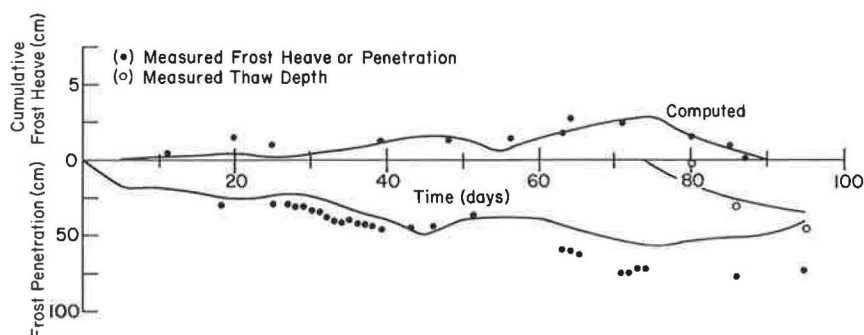


Figure 6. Simulated versus measured frost heave, frost penetration, and thaw depth for Ikalanian silt during 1978-1979 winter at Winchendon, Massachusetts, field site.



by many practicing engineers. We are attempting to simplify the code to provide a model that is versatile and usable on small, readily available computers. During the next year or more, a major effort will be to make the model more readily usable by the practicing engineer.

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Evaluation of a Self-Refrigerated Unit for Frost-Heave Testing

K.J. LOMAS AND R.H. JONES

The British Transport and Road Research Laboratory (TRRL) frost-heave test, in which specimens are frozen from the top downward in an open system for 250 h, is specified in terms of a cold room but is more often undertaken in a self-refrigerated unit (SRU). In both units the air temperature

above the specimens is maintained at -17°C and the water bath at $+4^{\circ}\text{C}$. The maximum permitted heave is 13 mm in England and 18 mm in Scotland. A comparative study involving six aggregates of 40-mm maximum size and covering a range of geological types and gradings was undertaken to estab-

lish whether the SRU should supersede the cold room as the preferred testing facility. Statistical analysis indicated that the two units produced similar results within the working range. Therefore, in view of its operational advantages and more widespread use, the SRU should become the preferred testing facility. Some variations in the imposed temperature conditions were observed in both facilities. However, there appeared to be no relation between the heave of individual specimens and the mean top-surface temperature. It was concluded that the main cause of scatter was specimen variability and that improved methods of specimen preparation are more likely to reduce scatter than are refinements to the testing facility. A subsidiary analysis showed that in the TRRL test frost susceptibility can be assessed at least as well after 96 h as after 250 h. The possible use of a shorter test, with appropriate limits, is being considered by TRRL.

In the United States and in a number of European countries, unrestrained heaving tests are used to assess frost susceptibility. Several types are used, including constant boundary temperature (CBT) (1,2), constant rate of penetration of zero isotherm (CRP) (3), and constant rate of heat extraction (CHE) (4).

There is some evidence that the various tests rank materials in the same order (5). To obtain a parameter that characterizes a material for design, a sufficient number of tests, all under the same conditions, must be undertaken to obtain a reliable average. The CBT test has the advantage of not requiring feedback from individual specimens, and therefore identical conditions should be easier to achieve. In addition, it can be argued that the CBT test more closely models the natural conditions in which the road structure responds to a change in boundary temperature.

In Britain, a form of CBT test developed by the Transport and Road Research Laboratory (TRRL), following early work at Purdue University (6), has been routinely used for frost-susceptibility testing in perhaps 20 laboratories for more than a decade. Modifications to the test specification have been introduced to improve reproducibility (2,7). Further modifications are envisaged, including a change from a cold-room (CR) testing facility to a self-refrigerated unit (SRU) and probably the introduction of a shorter testing period.

This paper presents the results of tests on six granular subbase materials in both the CR and the SRU and makes a preliminary evaluation of the relative merits of various testing facilities for undertaking CBT tests.

FACILITIES FOR TRRL FROST-SUSCEPTIBILITY TEST

In the TRRL test, nine cylindrical specimens 102 mm in diameter and 152 mm high are placed in an apparatus so that the air temperature above them can be maintained at $-17 \pm 1^\circ\text{C}$. The specimens rest on porous ceramic discs within copper carriers. The discs are in contact with water that is maintained at $+4 \pm 0.5^\circ\text{C}$. The sides of the specimens are wrapped with waxed paper, and the intervening space is filled with loose, dry sand (5- to 2.36-mm fraction). Push rods bearing on caps placed on top of the specimens enable the heave to be measured. From the start of the test, heave measurements and, if necessary, topping up of the water level are undertaken every 14 h. Usually, a test run will consist of three specimens of three different materials. Currently, materials are judged as frost susceptible if, during 250 h, the average heave of three specimens is more than 13 mm (in England and Wales) or 18 mm (in Scotland). Only if there is doubt about the classification will nine specimens of the same material be tested.

