Developments in Durability Testing of Soil-Cement Mixtures

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The conditions of soil-cement specimens during freeze-thaw and wet-dry tests were measured by several methods (weight loss, moisture gain, length change, compressive strength, pulse velocity and visual rating).

Results are analyzed to show: (1) a comparison of the efficiencies of the measuring techniques; (2) information, essential to the interpretation of data, on the effects of freezing-thawing and wetting-drying on soil-cement specimens; (3) an accumulation of sufficient data to indicate that the length change technique represents a superior, alternate method to the weight loss technique used in the standard freeze-thaw test (suggested length change criteria are well correlated with established weight loss criteria); and (4) a promising, but preliminary, correlation of an accelerated (5-day) freeze-thaw test to the standard freeze-thaw procedure.

Application of these results is indicated for improving the standard freeze-thaw and wet-dry procedures and in the analysis or development of other soil-cement testing procedures.

•ONE of the most important properties of soil-cement is that the stability of the material is retained over years of exposure to the destructive forces of weather. In this property lies the definition of the minimum quality of the material, the reason for its acceptance and widespread use and, pertinent to this discussion, the objectives of the mix design of the material.

The desire to obtain this property (whether it is termed retention of stability, long-term performance or, simply, durability) permeates the history and development (1) of soil-cement mix design procedures, specifically the standard (2) freeze-thaw and wet-dry tests and related criteria (3).

Recognizing that the investigation of durability is a major objective in soil-cement testing the Soil-Cement Laboratory of the Portland Cement Association has continued to study means of making the reliable standard procedures faster, more exact, and easier to use.

In this progress report, data from previous studies (4) on 4 soils are verified and amplified by similar investigations of 104 soils of various types, and the results of new studies are presented.

METHODS FOR MEASURING DETERIORATION IN FREEZE-THAW AND WET-DRY TESTS

In the development of environmental change testing procedures, a measure of the quality of the soil-cement specimens is required. The following is a discussion of some of the methods that have been used for soil-cement procedures. It is felt that the comments would apply not only for the standard freeze-thaw and

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wet-dry tests but for other types of environmental testing involving changes in moisture and temperature.

Three methods for measuring the resistance of cement-soil mixtures to wet-dry and freeze-thaw are specified in the standard procedures: weight loss, volume change and moisture gain. Others that have been studied are: length change, various measures of strength, pulse velocity and visual inspection. Each of these measures some property that reflects the quality of the cement-soil mixture. For some, the measurement may be more directly and sensitively related to deterioration. Therefore, it would be expected that, although all the methods may correlate for major differences in durability, minor differences might not be rated in the same order by all of the measures.

Before discussing the merits of each method, it is well to consider the objectives of the measurements. Retention of stability under the exposure conditions is the primary criterion. Therefore, the changes in values are of more concern than the absolute values. This is also true in concrete durability testing where criteria are based on changes in strength, changes in elastic properties or changes in shrinkage and expansion characteristics.

For soil-cement, Table 1 shows how each measure is related to various aspects of the condition of soil-cement specimens. Deterioration or loss in hardness is the condition to be measured. The other conditions, to the degree that they can be independent of the first condition, are extraneous and only mask the detection of deterioration.

TABLE 1

DEPENDENCE OF MEASURES ON THE CONDITIONS OF SPECIMENS

MEASURE	CONDITIONS[1] OF SPECIMENS			
	DETERIORATION (LOSS IN HARDNESS)	ABSOLUTE HARDNESS	SURFACE CONDITION (If different from overall condition)	SOIL TYPE
Final Weight Loss	x	x	x	x
Rate of Weight Loss	x x	x	x	x
Length Change (Volume Change)	x x	Independent	Almost Independent	Independent
Moisture Gain	x	Almost Independent	Almost Independent	x
Strength After Test (Absolute Value)	Independent	x x	Almost Independent	Independent
Strength Change (Loss during test)	x x	Almost Independent	Almost Independent	Independent
Pulse Velocity After Test (Absolute Value)	Independent	x x	Almost Independent	Independent
Pulse Velocity Change (Loss during test)	x x	Almost Independent	Almost Independent	Independent
Manual Inspection	Independent	x	x	Independent

Note: x - dependent, x x - greatly dependent

(1) Some of the conditions are obviously related. They are considered here separately only to the degree of independence with the first condition.

Some of the measures are expressed both as the absolute value and as the change in the value occurring during the test.

Weight Loss

This method (the manual brushing technique and the PCA weight loss criteria) has been the most extensively used procedure. It has been amply demonstrated that reliable results are obtained for all soil types. The absolute value of the final weight loss is strongly related to the degree of deterioration, but it is also dependent on the extraneous factors of absolute hardness, surface condition and soil type (Table 1). If a specimen were of unchanging hardness during the test and no deterioration occurred, a uniform rate of weight loss would be obtained. This rate would depend on the hardness of the specimen and the abrasive characteristics (soil type). It is well known that specimens passing the weight loss criteria may have large differences in hardness as measured by compressive strength. The abrasive variable is recognized in the three separate weight loss criteria for different soil types.

For some silty soils and fine sands, a surface scaling occurs in the freeze-thaw test which may complicate analysis of weight loss data. The degree of significance of this scaling to field performance is not fully established. The large surface-to-volume ratio of laboratory specimens would emphasize surface effects to a degree that may not be representative of the performance of pavements in service. Surface effects in concrete durability tests are not considered as necessarily reflecting the overall condition of the specimen.

The rate of weight loss is considered to be more dependent on deterioration and less dependent on the extraneous conditions (Table 1). Although the rate of weight loss is not specifically studied in this paper, it has been the general experience that increasing rates reflect deterioration.

Moisture Gain

The moisture gain technique specified in the standard procedures was not found to be a sensitive measure of deterioration for all soil types. The criterion of a moisture gain more than void accommodation at the time of molding reflects deterioration only in very advanced stages. Many specimens will fail weight loss criteria with moisture gains much less than that required for saturation. The moisture changes on freezing-thawing and wetting-drying are primarily a function of the capillary and permeability properties of the mixture.

In the freeze-thaw test, the capillary moisture gain is greatly influenced by soil type and to this extent moisture gains below the saturation limit are not necessarily indicative of deterioration.

In the wet-dry test, there is a progressive drying of most fine-textured mixtures that is independent of deterioration except in advanced stages.

However, deviations from moisture change patterns established by nondeteriorated specimens on a particular soil may indicate failure for specimens at lower cement contents even though a saturation limit is not reached.

Length Change (Volume Change)

The volume change technique specified in the standard procedures was found not to be a sensitive measure of deterioration for all soil types. The criterion of a 2 percent volume change reflected deterioration only in very advanced stages and many specimens fail weight loss criteria with much lower volume changes.

Recent studies measuring lengths with greater precision indicate that expansions of about 0.1 percent indicate failure for soil-cement specimens. This is the same value as the criteria (5) used in concrete durability testing.

Precise length change measurements are considered to be a very sensitive and direct measure of deterioration (Table 1). Studies with these measurements indicate that they are completely independent of absolute hardness, an extraneous factor. The amount of shrinkage on freezing or drying depends mostly on soil type and slightly on cement content. Variations in moisture content during the tests will also affect the degree of shrinkage or expansion. However, the expansions that accompany deterioration are of sufficient magnitude that they are not masked by effects of soil type, cement content or moisture content.

The direct relation of length change to deterioration is well established in concrete freeze-thaw tests. Other deteriorating effects such as sulfate attack, alkali reactivity, and distress due to differential thermal coefficients are also readily detected by length change measurements.

Strength Measurements

Because of the variation in soils' reactions with cement, it is not thought possible to set a single-valued strength criterion that will insure durability for all soil types. The change in strength, rather than the absolute value at start or end of a durability test, is the measure of deterioration.

For compressive strengths after periods of continuous moist-curing, about a 10 percent variation in accuracy is expected on single determinations. Variations are even greater on specimens after freeze-thaw or wet-dry tests. These variations indicate that replication of specimens may be required to develop or accurately apply compressive strength change criteria.

For concrete specimens, effects of freezing on compressive strengths are strongly influenced by the aggregates and the strengths are less sensitive to changes in the paste (5). There is some evidence that this may be true for soil-cement. Compressive strengths may not be detecting minute cracks or localized weaknesses. It is therefore felt, but not examined, that tensile or flexural tests might more sensitively detect deterioration in durability testing.

All things considered strength change testing, with adequate replication, is considered to be a direct measure of deterioration not significantly dependent on the extraneous factors.

Sonic Methods

Most of the previous comments for strength testing also apply to measures of the pulse velocity by the soniscope. Pulse velocities are basically related to the density of a material. However, for any given soil the density of cement-soil mixtures varies only slightly and therefore, the pulse velocity is related to the strength of the mixture. Examples of the relations are shown for one soil (see Fig. 7); additional data are presented in a previous study (4).

Pulse velocity is not thought to be significantly affected by the extraneous variables (Table 1). Although gross deterioration is reflected in major decreases in velocity, there are qualifications which may preclude the use for sensitive and accurate detection of deterioration. The sound pulse selects the best path through the specimen and may not indicate the overall condition. Furthermore, there are large experimental variations in velocities between replicate specimens and between repeated measurements on single specimens.

It seems likely that measurements of resonant frequency by sonic methods, although not examined in this study, might be a sensitive detector of deterioration for soil-cement durability tests. For concrete freeze-thaw tests, there is a close correlation of resonant frequency and expansion in measuring deterioration. The standard size soil-cement specimen would have to be modified to obtain a greater length to diameter (or width) ratio suitable for the sonic test.

