EFFECT OF MOISTURE CONTENT ON PERMEABILITY OF FROZEN SOILS

by

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INTRODUCTION

The general subject of permeability of frozen soil and particularly the infiltration rate of frozen soil is of particular interest to hydrologists in the Northwest. A great many of our worst floods have been caused by storms occurring when the soil was frozen such that the infiltration rate was extremely slow. When this occurs, all or nearly all of the storm precipitation appears as surface runoff. Some of the more recent storms of this type were during the winters of 1962 and 1964, when there were several of these flood occurances in various sections of Idaho, eastern Oregon, and Washington.

Before considering this particular research on the effect of moisture content on permeability, we should consider some background information. We will consider first the type of weather and topography in which this type of flood occurs. It has been observed that these floods are most common from bare agricultural or sagebrush lands that are below about 6500 feet in elevation. The weather usually consists of a fairly wet fall season followed by a cold spell of sufficient duration to freeze the soil at least several inches deep over wide areas. This is followed by a significant storm period which may be all rain, but more likely will consist of a significant snow fall followed by up to several days of rain. Of course, if the storm is of sufficient magnitude, there will be a flood regardless of whether or not the ground is frozen.

PREVIOUS RESEARCH

There have been many field studies of the infiltration rate of various soil types under frozen conditions. Some of these are the subject of articles by Augustine (1941), Post and Dreibelbis (1942), Komarov (1957a, 1957b), Kvasov (1957), Mosienko (1958), Stoeckeler and Weitzman (1960) and Haupt (1967). Several of these authors used some type of rainfall simulator as an infiltrometer and found that it is possible to obtain a higher infiltration rate when the soil is frozen than when it is not frozen. This often occurs when the soil frost is of the so-called stalactite type and is most common under forested conditions where there is considerable ground cover. Most of this research was more concerned with the effect of various types of ground cover and soil type on the infiltration rate than on the effect of soil moisture content. However, Post and Dreibelbis did report a limited amount of soil moisture data. They found that concrete frost occurred when the moisture content was greater than 46% but when honeycomb and stalactite frost occurred, the moisture content was as much as 103% of dry weight. They did not state whether this was under bare or forested soil. Mosienko mentions that initial moisture content was above 60-65% of field capacity when impermeable conditions occurred. In summary, there has been little work done towards relating the permeability or infiltration rate of frozen soil directly to the moisture content at which the soil was frozen.

Another area of research that should be considered briefly is that dealing with moisture movement both in vapor and liquid phases during the freezing process. These processes of movement have been dealt with in numerous publications. Moisture movement by these processes is largely responsible for the formation of ice lenses in the soil. In general, there is less movement of moisture in coarse grained soils than fine grained soils and less movement when freezing occurs rapidly.

LABORATORY RESEARCH

Initially in the laboratory work we attempted to freeze soil columns in such a way that ice lenses could form. That is, the columns, which were 2-1/2 inches in diameter, were insulated on the bottom and sides such that freezing would occur from the top only. This, of course, is the way that freezing occurs in the soil. However, it soon became apparent that it would be difficult if not impossible to reproduce in the laboratory all the possible combinations of soil type, depths to water table, non-uniform moisture conditions, diurnal temperature fluctuations and temperature extremes which may occur under field conditions. All of these factors have an affect on the formation of ice lenses. It was also noted in the literature that the freezing of the top four inches of soil has the greatest affect on the infiltration rate. Since ice lenses do not tend to form that near the surface under bare soil conditions, it is felt that ice lenses in the soil probably have a minor effect on the infiltration rate.

In the final work, therefore, the sides and bottom were not covered with insulation so that the soil columns were frozen from all sides. This allowed freezing to occur in such a way that there were no ice lenses.

In order to measure the permeability, it was decided to maintain a constant temperature below freezing such that no thawing would occur during the measurement. This made it necessary to use a fluid with a lower freezing point than water for the permeability measurement. Air was used although it was realized that permeability to air is not the same as to water, due to slip flow or the so-called Klinkenberg effect which occurs for flow of gases in porous media. It was felt, however, that it would be possible to obtain a relative value for the permeability.

