16. E.V. Edriss, Jr., and R.L. Lytton. Dynamic Properties of Fine Grained Soils. Proc., 9th International Conference on Soil Mechanics and Foundation Engineering, Tokyo, Vol. 2, 1977, pp. 217-224.
17. D.G. Fredlund, A.T. Bergan, and E.K. Sauer. Deformation Characterization of Subgrade Soils for Highways and Runways in Northern Environments. Canadian Geotechnical Journal, Vol. 12, No. 2, 1975, pp. 213-223.
18. D.G. Fredlund, A.T. Bergan, and P.K. Wong. Relation between Resilient Modulus and Stress Conditions for Cohesive Soils. TRB, Transportation Research Record 642, 1977, pp. 73-81.
19. Soil Manual. Wisconsin Department of Transportation. 1972.
20. S.D. Wilson. Small Soil Compaction Apparatus Duplicates Field Results Closely. Engineering News-Record, May 1950, pp. 34-36.
21. T.W. Lambe. The Structure of Compacted Clay. Journal of Soil Mechanics and Foundations Division, Proc., ASCE, Vol. 84, No. SM2, 1958, pp. 1-34.
22. A.W. Johnson and J.R. Sallberg. Factors That Influence Field Compaction of Soils. HRB, Bull. 272, 1960, pp. 29-48.
23. T.B. Edil and S.E. Motan. Soil-Moisture Equilibria and Behavior of Highway Pavement Systems. National Science Foundation, Grant ENG75-10558, 1978, 68 pp.
24. R.J. Krizek and T.B. Edil. Experimental Study of Clay Deformability in Terms of Initial Fabric and Soil-Water Potential. Rheologica Acta, No. 13, 1974, pp. 803-813.

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Comparison of the Precise Freezing Cell with Other Facilities for Frost-Heave Testing

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Identification of frost-susceptible materials on the basis of their physical properties is too imprecise for many practical purposes, and direct freezing tests need to be employed. Heave is measured by two main types of test: the constant rate of penetration test and the constant boundary temperature test. The latter has the advantage of greater simplicity of operation and is easier to model mathematically. Nevertheless, its reproducibility is relatively poor and improvements are being sought. The development of a self-refrigerated unit (SRU) is outlined and likely future revisions to the constant boundary temperature test specification discussed briefly. A precise freezing cell (PFC) that uses the Peltier effect and permits unidirectional freezing with the boundary temperatures controlled to ±0.1°C has been developed. Specimens heave much less in the PFC than in the SRU because the heat extraction is more rapid and a constant temperature is applied to the moving boundary (top of specimen) rather than to the stationary boundary. Thus the penetration of the zero isotherm is accompanied by high suctions that favor ice penetration over segregation. The role of the PFC lies in research, not in routine testing, particularly in connection with the development and evaluation of mathematical models.

The process of frost heaving, which occurs when the zero isotherm penetrates below the bound materials of a typical road structure (Figure 1), can be explained in terms of the capillary theory (1, 2, 3). This postulates that, to pass through the neck of a pore, the radius of curvature of the ice front (r_{iw}) must be reduced to a critical value (r_o) (Figure 2). The curved interface is associated with both a pressure difference and a freezing-point depression according to the equation

$$p_i - p_w = 2\sigma_{iw}/r_{iw} = L\Delta T/V_wT_o \qquad (1)$$

where

p_i, p_w = ice and water pressures respectively (Pa),
r_{iw} = radius of ice-water interface at a particular instant (m),
σ_{iw} = interfacial energy (ice-water) (J/m^2),
L = latent heat of fusion (J/kg),
ΔT = freezing point depression (K),
V_w = specific volume of water (m), and
T_o = 273 K.

Because in the absence of restraint p_i will not differ significantly from atmospheric pressure, p_w will be less than atmospheric, which will give rise to a suction that draws water continuously toward the freezing front. In frost-susceptible materials, there is a tendency for the radius of curvature to remain above r_o for long periods, which results in ice segregation and excessive frost heave. For materials with a range of grain (and hence pore) sizes, various suggestions have been made regarding the selection of a characteristic critical pore radius (4).

Identification of frost-susceptible materials continues to be a significant problem for both designers and research workers. Direct tests based on the fundamental work of Taber (5) have been developed by the U.S. Cold Regions Research and Engineering Laboratory (CRREL) (6-8) and by the U.K. Transport and Road Research Laboratory (TRRL) in Great Britain (9). In both, cylindrical specimens from either undisturbed samples or recompacted material are subjected to unidirectional freezing from the top, while their bases are kept in contact with unfrozen water.

