THE RELATION OF CERTAIN FROST PHENOMENA TO THE SUBGRADE

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In 1925 the State Highway Department of Michigan began a very comprehensive study of the condition of concrete pavements throughout the State in order to discover if possible those subgrade factors which were chiefly responsible for the annual damage from sources which were in no sense related to either design or loading of these pavements Concrete pavements were chosen because they are composed of a single material with properties reasonably well known, and because developed defects can be readily recognized and easily classified

Experience has shown that a very characteristic form of cracking or breakage develops in pavements when either an abrupt upheaval or a gradual settlement of the supporting base occurs It is therefore possible to differentiate in a general way between such failures and those apparently due to other more indefinite causes As one of the writers has previously pointed out, failure of pavement structures when due to the subgrade on which they rest is wholly a phenomenon of soil movement either vertically or latterally, or both This statement is subject to only minor exceptions Vertical movement in Michigan comes from two major sources, namely from the plastic flow of soils either in or beneath the subgrade and from expansion due to frost action

The problem of fill settlement on peat marshes was first attacked because the damage suffered was much more obvious, and research has very well settled on its cause and cure Results from the pavement survey mentioned indicate that about 33 per cent of unsatisfactory pavement is due to settlements obvious enough to be plainly visible to the pavement surveyor Not all of this damage is, however, due to fill settlement over peat marshes.

The most important soil movement in Michigan is caused from frost action resulting in damage to pavement structures both from rupture due to differential expansion of subgrades on freezing and also from settlement subsequent to thawing This class of damage accounts for the condition of something over 50 per cent of pavement which is classed as unsatisfactory In our studies the condition of pavement is considered to be unsatisfactory when the size of developed pieces is less than 10 square yards Taking both causes into consideration there is roughly between 75 and 80 per cent of unsatisfactory pavement age five years or less due to these two forms of soil movement This percentage is practically constant for pavements of all ages The total percentage of yardage which can be classed as unsatisfactory of course increases with age Percentages shown on the survey vary from 1 5 per cent the first year to 2 9 per cent at two years, 4 5 per cent at three years, 5 3 per cent at four years and 6 5 per cent at five years

It was noted years ago that differential expansion between saturated soils could not account for the amount of frost heaving commonly occurring in Michigan Experimental work with a dilatometer during the winter of 1926–27 demonstrated that only a small amount of heaving could take place from the simple freezing of certain soils Only a theory predicated on a natural moisture increase during the freezing period could possibly account for the excessive heaving which is followed in the Spring by a super saturation of the soil on thawing

It is well established in our State that the mere incorporation of reinforcement in pavements or added thickness of slab will not ordinarily prevent failures caused by differential frost heaving or resulting settlement in the subgrade A realization of these facts has emphasized the necessity of procuring sufficient knowledge by thorough research of the phenomena of frost action and fill settlement in subgrade soils, as it is felt that the remedy for this damage lies in correction of subgrade deficiencies rather than change in design of pavement surfaces

In order to fully investigate this problem, both laboratory and field studies were started During the Winter of 1928–29 frost heaving was unusually severe and ample opportunity was afforded for a study of these phenomena In February, 1929, field engineers of the Department were requested to secure certain information on the location and extent of all the major disturbances in their respective divisions The exact limits of each heave was staked out in the field and the location as staked was shown on maps forwarded to the main office so that the heaves might be easily located for future study The approximate height of each heave above the general profile was determined with a hand level Over 500 heaves were located in this preliminary survey, and during the following two summers detailed examinations were made of about 150 of these locations. Field examinations of the soil at the site of heave were made by trained soil men who investigated not only the soil itself, but prepared sketches which showed the condition of the road surface, grade of the road, depth of cut, direction of surface drainage, and all other factors which were considered to have any bearing on the problem

The subgrade soil surveys started in Michigan, also in 1925, have been consistently carried out by trained soil surveyors using the Bureau of Soils profile nomenclature Soil profiles are identified by these men wholly by visual inspection and "feel" of the texture The field studies of frost heaving were accordingly carried out in this same routine way Laboratory work has been confined to a study of freezing phenomena on the materials identified by soil survey, although mechanical analysis of the textures investigated were made as a check upon the identification.

It should be understood that field investigations to date have covered only that type of disturbance which is dangerous to traffic. It is entirely possible that while small in extent the mere difference in expansion on freezing two or more adjacent soils which are radically different in texture could easily cause abnormal cracking in concrete pavements. So far as any injury to the road surface is concerned it is possible then that there are many minor disturbances whose effect on pavement structure may be quite as serious as the larger heave whose effect is so plainly apparent.

Michigan being a glaciated state is particularly unfortunate in containing many soils which are conspicuous for their lack of uniformity in texture. Certain soil profiles show all variations from clay to gravel throughout the four foot depth of profile considered on soil survey. It must not be thought, however, that soil as indicated by a particular type profile is the cause of frost heaving because as will be shown later most of the frost disturbances occur in the parent material below the weathered zone comprising the standard type profile.

It is, however, plainly apparent from work already done that a comparatively few soil types are particularly dangerous because of the variation in texture commonly found in the parent material. It was apparent early in the investigation that Morainic soils were by far the most prolific sources of frost trouble. In addition certain soil types within the general classification of soils of Morainic origin were particularly frequent offenders. This is especially true of soils which we know as Bellefontaine, Coloma and Miami.

A classification of frost heaves occurring in different soil types show that these disturbances occur according to geological origin in the following order:

	Per cent
Moraine	65
Shallow Outwash	15
Till Plain	12
Lake Bed	4
Deep Outwash	4

As was stated before it is quite apparent that by far the larger number of frost disturbances are located in Morainic soils with the next most frequent occurrence in what is generally known as Shallow Outwash. This Shallow Outwash may not, however, be true Outwash Plain, because in certain instances what is termed Outwash may be wind-blown sand over an old clay lake bed. It does, however, mean that there is a comparatively thin layer of sand overlying a heavier material. Frost heaves noted in Till Plain are very frequently not in the true geological

Till material but are often in cut which goes completely through the Till of one glacial period into an old ground Moraine of a preceding glaciation Lake Bed and Deeper Outwash are comparatively free of soil textures which cause serious trouble from frost heaving

Of the 65 per cent of heaves occurring in Moraines, 65 per cent of these in turn are confined to the soil types already mentioned, namely Bellefontaine, Coloma and Miami, and their occurrence is about equally divided among the three It is therefore necessary in soil survey work for correction of subgrade deficiencies due to the presence of frost heaving textures, to pay particular attention to these three types While heaving occurs in other types of soil, yet it is comparatively infrequent as compared to those types singled out as being particularly subject to this type of disturbance