At first, the soil columns were packed and then wet to the desired moisture content, but it was difficult to obtain a uniform moisture distribution. In the final procedure, therefore, the soil was first mixed with water and the material was packed into the plastic column. This procedure worked well for the more granular material such as coarse or fine sand, but was less satisfactory for the finer materials.

The entire experimental procedure was as follows: The soil was mixed with water and packed into the plastic columns as uniformly as possible by vibrating. The samples were then placed in a cold room at approximately 20°F until completely frozen. This took at most a period of 24 hours. The sample was then connected to the pressure tank as shown in Figure 1. The pressure tank was pumped to a pressure several psi greater than atmospheric and the manometer was read. The valve was then opened at time zero to allow the air to flow through the sample. When the manometer reached a specified reading, the time was recorded and the test was ended. The permeability was then calculated by the following equation originally developed by Kirkham (1946):

$$k = \frac{2.3 L V \mu}{A P} \left(\frac{\log_{10} Y_1 - \log_{10} Y_2}{t_2 t_1} \right)$$

where k is permeability in units of length squared.

L is length of sample

A is cross-sectional area of sample

V is volume of the tank

μ is the absolute viscosity of air

P is atmospheric pressure

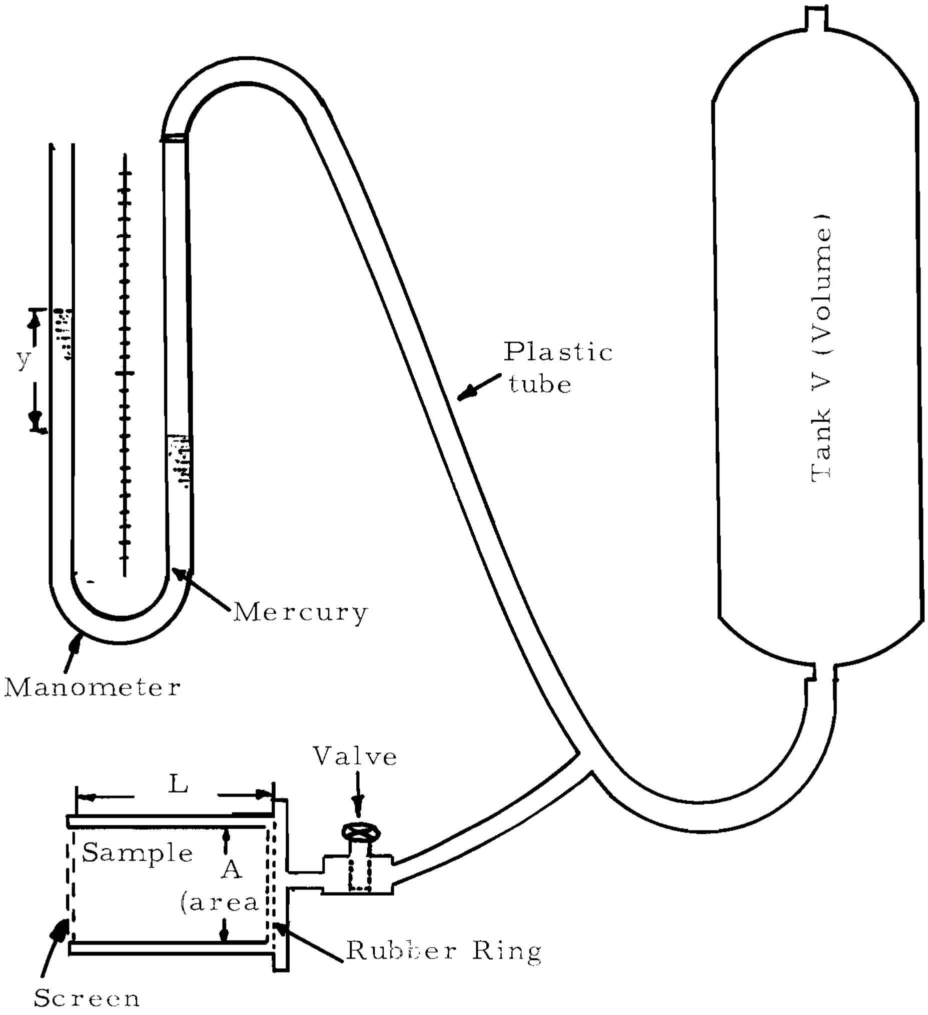

Fig. 1 - Schematic diagram of the equipment.

Y_1 and Y_2 are readings on the manometer and

t_1 and t_2 are the corresponding times

After the permeability was determined, the sample was weighed, oven dried, and again weighed to determine the porosity and the initial moisture content of the sample. The porous material was then used again at a different moisture content. It was possible to approximate the desired moisture content by controlling the amount of water which was mixed with the soil.

It was felt that the most significant parameter affecting the permeability should reflect the cross-sectional area of voids available for air flow after the soil is frozen. The parameter ϕ (1-S), where ϕ is the porosity and S is the saturation was determined to be the best parameter. This is because the porosity is the fraction of total cross-sectional area that is made up of pores and the saturation is the fraction of cross-sectional area of pores which are filled with water. The term (1-S), therefore, would give the fraction of cross-sectional area of pores which is available for air flow after the water is frozen.

The experimentally determined values of permeability are plotted versus ϕ (1-S) on semilogarithmic paper in Figures 2, 3 and 4 for a coarse sand, a fine sand, and a silt respectively. In Figures 2 and 3, a straight line was fitted to the data by the method of least squares. The coefficients of determination were 0.75 and 0.90 respectively; that is, 75 and 90 percent of the variation in permeability is accounted for by this parameter using a straight line relationship on semilogarithmic paper.

In Figure 4, a straight line was not fitted to the data since there was considerable scatter due to the experimental procedure of packing

