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The Geographic Distribution of Intensity and Frequency of Freeze-Thaw Cycles

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ABSTRACT

The correlation of laboratory freeze-thaw tests to actual field exposure has long been an item of interest for those persons involved in evaluation of rock as an engineering and construction material. Attempts at using the laboratory freeze-thaw durability test to predict the serviceability or performance of rock as a building material often do not correlate with actual field experience. Part of this lack of correlation is attributable to inaccurate measurement and incomplete understanding of field exposure. This, in turn, implies that testing procedures do not accurately reflect the conditions of field exposure.

The purpose of this paper is to provide a better understanding of the conditions and variables of field freeze-thaw exposure. It is only through a careful analysis of these variables and conditions that a more suitable laboratory test may be designed.

INTRODUCTION

There have been numerous attempts in correlating various rock properties with the laboratory freeze-thaw durability test (Wills et al., 1963; Meininger, 1964; Dunn and Hudec, 1965; Mellor, 1971; and Hudec, 1980). The real problem, however, lies not with the correlation of the various rock properties with the freeze-thaw test, but rather with the correlation of the freeze-thaw test with actual outdoor exposure conditions. Attempts to improve the understanding of this relationship were made by Kennedy and Mather (1953), Axon and others (1969), and, in increased detail, by Masters and Wolfe (1974). All authors have essentially reached the same conclusion: prediction of the behavior of a material under actual outdoor exposure conditions cannot be made from the laboratory freeze-thaw results; or, at least one cannot accurately predict such behavior. The differences seem to lie in the conditions of actual exposure.

This discrepancy between accelerated freeze-thaw testing and actual exposure conditions can generally be attributed to the following factors:

1. There is a size differential between the actual specified size of the required construction material and the test specimen.
2. Conditions of the field exposure may not have been accurately measured or understood.
3. The freeze-thaw test does not accurately reflect the field exposure conditions.
4. The change in rock properties is not accurately measured or defined following exposure.

Sample size differential has been recognized within the Corps of Engineers as a major factor. Attempts have been made to correct for the deficiency of test specimen size versus actual project specifications (Lienhart and Stransky, 1981; Lutton et al., 1981). The object of this paper is to define the conditions and variables of the freezing and thawing component under field exposure conditions.

DEFINITIONS

For a complete understanding of this paper it is important that certain terms be defined and/or explained.

Absorbed water is water that is mechanically held within the pore system of a rock mass and which possesses properties similar to those of ordinary water.

Adsorbed water is water that is drawn into and held by a rock mass through capillary forces. It may have properties that differ from those of water filling larger pores. If a rock mass had only megascopic pores and no microscopic pores then it could be fully saturated only through submergence and all of its water would be absorbed water. If, however, a rock mass had only microscopic pores and no megascopic pores it could be almost fully saturated by exposure to air with a relative humidity of almost 100 percent. In actuality, though, a rock mass contains both microscopic and megascopic pores. Through submergence then, both types of pores are filled and the "absorption" equals absorbed water plus adsorbed water. When the rock mass is exposed to air with almost 100 percent relative humidity the resulting "adsorption" equals adsorbed water only.

Days of maximum temperatures of 32°F (0°C) and below is an expression used by the National Oceanic and Atmospheric Administration (NOAA) to describe days which do not possess a thawing cycle.

Days of minimum temperatures of 32°F and below are days which possess a minimum temperature of 32°F or less. These days could possess a maximum temperature of either less than 32°F or more than 32°F. Hence, if the quantity of "days of maximum temperatures of 32°F and below" is subtracted from the number of "days of minimum temperatures of 32°F and below," the result will be the "freezing cycle days."

Freezing cycle days are those days which possess a minimum temperature of 32°F and below and a maximum temperature of 32°F and above.

Durability may be defined as the capability of a product to maintain its serviceability throughout its required design life for a particular type of environment. For the "freeze-thaw durability" of rock, then, we are concerned with the ability of a particular rock type to withstand the rigors of an environment of freeze-thaw cycling in the presence of moisture.