In the CRREL procedure, the top temperature is adjusted to give a specified rate of penetration, while in

Figure 1. Typical road structure.

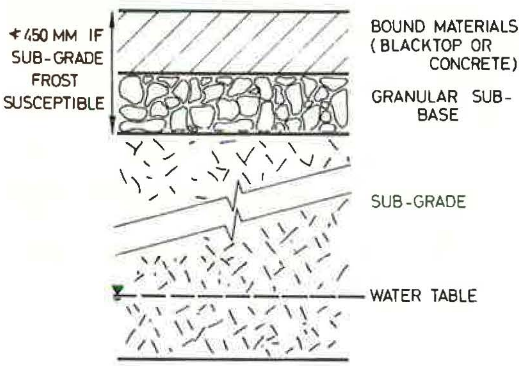
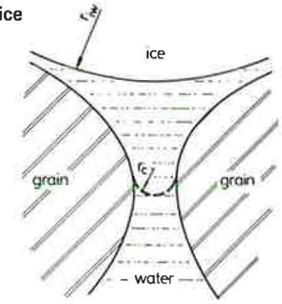


Figure 2. Capillary model of ice penetration.



the TRRL test the air temperature above the specimens remains constant. The classification of materials is, however, broadly similar for both tests (10). Several alternative direct tests have been proposed (11), including those in which the development of heaving pressure during restrained heave tests (which mirrors the heave in an unrestrained test) is measured.

In addition, many attempts have been made to assess frost susceptibility indirectly on the basis of material characteristics such as grain- or pore-size distributions (12). For example, an osmotic suction method has shown promise in ranking the frost susceptibility of limestone subbase materials (13). Nevertheless, whatever approach is used, there are considerable reservations about the accuracy of the assessment of frost susceptibility, and investigations, including those described in this paper, are continuing to develop simpler and more reliable methods.

Even so, the assessment of frost susceptibility of the materials subject to ice penetration is only a first step in determining the precautions necessary to prevent frost-heave damage. It is then necessary to assess whether the amount of heave of the road surface will be acceptable. The heave that can be tolerated will depend on the importance of the road, its construction, and economic factors. The actual heave will depend on climatic conditions (which largely control the depth of frost penetration), the depth of the water table, and the capillarity and effective permeability of the materials between the water table and the freezing front.

An additional factor when the freezing front remains in compacted materials (which is typical of British conditions) is that the density or grading of the material as compacted on site may differ from those achieved in the laboratory (14, Chap. 3).

Relationships between the results of laboratory frost-susceptibility tests and the design of actual roads built on or with the materials tested have been developed (9, 15). In Great Britain, where hard winters occur infrequently, the empirical correlation between laboratory and field performance originally made for subgrade soils has also been applied to subbases. The introduction of mathematical models, (16-20) mainly based on the capillary theory heralds a more rigorous approach not only to the interpretation of past and future field observations and pilot scale trials but also to the design process itself.

However, while progress has been made in several aspects of mathematical modeling, current models require further development to deal fully with the central problem of coupling the heat and water flows (21). We are developing an improved model in which we hope to quantify the variations in space and time of suction, suction gradient, and effective permeability in relation to one or more of the physical characteristics of the materials.

For steady-state conditions, the continuity equation requires that the product of suction gradient and effective permeability be constant. However, individually, neither the suction gradient nor the permeability (which is suction dependent) is constant (22, 23). In view of the complexities and uncertainties, any proposed mathematical model of frost heaving requires rigorous experimental verification before it can be adopted with confidence.

Against this background, precisely controlled direct frost-heave tests have a multiple role in providing (a) a measurement of frost susceptibility under standard conditions, (b) an insight into the frost-heaving process, and (c) a means of verifying proposed mathematical models. Although constant boundary temperature tests are simpler to perform than constant rate of penetration tests and have the advantage of subjecting all the specimens to the same conditions, the poor reproducibility of the original TRRL test (24) was of considerable concern.

This paper describes two developments of this type of test. The first deals with routine commercial testing and the move toward recognizing the self-refrigerated unit (SRU) rather than the cold room (CR) as the principal testing facility. The second development is of a precise freezing cell (PFC) incorporating Peltier cooling, in which a single specimen is subjected to closely controlled conditions. Results obtained in the various units are presented and the implications discussed.