EFFECTS OF FREEZING AND THAWING ON SOIL-CEMENT SPECIMENS

The following effects of freezing and thawing were measured under the standard freeze-thaw test conditions unless otherwise noted. Details of the measuring techniques are given in the Appendix.

Length and Moisture Changes

The normal pattern of length changes for undeteriorated soil-cement specimens is shown in Figure 1. The degree of shrinkage on freezing depends primarily on soil type and especially on the silt and clay content. On thawing, specimens expand back towards the original length but never significantly exceed the original length (unless considerable moisture is absorbed in the thawing process). This constant pattern of length changes continues throughout successive freeze-thaw cycles a gradual rise occurs in the pattern, however the relative amount of shrinkage and expansion (the amplitude) remains about the same.

The effect of soil type on length change is indicated in Figure 2. Shrinkages on freezing vary from 0.05 percent for soils of AASHO Classifications A-1, A-2 and A-3 up to 0.60 percent for soils of the A-7 classification. For each soil group there is considerable variation from the average shrinkage.

These observations are made for undeteriorated specimens only. When deterioration starts there is a rise in the volume change pattern (Fig. 3). The envelope of frozen lengths usually starts to rise first, showing successive reductions in shrinkages on freezing. The thaw envelope also rises but to a lesser degree. As deterioration progresses both the thawed lengths and the frozen lengths exceed the original length. At severe deterioration the freeze envelope rises above the thaw envelope, i.e., expansion on freezing, shrinkage on thawing. Several characteristics of the pattern are suggested as detectors of deterioration: (a) expansion on thawing above original length or above first thaw length, (b) expansion on freezing above original length or above first freeze length, (c) progressive reduction in the magnitude of shrinkage on freezing, and (d) expansion on freezing. It is indicated that only two measurements, one at the start of a freeze-thaw test and one at the end, may be required to detect deterioration.

The shrinkage of soil-cement specimens containing appreciable fines is much greater than that which can be explained by thermal effects. Thermal coefficients for soil-cement range from 4 to 7 μ-in./in./° F. It is presumed that this extra shrinkage is caused by a redistribution of the water in the specimen similar to mechanisms that occur in concrete as reported by Powers (6). That is, the unfrozen water in the fine fraction of the mixture is migrating toward the ice being formed in larger void spaces, in effect drying the fine fraction. An example of the amount of shrinkage attributed to drying of the fines can be ascertained by comparing the shrinkage of moist specimens to those of dry specimens (Fig. 4). Inasmuch as drying shrinkage depends on the amount of fines, this mechanism is accepted as explaining the direct relation of increasing freezing shrinkages with increasing silt-clay contents.

This introduces the possibilities of failure mechanisms other than the growth of ice crystals. For soil-cement, as in concrete, hydraulic pressures may contribute to deterioration. The differential

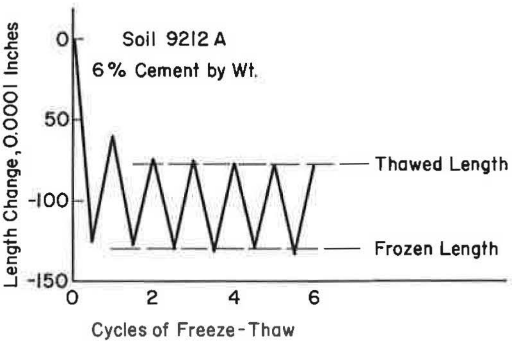

Figure 1. Length changes during freeze-thaw test.

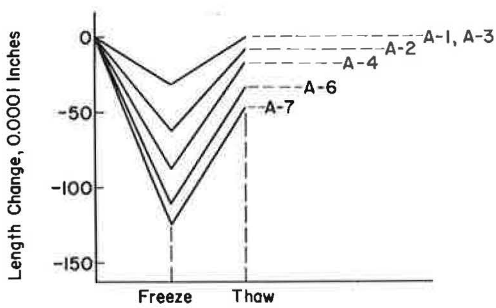

Figure 2. Effect of soil type on length changes during freeze-thaw test.

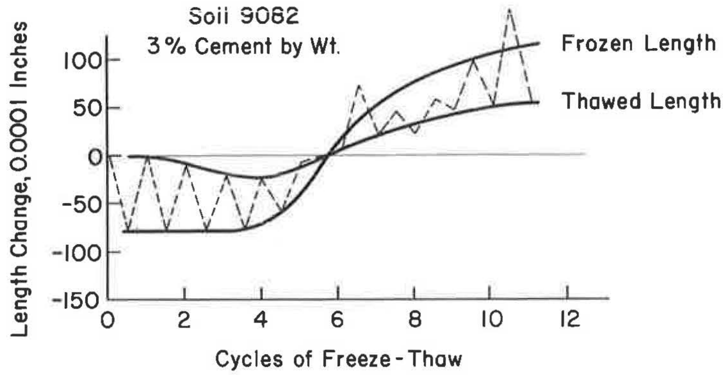

Figure 3. Length changes for deteriorating specimen in freeze-thaw test.

volume change mechanism is presumed to have a greater effect on soil-cement than it does on concrete. This seems logical in view of (a) the greater freezing shrinkages obtained for soil-cement, which depending on soil type, may be several times that of concrete, and (b) the likelihood of having wider differences in the volume change properties of the different soil constituents than for concrete aggregates.

A study of the pattern of length changes on several cycles of freezing and thawing indicates that the initial weakening is not necessarily caused by the ice growth mechanism. In many cases, specimens will maintain a constant pattern of shrinkage and expansion through several cycles of freezing and thawing and then start expanding abruptly (Fig. 3). If the specimens had absorbed additional water the abrupt failure could possibly be explained by the critical saturation concept (6). However, additional moisture was not absorbed. If ice growth damaged the specimen in the first cycle then progressive damage would follow in subsequent cycles and result in a rising pattern of length changes from the start. It is presumed that during the cycles of the constant length change pattern, other mechanisms such as volume changes or hydraulic pres-

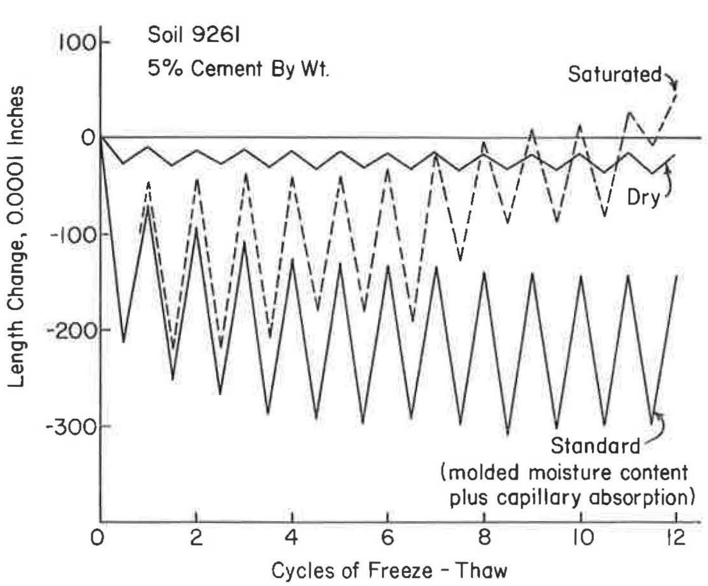

Figure 4. Effect of moisture condition in freeze-thaw test.

sures may gradually break down sufficient bonds of cementation. Between the condition of the steady length change pattern and the severe condition of expansion on freeze it is thought that ice growth becomes the predominant failure mechanism only after the material is weakened by other mechanisms.

Thus, for all soils except those completely devoid of fines, the standard freeze-thaw test measures the deteriorating effects of drying shrinkage.

A mechanism of failure that is discounted for most materials is the failure of the aggregate particles. Even though the plus No. 4 sieve material is saturated at the time of molding, observation of failed specimens indicates that the aggregate particles are not broken. Failure occurs in the matrix between the aggregate particles. An exception to this is made for soft or unstable aggregates such as shales.

Records of the weights of specimens during freezing and thawing indicate that the 25 to 35 percent voids in soil-cement specimens are not completely filled with water; there is from 5 to 10 percent air in the specimens and this air-water-solids proportion does not change during the freeze-thaw test for most soils. Failure of specimens in the standard freeze-thaw test does not depend on the absorption of additional water. On the other hand, specimens of A-4 soils absorb considerable water in the test regardless of their hardness or state of quality. Of course, the absorption of water in itself produces a greater susceptibility to frost damage in the case of silts leading sometimes to a higher cement requirement than that for clay soils.

Undeteriorated specimens of A-1 and A-2 soils on the average gain little moisture, if any, during the test; extremes up to 2 percent by dry weight have been absorbed by some specimens. A-3 soils also usually gain very little but extremes can run up to 4.0 percent for very fine sands. Specimens of A-4 soils usually pick up considerable moisture, from 3 to 5 percent, with extremes of poorly-graded silts gaining 7 percent moisture, just short of saturation. A-6 soils absorb only a small amount of moisture, extremes up to 3 percent.

Scaling of some silt and fine sand specimens is associated with large moisture gains. In this study, all specimens that scaled had previously absorbed at least 4 percent additional moisture. Specimens of the same soils at higher cement contents also absorbed large amounts of moisture but did not scale.