Cold Room

The test was originally specified (1) in terms of a

CR. The Nottingham CR is 3.8x2.1x1.8 m, and the temperature is controlled by a 1.5-kW condensing unit (Prestcold AS 200 M) used in conjunction with a ceiling-mounted electric defrost cooler ECL 120. The cooler incorporates two 90-W fans that maintain air circulation. There is a 20-min defrost period every 12 h.

Four trolleys are available; these are closely modeled on the TRRL design (1) but with the addition of stirrers and mercury contact thermometers (8). Foamed polyurethane insulation, used instead of granulated cork, gave similar thermal insulation in reduced width and permitted the trolleys to pass through the existing CR door. The tests described in this paper were all undertaken in the same trolley.

Self-Refrigerated Unit

Although the TRRL test is specified currently in terms of a cold room, an SRU is likely to become the preferred testing method in the future (7). A unit based on a prototype developed at the University of Nottingham (9) (see Figure 1) is now available commercially. This type of SRU is more convenient to operate, does not require defrosting during the test, and is fitted with a Mariotte vessel to maintain a constant water level. In the standard SRU, both air and water are cooled from a common refrigeration circuit. A separate water-cooling system can be incorporated as an optional extra. However, since the main aim of the present series of tests was to evaluate a standard SRU, an additional cooler was not fitted.

DESCRIPTION AND PROPERTIES OF MATERIALS USED

The aggregates used in this investigation were supplied from the standard stocks maintained by TRRL, and their reference numbers are included in the descriptions. The six materials included several geological types, and the gradings at which they are commercially available (see Figure 2) span the U.K. Department of Transport type 1 and type 2 envelopes (10).

Three of the materials were supplied as dug (i.e., uncrushed) within the type 1 grading: Ashton Keynes (102) is a sand and gravel that consists of weathered fragments of Jurassic limestone. The particles are smooth, rounded, and flattish. Spencers Farm (103) is a flint gravel-sand-fines mixture (i.e., a hoggin). Many of the flint particles have a chalk coating. Stanley Ferry (106) is a flood-plain sand and gravel with rounded but very rough gritstone particles.

There were two crushed rocks that conformed to the type 1 grading: Croft (105) is a crushed granite that consists of angular, rough-textured particles, some of which appeared honeycombed. Dene (119) is a crushed carboniferous limestone that consists of angular, rough-textured particles.

Completing the set was a fine type 2 aggregate, Woodhall Spa (114), a sandy hoggin that contains elongated, glassy flint particles and rounded, smooth chalk particles.

All six materials were separated at TRRL into four component fractions--40-20 mm, 20-10 mm, 10-5 mm, and 5 mm-75 μm --before being dispatched to Nottingham. Subsequently, the finest fraction was divided into two on a 600- μm sieve for all type 1 materials and into three on the 600- and 300- μm sieves for the type 2. The individual fractions were then recombined in an attempt to reach the target gradings shown in Figure 3. This method was devised to produce specimens with repeatable gradings. However, there was generally a shortage of

Figure 1. Self-refrigerated unit.

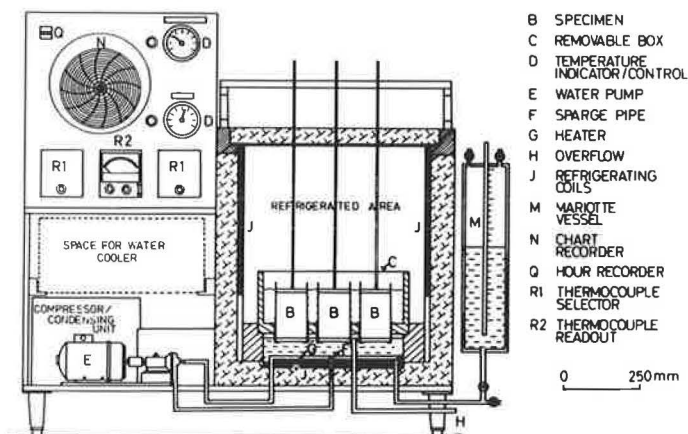
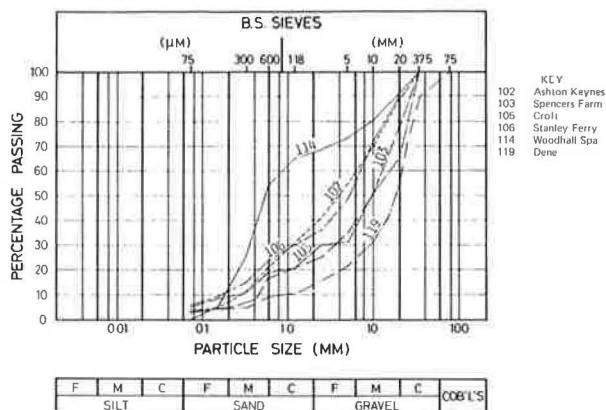


Figure 2. Grading curves for aggregates as available commercially.



finer, so that the actual gradings tended to be coarser than the target below the 300- μ m size. In particular, not more than 4 percent passing a 75- μ m sieve could be achieved. This was not considered a major drawback, since the main aim was to compare testing facilities rather than to assess the frost susceptibilities of commercially available materials.