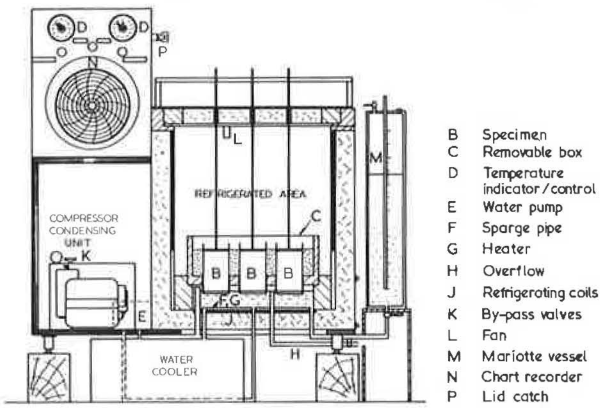
DEVELOPMENT OF THE TRRL TEST

In the TRRL test (9), nine cylindrical specimens 102 mm in diameter and 152 mm high are placed in an insulated trolley that is wheeled into a cold room operating at -17°C. The specimens rest on porous ceramic disks inside copper carriers. The disks are in contact with water maintained at +4°C. The sides of the specimens are wrapped with waxed paper and the intervening space filled with loose, dry sand (5-2.36 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 topping up of the water level are undertaken every 24 h. Materials are judged frost susceptible if, during 250 h, they heave more than 13 mm (in England and Wales) or 18 mm (in Scotland).

At Nottingham, improved repeatability resulted from modifications introduced to give a closer control of the water-bath temperature (25). More recently, a revised interim specification for the test has been introduced by TRRL in which the cold-room facility and procedure, including specimen preparation, is defined more closely (26). Granular specimens continue to be compacted in two stages (tamping in layers followed by static compac-

Figure 3. Self-refrigerated unit.



ting), but there have been significant changes in detail. A further revision is expected in which compaction by vibrating hammer and testing in an SRU will be included (27).

These changes have been anticipated in our laboratory where granular specimens have been prepared by precompaction in layers with a vibrating hammer followed by a final static compaction since 1973 (25). The static loads required are much reduced, less than 100 kN even for subbase aggregates, compared with the maximum of 400 kN needed by the TRRL procedure (26). The specimens are extruded from their molds by a hydraulic jack.

The TRRL interim specification stipulates that the air temperature shall be maintained at -17 ±1°C. However, during defrosting periods, which occur every 8 or 12 h in the cold rooms in current use, it is recognized that greater variations will occur. At Nottingham, evidence that the defrosting periods could significantly affect results was obtained from heaving pressure tests (22), and attention was switched to the development of an SRU in which defrosting during the test was unnecessary.

Development of SRUs in the United Kingdom commenced in the mid-1960s, when the TRRL test was adopted as a compliance test for subbase materials (28). Several workers developed chilled tank units (29, 30) or forced-air units (31). The former are similar to domestic deep freezes, but the latter have fan-assisted units that blow cold air over the specimens and are thus in effect miniature cold rooms. Only the forced-air units require defrosting during the test.

For this reason the chilled-tank principle was chosen for further development. A prototype (Figure 3) that incorporated satisfactory features of existing designs was developed in our laboratory in conjunction with P.S. Snow and Company of Leicester. Like most other British units, it was designed to operate under normal laboratory temperatures. The chilled tank is cooled by refrigerant circulating from a 0.4-kW compressor through tubes embedded within the walls. The internal dimensions of the tank and water bath, the configuration of specimens, and the specimen support system match those of the cold-room trolley.

Facilities additional to those then (1976) featured on commercially available units include a chart recorder that gives a continuous trace of air and water temperatures, independent cooling systems for air and water, an air-circulating fan, and a Mariotte tube (29) to maintain a constant water level throughout the 250-h test. In addition, an alternative inner box was made to permit testing of specimens 152 mm in diameter.

Previous SRUs had relied on the low temperature of the tank walls and the enclosed air space to promote sufficient cooling of the water bath. This had not always been successful, particularly in very hot summers (32), and a more positive system was thought necessary. Originally, a heat exchanger consisting of a coil wound around the copper pipe taking the refrigerant from the compresser to the tank cooling coils was fitted. This system gave unacceptable temperature fluctuations and was abandoned.

Two further systems were tried. First, cooling coils beneath the water bath, in series with the tank coils, were brought into use. Second, with these coils bypassed, using valve K (Figure 3), a separate water cooler was connected into the circuit. Although the independent cooler is preferred for research tests, the series coil system has been adopted for the subsequent units that are now available commercially. Fine control of the water temperature is obtained from heaters activated by a mercury contact thermometer. In the prototype unit, the standard deviation of the water temperature beneath the specimens is 0.35°C and that of the top of the specimen is 1°C when all nine specimens are considered.