Experiments with soil-cement specimens subjected to concrete freeze-thaw tests (freeze and thaw in water) show that the saturated condition is much more severe than the unsaturated condition used in the standard soil-cement freeze thaw test. Figure 4 shows length changes for freeze-thaw cycles conducted under three moisture conditions: saturation (immersion in water before test and during thaw cycles), the standard method (water absorbed through a felt pad), and completely dry. It is obvious that a much greater cement content would be required to resist the freeze-thaw test at saturation.

Therefore, the severity of a particular freeze-thaw test depends largely on the moisture conditions prevailing in the procedure. Since the moisture content in road bases is usually less than saturation a test condition of saturation is unrepresentatively severe. The capillary absorption condition used in the standard test seems more rational since it permits an absorption that will be determined by the natural capillarity and permeability properties of the soil-cement.

Strength Changes

During the 12 thaw periods of the standard freeze-thaw test there is an opportunity for a strength gain equivalent to about 10 days of additional moist-curing. Figure 5 shows the strength gain during the standard test. Curve 1 represents the strength gain during continuous moist-curing conditions. The maximum values of strength possible for undamaged specimens are represented by curve 2 which terminates at a strength equivalent to 17 days of continuous moist cure. Curve 3 represents the strengths of a specimen slightly damaged by freezing and thawing within the limits permitted by weight loss criteria. Thus, for specimens passing the weight loss criteria it is expected that strengths-after-test will exceed the 7-day strengths by an amount that is in proportion to the increase in strength due to an additional 10 days of moist-curing. Failing specimens may have strengths below curve 3 and yet exceeding the 7-day value while badly deteriorated specimens would have strengths-after-test below the 7-day value.

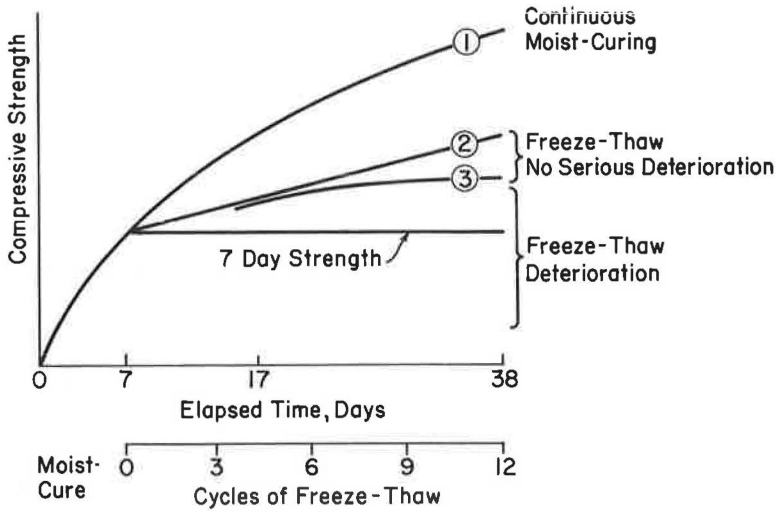

Figure 5. Strength gain during freeze-thaw test.

EFFECTS OF WETTING AND DRYING ON SOIL-CEMENT MIXTURES

An earlier study (4) reported results of weight losses, moisture changes, compressive strength changes and pulse velocity changes during the standard wet-dry tests on four soils. Further examination of the effects of wetting and drying may be of value in two applications: (a) to determine if a more sensitive and direct measure of deterioration can be developed for the standard wet-dry test, and (b) to evaluate the conditions of the test when it is used alone (with no freeze-thaw test) as a durability test for mild climates. The critical evaluation of the standard wet-dry test and suggestions for modification refer to the second application only.

Length changes in the standard wet-dry test depend on soil type. Shrinkages on the first drying vary from 0.05 percent for granular soil-cements to 1.00 percent for clayey soil-cements. For any given soil the first drying shrinkage is roughly twice the freezing shrinkage occurring in the freeze-thaw test. Subsequent length changes on wetting and drying are usually less than length changes in the freeze-thaw test.

The pattern of length changes for undeteriorated specimens is fairly constant (Fig. 6). For deteriorated specimens there is a definite rise in the length change pattern.

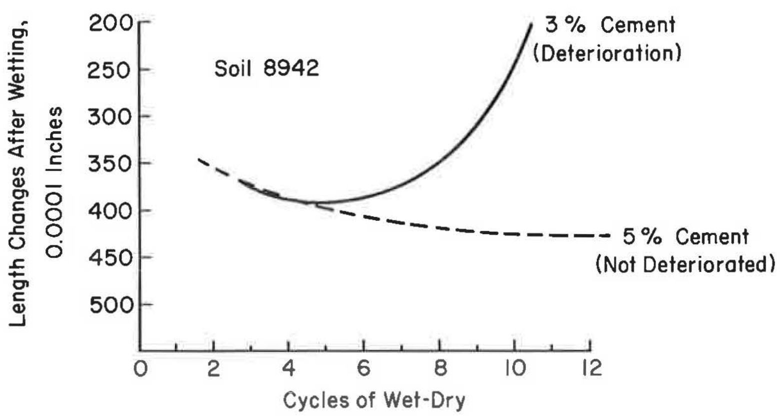

Figure 6. Length changes during wet-dry test (wet lengths only).

Additional studies are required to determine if a length change criteria can be developed to correlate with weight loss criteria in the standard wet-dry test.

The moisture contents of specimens in the wet-dry test also depend on soil type. On drying, moisture contents vary from about 2 to 6 percent moisture, the dryer for soils containing less clay. On wetting, the moisture contents vary from the saturated moisture content to several percentage points below the molded moisture content, the wetter for soils containing less clay. In additional experiments with soil-cement specimens of heavy clay soils, weights on wetting and drying indicate that the specimens are progressively dried in the standard test. In the latter cycles the specimens do not absorb sufficient water to test their great volume change properties. On examination of some of these specimens after wetting it was observed that water had penetrated only into the outside ³⁄₈ in. of surface.

Results of the earlier study show that the 160 F oven-drying condition used in the standard test causes an accelerated strength gain. This may unduly benefit specimens that might not otherwise pass the wet-dry test. The strength data for specimens of 14 soils at a range of cement contents are summarized in Table 2. Additional data (Table 3, Appendix) show the magnitude of the strength gains in the wet-dry test.

In a separate experiment the 160 F ovendrying condition was replaced by 73 F air-drying. Weight losses, length changes, compressive strengths and pulse velocities were measured on specimens of a gravelly loamy sand. Results of all the measures showed that the 73 F drying condition was more severe than the standard 160 F drying condition.

In the development (1) of the standard testing procedures the possibility of an accelerated strength gain due to the high temperature in the wet-dry test was recognized. This is one of the reasons that the two procedures, the freeze-thaw test and the wet-dry test, were selected to be used together to measure the properties of soil-cement mixtures.

Another effect of the 160 F drying condition is shown in Figure 7. The relation between compressive strengths and pulse velocities is considerably different after the wet-dry test (160 F) from the relation after other environmental conditions (73 F) of continuous moist-curing of freeze-thaw cycles. After the wet-dry test, the pulse velocities decrease appreciably (compared to the pulse velocity at start of test) even though the compressive strengths have increased. Apparently, the high temperature has modified the structure or composition of the soil-cement. A possible, but unsupported, explanation is that the high temperature has caused minute cracking that does not affect compressive strength but greatly reduces pulse velocity.

The volume changes of specimens are also affected by the high temperature. On drying, the drying shrinkage is counteracted by the thermal expansion of heating to 160 F; and on wetting, the expansion due to wetting is counteracted by the cooling to room temperature. This counteraction is shown in Figure 8 where the thermal effect is greater than the moisture effect for specimens of a gravelly loamy sand. For different soil types it is estimated that the thermal effect cancels from 16 percent (for clayey soil-cement) to 100 percent (for soils containing 10 percent clay or less) of the length changes due to wetting and drying.

TABLE 2

SUMMARY OF STRENGTH GAINS IN WET-DRY TEST

Strength after wet-dry test				Weight Loss in wet-dry test, per cent	
per cent of 7 day strength					
average	extremes	average	extremes	average	extremes
240	160-420	160	101-290	11	1-57

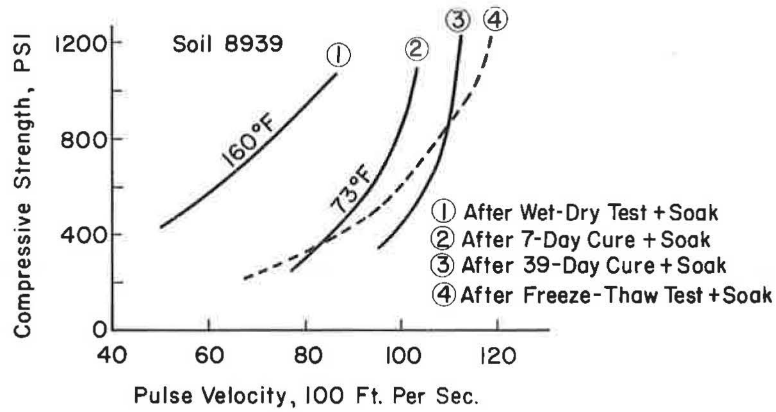

Figure 7. Relation of compressive strength to pulse velocity, different environmental conditions.