Within the soil type itself the cause of heaving is due to definite associations of material favorable to this phenomenon It should be further pointed out that from all indications to date, frost heaving due to ice segregation does not occur in material of a size greater than that in which capillary phenomena prevail

It is quite definitely indicated from the information disclosed by the field studies that a layer or pocket of fine textured material surrounded by a coarser, better drained soil is a condition favorable to the development of frost heaves Also, that where a relatively small area of silt or very fine sand outcrops in a loam or clay soil, trouble from frost heaving is very apt to occur It is definitely indicated, further, that heaves are very likely to develop in medium to fairly coarse sands when the water table is abnormally high or where an underlying impervious clay layer cuts off the downward movement of gravitational water Also, that heaves may occur where water is fed under pressure to moderately coarse soil textures

A detailed analysis of the cause and effects of the 156 heaves examined in the field showed that 94 occurred in a layer or pocket of fine textured material such as silt, very fine sand and silt, silty clay, clay or sandy clay surrounded by coarser better drained material, 22 occurred in a pocket of silt of very fine sand and silt surrounded by clay, 30 occurred in medium to fairly coarse sand and six occurred in moderately coarse textures The remaining four of the 156 heaves occurred where the subgrade soil appeared uniform with respect to character and moisture content

In regard to the 94 heaves which occurred in finely divided soils, study showed that 5 3 per cent of this number developed in silt, 32 per cent in very fine sand and silt, 4 3 per cent in very fine sand, 30 per cent in clay, 8 per cent in silty clay and about 17 per cent in sandy clay Of the 22 heaves which occurred in finely divided textures surrounded by clay, 45 per cent of the number developed in silt, 23 per cent in very fine sand

and silt, 18 per cent in silty clay and 14 per cent in sandy clay Additional information disclosed from these studies which showed that the average length of deposit of these finely divided textures was somewhat less than 60 feet was significant

In regard to the vertical extent of the heaves the data showed that generally the upheaval was greater where silt was involved The height was somewhat less for sandy clays or loams than for clays The average height for all the heaves occurring in silt was 6 inches, in very fine sand and silt 5 inches, in very fine sand 4 inches, in clay 4 inches, in silty clay 5 inches and in sandy clay 3 inches

In case of the heaves studied 80 per cent occurred in cuts, 2 per cent on fills and 18 per cent on locations extending from cut to fills Of the

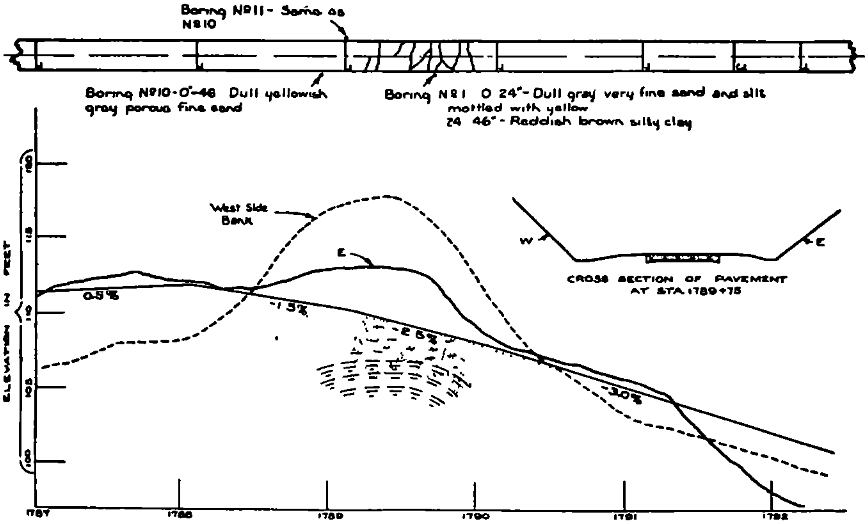


Figure 1. Frost Action in Very Fine Sand and Silt Causes Excessive Pavement Cracking

500 heaves located in the preliminary survey 76 per cent occurred in cuts, 10 per cent on fills and 14 per cent on cut to fill locations Of the 141 heaves studied in cuts 80 per cent were located at a depth of 4 feet or more from the original ground line elevation

Figures 1, 2 and 3 show plan and longitudinal profile views of several typical frost heaves In Figure 1, a pavement slab laid directly upon a pocket of very fine sand and silt underlain by clay and surrounded by well drained sand is badly cracked In Figure 2 a slab laid on a pocket of reddish brown clay surrounded by well drained sand is likewise badly cracked Figure 3 shows a cut where two distinct abrupt heaves developed in a gravel road surface At the point of each disturbance the subgrade consists of very fine sand and silt A well drained sand prevails throughout the remainder of this cut

Additional information was obtained concerning the occurrence of frost heaves by locating slabs with very characteristic cracking on the pavement condition survey records In 534 miles, 107 slabs were spotted,