The specific gravities and water absorptions of fractions of the various materials finer than 20 mm were determined. Typical values are given in Table 1 together with the maximum dry densities and optimum moisture contents determined by the vibrating hammer test (test 14 BS 1377:1975). A fresh sample was used for each compaction point to avoid the risk of progressive degradation.

SPECIMEN PREPARATION

The component size fractions of each material were thoroughly mixed, first dry and then with the required amount of water added. The moist material was then allowed to stand for about 10 min.

One-third of the required mass of the specimen was then placed into the standard tapered mold (1) with the removable bottom plug in place. The material was compacted to a depth of 56 mm by 25 blows with a tamper, and this was followed by the application of a vibrating hammer. The process was repeated for a second layer of equal mass to give a total depth of 106 mm. For the final layer, after tamping and about 20-30 s of vibration, the top end

Figure 3. Grading curves for aggregates as reconstituted for testing.

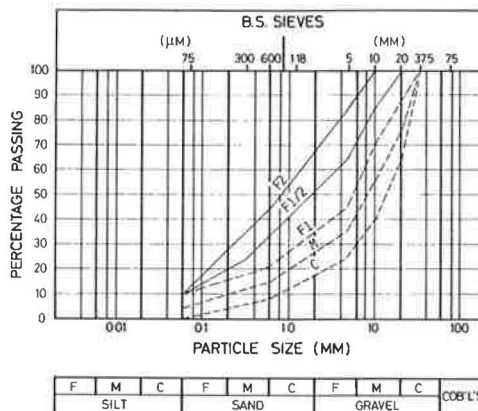


Table 1. Properties of test aggregates.

Aggregate	Grading	Maximum Dry Density (Mg/m ³)	Optimum Moisture Content (%)	Specific Gravity	Water Absorption (%)
Ashton Keynes	C	2.06	7.2	2.46	3.96
	M	2.11	7.3	2.45	3.99
Spencers Farm	F1	2.14	7.4	2.45	3.99
	C	2.10	8.0	2.45	2.70
Stanley Ferry	M	2.14	6.6	2.46	2.72
	F1	2.16	6.5	2.46	2.77
Croft	C	2.04	8.6	2.47	3.98
	M	2.12	7.5	2.47	3.97
Dene	F1	2.19	6.8	2.48	3.94
	C	1.96	7.0	2.58	1.56
Woodhall Spa	M	2.15	6.9	2.58	1.59
	F1	2.11	6.8	2.58	1.59
Woodhall Spa	C	2.05	6.7	2.55	2.06
	M	2.17	5.4	2.56	2.05
Woodhall Spa	F1	2.18	5.3	2.56	2.05
	F1/2	2.13	6.9	2.45	3.45
Woodhall Spa	F2	2.04	7.9	2.48	2.88
	F2	1.96	8.9	2.51	2.36

plug was inserted, the mold was inverted, the other end plug was removed, and a similar period of vibration was applied to the other end. Vibration was then applied in equal intervals to each end of the specimen alternately until its height was reduced to 152 mm. This method is an advance on that currently used in compliance testing and is similar to the method proposed by TRRL as a result of studies that have shown that it produces more uniformly compacted specimens.

After compaction, each specimen was pushed from the mold with a hydraulic extruder, wrapped in waxed paper, and placed on a porous disc within a copper specimen carrier. Weighings were made to determine the initial mass, and the specimen was then tempered in the unit for 24 h. The free-water level was maintained at the top of the porous disc.

TESTING PROGRAM AND RESULTS

Heave Measurements

Thirteen test runs were made in each of the two facilities. Sets of nine specimens were tested at C grading (Figure 3) for Dene, at M grading for the remaining type 1 aggregates, and at three F gradings for Woodhall Spa (type 2). In addition, all of the type 1 aggregates were tested in sets that consisted of three specimens at each of the C, M, and F1 gradings.

Readings of heave were taken daily in the usual manner, and the amount of water added in the CR trolley or the water level in the Mariotte tube of the SRU was noted. After the final reading at 250 h, the specimens were taken out of the apparatus, and the depth and thickness of the terminal lens were recorded. The specimens were then weighed, oven dried, and reweighed. A check was made on the initial density and moisture content (the dry mass and initial wet mass were known). From each run, one randomly selected specimen of each nominal grading was wet sieved.

A summary of the heave measurements is given in Table 2.

Temperature Measurements

Continuous traces of air temperature in the CR and of both air and water temperatures in the SRU were obtained on circular chart recorders actuated by mercury in steel capillary thermometers. In addition, in this investigation, each specimen was instrumented with copper-constantan thermocouples that were placed in contact with the top and bottom sur-

faces of the specimen and in the water at the lower surface of the porous disc. Furthermore, five thermocouples were positioned on each of four wooden dowels that protruded into the air space above the specimens. In the CR, where there was considerable air movement, the thermocouples were loaded with 5-mm-diameter phosphor bronze balls.