The significance of these effects of the temperature and moisture conditions must be considered if only the standard wet-dry test is to be used in the development of procedures for mild climates. For such use, not the intention of the original development of the standard procedure, several modifications of the conditions used in the standard wet-dry test are suggested. First, and most important, it is suggested that the 160 F ovendrying condition be replaced by air-drying at room temperature or at a temperature not exceeding the extremes of natural conditions. This would reduce the previously discussed accelerated strength gains, changes in structure of material and counteraction of volume changes by thermal effects. Second, it is suggested that a greater degree of wetting and a lesser degree of drying would be more representative of natural conditions. This would eliminate the progressive drying and small moisture changes obtained with heavy clay soil-cement. It is felt that this could be accomplished in the same or less time than that required for the standard cycle by use of a deep soaking tank to accelerate wetting, and by use of a shorter drying period.

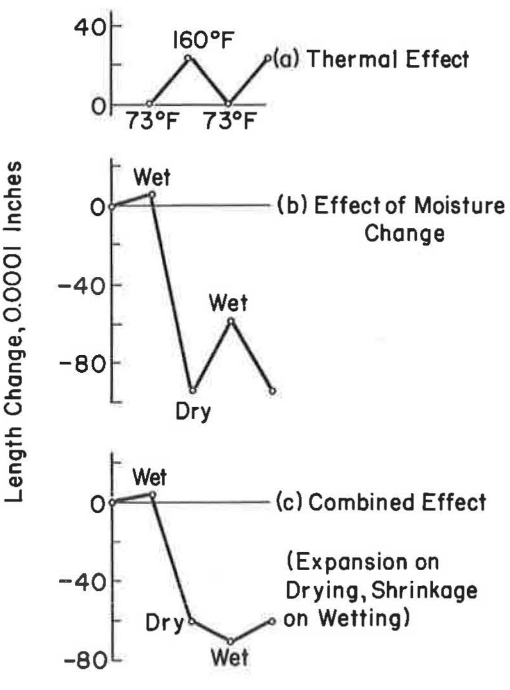

Figure 8. Effects of temperature and moisture changes on lengths of specimens in wet-dry test (soil 9328 - gravelly loamy coarse sand).

CORRELATION OF LENGTH CHANGE, WEIGHT LOSS AND COMPRESSIVE STRENGTH DATA IN THE STANDARD FREEZE-THAW TEST

Weight losses, moisture gains, length changes, compressive strengths and condition by manual inspection were recorded during standard freeze-thaw tests on 235 specimens molded of 86 soils. Measuring techniques are described in the Appendix and results are given in Table 4.

An attempt was made to correlate results from the various measures to indicate if the specimens had passed or failed the test as primarily defined by weight loss criteria. Best agreement was found by using the following limits of test values of the various measures:

1. Weight Loss.—PCA criteria of maximum weight loss of 14 percent, 10 percent or 7 percent depending on soil classification.
2. Length Change.—Twelfth cycle frozen length not exceeding first cycle frozen length by 0.0050 in. (The other changes in the length change pattern discussed previously may be equally effective in detecting deterioration.)
3. Compressive Strength.—When strengths-after-test are 145 percent or more of the 7-day values the specimens always pass the test; when strengths-after-test are less than 90 percent of the 7-day value the specimens always fail the test; strengths between 90 and 145 percent of the 7-day value may occur for failed or passed specimens with increased probability of passing as the upper limit is approached.
4. Condition of Specimens by Inspection After Test.—A minimum condition of "fair to O.K." as defined by arbitrary ratings is usually required for passing the test.

The results are discussed primarily as comparisons of length change data and weight loss data because the former is considered to be the most accurate and sensitive detector of deterioration, and the latter is considered to give the cement requirement best correlated to field performance.

Expansions and weight losses are in exact agreement as to whether the specimens passed or failed the test in 205 out of 235 cases (87 percent). They are in slight disagreement in 21 cases (9 percent) and in serious disagreement in 9 cases (4 percent). The cases of exact agreement are shown in Figure 9 and cases of slight and serious disagreement in Figure 10. Strength-after-test data are also indicated as additional evidence of failure or passing.

Data in Figure 9 establish the significance of the strength-after-test data. For all the points in the lower left quadrant, expansions and losses agree that the specimens passed the test. For all the points in the upper right quadrant, expansions and losses agree that the specimens failed the test. Major strength increases indicated by the "x" and "o" points, fall into the proper quadrant with only five exceptions. Thus, expansions and losses are in 100 percent agreement. For these data, strength data corroborate in 93 percent of the cases.

In Figure 10, expansions and losses are in slight or serious disagreement. In all cases strength data agree with the expansion data, disagreeing with weight loss data, as to whether the specimen has failed or passed.

For most of the cases where excessive losses occurred without serious expansion, the losses were affected by scaling of the specimens. These are indicated in the upper left quadrant by squares.

Figure 11 illustrates a consideration for points in the lower right quadrant of Fig. 10. In some cases where expansion did not start until the latter cycles the test was continued past 12 cycles. Weight losses then increased beyond that allowed by criteria showing the deterioration measured by expansion a few cycles earlier.

The particular expansion value shown in these plots is considered to be in the correct range but not as a final criterion to be adopted without more development. Thus, close agreement between expansion and weight loss data was obtained in 96 percent of the cases, strengths corroborating. For the few cases of disagreement between expansion and weight loss data, consideration of strength data, delayed weight losses and instances of scaling validate the expansion data. For all cases, there is strong evidence that length changes are more sensitive, accurate and immediate in detecting deterioration.

Due to the demonstrated efficiency of length change measurements in the standard freeze-thaw test the technique is recommended for: the development of modifications or accelerations of the standard procedures, the development of durability tests for specific climate areas, or the comparison of the severity of different durability tests.

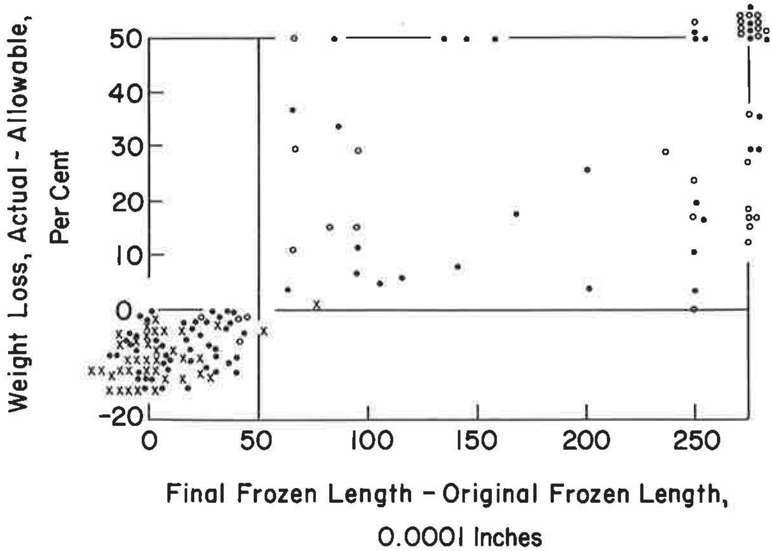

Figure 9. Correlation of measures in freeze-thaw test, agreeing cases— x = strength-after-test more than 145 percent of 7-day strength; o = strength-after-test less than 90 percent of 7-day strength; • = strength between above limits or incomplete data.

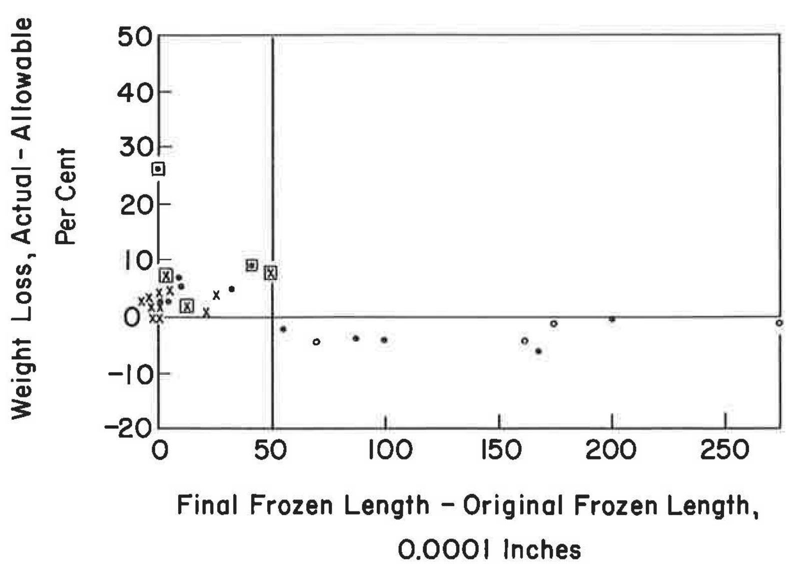

Figure 10. Correlation of measures in freeze-thaw test, disagreeing cases— x = strength-after-test more than 145 percent of 7-day strength; o = strength-after-test less than 90 percent of 7-day strength; • = strength between above limits or incomplete data.

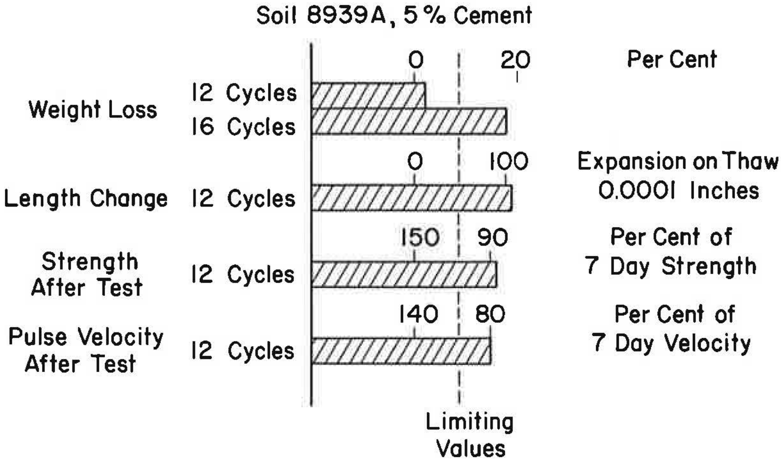

Figure 11. Comparison of freeze-thaw results by four measures.