THE PRECISE FREEZING CELL

Previous Work

Greater control of the temperature at the top of the specimen can be better achieved by direct refrigeration of an individual top cap than by controlling the temperature of the air space above a number of specimens. Direct refrigeration is conveniently provided by a thermoelectric device in which electric current passing through a series of dissimilar semiconductors exhibits the Peltier effect (33). This may be thought of as a reverse thermocouple so that cold and hot faces are produced. The cold plate is in contact with the specimen, and the hot plate is cooled by circulating cooling water. The heat extracted by the cold plate Q_c (watts) is given by

$$Q_c = a_m T_c I - \tfrac{1}{2} I^2 R_M - K_m \Delta T \quad (2)$$

where

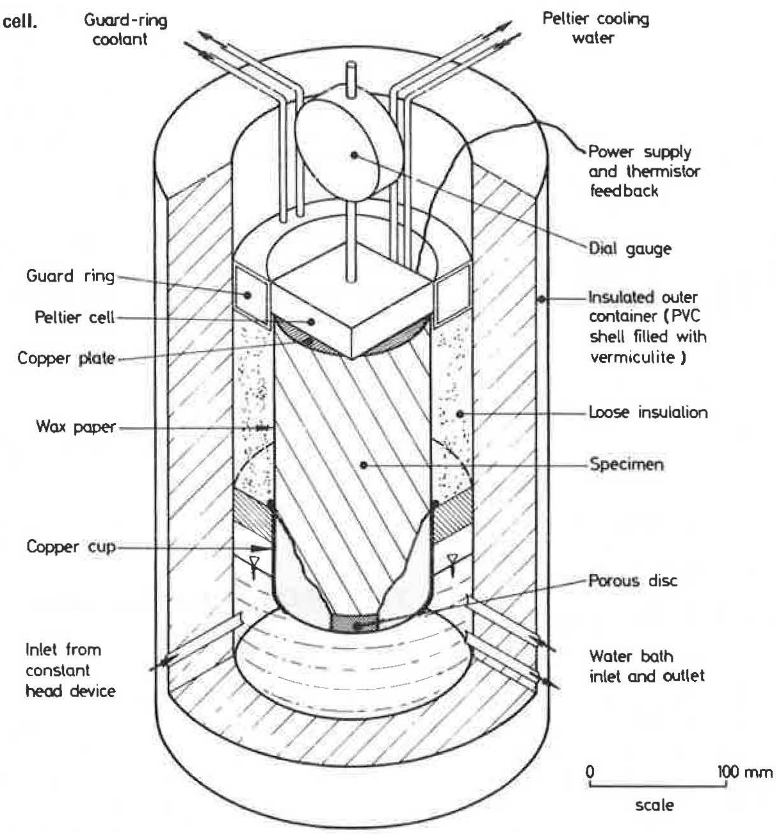
a_m = mean value of the Seebeck coefficient (V/K),
R_M = mean value of the resistance (ohms),
K_m = mean value of the thermal conductance (W/K),
T_c = temperature of the cold plate (K),
I = current (A), and
ΔT = difference between hot- and cold-plate temperatures (K).

Peltier cells of 16- to 88-W capacity have been used by many other investigators, particularly in connection with heaving pressure measurements (11, 34, 35), although proposals for using a Peltier device for heave measurements have been made (36). In the early days, Peltier devices were criticized for being costly and unreliable and for giving nonuniform temperature distributions (37), but their use in conjunction with servo-controls maintained temperatures within close limits (±0.02°C) (35). With improved semiconductor technology and quality control, the Peltier system appeared to be both feasible and economical for the maximum of four units envisaged in this research.

Description of the Cell

A cutaway isometric view of the cell is shown in Figure 4. The principal dimensions are 300 mm outside diameter, 200 mm inside diameter, and 400 mm overall height. The body is formed of thin PVC tubes closed at

Figure 4. Precise freezing cell.



their lower ends and separated by approximately 50 mm of vermiculite insulation. The lower part of the inside of the cell, being watertight, forms a water bath of 2.4-L capacity, which is serviced by three ports that pass through the cell wall. Two of these ports connect to a pumped circulatory system incorporating an external cooler operating at +4 ±0.1°C. The third port connects to a Mariotte vessel that provides a constant head supply similar to that used in the SRU (Figure 3). A scale on this vessel permits measurement of the rate at which water is taken up.

A wooden staging with a central hole enables thc specimen to be supported on a porous disk within a copper cup in exactly the same way as in the TRRL test. Likewise, the annular space was filled with loose, dry sand.