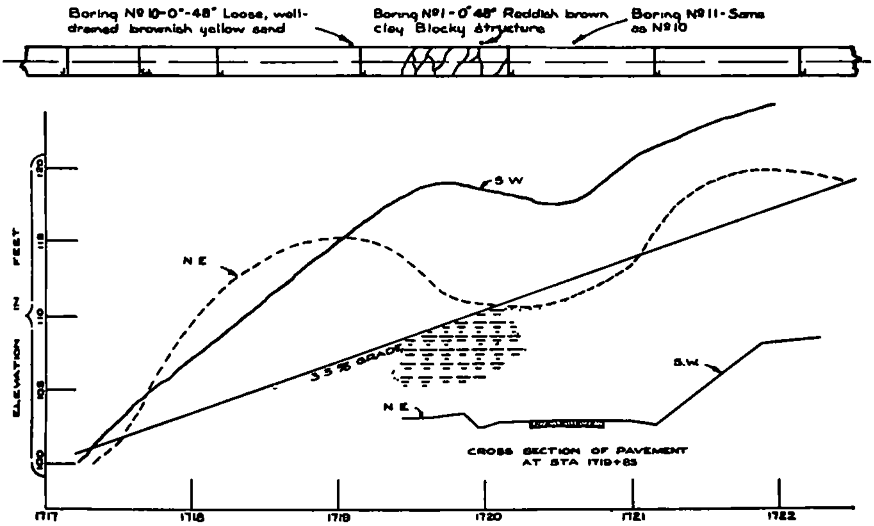


Figure 2. Frost Heave in Clay Pocket Responsible for Pavement Failure

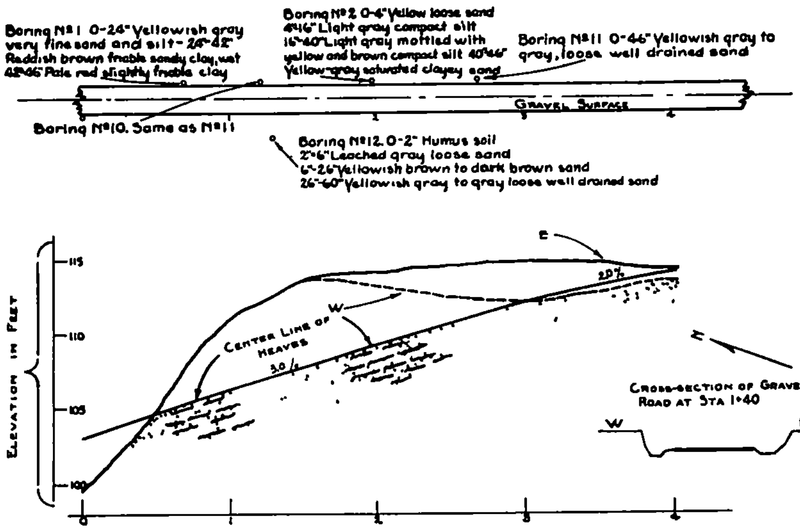


Figure 3. Two Typical Frost Heaves Located in the Same Gravel Road Cut

practically all in cuts, where unquestionably an abrupt upheaval of the supporting base had occurred A study of the available data served to substantiate the statement previously made that severe disturbances generally are restricted to morainic soils The possible benefits which might be gained by maintaining or raising new pavement grades over gravel road beds were also indicated inasmuch as 0 33 of these disturbances per mile were located where the grade had been lowered, 0 10 per mile where the old grade was maintained and only 0 03 per mile where a fill had been constructed above the existing gravel surface It was also indicated that the use of reinforcement in the pavement or the installation of tile drains in the subgrade was not effective in preventing frost disturbances

Practically the knowledge gained from the studies discussed in foregoing paragraphs suggests the possibility on new work of locating in the great majority of cases, associations and conditions of soil textures which cause excessive frost disturbances. In this connection it is felt by those who have been actively engaged in this work that this applies particularly to silt textures Invariably this grade of soil exists in a wet although stable condition, unless manipulated, even during periods of drought Furthermore, information obtained from 200 miles of general soil work this past summer shows definitely that trouble from frost action unquestionably occurs wherever this grade of soil prevails On the other hand, however, it was found that excessive heaving does not always occur in clay or sandy clay pockets even when surrounded by sand, as association of disastrous proportions where silt is involved If clay or sandy clay pockets are quite far removed from sources of water, the chances are that no serious trouble from frost action will occur. It is in some cases, then, largely a question of judgment where clay or sandy clay is involved but never in case of silts

LABORATORY INVESTIGATIONS

In 1928 in order to study the phenomena of frost heaving, a cold room 9 by 12 feet in size, was built in the State Highway Department Laboratory at the University of Michigan in Ann Arbor, in cooperation with the Civil Engineering Department of the University Temperatures in this room are controlled automatically so that it is possible to maintain a temperature within about 2° between the limits of 0 to $-35°C$ An air lock is provided between the laboratory itself and the cold room proper so that entrance to the freezing chamber is never made directly from the warm air of the laboratory Investigations planned for this room had only fairly gotten under way before the classic experiments of Professor Taber at the University of South Carolina eliminated the necessity for certain work and pointed the way to the desirability of still further study in other directions

Tabor's experiments had quite definitely indicated that ice segregation in soils was restricted to clays or material of a similar particle diameter size Our field investigations on the other hand had disclosed the fact that by far the most serious disturbances occurred in silts with an ice formation or banding very similar to that discribed in Tabor's experiments for clay It was felt that perhaps the size of sample used by Taber might have considerable to do with the results obtained because of possible radiation losses in specimens of small size Very large specimens were therefore used which had actually been cored out from known frost heave locations

The initial freezing experiments were conducted on 3 feet by 1 foot diameter undisturbed specimens of soil These specimens were obtained by forcing a split steel cylinder into the soil by means of a hydraulic jack and superimposed truck load They were then transported to the laboratory, removed from the cylinders and placed into split cylindrical wooden containers of the same diameter The sample rested on a layer of gravel contained in a metal pan which in turn was supported by a metal drum through which water at any desired constant temperature could be circulated Water could also be circulated through the gravel layer on which the test specimen rested The wooden containers were then placed in rectangular boxes and the intervening spaces filled with sawdust Thermocouples were installed at different points in the soil specimens and samples of the soil were also obtained for physical analysis and moisture content determinations

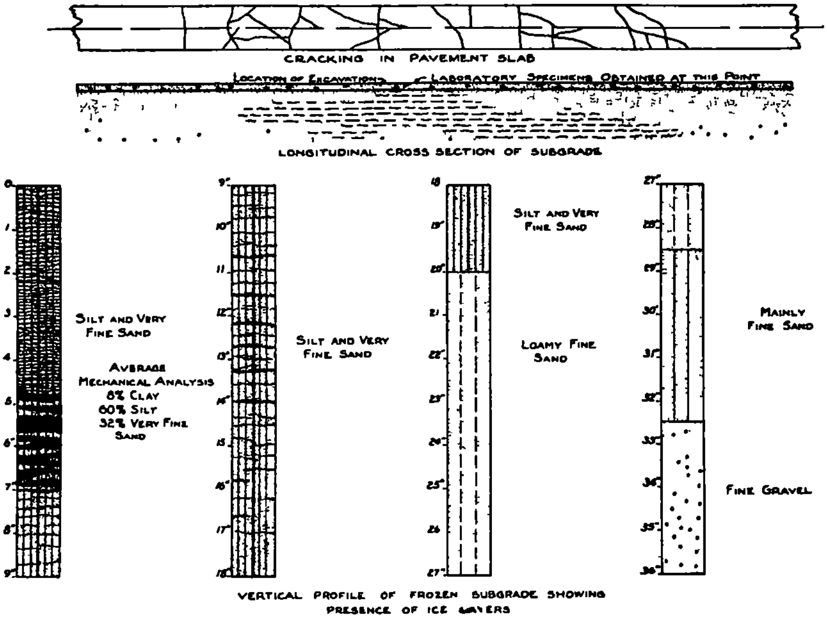


Figure 4

Specimens were frozen in sets of two, one containing an inserted porous layer of material at its midpoint. Freezing took place gradually from the top down, periodic measurements of the temperature being obtained by means of the thermocouples. The first two specimens consisted of an almost uniform silt taken from a location where an exceptionally bad heave had occurred. (See Figure 4.) They were frozen first without access to additional water, then thawed and refrozen with water circulating through the sandy gravel layer at the base of the specimens.