ACCELERATED PROCEDURE FOR FREEZE-THAW TESTING

It is well established that the standard ASTM freeze-thaw test procedure and the related PCA criteria determine a cement content that will produce a durable construction material. However, the fact that the standard test requires from 6 to 7 weeks to complete restricts its use in some instances.

It is not intended to establish a new and independent method of determining the cement requirement for soil-cement mixtures. It is intended, rather, that the accelerated procedure would result in a cement requirement equal to that obtained from the standard procedure.

In the 24-hr thaw periods of the standard test only 8 hours are required for thawing and for a rise of specimen temperature (interior) to room temperature; the other 16 hours represent additional moist-curing.

In the 24-hr freeze periods, 8 hours at the most are required to bring the specimen temperature (interior) to -10 F. During the other 16 hours it is presumed that no significant damage is effected in this closed system of freezing (additional water not available).

Thus, of the 24 working days required for 12 cycles of the test, there is a period equivalent to 16 days that might be eliminated without defeating the objectives of the test.

Reduction in the length of thaw periods would result in changes in the interpretation of results from various measures of the quality of specimens. Strengths would be lower in an accelerated test because there is less moist-curing time. Weight losses in the accelerated test would be greater, with an equal amount of brushing, than those in the standard test since the specimens cannot gain as much strength. Moisture gains would be lower because there is less time available for absorption; however, this would be significant only for those few soils that absorb appreciable moisture in the standard test. On the other hand, it is thought that interpretation of length change data would be almost the same as in the standard test.

The effect of rate of cooling, in addition to the effect of shorter thaw periods, was considered important. It was decided not to exceed the rate of cooling (10° F. per hr) of the freezer used for the standard test, especially since an increased rate might alter the failure mechanism as it does in concrete freeze-thaw testing (6).

It was desired to select an accelerated freeze-thaw cycle whose severity did not greatly exceed the standard cycle. The cycle selected, after preliminary studies with several variations of freeze-thaw temperatures and durations, is shown in Figure 12 and compared to the time-temperature used with standard tests.

The equipment for automatic freezing and thawing is shown in Figure 13. Its essential components are: a copper-lined cabinet insulated with styrofoam, a ⅓-hp condenser with reverse cycle controlled by solenoid actuated valves, 60 ft of ⅜-in. copper tubing coiled in the sides and bottom of the cabinet, an air-circulating fan and an adjustable,

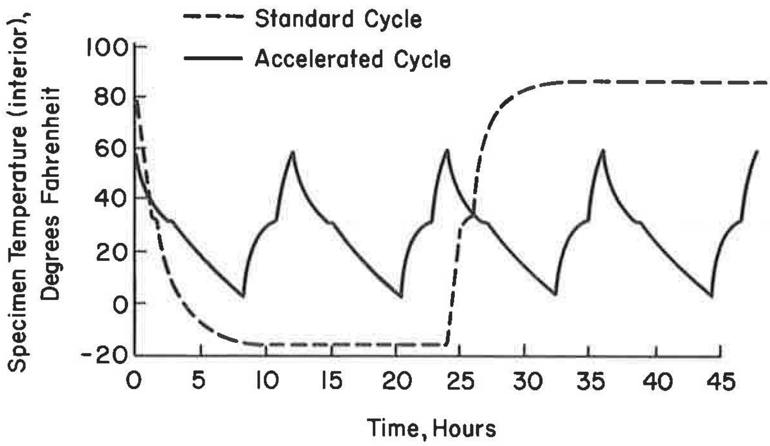

Figure 12. Time-temperature cycles for freeze-thaw test, standard and accelerated.

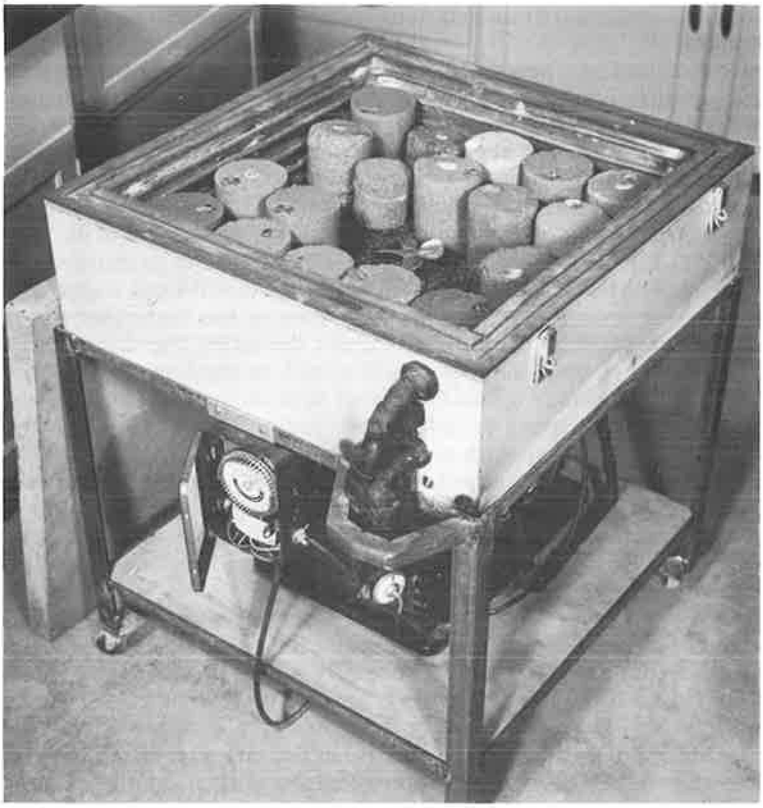

Figure 13. Automatic freeze-thaw equipment used in accelerated tests.

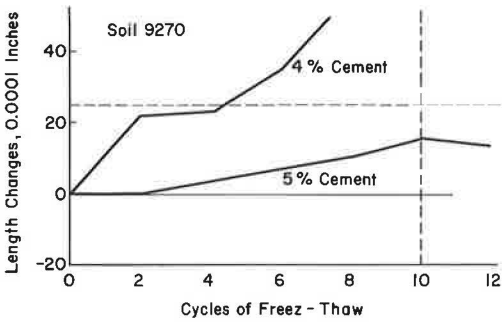

Figure 14. Length changes in accelerated freeze-thaw cycles (thawed lengths only).

electric time switch. The cabinet has a capacity for 24 specimens; dummy specimens were used when required to keep the freezing load constant.

Standard size specimens molded from 20 soils were subjected to the accelerated test after a 7-day moist-curing period. Sixteen cycles were conducted at a rate of 2 cycles per day, four times faster than the standard rate. During the test the specimens were kept on a water-saturated felt pad.

Data on length changes, compressive strength, and weight losses were recorded on replicate specimens during the test (Table 5, Appendix). These data were studied to define a limiting value at a particular cycle that would consistently give the same cement requirement already determined by standard procedures.

Figure 14 shows typical length change data for the accelerated cycles. Specimens at the cement content (5 percent by weight) required to pass the standard test exhibited only slight expansions. Specimens with less cement expanded considerably. (Expansion values in this section are changes in the thawed lengths computed from either the original length or the first measure thaw length, whichever gives the greater value.)

The accuracies of six limiting expansion values in giving the standard cement requirements are compared in Figure 15. An expansion value of 0.0025 in. after 10 cycles of testing was selected as the most suitable. Consideration was given to the selection of a minimum number of unsafe cases, i.e., cement requirements from the accelerated test less than that for the standard test.

Compressive strength tests were performed on specimens at three stages of testing; before starting the freeze-thaw (at 7 days' moist cure), during the test after either 6 or 8 cycles, and at the completion of the test which was usually at 16 cycles but sometimes at 12 cycles. An exact trend of strength changes differentiating between failed and passed specimens was not established. However, the 6-, 8-, 12- or 16-cycle strengths

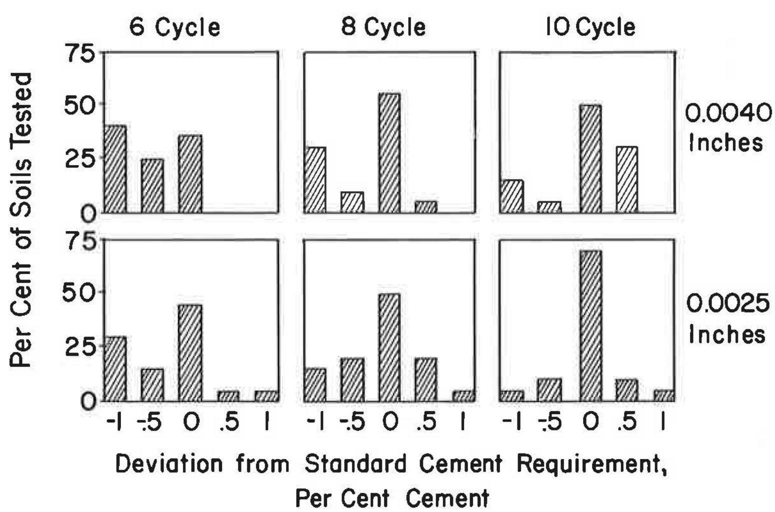

Figure 15. Accuracies of 6 limiting expansion values in accelerated freeze-thaw test, expressed as deviation in cement requirements (accelerated — standard).