The output voltages from the thermocouples were monitored on a 120-channel Solartron data logger, which was used to scan all of the thermocouples in one of three modes: (a) at 2-h intervals throughout the test at a scanning speed of 1.25 s/channel; (b) at 30-min intervals for either part or all of a test, again at a scanning speed of 1.25 s/channel; and (c) at 2-min intervals, usually for periods of about 2 h, at a scanning speed of 0.1 s/channel.

The voltage output was displayed, to the nearest millivolt, on a digital voltmeter and recorded on punched tape for subsequent analysis.

Every thermocouple was individually calibrated by recording the voltage output at each of 40 temperatures covering the expected operating range. Conversion constants, voltage to temperature, were obtained by linear regression. Correlation coefficients were always greater than 0.99, which corresponds to 95 percent confidence intervals of better than $\pm 0.1^\circ\text{C}$.

For each frost-heave test, the paper tape was processed by an ICL 1900 series computer and the calibration data were used. The output consisted of tables that showed individual temperature readings and salient average temperatures with the corresponding standard deviations and also graphs of the variation of temperature with time. Sections of two such graphs from 2-min scans (starting at 132 h for the CR and 96 h for the SRU) within the nonpenetrating isotherm stage (9) are shown in Figure 4. The instantaneous air temperatures in Figure 4a are the mean of four readings in the same horizontal plane over a period of 4 h in the CR and 2 h in the SRU (only parts of these periods are shown in Figure 4). The remaining temperatures are the means of nine over the same periods.

Particularly noteworthy in Figure 4 are (a) the defrost period in the CR; (b) the controller-induced cycling of the SRU air temperature, which is not reflected in fluctuations of the top-of-specimen temperature; and (c) the very small variations in the bottom-of-specimen temperatures in both units.

COMPARISON OF CR AND SRU RESULTS

Heave

The 250-h heave results from Table 2 are shown graphically in Figure 5.

Two-way analysis of variance of all tests containing nine similar specimens (Table 3) revealed that the heave of an individual specimen was independent of its position in either the CR trolley or the SRU.

For each unit, all of the results at 250 h for the same aggregate and grading were combined, and the average and standard deviation were calculated. Statistical analysis using t-tests revealed no significant difference, at the 5 percent level, between the CR and the SRU on sets of 12 results from type 1 materials (see Table 4). Two significantly different values were obtained from the sets of three. Of these, the Croft aggregate had such a low heave that the difference is not of engineering significance. The remaining large difference given by the Ashton Keynes C grading may have been due to the difficulty of producing coarse, open-graded specimens. However, with the type 2 material, for which sets of 9 results were tested, two out of the three gradings

Table 2. Heaves and standard deviations.

Aggregate	Grading	No. of Specimens ^a	SRU		CR	
			Heave	SD	Heave	SD
At 96 h						
Ashton Keynes	C	Three	8.7	1.9	6.2	0.8
	M	Three	9.0	0.5	10.5	0
		Nine	11.7	1.0	11.0	1.2
Spencers Farm	F1	Three	11.5	0.5	11.7	1.3
	C	Three	3.0	0.9	3.7	0.3
	M	Three	5.0	0.9	3.3	0.8
Stanley Ferry		Nine	4.8	1.0	4.3	2.9
	F1	Three	4.7	0.3	4.5	0.5
	C	Three	4.5	0.9	3.5	1.8
Croft	M	Three	5.2	0.6	4.3	0.8
		Nine	4.2	0.6	5.1	0.8
	F1	Three	6.2	0.3	5.8	1.0
Dene	C	Three	1.2	0.3	0.7	0.3
	M	Three	1.5	0	0.8	0.3
		Nine	1.6	0.4	1.5	0.3
Woodhall Spa	F1	Three	1.3	0.3	0.7	0.3
	C	Three	4.0	0.9	3.3	0.3
		Nine	3.1	0.9	2.9	1.2
Woodhall Spa	M	Three	3.8	0.8	5.0	1.0
	F1	Three	4.7	0.3	5.2	0.6
	F1	Nine	15.1	1.7	14.7	1.6
Woodhall Spa	F1/F2	Nine	14.7	2.1	13.0	1.0
	F2	Nine	11.3	1.3	9.3	1.7
At 250 h						
Ashton Keynes	C	Three	13.8	2.6	8.2	1.3
	M	Three	14.2	1.0	13.3	0.6
		Nine	16.4	1.2	16.0	1.7
Spencers Farm	F1	Three	16.5	3.0	16.0	1.7
	C	Three	4.5	1.5	6.7	1.0
	M	Three	7.5	1.8	5.7	1.5
Stanley Ferry		Nine	8.3	3.0	7.1	4.7
	F1	Three	7.2	0.3	7.7	1.3
	C	Three	7.5	1.5	5.3	1.8
Croft	M	Three	8.0	1.0	7.8	3.1
		Nine	6.8	1.1	8.0	1.4
	F1	Three	10.2	0.8	8.5	2.3
Dene	C	Three	2.2	0.3	1.3	0.3
	M	Three	2.5	0	1.8	0.3
		Nine	2.8	0.5	2.7	0.7
Woodhall Spa	F1	Three	2.3	0.3	1.8	0.3
	C	Three	5.5	0.9	5.8	0.8
		Nine	4.7	1.3	4.7	1.7
Woodhall Spa	M	Three	6.0	0.9	7.3	1.0
	F1	Three	7.0	1.3	7.3	1.2
	F1	Nine	26.0	2.8	23.2	2.7
Woodhall Spa	F1/F2	Nine	23.8	3.1	20.8	2.8
	F2	Nine	17.8	2.4	16.8	1.7

^aNumber of individual results used to determine mean values.