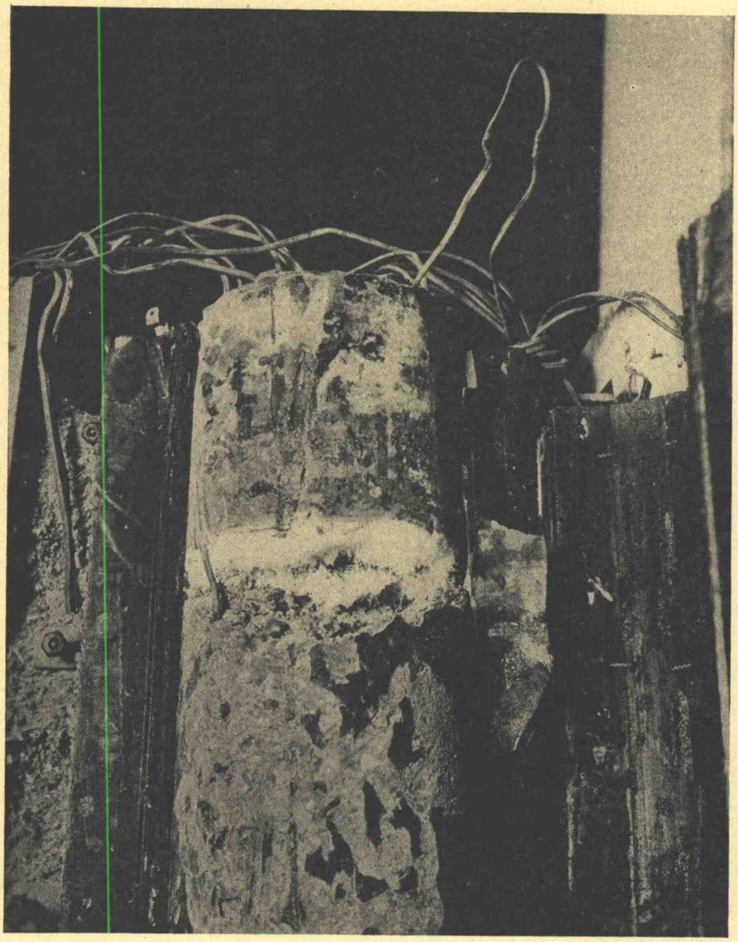


Figure 5. Frozen Silt Cylinder Containing Inserted Gravel Cut-off

Hoar frost formed in void space created by settlement of gravel into the wet soft material beneath.

The moisture content of the silt composing the specimens prior to the first freezing was about 16 per cent. No heaving or expansion of the two specimens occurred. On the second freezing, however, with the introduction of water to the bottom of the specimens 0 74-inch uplift occurred in case of the column without the gravel cut-off and 0 46-inch in case of the column containing the gravel layer On removal and examination of the specimens at the termination of the test it was found that the uplift was apparently due both to a general expansion of the material on freezing and to a very minute form of segregation One interesting phenomenon was noted, however, that of the settlement of the individual pieces of gravel composing the cut-off into the silt beneath, a movement which evidently occurred when the specimen was thawed after the initial freezing Some of the pieces were located at a distance of a foot beneath their original position (See Figure 5) This serves as an explanation of loss of metal from gravel and macadem road surfaces, which is quite a common occurrence in Michigan The moisture gain of the silt in these specimens was about 16 per cent except for the portion above the gravel layer which was about 9 per cent The silt, according to the mechanical analysis with the Bouycoucos Hydrometer, contained about 8 per cent of clay, 60 per cent of silt and 32 per cent of sand

The fact that segregation of water into ice plates of appreciable thickness occurred every winter at the location where these samples were obtained and not in the Laboratory tests led to the opinion that natural conditions in the field were not reproduced in the Laboratory. This particular frost heave had been the subject of considerable investigation previous to the Laboratory tests Attempts had been made to correct the condition by an extensive system of lateral tile drains and transverse bleeders without visible success. Also, an excavation along the edge of the pavement had been made when the subgrade was frozen and a sketch prepared showing the developed ice plates in the soil profile This is reproduced in Figure 4 The total uplift at this point was approximately 10 inches

Another pair of specimens taken from a second "silt" heave were installed and also frozen in the wooden containers They were first given access to water from below until the specimen not containing the gravel layer became moist on top Results obtained insofar as heaving was concerned were almost negative although examination of the frozen specimens did reveal evidence of slight segregation in a 4-inch silty clay layer existing at a depth of 6 inches below the top of the two soil columns It was slightly more pronounced in the specimen not containing the gravel layer The silty clay material analyzed about 35 per cent clay, 45 per cent silt and 20 per cent fine sand The moisture content of this material after test was 82 per cent representing a gain of approximately 50 per cent in the specimen without the gravel cut-off and 30 per cent, or a gain of about 10 per cent, for the other. These specimens were then gradually thawed and later refrozen On the refreeze no additional expansion of or segregation in the material was noted

The purpose of introducing a layer of porous material in certain of the specimens was to determine if water in a vapor form is transferred through a material with a large void space when freezing takes place above This unquestionably took place in case of the two specimens frozen The moisture content increase in the silt above the porous layer in both cases, as previously noted, was about 10 per cent. It was observed, moreover, on examination of the specimens after test that the voids in the gravel were almost entirely filled with hoar frost. (See Figure 5)

Later experiments in the Laboratory involved further attempts to develop the formation of ice plates in those silts in which excessive heaving had developed in the field Test samples were prepared for freezing in several different manners and in containers of various types and sizes A series of specimens were prepared by dispersing a definite quantity of silt and permitting the material to settle out into glass tubes 8 inches in height and 65 m m. in diameter by the use of a funnel shaped container This gave a graded specimen of the material, the coarser particles existing at the bottom and the finer at the top of the tube Other samples were prepared by tamping the material into tubes, and setting them upright in water until the soil at the top became moist. A series of each of these samples were first frozen in an oil bath, provisions being made to supply heat and water to the bottom of the tubes. Later on similar specimens were inserted in an insulated air tight box in which the temperature could be held constant and at any desired level, so that freezing took place from the top downward If desired, the specimens could be given access to water from a reservoir within the box

In case of the specimens prepared by dispersion and deposition into glass tubes, it was found on freezing that ice plates invariably developed in the upper part of the tube or in that portion of the material having a particle diameter size less than 0 005 m m (See Figure 6) Only a form of microscopic segregation occurred in case of silt specimens prepared in other ways. However, after a series of the latter were frozen several were thawed from the bottom up and a break or void in the soil followed the thawing line which gradually increased in width as the thawing line progressed upward This void filled with water and on refreezing before the thawing line had reached the top of the specimen this water was converted into a pure ice layer. A second ice layer was later developed below the first in a similar manner. (See Figure 7.)