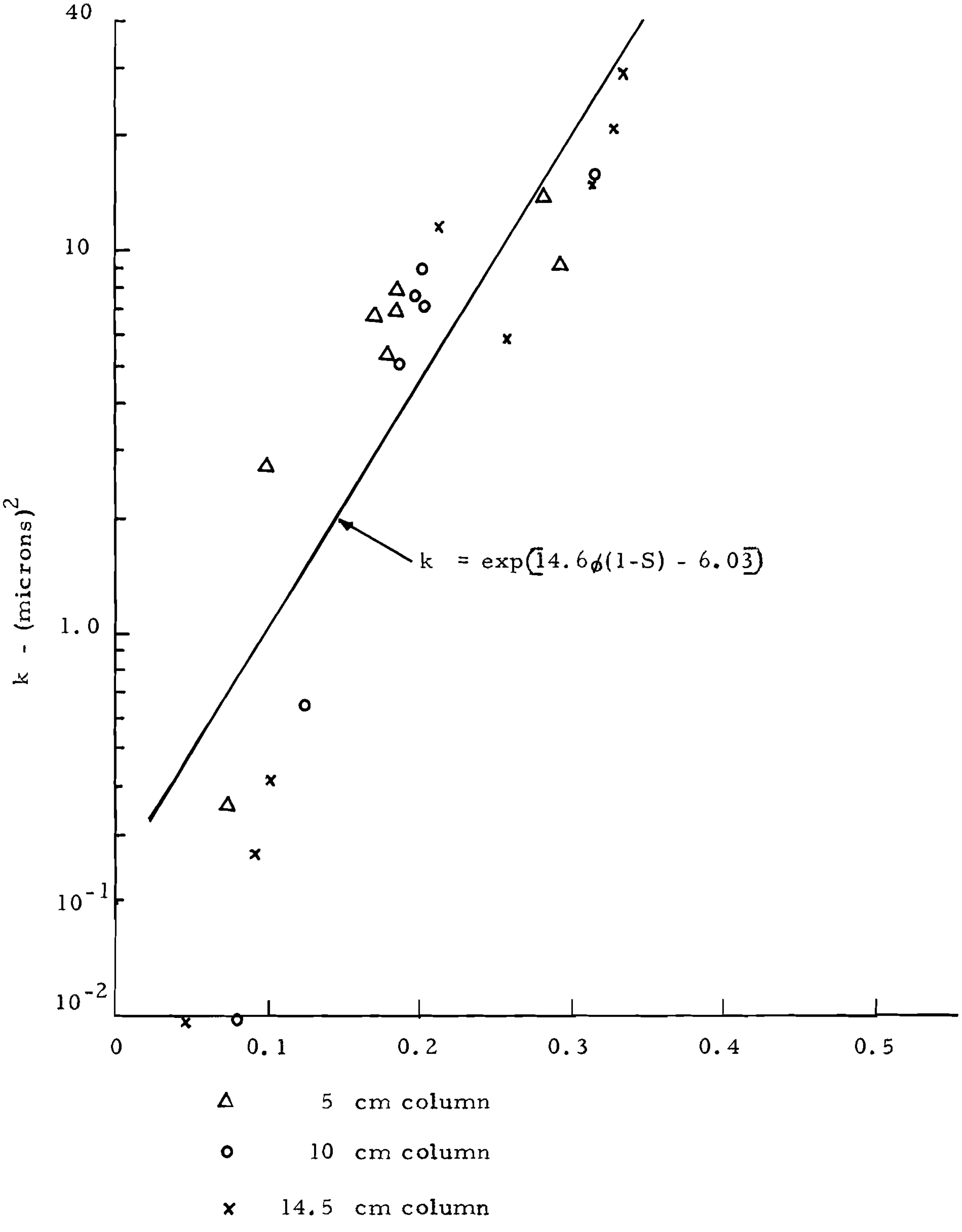

Fig. 2 Relationship between k and ϕ(1-S) for course sand.