Figure 4. Typical temperature fluctuations in CR and SRU.

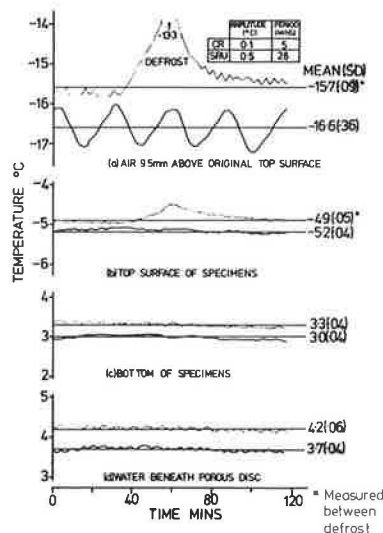


Figure 5. Heave results at 250 h.

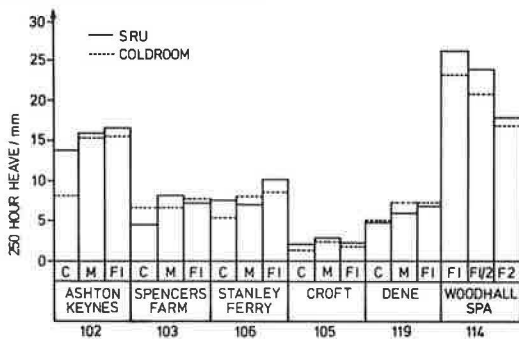


Table 3. Two-way analysis of variance of individual heaves.

Unit	Source	Sum of Squares	Degrees of Freedom	Mean Square	F
CR	Position	41.65	8	5.21	0.84
	Aggregate	3801.30	7	543.04	87.87 ^a
	Residual	346.20	56	6.18	
	Total	4189.15	71		
SRU	Position	20.44	8	2.56	0.52
	Aggregate	4969.08	7	709.87	144.58 ^a
	Residual	274.98	56	4.91	
	Total	5264.50	71		

Note: Critical F-values at 5 percent significance level (two-tailed test) are 2.43 (position) and 2.49 (aggregate).

^aResults significantly different (i.e., $F > \text{critical } F$).

gave significantly different heaves in the CR and the SRU. These gradings produced the largest heaves observed in this study: Both were well in excess of the 18 mm that is the maximum currently acceptable anywhere in the United Kingdom. Nevertheless, the comparisons, taken as a whole, cover a wide range of gradings and material types and support the conclusion that the SRU and the CR give the same heave results, at least for heaves in the working range.

The F-values in Table 4 indicate that there are no significant differences in within-run repeatability between the CR and the SRU. The within-run repeatability of the sets of nine Spencers Farm M specimens (Table 2) was much poorer than that found in corresponding runs with other materials. This appears to reflect a variability in the specimens that arises from the influence of chalk, partic-

ularly where it occurs as a coating on the flint particles.

In passing, it is also interesting to note the effects of grading on heave. Taking the best estimate of heave as the average of all results for each material and grading, the relation between 250-h heave and the effective size D_{10} after testing is shown in Figure 6. For the type 1 aggregates, the 250-h heave generally increases with fineness. An exception was Croft, which, in any case, did not heave much at any of the gradings tested in this investigation. The type 2 aggregate showed a reduction in heave with fineness. A maximum heave within the type 2 envelope has been observed before (11,12) and may be attributed to an "optimum" between particle pore size. However, in the case of the Woodhall Spa aggregate, the decrease in the proportion of chalk, the most frost-susceptible material, with increasing fineness may also be a factor.

Temperatures

From Figure 4, which is typical of the data obtained from the tests, it can be seen that the fluctuations of both the water bath and the bottom-of-specimen temperatures were very small in both units. There was a greater variation in the top-of-specimen temperatures. The defrost period appeared to have no influence on the CR water-bath temperatures. In the SRU, there was a general tendency for the corner specimens to be colder than average and the middle specimen to be warmest (see Table 5). No such simple pattern was obvious in the CR tests. There was a tendency, particularly in specimens that exhibited large heave values, for the top-of-specimen temperature to fall throughout the test (see Figure 7). This is an inherent feature of the TRRL test, in which the aim is to maintain a constant temperature in the air some distance above the specimen (9).