It was possible to remove the glass tubes containing the specimens from the freezing box and observe developments at any time As the thawing line progressed upward, the individual silt particles were released from the frozen mass above and could be seen settling down through the clear water layer to the unfrozen soil beneath

The possibility that fluctuations in the air temperatures during the winter months may cause a shifting vertically of the frost line in the ground was clearly indicated from a study of the temperature movements in the freezing experiments on the large soil columns. In one instance the ammonia pumps broke down and a gradual raise in the

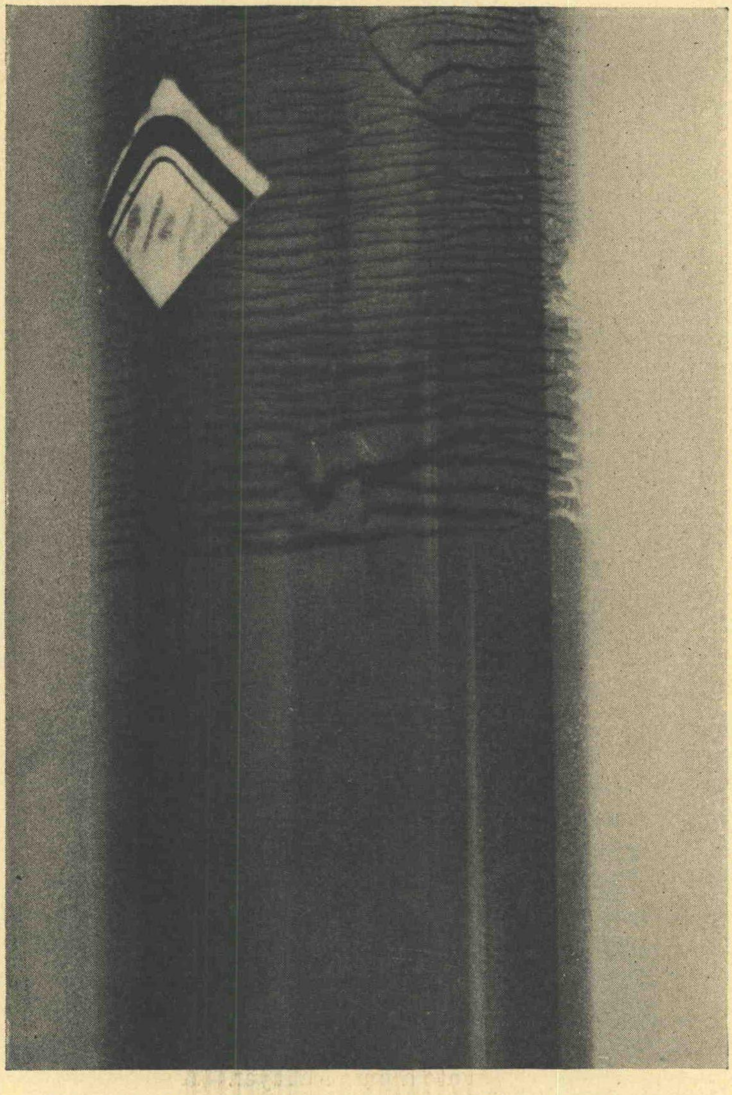


Figure 6. Glass Tube Containing Graded Frozen Silt Specimen

Segregation (upper part of tube) in material having a particle diameter size less than 0.005 millimeters.

freezing room temperature from −30°C to −23°C over a period of two days occurred. This resulted in a shifting of the freezing line toward the surface from a depth of about 12 to 8 inches. In nature, of course, the depth of frost penetration is more than likely a decided variable, the extent depending upon local variations in soil character and texture, amount of moisture present in the soil, etc. Fluctuation of the air temperature in turn promotes thawing to unequal degrees beneath the surface which in all probability results in a very irregular vertical profile of the thawing or freezing line. When soils freeze expansion takes place in proportion to the amount of water present. If thawing then occurs from underneath, the frozen material will suffer a decrease in volume in proportion to the amount of expansion that has occurred and voids of variable dimensions and variable distances from the ground surface may develop. Water liberated fills the voids and then freezes at subsequent downward movements of the frost line. A number of repetitions of this phenomenon could easily cause excessive heaving.

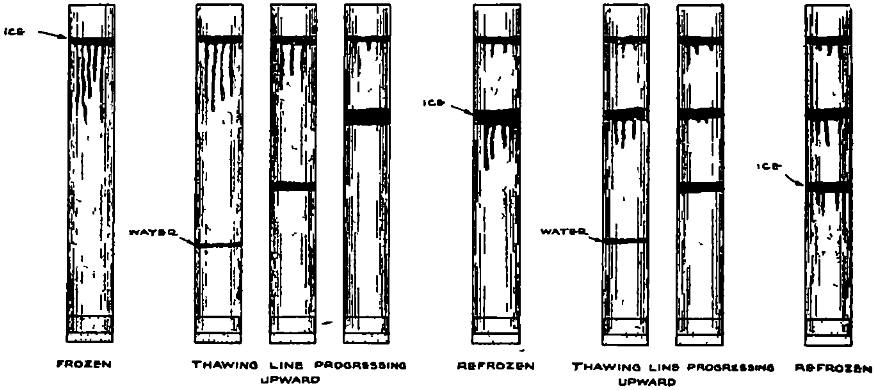
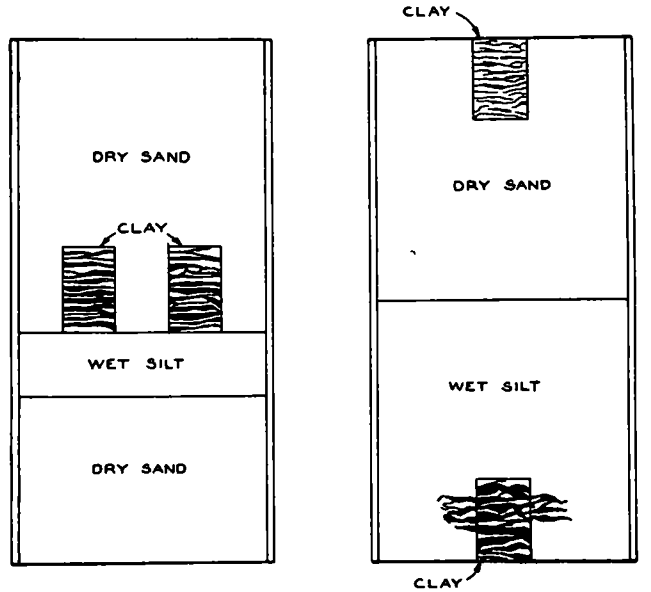