FREEZE-THAW DURABILITY

Significance of Moisture

Freezing and thawing in the absence of moisture is merely thermal cycling. Although fracturing of rock may occur under these conditions, it is the presence of moisture which accelerates the fracturing process. This is a significant problem with rock used as construction material, whether the material is concrete aggregate, rock for erosion control (gabion-fill, riprap, armor, etc.) or building stone. The problem stems from the hydrostatic pressure developed during the freezing process. According to Powers (1965), Bowles (1982), and Ollier (1984), the development of hydrostatic pressures in a saturated system may range from 2,000 PSI at 30°F (−1°C) to almost 30,000 PSI at −7.6°F (−22°C), well above the tensile strength of any rock (Figure 1).

Mellor (1970), in his work with partially saturated, frozen rock, found that rocks with at least a 50 percent saturation may develop a "freezing strain . . . sufficient to cause internal cracking of rock." This means then, that those rocks with adsorption : absorption ratios of 0.5 or more, and exposed to conditions of high humidity and/or precipitation, may be susceptible to freeze-thaw deterioration.

Work by Fukuda (1983) seems to indicate a mechanism for this deterioration. In a partially saturated rock particle, water moisture in the rock will begin freezing at the surface. As freezing takes place, water from the interior of the rock particle will migrate toward the inwardly-moving "freezing front." Ahead of the front, negative pore pressures in the order of minus 2.9 in. of mercury (0.1 atmospheres) may develop because of low permeability of the rock. With continued freezing however, the freezing front continues its inward movement resulting in a reversal of pore pressures and eventually, hydrostatic fracturing. For fully-saturated rock particles there is only a continued increase in pore pressures and finally, hydrostatic fracturing.

One may now hypothesize the process involved in the various types of deterioration attributable to freezing and thawing. Spalling, for example, may involve partially saturated rocks of very low permeability in which the freezing front advances with accompanying pore pressure build-up just ahead of the freezing front. With sustained freezing and decreasing temperatures hydraulic fracturing takes place along a surface parallel to the freezing front. This could explain the sheet-like exfoliation of granites.

Splitting may involve almost-saturated rock particles that possess a directionally dependent permeability; that is, the permeability may be greater in one direction than another. The result would be an increase of pore pressures along the axis of greatest permeability. Splitting would then occur normal to the axis of greatest permeability (Figure 2). Once

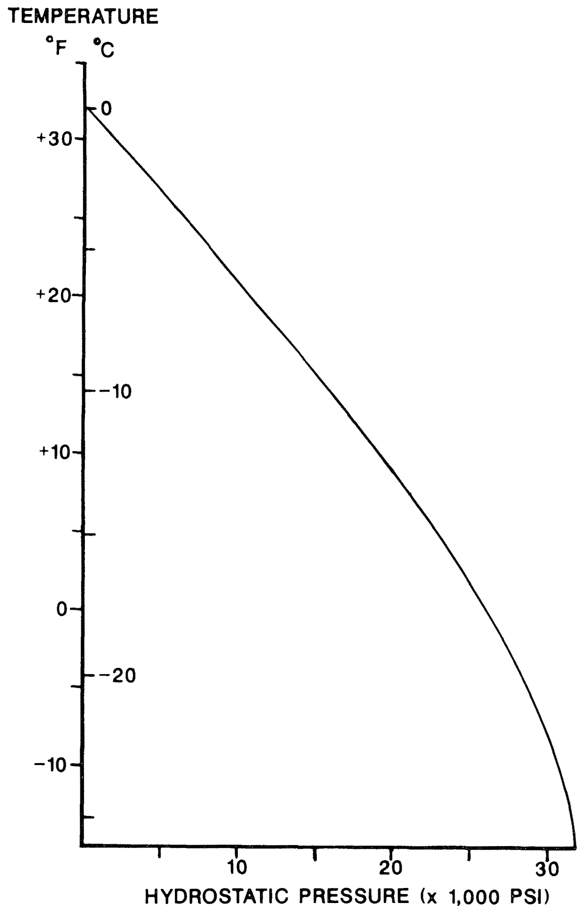

Figure 1. Development of hydrostatic pressure with decreasing temperature in a closed, saturated system.

splitting has taken place and an open fracture (hydraulically open system) exists, frost-wedging may develop and displacement may occur. Displacement may be quite large in the case of alternating cycles of freezing and thawing.