The influence of cold-side temperature on the heaving rate of soils under particular test conditions has been demonstrated elsewhere (13). However, in the present series of tests, there was no obvious dependence between the 250-h heave and the mean surface temperature (after initial pull-down). Thus, although the central specimen in the SRU was always warmer than the corner ones, the heave was independent of position. Fluctuations of temperature at the freezing front have also been proposed as a cause of variability in the frost-heave test results (8), but in this series of tests these fluctuations are very small and are unlikely to be a major source of scatter.

Relative Merits of Constant Boundary Test Facilities

The results indicate that the TRRL test can be performed satisfactorily in either the CR or the SRU. The SRU gave better repeatability for most of the materials. It also has the advantages that (a) it does not need defrosting during a test; (b) a Mariotte tube is standard so that water-level fluctuations are avoided; (c) thermocouple monitoring of specimens is self-contained whereas the CR requires trailing leads; (d) the operator works in room temperatures, which reduces the risk of gross errors in readings; and (e) for a single unit, to test nine specimens, it is cheaper. For these reasons, it is logical to make the SRU the preferred testing facility.

Nevertheless, satisfactory results can be obtained in the CR, especially if the facility were designed, as was the original TRRL CR at Harmondsworth, with an entrance lobby and a double refrigeration system so that temperatures could be maintained during door opening and defrost periods.

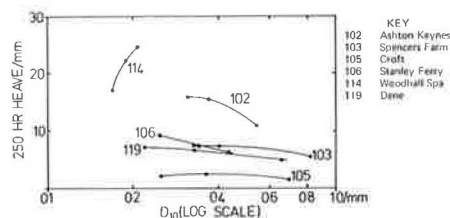
Table 4. Statistical analysis of 250-h CR and SRU heaves.

Aggregate	Grading	No. of Specimens	SRU		CR		F	S _B /mm	t
			Heave (mm)	SD (mm)	Heave (mm)	SD (mm)			
Ashton	C	3	13.8	2.57	8.2	1.26	4.16	2.02	3.40 ^a
Keynes	M	12	15.8	1.51	15.4	1.91	1.60	1.72	0.57
	F1	3	16.5	3.04	15.5	1.32	5.30	2.34	0.52
Spencers	C	3	4.5	1.50	6.7	1.04	2.08	1.29	2.09
Farm	M	12	7.9	2.60	6.7	4.31	2.75	3.56	0.83
	F1	3	7.2	0.29	7.7	1.36	21.99	0.91	0.67
Stanley	C	3	7.5	1.50	5.3	1.76	1.38	1.64	1.64
Ferry	M	12	7.1	1.17	8.0	1.78	2.31	1.51	1.46
	F1	3	10.2	0.76	8.5	2.29	9.08	1.71	1.22
Croft	C	3	2.2	0.29	1.3	0.29	1.00	0.29	3.80 ^a
	M	12	2.7	0.45	2.5	0.69	2.35	0.58	0.84
	F1	3	2.3	0.29	1.8	0.29	1.00	0.29	2.11
Dene	C	12	4.9	1.20	5.0	1.58	1.73	1.40	0.17
	M	3	6.0	0.87	7.3	1.04	1.43	0.96	1.66
	F1	3	7.0	1.32	7.3	1.15	1.32	1.24	0.30
Woodhall	F1	9	26.0	2.77	23.2	2.72	1.04	2.75	2.16 ^a
Spa	F1/F2	9	23.8	3.11	20.8	2.79	1.24	2.95	2.16 ^a
	F2	9	17.8	2.39	16.8	1.72	1.93	2.08	1.02

Note: Critical F-values at the 5 percent significance level for 3, 9, and 12 specimens, respectively, are 39.00, 4.43, and 3.48, and critical t-values are 2.78, 2.12, and 2.07.

^aResults significantly different (i.e., $t > \text{critical } t$).

Figure 6. Effect of grading on heave.



Ideally, a heated Mariotte vessel should be connected to the specimen trolley.

It may well be possible to improve further the temperature conditions within the SRU. Suggestions include closer control of the air temperature, insulating the gap between the specimen box and the inner surface of the SRU (the optional extra water cooler may then be needed), and installing an internal fan to give a better distribution of air temperatures. Alternatively, units that give individual control of the top temperatures by using either Peltier modules (3,9) or a circulating fluid system (14) could be substituted. These have the advantage of applying a constant boundary temperature to the top surface but may require guard ring systems and fairly complex controllers.

However, since the heave was independent of mean temperature, it would appear that test conditions in the CR and the SRU are satisfactory and that the scatter of heaves reflects variations in the specimens. Obviously, this conclusion needs verification for a greater range of materials, including subgrade soils. In the meantime, for aggregates at least, attention should be directed toward improved specimen preparation as the most likely means of reducing scatter.