Figure 7. Showing Development of Ice Layers in Silt from Alternate Freezing and Thawing Below Surface

It is noteworthy and significant that Tabor in his laboratory studies of the freezing and thawing of soils never obtained appreciable segregation of ice in the form of horizontal plates in soils having a particle diameter size larger than 0.006 m.m. The majority of silts in which frost disturbances have occurred under roads in Michigan contain from 10 to 20 per cent clay, 60 to 80 per cent silt and 20 to 30 per cent fine sand and sand, or on an average 70 per cent of such textures has a size range from 0.005 to 0.010 m.m. The theory of alternate freezings and thawings of the ground below the surface and the resulting formation of ice layers as offered above serves as an explanation of the excessive disturbances that occur in materials having a particle diameter size larger than 0.005 m.m.

It is also significant that no difficulty has been experienced in promoting the formation of ice plates in clays and silty loam soils, a few specimens of which were frozen simultaneously with the silt specimens. Marked segregation invariably took place in these materials regardless of the rate of freezing, method of preparation of the specimens, and the type or size of the containers.

That ice segregation of the nature described by Tabor will occur in clays and not in silts when frozen in the laboratory was clearly demonstrated by a series of special tests. On a layer of wet silt about 2 inches in thickness, two clay specimens, containing about 15 per cent moisture, 1 inch in diameter and 3 feet in height were placed in an upright position This was then buried in dry sand and frozen with the result that the moisture was almost entirely drawn out from the silt to form ice segregation in the clay. In another instance a clay cylinder was buried in wet silt above which was placed a thickness of dry sand in which another clay specimen was placed flush with the top of the container On freezing only very slight segregation developed in the upper clay specimen while in the lower very marked segregation was noted (See Figure 8) Directly opposite the middle of the lower clay specimen some segregation occurred in the wet silt This was unquestionably due to voids or



SHOWING FORMATION OF ICE PLATES IN CLAY SPECIMENS RESTING ON WET SILT

SHOWING FORMATION OF ICE PLATES IN CLAY SPECIMENS BURIED IN WET SILT AND DRY SAND RESPECTIVELY

Figure 8

segregations which developed in the silt adjacent to the expanding clay specimen that filled with water and later froze No evidence of segregation in the silt above the level of the clay specimen occurred

A series of additional freezing experiments in the laboratory for the purpose of obtaining further information upon the observed phenomena have been started An auxilliary air tight compartment in which an automatic control mechanism will effect a periodic fluctuation of the freezing temperatures has been constructed This rests upon part of the insulated air tight box in which samples can be inserted, flush with the top, and in which the temperature can be held constant (See Figure 9) It is possible then to freeze one series of specimens at a constant rate of cooling and a duplicate series at any desired rate of change of cooling

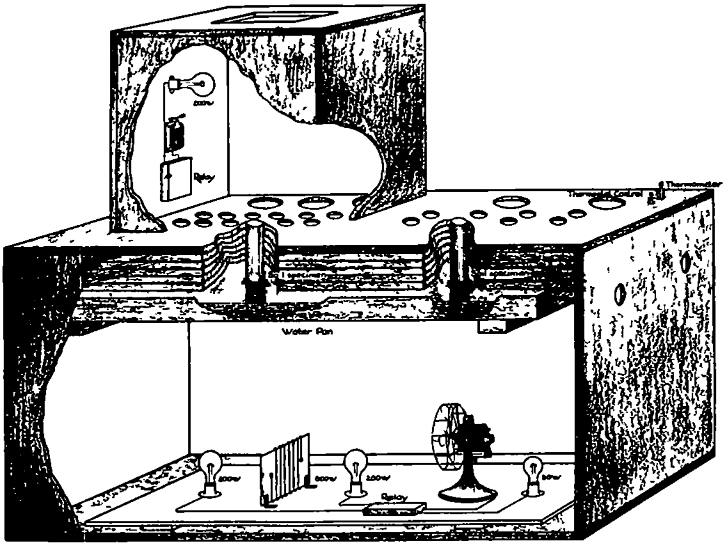


Figure 9. Temperature Control Freezing Boxes

Also, a series of field studies embodying the determination of the amount of heave of road surfaces by means of precise levels and the nature of the expansion within the soil by excavations and visual examinations have been planned for this coming winter. Thermocouples will be installed at different depths for the purpose of measuring the temperature movements in the soil It is expected that many of the points in question concerning the nature of the phenomena of heaving in silts, sands and clays will be cleared up by this investigation A total of 20 stations have been established, some at locations where severe disturbances have occurred and others in soils of a questionable character and yet in which no trouble has developed

PRACTICAL APPLICATION OF RESULTS

Starting early in 1930 preconstruction soil surveys were made on all pavement projects as a matter of routine The road line is examined by a soil surveyor immediately after the construction survey is made and all soil types are shown on the plan when it is drawn up Construction features involved in grade design, methods of drainage, subgrade treatment, etc , are considered in their relations to this soil information and plans are drawn accordingly Due to the detailed study of soil formations necessary to locate areas liable to frost heaving it is necessary for the soil men to visit the jobs from time to time during the course of grading and inspect the subgrade carefully when it is exposed to view Subgrade treatment and drainage measures previously recommended are reviewed and checked and any changes deemed necessary from the information disclosed by the detailed study are ordered and made

Silt pockets, wet clay areas, saturated sand layers over clay and areas affected by seepage are definitely located and then measures are applied for the purpose of eliminating or reducing frost heaving Inasmuch as little doubt exists concerning the invariable tendency of heaving in silts, silty clays and very fine sands, these materials are generally removed from the grade and replaced with a proper material The depth of excavation in the work done to date has been varied in some cases as a matter of experimentation, although this now is governed largely by the location in the State, north or south, and the length of the deposit In a few instances where unusually long deposits of these textures were encountered it was found more economical to raise the pavement grade than to excavate and replace the material with a satisfactory grade of soil Inasmuch as the majority of these undesirable textures, as brought out before, prevail in the subsoil of sandy moraines it is simply a question of wasting the excavated material and using the surface soil for backfilling purposes In some instances tile drains were installed in addition to removal and replacement of the material This added precaution was taken in the cases where silt or very fine sand pockets were surrounded by clay and coarser material was used to replace the objectionable type of soil