The key to this process seems to be the sustained length of time of freezing. With the cycling of short periods of sustained freezing followed by complete thawing, the process seems to resemble fatigue; that is, a constant cycling of build-up of internal stress followed by stress release. With long periods of sustained temperatures of 25°F (−4°C), and below, the process is merely one of hydrostatic fracturing.

Prediction of Freeze-Thaw Intensity

The intensity of a freezing and thawing environment depends on the freezing temperature, the duration of the freezing cycle, the available moisture, the slope direction, degree of saturation, and permeability. As the first four of these factors depend

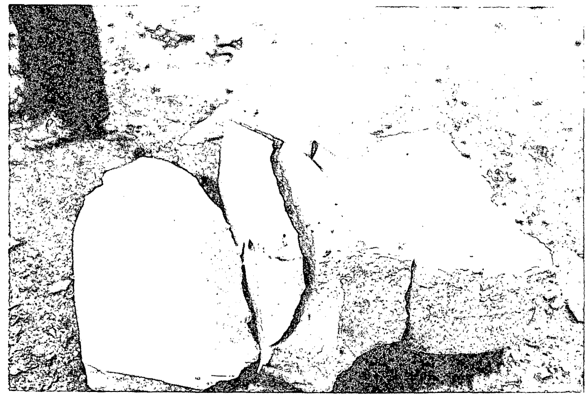

Figure 2. Development of the splitting phenomenon in a piece of recently quarried, saturated dolomite.

on geographic area and the last two factors are merely rock properties, then freeze-thaw intensity must be largely dependent upon geographic area.

This fact was the basis for the development of the old Weathering Index Map from *Specifications for Clay Building Brick,* ASTM C 62 (American Society for Testing and Materials, 1969). Although this map is labeled as a weathering index map, it was developed by plotting the isolines of the product of the "average annual number of freezing cycle days" and "average winter rainfall in inches" for a given locality. Hence, it is a map of moist freeze-thaw cycles. The map has since been updated and now apears in *Standard Specifications for Concrete Aggregates,* ASTM C 33-86 (American Society for Testing and Materials, 1986). The problem with this map is that it is divided into only three "weathering" regions, separated by two isolines. The result is that Vicksburg, Mississippi, and Bangor, Maine, fall in the same weathering region. Obviously, freeze-thaw conditions for these two localities are not the same.

Trewartha (1954) discusses freeze-thaw days in some detail, but his discussion is limited to the so-called "highlands" areas; specifically, those areas in excess of an altitude of 6,000 ft. His maps are only single element maps showing, for instance, heating degree days or number of days of dense fog but not the two together. Visher (1945) developed a map of the "average annual number of times of freeze and thaw." His map was based on the night frost minus freezing days. Again, though, the map does not account for any presence of moisture. Hershfield (1974) also developed a similar map based on over 800 weather stations. It too, does not account for the presence of moisture.