LENGTH OF TEST

The 250-h period required for the present test is a major disadvantage and many investigators have suggested shortening the test (8, 15-17). Since this possibility is being considered by TRRL (18), the results of all of the tests described here were examined to see whether the testing need continue beyond 96 h. The relation between 96- and 250-h heaves is summarized in Table 6 for both the present series and for other tests under comparable condi-

tions on various materials that were either type 1 aggregates or sand-limestone-filler mixtures. On average, the 96-h heave is approximately two-thirds of the 250-h heave. Both the standard deviation and coefficient of variation of the heaves are less at 96 h than at 250 h, although the relative improvement, as measured by the coefficient of variation, is small. Nevertheless, it would seem that for the materials examined there is no advantage in continuing the test beyond 96 h. Clearly, revised limits would need to be set for the shortened test, and the question of what these should be is being considered by TRRL.

In the TRRL test, the 250-h heave occurs initially with the zero isotherm penetrating and finishes with a nonpenetrating phase. Ending the test at 96 h foreshortens or even eliminates the nonpenetrating phase. It would therefore appear that the relative ranking of materials is the same in both penetrating and nonpenetrating phases. A similar conclusion was reached in a comparative study of CRP, CHE, and CBT tests (5).

CONCLUSIONS

1. The heaves obtained from six aggregates covering a wide range of gradings and geological types in the CR and SRU were not significantly different within the working range. Five of the aggregates were within the U.K. Department of Transport type 1 grading, and one conformed to the finer type 2 grading.

2. There is no significant difference in the within-run repeatability obtained in the two units.

3. Generally, heave increased with fineness through the type 1 grading envelope but decreased with increasing fineness through the type 2 envelope. This behavior was broadly in accordance with previous experience.

4. The water temperature is controlled satisfactorily in both units. The top-of-specimen temperatures are lower than average in the corner and highest in the center in the SRU; for the CR, no simple pattern of temperature distribution appears obvious. Apart from defrost periods, the top-of-specimen temperatures are less variable in the CR than in the SRU.

5. In both units, although the air temperature remains nominally constant, there is a tendency, particularly for specimens with a high rate of heave, for the top-of-specimen temperatures to fall throughout the test.

Table 5. Typical top-of-specimen temperatures.

					Temperature (°C)											
Unit	Aggregate	No. of Specimens	Grading	Time into Test (h)	Plan Position									Instantaneous Avg	SD	
					a	b	c	d	e	f	g	h	k			
CR	Ashton Keynes	Three	C, M, F1	241	-6.0	-6.5	-6.4	-6.5	-5.5 ^a	-6.6 ^b	-6.6	-6.3	- ^c	-6.3	0.4	
		Nine	M	264	-7.6	-7.6	-6.7	-7.7 ^b	-6.5	-6.2 ^a	-6.7	-6.7	-6.7	-6.9	0.6	
	Spencers Farm	Nine	M	117	-5.1	-6.2	-3.5 ^a	-4.9	-5.4	-4.5	-5.8	-6.0	-7.2 ^b	-5.4	1.1	
		Dene	Three	C, M, F1	219	-4.8 ^a	- ^c	-6.0	-5.4	- ^c	-6.5	-5.9	-6.1	-7.6 ^b	-6.0	0.9
			Nine	C	250	-4.8 ^a	- ^c	-5.3	-5.8 ^b	-5.1	-5.0	-5.0	-5.2	-5.1	-5.1	0.3
SRU	Woodhall Spa	Nine	F1/F2	203	-6.0	- ^c	-4.8 ^a	-5.7	- ^c	-5.1	-6.2 ^b	-5.9	-6.2 ^b	-5.7	0.5	
	Ashton Keynes	Three	C, M, F1	146	-6.9	-5.9	-7.4 ^b	-6.1	-5.5 ^a	-6.2	-6.9	-6.8	-6.8	-6.5	0.6	
		Croft	Three	C, M, F1	176	-6.0	-5.5	-7.0	-5.2	-5.0 ^a	-5.2	-7.2 ^b	-5.4	-6.7	-5.9	0.9
		Nine	M	250	-6.5 ^b	-6.2	-6.5 ^b	-5.5	-5.0 ^a	-5.5	-6.3	-5.9	-6.0	-5.9	0.5	
	Dene	Three	C, M, F1	208	-5.8	-5.5	-6.6 ^b	-4.9	-4.0 ^a	-5.6	-6.0	-5.0	-6.0	-5.5	0.8	
			Nine	C	250	-6.4	-5.1	-6.9	-6.3	-5.1 ^a	-6.1	-8.7 ^b	-6.3	-6.7	-6.4	1.1
	Woodhall Spa	Nine	F1	244	-6.9	-7.1	-7.4	-6.5	-5.6 ^a	-6.2	-6.7	-6.5	-7.5 ^b	-6.7	0.6	
			Nine	F1/F2	196	-5.9	-5.5	-5.8	-5.1	-4.8 ^a	-4.9	-6.2	-5.0	-6.3 ^b	-5.5	0.6

^aWarmest position.^bColdest position.^cBroken thermocouple.

Figure 7. Variation of top-of-specimen temperature with heave: average temperature at top of nine specimens.