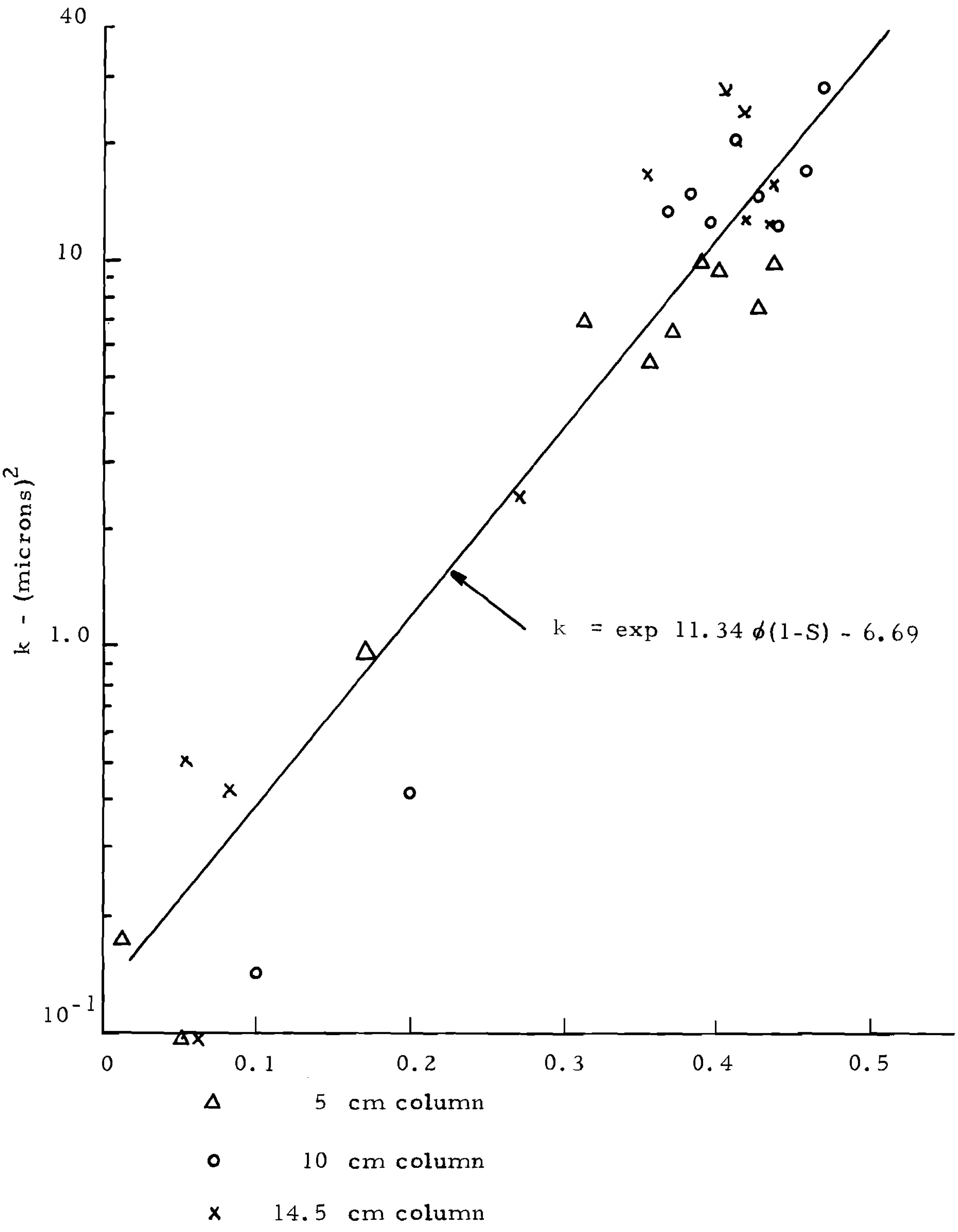

Fig. 3 Relationship between k and $\phi(1\text{-}S)$ for fine sand.