As no map which better defined the average annual moist freeze-thaw cycles could be found in the

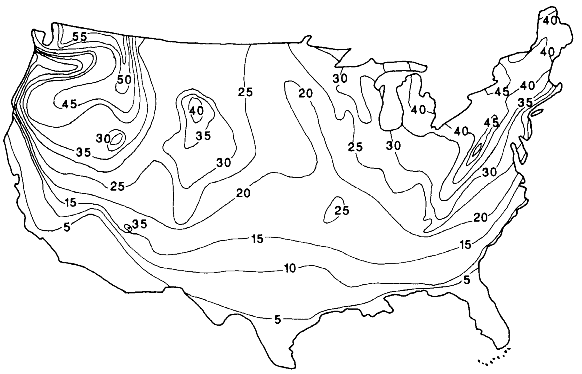

Figure 3. Isoline map of the "moist freeze-thaw index" for the contiguous United States.

literature, it was decided that a new map had to be developed. To develop such a map for the contiguous United States, Local Climatological Data sheets were obtained from 254 weather stations from the National Oceanic and Atmospheric Administration (NOAA) (Annual Update) of the Department of Commerce. From the NOAA data sheets it was found that by subtracting the quantity ("mean number of days of maximum temperatures of 32°F and below," for each month) from the quantity ("mean number of days of minimum temperatures of 32°F and below," for each month), the difference was the "mean number of freezing cycle days" for that month. These monthly freezing cycle days could then be added to find the "mean number of freezing cycle days per year." Since the presence of moisture is significant in the freeze-thaw durability environment it was decided to take (the mean number of days of precipitation of 0.01 in. or more) for those months in which freezing cycle days occur and divide by (the total number of days in the months in which freezing cycle days occur). The result is:

"Percent days of precipitation of 0.01 inch or more during the freezing cycle month."

This quantity was multiplied by:

"Mean number of freezing cycle days per year."

The product was termed "moist freeze-thaw index" in order to indicate the process of freezing and thawing in the presence of moisture.

The "moist freeze-thaw index" was calculated and plotted on a map for each weather station. All plots were subsequently contoured to produce an isoline map of the "moist freeze-thaw index" for the contiguous United States (Figure 3).

SUMMARY

The entire process of freeze-thaw deterioration of quarried stone has been found to be dependent upon the following conditions:

1. The sustained time of freezing must be of such duration that pore pressures are allowed to build to sufficient pressure to cause hydrostatic fracturing.
2. The rock mass must be at least 50 percent saturated (according to Mellor, 1970).
3. If the rock mass is not at least 50 percent saturated, then a sufficient number of freeze-thaw cycles must occur (moisture must be available during the thaw cycle) to allow for a gradual build-up in moisture content. The freeze cycle will gradually concentrate the water toward the freezing front zone.
4. The intrinsic permeability will affect not only the saturation level, but also the type of deterioration (due to the rate at which water may move toward the freezing front and the rate of pore pressure increase).
5. Pore size affects the temperature of ice formation, therefore, a temperature range of 23°F (−5°C) to 14°F (−10°C) for the freezing cycle is important (Hallet, 1983).
6. The presence of a "hydraulically closed system" versus a "hydraulically open system" is of utmost importance. A "closed system" may be exemplified by a rock particle upon whose entire surface a freezing front inwardly advances. Conversely, an example of an "open system" is a rock outcrop. Here, the freezing front advances in only one direction and unless the rock has rather low permeability, the pore pressures may be dissipated inwardly into the rock formation.
7. Finally, but most important, the presence of water either in the form of precipitation, standing pools, or high humidity is the key factor in freeze-thaw deterioration.

CONCLUSIONS

The "moist freeze-thaw index" map helps to define actual freeze-thaw conditions in nature. This is but one more step along the road to correlation of laboratory testing and field exposure. Work must now begin to design a laboratory freeze-thaw test which more closely resembles the actual exposure conditions. These conditions vary from one area of the country to another, so the test procedures will have to vary depending on the construction location. The conditions in the northeast, for example, involve the presence of substantial moisture, a prolonged period of freezing, lower temperatures, and a wider range of temperatures. If, however, the location of interest was the southeast, we would have to design a test involving moderate moisture, short freezing periods, temperatures only slightly below freezing, and a narrower range of temperatures. The "moist freeze-thaw index" map reflects most of these variations in intensity of freeze-thaw conditions.

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