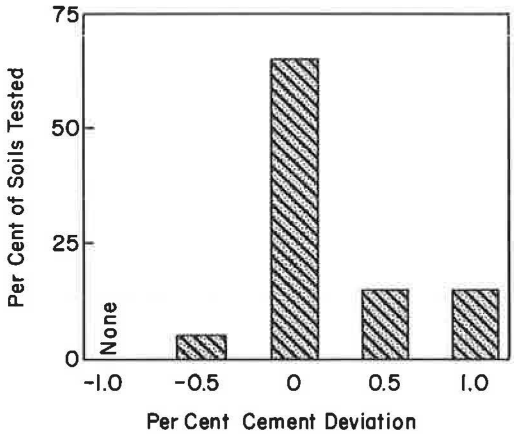

Figure 16. Accuracy of dual limiting values in accelerated freeze-thaw test, expressed as deviation in cement requirements (accelerated — standard).

of specimens with adequate cement contents exceeded 75 percent of the 7-day strength value with few exceptions.

Weight loss data are also given in Table 5. Due to the automatic cycling, brushing of specimens could only be performed on alternate cycles on weekdays and not at all on weekends. In view of the variations inherent in this procedure, no analysis of weight loss data was made.

The best correlation to the cement requirements of the standard procedure was found by applying dual limiting values: a limiting expansion value of 0.0025 in. at 10 cycles and a 10-cycle compressive strength greater than 75 percent of the 7-day value. With these limiting values the cement requirement by the accelerated procedure was the same or up to 1 percent cement greater than the standard requirement for 19 of the 20 soils tested. For one soil the accelerated requirement was 0.5 percent cement less than the standard requirement. The distribution of these deviations is shown in Figure 16.

Within the limited scope of this study there is a promising indication that a greatly accelerated freeze-thaw procedure can be developed to determine the same cement contents as required by the standard freeze-thaw test. However, these results are definitely exploratory and the testing of a great quantity and variety of soils is needed to develop fully a completely reliable accelerated method. Further studies are contemplated and will include more soils, different time-temperature cycles and attempts to develop criteria based on a single measuring technique.

SUMMARY

Methods for Measuring Deterioration in Freeze-Thaw and Wet-Dry Tests

Several methods (weight loss, volume change, moisture gain, length change, strength, sonic methods and visual inspection) were discussed relative to the degree of their direct relation to deterioration. Of these methods, four are judged as primarily measuring deterioration and relatively free of extraneous influences: length change, strength change, rate of weight loss and pulse velocity change. The length change method is superior in immediate sensitivity and accuracy in detecting deterioration.

It is emphasized that in the development of criteria for any of these measures, correlation to weight loss results and weight loss criteria will insure a tie-in to long-term field performance.

Effects of Freezing and Thawing on Soil-Cement Specimens

Data were presented to show that the initial volume (length) and moisture change characteristics of specimens on freezing and thawing depend primarily on soil type and, only to a limited extent, on cement content.

When deterioration occurs volume changes become abnormal (expansion), whereas the moisture change characteristics may not be immediately affected.

In the standard freeze-thaw test there is evidence that ice growth becomes a failure mechanism only after the material is weakened by other forces such as hydraulic pressures and absolute or differential volume changes. It is indicated that failure occurs when sufficient bonds of cementation are broken in the matrix between particles and, for most materials, that failure does not occur by disruption of the saturated aggregate particles.

For all but the very clean soils results show a degree of volume change, increasing with the amount of fine particles in the soil, that cannot be assigned to thermal effects alone. Similar to mechanisms in concrete, and more pronounced, these volume changes are attributed to the dessication of the fines on freezing.

Comparison of the results of two experimental freeze-thaw tests (one with dry specimens and one with saturated specimens) with the results of the standard test (moisture content depending on capillary absorption) indicates the great influence of the moisture conditions used in a freeze-thaw test.

The effect of freezing and thawing on the compressive strengths of specimens is considered essential to the interpretation of strength-after-test data in the standard test.

Effects of Wetting and Drying on Soil-Cement Specimens

The initial volume (length) and moisture change characteristics of specimens on wetting and drying are shown to depend primarily on soil type and, only to a limited extent, on cement content. When deterioration occurs volume changes become abnormal (expansion), whereas the moisture change characteristics may not be immediately affected.

Effects of the high temperature used in the standard wet-dry test are apparent in three manifestations: an accelerated strength gain, a counteraction of the volume changes due to moisture changes by thermal effects and a possible alteration of the structure of the material. Experimental wet-dry tests (drying at 73 F) were more severe than the standard test (drying at 160 F).

Knowledge of these effects is essential to the interpretation of volume change, moisture change and compressive strength data in the standard wet-dry test.

(Because of these effects the standard wet-dry test is not considered suitable for use alone as a procedure for non-frost areas. For this purpose modifications in the moisture and temperature conditions are suggested that are more representative of natural conditions. These modifications may serve better as a basic procedure on which to develop criteria related to long-term field performance in non-frost areas.)

Correlation of Length Change, Weight Loss and Compressive Strength Data in the Standard Freeze-Thaw Test

A close correlation was obtained between weight loss and length change data for 235 specimens molded of 86 soils. In 96 percent of the cases, expansions of 0.1 percent served to correlate with PCA weight loss criteria to indicate failure of the test specimens. In the few cases of disagreement between length change and weight loss data there is substantial evidence that the length change data are more sensitive.

A general, but not exact, correlation was established for compressive strength data.

It is suggested that sufficient data have been accumulated on a wide range of soil types to show that the length change method represents an improved, alternate technique to the brushing procedure used in the standard freeze-thaw test.

Accelerated Procedure for Freeze-Thaw Testing

Parallel tests, with standard freeze-thaw cycles and accelerated freeze-thaw cycles, were conducted on specimens molded from 20 soils. An automatic freeze-thaw cabinet was used for the accelerated cycles. Length changes, compressive strengths, weights and moisture contents were recorded to measure the quality of the specimens. These data were analyzed in an attempt to correlate results of the accelerated procedure to give the same cement requirement as determined by the standard procedure. A fair correlation was obtained with length change and strength data.

The promising indications that an accelerated test, correlated to the standard test, can be performed in 5 days are considered exploratory and in need of verification with a large number of soils of varied types.

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Appendix

TESTING PROCEDURES, MEASURING TECHNIQUES AND MATERIALS

Standard size specimens, 4.0-in. diameter by 4.6-in. height were molded at optimum moisture and maximum density as determined by the standard procedure, ASTM Desigation: D 558-57. Specimens were molded at a range of cement contents above and below the cement requirement determined by the standard freeze-thaw test and PCA weight loss criteria. These were moist-cured for 7 days before freeze-thaw and wet-dry tests.

The freeze-thaw and wet-dry tests were conducted on specimens that were brushed using the standard brushing procedures and on companion specimens that were not brushed but used for length and compressive strength measurements.

Weights of all specimens were periodically recorded during these tests so that weight losses and moisture changes could be computed.

Length measurements at each environmental change were made on unbrushed specimens. During the moist-curing period copper washers (No. 9 rivet burrs) were cemented as reference points to the top and bottom of each specimen. The mixture used for attaching reference points was prepared as follows: Polyester Selectron 5119 (Pittsburgh Plate Glass) and silica flour were mixed to the consistency of a heavy syrup; to this was added an accelerator, MEK Peroxide (American Resin Corp.) at the rate of 1 drop per gram. Lengths were measured in a length comparator equipped with a dial gage graduated to 0.0001 in. The first (reference) length was measured at the end of the 7-day curing period.

Compressive strengths were determined after certain periods of moist-curing, at certain cycles of the freeze-thaw and wet-dry test and at the end of these tests. In all cases the specimens were soaked for 4 hours before being capped and broken.

Pulse velocities by soniscope were determined on some of the specimens during and after the tests. Velocities reported here were determined on specimens that had been soaked for 4 hours.

In the current studies of length changes, strength changes and pulse velocities, specimens of 104 soils were investigated. These soils represent a wide range of soil types from most of the states. General comments on strengths and durabilities are based on standard soil-cement tests on hundreds of soils.

The Type I portland cement was a blend of four commercial brands purchased in the Chicago area.

Tabulation of Results

Tables 3, 4 and 5 list the essential portion of raw data on weight losses, length changes, and compressive strengths obtained in the standard freeze-thaw test, the accelerated freeze-thaw test and the standard wet-dry test.