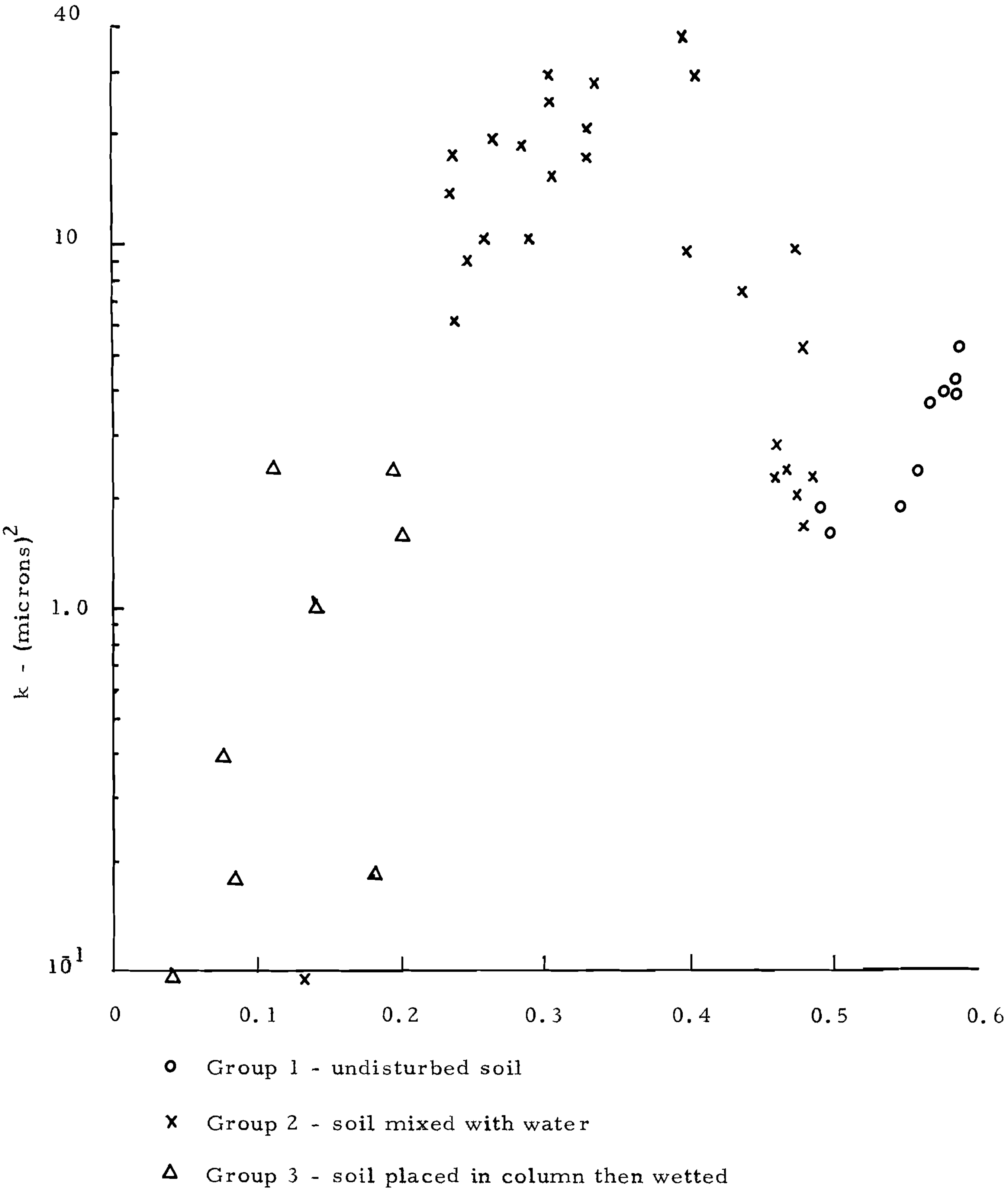

Fig. 4 Relationship between k and $\phi(1-S)$ for silt.

the soil after it was wet. Although this procedure was satisfactory for granular materials such as sand, it did not work well with silt since there was considerable aggregation which gives non-uniform conditions throughout the sample. In this figure is also shown the effect of using various other procedures for wetting the soil.

For all three types of material there were several samples that had zero permeability. These data points are plotted below the horizontal axis but were not used in the regression analysis since zero cannot be used on a logarithmic scale. In all cases ϕ (1-S) was less than 0.13 when the permeability was zero. Theoretically, ϕ (1-S) would be zero when the permeability was zero; practically, however, when ϕ (1-S) is small, the pores which remain empty are likely to be non-interconnected and therefore this soil would have zero permeability. It seems likely that in any type of soil there is some value of ϕ (1-S) below which the permeability approaches zero.

Assuming that natural soils of the type worked with here have typical porosities in the neighborhood of 0.4 and that the maximum value of ϕ (1-S) at which a negligible permeability occurs is 0.15; saturation would have to be at least 0.625 to have negligible permeability when the soil is frozen. This is quite wet - greater than the field capacity for many soils. As previously mentioned, Mosienko mentioned a moisture content of 60 to 65% of field capacity when impermeable conditions occurred.

In summary, this laboratory work gives information on the mechanics of flow in a frozen soil by developing a parameter which is a good index to the permeability. More work will have to be done in the field on soils in situ to determine critical values of ϕ (1-S) for various soil types, that is, the values of ϕ (1-S) at which the permeability is nearly zero. This field work could be done using an air permeameter under frozen soil conditions. If the critical values of ϕ (1-S) were determined for all the soil types in an area, then it would only be necessary to determine the porosity and saturation from field samples to determine whether there is the possibility of nearly impermeable conditions occurring when the soil freezes. This information could then be used in a flood warning program.

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