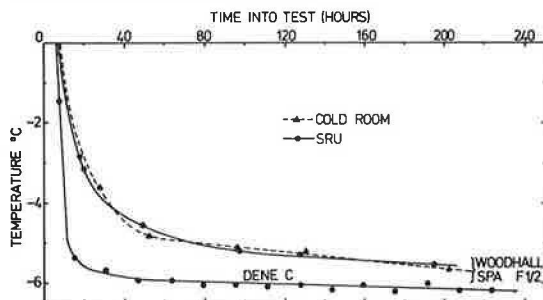


Table 6. Relation between 96- and 250-h heaves.

Test	Unit	No. of Sets ^a	Heave (mm)	
			H ₉₆ /H ₂₅₀	SD
Current series	CR	32	0.640	0.067
	SRU	31	0.640	0.050
Other tests	CR	9	0.676	0.058
	SRU	12	0.665	0.059
All		84	0.647	0.060

Note: H₉₆ = heave after 96 h, and H₂₅₀ = heave after 250 h.^aSets of three individual specimens with average heave >5 mm.

6. Although the SRU should become the preferred facility for routine testing in the future, satisfactory results can be achieved in the CR.

7. No relation was found between the observed heave of a specimen and its mean cold-side temperature. The scatter of results may thus be caused by actual differences in specimens rather than by slight differences in the testing regime experienced by individual specimens. Reduction in scatter is, therefore, more likely to come from improved specimen preparation than from further refinements to the apparatus.

8. Since frost susceptibility can be assessed at least as well at 96 h as after 250 h, a shorter test with appropriate limits should be specified.

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Effect of Variable-Drainage Freeze-Thaw Tests on Post-Thaw Shear Strength

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Research is reported that shows that the effect of freeze-thaw on post-thaw shear strength can be determined by observing the effect of freeze-thaw on the preshear effective consolidation and overconsolidation ratio. It is also shown that availability of water is one of the primary factors that controls the preshear conditions in a saturated soil subjected to freeze-thaw. In order to quantify the effect of freeze-thaw on post-thaw strength, a series of consolidated undrained triaxial tests was conducted on a Manchester silt subjected to drained and undrained conditions during freeze or thaw. Each combination of drained or undrained freeze followed by drained or undrained thaw produced a set of unique and predictable preshear conditions. Based on the results from the variable-drainage freeze-thaw tests, it is concluded that laboratory triaxial tests could be used to study the effect of freeze or thaw on post-thaw shear strength. Specifically, it is shown that (a) freeze-thaw conditions that cause an increase in preshear water content produce a reduction in post-thaw shear strength, (b) freeze-thaw conditions that cause a reduction in preshear water content produce an increase in post-thaw shear strength, and (c) freeze-thaw at constant water content causes a slight reduction in post-thaw shear strength.

Frost action in soils can cause several detrimental effects. The effect most people are aware of is frost heave. A lesser known but equally serious problem is the reduction in soil strength that occurs after freeze-thaw. This problem has been reviewed (1) and researched (2), and still there is no clear link to conventional soil mechanics. The purpose of the research described here is to help establish this link.

For an unfrozen soil unconditioned by freeze-thaw cycles, the shear strength is primarily a function of the preshear history and consolidation stress of the soil. Any factor that affects these conditions, such as an induced pore pressure, will also affect the resulting shear strength. Therefore, because temperature changes can induce pore pressures, it is postulated that the effect of freeze-thaw on shear strength can be defined by observing its effect on the preshear conditions in the soil. Then, once the preshear conditions are known, conventional effective stress analysis can be used to determine the post-thaw strength of the soil.

To explore the effect of freeze-thaw on preshear conditions, a series of tests was conducted in which the soil specimens were subjected to a single

freeze-thaw and then to undrained shear tests. The drainage condition during the freeze or thaw phase was either drained or undrained. These conditions were used as an expedient to simulate the effect of various rates of temperature change on the preshear conditions. The drained condition is associated with slow temperature change and the undrained condition with a fast temperature change.

The basic laboratory test used throughout the test program was a consolidated undrained triaxial test with measurement of pore pressure. This test was conducted on all samples after the appropriate temperature and drainage conditioning. In order to observe the possible effect of overburden on soils subjected to freeze-thaw, consolidation pressures from 6.9 to 69 kPa were applied before temperature and drainage conditioning.

BACKGROUND

It has been recognized for some time that certain combinations of soil type and moisture conditions, when subjected to freezing and thawing, result in significant heave and/or reduction in the strength of the soil. The magnitude of the heave and the seriousness of the loss of strength associated with freezing and thawing are a function of many physical and environmental conditions. Climate, ground cover, location of the groundwater table, soil moisture, and rate of freezing and thawing are only a few of the factors that influence what is called frost action. Of the many factors that contribute to frost action, the main villains are pore water and water transported to the freezing front by temperature-induced suction.

The movement of water within soil is limited by conditions that are comparable to the triaxial tests termed "drained" or "undrained". A drained system is associated with movement of water from some external point toward the freezing front, whereas an undrained system is not associated with movement of water other than local redistribution. In the field, the drained condition would be achieved if