TABLE 3

RESULTS OF WET-DRY TESTS

Weight Losses and Compressive Strengths

Soil No.	Cement content, per cent by weight	Weight loss, per cent	Compressive Strength, psi 7 day	28 day	After Wet-Dry test
S-1	3	17	248	334	450
	5	4	385	637	950
	7	2	595	809	1400
SD-20	3	7	302	376	585
	5	4	458	650	1000
	7	1	602	820	1180
SD-35	3	12	248	310	600
	5	5	357	510	940
	7	3	372	650	1550
SD-40	3	12	283	375	540
	5	6	398	540	950
	7	3	372	590	1300
SD-45	3	20	274	340	585
	5	6	293	445	1050
	7	2	414	585	1420
MC-1	3	10	137	155	280
	5	4	210	250	610
	7	3	255	300	875
MC-2	3	20	220	280	440
	5	9	360	530	900
	7	4	400	740	1270
MC-3	3	15	250	360	560
	5	6	360	560	860
	7	3	515	790	1265
FS	7	32	137	261	280
	9	11	220	366	480
	11	7	254	537	540
FS-8	4	57	86	145	230
	6	20	172	251	388
	8	9	269	408	435
FS-16	3	34	94	209	394
	5	13	172	296	465
	7	6	255	393	540
FS-24	3	25	150	228	380
	5	12	239	357	450
	7	5	342	538	545
FS-32	3	27	205	350	460
	5	12	318	468	590
	7	6	481	729	770
FS-48	4	11	320	417	670
	6	5	403	519	795
	8	3	407	618	1060

TABLE 4

RESULTS OF FREEZE-THAW TESTS

Weight Losses, Length Changes and Compressive Strengths

Soil No. & AASHO Class.	Cement Content, per cent by wt.	Weight Loss, per cent	Length Changes 0.0001 Inches 1st Freeze	1st Thaw	12th Freeze	12th Thaw	Compressive Strength, psi 7 Days	After Test
8295	3	14	-	0	238+	100+	200	235
A-4(5)	3	14	-92	43	120+	85+	216	250
	5	6	-97	2	-37	-2	224	284
	5	8	-102	-30	-25	-12	243	407
	7	3	-76	-17	-	-	341	481
	7	3	-86	-28	-94	-36	403	525
	10	2	-67	-3	-62	-4	577	740
	10	2	-66	-3	-36	-4	586	796
	13	1	-58	-19	-59	-2	867	987
	13	1	-61	-5	-46	3	851	1002
8939	2	29	-	5	66	100	190	377
A-1-b(0)	2	26	-12	5	78	87	197	332
	3	3	-	0	16	30	312	605
	3	3	-	0	39	40	326	581
	5	2	-	0	-	-	702	1131
	5	2	-	0	-29	-10	703	1154
	7	1	1	0	-33	3	1123	1831
	7	2	-35	2	-20	12	1120	1791
8939A	3	54	-	15	-	300	180	85
A-1-b(0)	5	2	-	5	-	240	538	463
(No. +4)	7	1	-	3	-	-5	907	1140
8942	3	-	-189	60	774+	451+	92	78
A-6(10)	3	-	-184	45	535+	291+	84	92
	5	19	-198	-40	435	357	215	273
	5	23	-212	-45	285	189	240	271
	7	10	-	-	36	94	325	407
	7	9	-107	-2	116	134	363	461
	10	2	-147	-28	-175	-78	477	608
	10	2	-136	-17	-174	-63	504	-
	13	1	-118	-22	-154	-60	573	652
	13	1	-122	-26	-149	-62	506	678
9064	4	28	-130	-35	35	25	356	390
A-4(3)	6	1	-105	-40	-80	-40	465	609
9069	8	34	-28	3	124+	66+	530	822
A-4(8)	8	38	-31	3	318+	144+	525	771
	10	15	-31	3	111	95	693	1082
	10	18	-30	3	80	85	640	1051
	12	8	-29	2	-16	17	780	1280
	12	7	-28	3	4	39	772	1345

TABLE 4

RESULTS OF FREEZE-THAW TESTS (Continued)

Soil No. & AASHO Class.	Cement Content, per cent by wt.	Weight Loss, per cent	Length Changes 0.0001 Inches 1st Freeze	1st Thaw	12th Freeze	12th Thaw	Compressive Strength, psi 7 Days	After Test
9069 (Cont')	14	2	-34	2	-29	2	1060	1392
A-4(8)	14	2	-36	3	-25	6	948	1562
9073	2	100	-50	-15	35	30	-	151
A-1-b(0)	4	4	-50	5	-5	15	-	490
9076	7	39	-90	2	145	105	445	174
A-4(5)	9	21	-95	-15	-30	0	670	478
9079	9	6	-75	10	-50	10	-	544
A-6(9)	11	5	-70	10	-40	20	379	560
9081	4	3	-35	2	-32	-10	468	572
A-1-b(0)								
9082	3	100	-75	0	200	75	-	-
A-2-4(0)	5	19	-70	-5	-65	5	346	685
9085	5	17	-30	-5	-30	-5	111	119
A-2-4(0)	7	7	-30	-5	-25	-5	-	310
9089	4	100	-30	-15	105	80	-	88
A-3(0)	6	51	-20	0	45	60	-	221
9090	2	13	-30	15	13	30	-	236
A-1-b(0)	4	3	-20	5	4	14	-	490
9091	11	10	-100	0	-65	25	512	-
A-4(8)	13	3	-90	-5	-60	5	-	-
9092	9	16	-190	-40	-76	-12	-	358
A-4(8)	11	4	-170	-35	0	0	509	473
9110	8	7	-25	0	-39	-3	254	495
A-3(0)	10	5	-25	0	-34	15	421	748
9112	10	2	-140	-40	-129	-37	286	414
A-4(4)	12	1	-115	-30	-109	-38	360	572
9113	8	100	-25	0	282	216	191	231
A-2-4(0)	10	2	-25	0	-38	4	354	701
9115	12	6	-20	0	-32	5	296	597
A-3(0)	15	0	-30	-5	-26	2	-	876
9116	11	4	-30	0	-37	-7	142	454
A-3(0)								
9117	3	4	-25	0	-34	-9	409	486
A-1-b(0)	5	2	-20	0	-28	-4	748	955
9118	3	8	-30	5	137	97	359	355
A-1-b(0)	5	0	-30	5	-13	9	748	796
9119	4	10	-25	0	45	25	195	154
A-1-b(0)	6	2	-25	0	-25	0	451	470
9130	2	100	-30	2	113	118	-	-
A-1-a(0)	3	6	-25	0	-23	0	438	-
9131	9	18	-105	10	-55	15	267	490
A-4(8)	11	7	-90	-10	-40	20	439	675
9132	8	13	-290	-70	-119	3	631	591
A-2-4(0)	10	7	-265	-105	-224	-98	715	716

TABLE 4

RESULTS OF FREEZE-THAW TESTS (Continued)

Soil No. & AASHO Class.	Cement Content, per cent by wt.	Weight Loss, per cent	Length Changes 0.0001 Inches 1st Freeze	1st Thaw	12th Freeze	12th Thaw	Compressive Strength, psi 7 Days	After Test
9137	6	100	-30	10	200+	200+	-	-
A-3(0)	6 + $CaCl_2$	100	-30	10	200+	200+	-	-
9138	7	11	-140	-40	-105	-20	407	385
A-2-4(0)	9	5	-110	-5	-74	6	503	565
	11	3	-100	-5	-70	7	-	748
9139	6	21	-100	65	200+	200+	-	289
A-4(4)	8	8	-165	-40	-125	-26	620	489
	10	4	-140	-20	-99	-2	740	533
	12	2	-140	-30	-103	-18	-	748
9140	6	14	-75	-5	-47	15	-	369
A-2-4(0)	8	7	-45	5	-34	12	314	568
	10	3	-45	5	-36	16	-	653
9141	5	23	-28	5	15	31	-	150
A-3(0)	7	12	-25	5	-10	24	-	231
	9	8	-31	-11	-15	22	-	382
	11	7	-14	6	-15	21	513	537
	13	5	-27	7	-16	23	-	716
9143	4	48	-20	5	66	77	-	120
A-1-b(0)	6	8	-20	5	6	40	313	303
9144	3	3	-25	0	-19	7	329	844
A-1-b(0)	5	1	-25	0	-32	-8	469	1099
9145	3	7	-28	-2	-21	10	180	688
A-1-b(0)	5	3	-28	-2	-18	17	428	705
9146	3	9	-21	-15	-48	-27	304	-
A-1-b(0)	5	2	-26	-3	-20	-13	650	-
9147	4	20	-17	-2	-8	18	-	254
A-2-4(0)	6	11	-33	-8	-44	-15	318	258
9148	4	100	-25	5	490	223	-	21
A-1-b(0)	6	13	-25	5	18	38	216	178
	8	5	-25	5	-7	23	428	404
9151	8	10	-35	35	135	138	418	387
A-4(3)	10	6	-35	30	-35	38	505	637
9152	4	5	-25	5	-8	25	227	629
A-1-b(0)	6	2	-25	5	0	24	461	1083
9153	6	6	-70	-5	-60	-8	-	-
A-2-4(0)	8	4	-85	-10	-60	-20	-	-
9155	7	100	-60	15	353	270	302	88
A-4(2)	9	36	-50	-5	-27	10	501	522
9156	4	14	-60	-20	-3	41	250	263
A-4(1)	6	8	-80	20	-40	30	450	511
9157	3	29	-92	-15	-15	-9	310	205
A-2-4(0)	5	6	-75	-10	-36	4	455	422

TABLE 4

RESULTS OF FREEZE-THAW TESTS (Continued)