In case of areas of pockets of wet clay surrounded by well drained sand or layers of wet sand over clay, steps are taken to intercept possible sources of lateral seepage water and to lower the ground water level by systems of tile drainage In view of the lack of definite information obtained in the field studies concerning the occurrence of frost heaves in clay, the removal of this type of soil and substitution of unquestionable material does not seem to be justified

In all about 200 questionable locations in the grade of new paving projects were accorded some form of special treatment during the construction season of 1930 Special drainage structures were installed at approximately 125 of these locations while in most of the other cases the material in question was removed and replaced with a suitable soil. Detailed records, of course, have been kept as to the nature of the corrective measures applied to each particular location in question and it is anticipated that within the space of a few years a great deal of interesting and useful information will be forthcoming from this work

DISCUSSION

ON

THE RELATION OF FROST PHENOMENA TO THE SUBGRADE

Mr E A Willis, *U S Bureau of Public Roads* Mr Burton and Mr Benkelman are to be congratulated on the very important information which they have furnished with respect to the occurrence of frost heave in subgrades Particularly noteworthy is the fact that in their laboratory they have been able to reproduce frost heave in silt soils

Prior to this time investigators have been able to reproduce frost heave only in the so-called clay soils It has been recognized for some time, however, that frost heave is especially likely to occur in silt subgrades and also that important heave is likely to occur in certain types of clay subgrades and not in others even though their mechanical analyses are distinctly similar Furthermore, it has been pointed out by Prof Stephen Taber that ice segregation occurred in certain fine grained soils during freezing experiments while in other soils equally as fine ice segregation did not readily occur under similar treatment As a consequence the significance of the term "clay" is vey much limited with respect to the occurrence of frost heave unless the character of the clay is disclosed

It is for this reason that reports of the U S Bureau of Public Roads subgrade investigations generally attempt to distinguish those clays in which frost heave is likely to occur from those in which it is not Thus, for instance, the former are referred to as clay soils with relatively low cohesion and the latter as clay soils containing colloids having sticky or gluey properties Every effort is being made to make possible this differentiation by means of tests which disclose the physical characteristics of the soils

Mr Hogentogler, in his discussion of Professor Krynine's report during the Ninth Annual Meeting of the Highway Research Board, stressed the fact that particle size alone is inadequate to furnish complete identification of subgrade characteristics

In addition, the mechanical analysis is very much limited in its ability to disclose accurately the size of the smaller soil particles which must be determined by means of some method of sedimentation instead of sieves.

Thus for grains smaller than about 0.074 mm. (No. 200 sieve) in diameter the following sources of error are present:

(a) The grain diameters furnished by the mechanical analysis instead of being the diameters of the grains tested are the diameters of spheres which according to Stokes law settle in water at a rate equal to that of the particles of soil being analyzed.

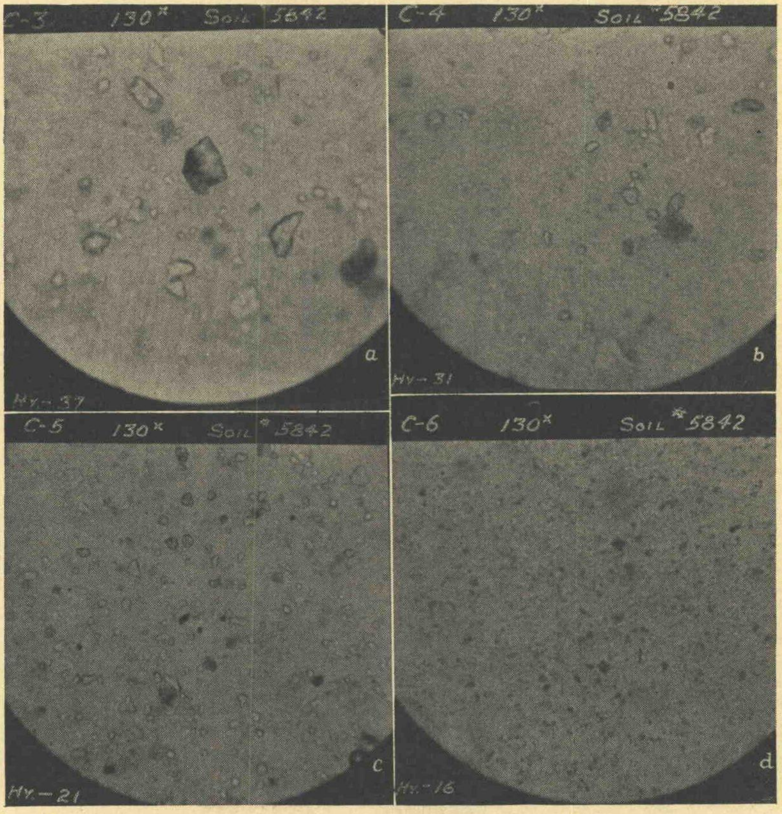


Figure 1. Photomicrograph of Suspension of Soil 5842, after One, Two, Five and Fifteen Minutes

Note shape of particles. a, 1 minute; b, 2 minutes; c, 5 minutes; d, 15 minutes

(b) The rate at which small soil particles settle depends upon the extent to which the soil is dispersed and this in turn depends upon both the method of agitation and the chemical reagent used in dispersing the soil.

Thus, for instance, a soil which according to the mechanical analysis contains clay in amount equal to 50 per cent does not necessarily contain this amount of particles possessing diameters smaller than 0 005 mm but instead contains this amount of particles which settle through water at a rate equal to that of spherical particles not exceeding 0.005 mm in diameter

Figure 1, which shows photomicrographs of soil suspension at different periods of time after dispersion, discloses how very much the shape of soil particles is likely to vary from spheres

Table I, furnished by L B Olmstead, L F Alexander and H E Middleton[1] illustrates how the type of dispersing agent influences the silt and the clay contents furnished by the mechanical analysis.

