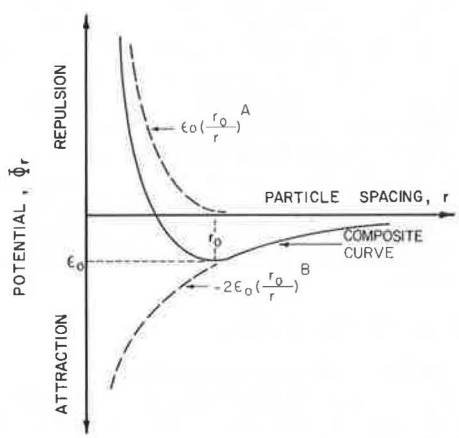

Figure 5. Ion-concentration exponent as a function of resistivity.

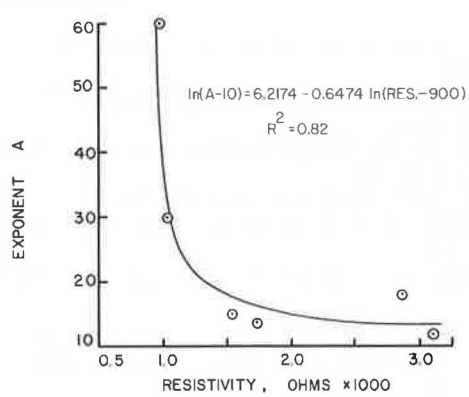

Figure 6. Specific-surface-area exponent as a function of specific surface area.

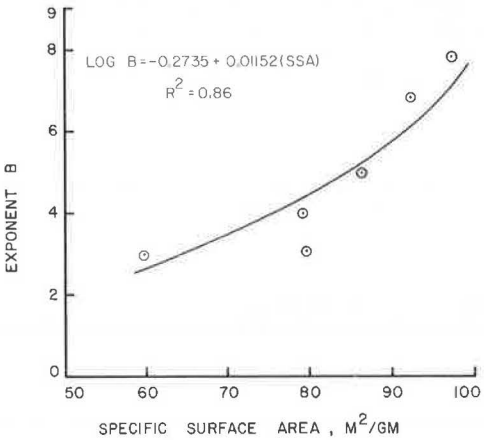

Figure 3. The combination of the separate curves in Figure 3 is shown in Figure 4. When the A exponent is set equal to 12 and the B exponent is set equal to 6, the resulting curve is the Lennard-Jones potential for intermolecular forces, developed in statistical mechanics. This curve is identical to the curve for freeze coefficient and suction given in the study by Carpenter, Lytton, and Epps (1), except that the freeze coefficient replaces the force potential and suction replaces particle spacing.

Because the energy change is similar for all samples, the resulting deformation depends on the existing interparticle forces and any forces activated by the freezing process. The freeze coefficient may thus be considered analogous to the force potential. Suction is related to particle spacing in that a dry sample has a flocculated structure with large center-to-center spacing and a high suction. A moister sample has a dispersed structure with a smaller center-to-center spacing and a low suction. A unique relation is not available although the trend for both quantities is the same and they may be considered analogous. Thus, the behavior of a sample during freezing is influenced by the ion concentration and the specific surface area of the material, as shown in Figure 4, and these two quantities may be considered as material properties.

MATERIAL PROPERTY RELATIONS

As demonstrated by the previous discussion, the interrelation of particle size and ion concentration will produce a freeze coefficient-suction curve. Data for this curve for the six tested materials (1) were regressed against the equation developed from Figure 4, which is

$$FC = FC_{max}(\log h_o/\log h)^A - 2(\log h_o/\log h)^B \quad (1)$$

where

- FC = freeze coefficient (strain per degree centigrade),
- FC_{max} = maximum freeze coefficient (strain per degree centigrade),
- h_o = suction of the sample with the maximum freeze coefficient (Pa),
- h = suction at which FC is desired (Pa),
- A = exponent denoting the effect of ion concentration, and
- B = exponent denoting the effect of specific surface area.

This regression analysis produced the exponents given in the following table. Test materials are those designated by Carpenter, Lytton, and Epps (1).

Test Material	Specific Surface Area	Ion Concentration
4	6.8	18
5	5	12
6B	4	30
6JD	8	14
7SA	3.5	15
6FS	3	60

The relation of the A exponent with the ion concentration is shown in Figure 5. Resistivity measurements taken on 1-cm-thick samples of base-course material mixed to a moisture content of 13 percent are used to represent the relative ion concentration of each material. The resistivity is inversely related to the ion concentration. A pore fluid with a high resistance to flow lacks ions to aid conduction; a pore fluid with a higher ion concentration will conduct electricity and have a low resistance. The proposed relation in Figure 3 is verified by Figure 5 in which the larger ion concentration (lower resistivity) has a larger A exponent.

The relation of the B exponent with the specific surface area of each material is shown in Figure 6. This relation clearly shows that a larger specific surface area produces a larger B exponent.

CONCLUSIONS

The importance of predicting the magnitude of the freeze coefficient in the relation of freeze contraction and pavement damage becomes evident as a base-course layer contracts during a freeze. This produces a buildup of tensile stress (1), which, when it exceeds the tensile strength, causes the base course to crack. Repeated freeze cycles will propagate the crack through the asphalt surface. The larger the freeze coefficient is the higher the stresses and the greater the damage will be.

The granular materials investigated in this study show contraction on freezing for the climatic area of west Texas and much of the Southwest. This contraction is controlled by the properties of the clay minerals and the unique, membranelike clay particle structure they form around the larger silt particles. The freezing process forces the clay particles to reorient, which produces the noted volume contraction shown in the scanning electron microscope study. The amount of reorientation, and thus of volume change, is controlled by the specific surface area and the ion concentration.

The specific surface area is a property of the clay fraction of the material. The ion concentration (resistivity) is a property of the granular portion of the material and represents the relative durability or solubility of the material. The ability of these two properties to model the freeze behavior is important because it shows how the coarse and fine-grained fractions of a material fit together and influence the environmental behavior of the material under freeze-thaw activity.

REFERENCES

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