Soil No. & AASHO Class.	Cement Content, per cent by wt.	Weight Loss, per cent	Length Changes 0.0001 Inches 1st Freeze	1st Thaw	12th Freeze	12th Thaw	Compressive Strength, psi 7 Days	After Test
9160	10	15	-35	0	40	60	91	156
A-3(0)	12	6	-35	0	-20	15	127	250
9161	6	100	-25	0	188	158	-	65
A-3(0)	8	13	-25	8	-30	15	-	110
9162	5	0	-25	0	-37	-11	-	697
A-1-b(0)								
9164	3	100	-160	-40	600+	500+	-	-
A-4(5)	5	29	-170	-45	110	68	250	95
9165	2	100	-30	30	127	92	-	174
A-1-b(0)	3	10	-30	15	40	38	263	290
9169	2	3	-91	-66	-45	-20	-	318
A-1-b(0)	3	1	-145	-107	-25	15	420	438
9174	5	15	-130	10	(1)	(1)	391	430
A-2-4(0)	7	9	-105	5	(1)	(1)	423	578
9175	4	100	-95	5	700+	500+	-	33
A-6(5)	5	100	-115	10	700+	500+	284	16
	6	100	-102	8	700+	500+	-	16
	7	100	-98	2	700+	500+	439	17
9181	4	100	-39	-4	761	390	147	25
A-2-4(0)	6	100	-26	7	376	215	206	216
	8	33	-50	-10	60	45	-	650
9182	3	100	-25	5	400+	100+	46	0
A-1-b(0)	7	16	-25	5	-19	3	207	293
9183	12	100	43	83	200+	100+	114	0
A-2-4(0)	8 $CaCl_2$	17	-25	0	-25	0	107	499
	10 $CaCl_2$	4	-25	0	-25	0	173	689
9203	6	6	-25	0	-25	0	325	611
A-4(0)	8	4	-25	0	-25	0	-	979
9204	3	16	-20	0	-30	-2	205	439
A-1-b(0)	4	11	-20	0	-27	4	350	629
	5	5	-20	0	-33	-2	494	812
9207	4	9	-30	10	-27	15	-	400
A-4(2)	6	4	-30	5	-50	-10	210	412
9209	3	31	20	30	183	144	221	174
A-2-4(0)	5	14	-5	10	240	202	345	304
9210	4	21	-70	-25	25	45	-	371
A-1-b(0)	5	6	-60	-10	-40	-5	281	524
9211	8	15	-25	0	-28	-9	129	-
A-3(0)	10	10	-25	0	-26	-3	325	408
9212A	6	5	-123	-60	-222	-78	-	231
A-4(2)	8	6	-116	-62	-190	-80	302	446

(1) -- Loose reference point, no expansion at 9 cycles.

TABLE 4

RESULTS OF FREEZE-THAW TESTS (Continued)

Soil No. & AASHO Class.	Cement Content, per cent by wt.	Weight Loss, per cent	Length Changes 0.0001 Inches 1st Freeze	1st Thaw	12th Freeze	12th Thaw	Compressive Strength, psi 7 Days	After Test
9217	11	10	-	-	-	-	-	-
A-7-6(14)	13	7	-100	12	-75	-1	420	451
	15	4	-100	0	-81	-9	436	422
9218	4	27	-36	19	200+	200+	-	178
A-4(1)	6	9	-69	-3	-47	-1	325	287
9221	10	14	-35	3	-44	4	362	362
A-4(8)	12	2	-35	3	-48	-4	-	372
9222	6	15	-73	-9	-85	-5	-	178
A-4(6)	8	9	-78	-8	-80	-21	-	275
9246	5	100	-48	-3	200+	200+	170	100
A-3(0)	7	9	-20	15	-29	-2	220	229
	7	7	-32	5	-29	-10	-	169
9247	10	10	-123	-12	-87	-19	326	375
A-4(8)	12	3	-	-	-	-	587	-
9248	4	66	-40	0	200+	200+	225	-
A-1-b(0)	4	40	-51	-9	-53	3	-	-
	6	4	-15	-5	-46	-14	334	494
	6	7	-5	5	-7	-1	310	491
9261	3	46	-200	-35	190	127	466	358
A-4(2)	3		-200	-20	107	132	-	-
	5	11	-197	-56	-252	-104	592	-
9262	7	16	-35	-15	-51	-21	116	338
A-1-b(0)	9	4	-30	15	-35	-14	188	463
9263	2	31	-70	-18	211	47	242	80
A-2-4(0)	2	30	-65	5	207	29	-	64
	3	10	-70	-12	-94	-55	393	459
	3	6	-78	-12	-111	-63	-	527
9268	4	20	-45	5	-34	-5	340	365
A-2-4(0)	4	17	-30	5	-44	1	-	384
	5	9	-40	3	-35	3	455	531
	5	10	-45	6	-22	-2	-	427
9269	3	-	-31	5	1	14	-	212
A-2-4(0)	5	13	-18	-2	-47	-11	288	450
	6	8	-20	7	-14	19	370	443
	6	-	-35	7	-30	5	-	421
9270	3	18	-46	18	101	67	268	197
A-2-4(0)	4	15	-25	40	-5	35	412	437
	4	-	-15	15	-6	30	412	425
9271	2	-	-66	-29	129	33	260	140
A-2-4(0)	3.5	17	-35	3	-48	-7	-	338
	3.5	16	-45	-5	-33	9	-	-
	5	10	-32	15	-35	6	410	466
	5	-	-41	0	-36	-1	410	427

TABLE 4

RESULTS OF FREEZE-THAW TESTS (Continued)

Soil No. & AASHO Class.	Cement Content, per cent by wt.	Weight Loss, per cent	Length Changes 0.0001 Inches 1st Freeze	1st Thaw	12th Freeze	12th Thaw	Compressive Strength, psi 7 Days	After Test
9282	6	17	-114	-31	-106	-46	202	312
A-4(8)	8	14	-81	-23	-78	-39	260	411
	8	-	-99	-29	-78	-47	-	420
	10	12	-70	-15	-74	-33	330	460
	12	6	-	-	-	-	395	-
9283	9	100	-155	-40	200+	200+	353	258
A-4(8)	9	100	-115	-18	200+	200+	-	268
	11	100	-139	-42	189+	47+	425	-
	13	40	-131	-28	157	146	484	-
9287	3	12	-37	-5	-27	-4	393	525
A-1-a(0)	5	3	-18	-8	-28	-3	538	995
	5	3	-10	2	-34	-7	-	935
9294	4	15	-52	-4	-20	1	355	350
A-2-6(1)	6	10	-55	-10	-14	20	393	429
	8	5	-47	-8	-26	13	528	481
9295	6	76	-40	-10	200+	200+	194	-
A-2-4(0)	6	34	-40	-10	200+	200+	-	-
	8	11	-48	-1	-60	-24	223	468
	10	6	-48	-1	-60	-24	-	495
9296	4	44	-30	-3	35	31	246	77
A-1-b(0)	4	100	-38	-4	27	28	-	315
	6	3	-34	-2	-64	-30	394	780
9307	7	12	-23	2	-21	-14	194	318
A-3(0)	9	10	-25	-2	-22	-1	-	-
	9	10	-25	-2	-12	-6	250	275
9312	8	6	-58	25	-90	24	364	510
A-4(7)	8	5	-108	-17	-97	-27	-	540
9319	3	43	-57	-5	35	15	251	209
A-2-4(0)	5	4	-45	-5	-30	-12	406	595
	5	4	-45	-5	-26	7	-	604

TABLE 5

RESULTS OF ACCELERATED FREEZE-THAW TESTS

Weight losses, Length changes and Compressive strengths

Reference No.	Soil No.	Cement content used in actual test procedure	2 cycle	6 cycle	10 cycle	12 cycle	Compressive strength % of 7 - day strength: 6 cycle	8 cycle	12 cycle	16 cycle	Loss in weight after 10 cycle % of original wt.
1	9246	7.0	- 2	8	43	80	150			127	10
		8.0	5	2	11	14			163		
2	9247	10.0	- 9	19	63	80	50			35	7
		11.0	5	6	106	400		38	45		27
3	9248	6.0	- 5	23	48	58		98		90	10
		8.0	- 9	-10	-10	- 6		145	150		1
4	9261	5.0	-14	40	160	250		47		35	22
		6.0	-30	-32	0	-10		62		62	1
5	9262	7.0	-10	-11	-12	- 2		124		168	14
		9.0	-14	- 8	- 8	- 8	164			144	1
6	9263	2.0	-13	1	17	28		68		64	-
		3.0	- 4	10	15	30				81	-
7	9268	4.0	3	4	10	17		59	72		7
		5.0	- 2	7	10	0		65	68		3
8	9269	4.5	31	80	122	360		56	70		21
		5.0	- 5	1	5	5					6
9	9270	4.0	22	23	34	70	50			72	8
		5.0	0	5	16	14			65		2
10	9271	3.5	- 7	- 5	- 3	5		80		78	5
		5.0	6	5	18	28	70			88	5
11	9282	8.0	- 9	-14	Failed	-		117		100	4
		10.0	- 4	-16	-13	- 5		126		129	1
12	9283	9.0	79	150	Failed	-		57	5		100
		11.0	-24	100	Failed	-		-	25		100
13	9287	3.0	- 6	- 2	3	33			100		2
		5.0	- 7	- 5	3	8		126		108	3
14	9295	6.0	- 4	- 4	33	44		82		28	6
		7.0	-13	-13	4	21		105		115	0
15	9294	6.0	1	13	50	95		66	37		6
		7.0	0	5	18	40		137	130		0
16	9296	4.0	- 4	5	50	100		84	80		16
		5.0	-15	-13	5	21		100	125		2
17	9297	5.0	-	6	41	35	65		60		13
		7.0	1	3	4	5	-		140		-
18	9307	7.0	- 3	- 4	0	0		-	125		-
		8.0	- 3	- 2	3	10		100	130		5
19	9319	3.0	- 9	-13	27	30	73			59	42
		5.0	- 4	-10	- 7	- 5	84			116	4
20	9309	3.0	-	-	-	-	58		62		2
		5.0	- 2	5	9	17	-		125		-