It should be remembered also that when grain size is computed from a knowledge of rate of settlement of particles in water, it is assumed that all of the grains in the soil being tested possess equal specific gravities and this is not necessarily true

TABLE I

YIELD OF CLAY OBTAINED WITH VARIOUS DISPERSING AGENTS*

Soil type and source	Percentage of clay obtained from treatment with							
	Ammonia		Sodium hydroxide		Sodium carbonate		Sodium oxalate	
	0 005 mm	0 002 mm	0 005 mm	0 002 mm	0 005 mm	0 002 mm	0 005 mm	0 002 mm
	per cent	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
Wabash silt loam (Neb)	30 7	24 1	33 2	28 5	33 1	28 3	34 5	29 6
Houston black clay (Tex)	38 4	26 4	44 5	30 6	61 3	53 5	63 8	53 8
Carrington loam (Iowa)	7 8	6 4	24 9	21 8	23 4	19 9	24 7	22 9

* Average of duplicate determinations

Thus grain diameter fails to disclose, except to a limited extent, the character of subgrade soils and furthermore the mechanical analysis discloses only approximately the diameters of small size soil particles Consequently, results furnished by the mechanical analysis possess but a limited significance with respect to the identification of important soil characteristics

To illustrate how very inefficient the term "clay" is for disclosing the ability of soils to resist frost heave, reference is made to Tables II and III, which show, repectively, both the constants and the mechanical analyses of a limited number of soils, some of which heave and some of which do

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[1] L B Olmstead, L T Alexander, and H E Middleton A Pipette Method of Mechanical Analysis of Soils Based on Improved Dispersion Procedure, U S D A Tech Bull No 170, Jan , 1930, p 10

not Samples 1 and 2 represent sands which do not heave. Samples 3 and 4 represent clays which do not heave Samples 5, 6 and 7 represent silts, and samples 8 and 9 represent clays which are known to heave in service

The sands which do not heave generally possess centrifuge moisture equivalents less than 12 The clays which heave possess relatively low plasticity indices and relatively high shrinkage limits Thus, for instance, samples 3 and 4, which do not heave, contain but 43 per cent of clay and possess plasticity indices equal to 40 and 38, and shrinkage limits equal to 12 and 17, respectively On the other hand, samples 8 and 9, which do heave, although containing over 60 per cent of clay, possess plasticity indices equal to but 8 and 18 and shrinkage limits equal to 30 and 37, respectively It is also interesting to note that sample

TABLE II

CONSTANTS POSSESSED BY MATERIAL PASSING THE NO 40 SIEVE

Sample number	Liquid limit	Plasticity index	Shrinkage		Moisture equivalent	
			Limit	Ratio	Centrifuge	Field
1	20	0			3	21
2	22	0			4	21
3	57	40	12	1 9	45*	28
4	63	38	17	1 8	60*	46
5	27	0	27	1 6	23	27
6	38	13	22	1 6	35	30
7	37	11	33	1 5	41	35
8	37	8	30	1 5	51*	32
9	45	18	37	1 4	54	37

* Waterlogged

TABLE III

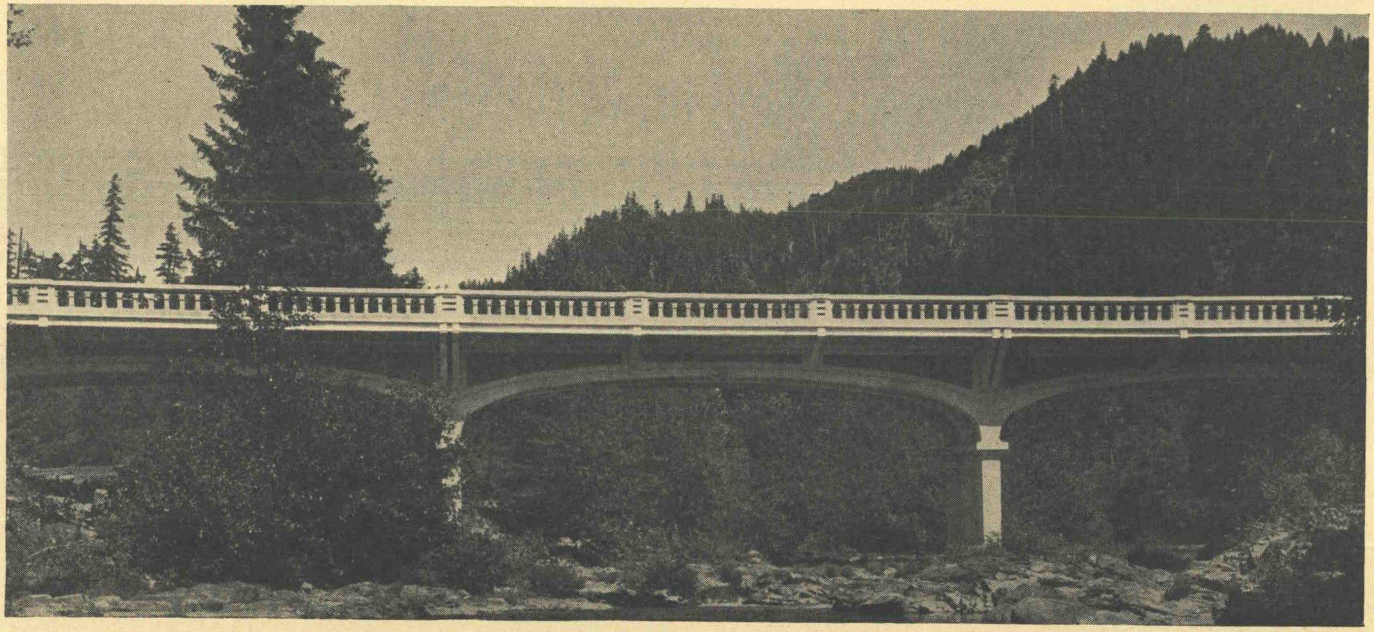
MECHANICAL ANALYSES

Sample number	Gravel particles larger than 2 0 mm	Coarse sand 2 0 to 0 25 mm	Fine sand 0 25 to 0 05 mm	Silt 0 05 to 0 005 mm	Clay below 0 005 mm	Colloids below 0 001 mm
	per cent	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
1	0	20	78	1	1	0
2	0	41	56	2	1	0
3	16	25	12	30	43	27
4	0	1	13	43	43	24
5	0	13	21	42	24	2
6	1	7	20	52	21	4
7	0	1	5	60	24	2
8	0	2	5	16	77	17
9	0	1	6	32	61	8

No 7, which only contains 24 per cent of clay, has constants similar in magnitude to those of sample No 8, which contains 77 per cent of clay

Investigations now being conducted indicate that frost heave is not likely to occur in the sandy soils which have centrifuge moisture equivalents less than 12 and which do not have plasticity nor in those clay soils which have liquid limits greater than 50 and whose plasticity indices are appreciably greater than the ratio $\frac{\text{Liquid limit}-14}{1\ 60}$ and whose shrinkage limits do not greatly exceed the ratio $21-1\ 1\sqrt{\text{Liquid limit}-\frac{(\text{Liquid limit})^2}{800}}$

These tentative values are presented with the hope of stimulating further research along this line When qualified by the proper factor of safety they may be used as a basis for the selection of material to be used as back fill where dangerous soils have been excavated. Thus, for instance, material possessing a centrifuge moisture equivalent of less than about 7 or 8 could be used without danger of important frost heave



View of a Three Span Multiple Elastic Frame, 200 Feet Total Length