The specimen is surmounted by a copper plate of the same diameter on which the Peltier unit (Cambion 806-7242-01, 19-W capacity) rests. A coating of zinc-oxide-loaded silicon grease between the plate and the unit ensured good thermal contact. A thermistor, embedded in the lower face of the copper plate, is coupled to the feedback control capable of maintaining a constant temperature to within ±0.1°C. The Peltier unit was cooled by water that was run to waste. On top of the sand insulation is a guard ring through which methyl alcohol is circulated. The alcohol is cooled by being circulated through a coil in the adjacent cold room and maintains the guard-ring temperature at ±0.5°C. The heave was measured by a dial gauge fixed above the Peltier unit.

The cells are housed in a commercial refrigerator that has two chambers 0.5x0.5x1.2 m giving a +4 ±1°C environment. Cooling is from refrigerated coils and temperature uniformity is improved by using a small supplementary fan. Defrosting during testing is not necessary. With some difficulty, the refrigerator could accommodate four cells and their ancillary equipment, but to date the system has operated with two cells.

The capital cost per specimen of the PFC facility (including controller) is perhaps three times that of an SRU.

Control and Monitoring System

To ensure electronic stability, all the control and monitoring equipment is situated in a constant-temperature (21 ±1°C) enclosure.

Since the coefficients of Equation 2 are temperature dependent, a controller is needed to ensure either a constant rate of heat extraction or, as in this case, maintenance of constant temperature. The system adopted obviates the need for precise control of the cooling-water temperature and protects the Peltier unit from electrical overload.

Three power-pack and control units have been constructed, each of which provides a current of up to 6 A at not more than 5 V. The power supplied to the Peltier battery is regulated by the feedback signal from the thermistor embedded in the top cap. In controller 1 the feedback device operates as an on-off control to the power supply so that the temperature is maintained within the tolerance. The operating voltage can be set manually to give some control of the rate of cooling. A proportional system is used in controllers 2 and 3 so that the rate of cooling slows down as equilibrium is approached. In principle, the second method should give more precise control. However, the damping effect of the thermal mass of the Peltier battery and the top cap masks this effect, and the control achieved by the two types of unit is not significantly different.

Controllers 1 and 3 are fitted with a cycling facility. Essentially, each has two channels that could be set at

Figure 5. Thermocouple positions and vertical temperature gradient.

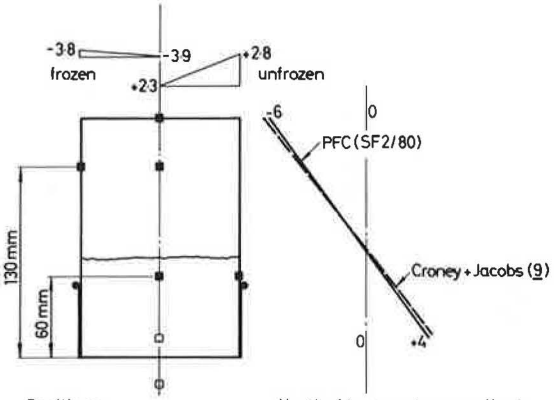
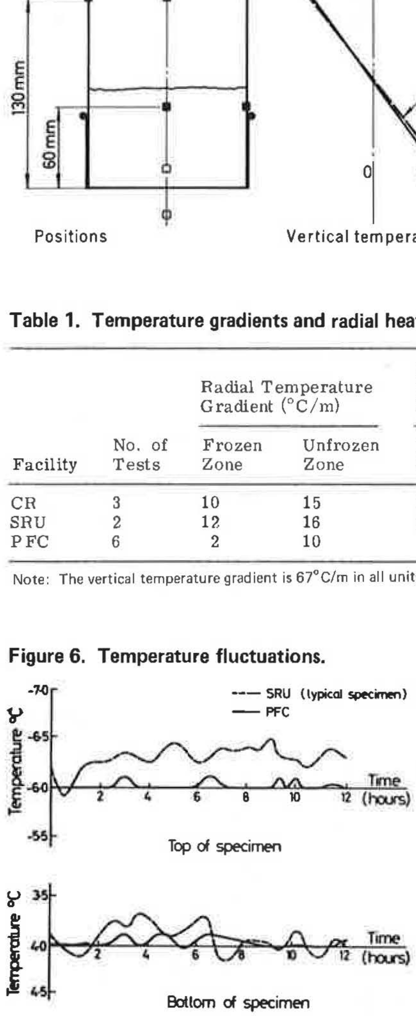


Table 1. Temperature gradients and radial heat flow.

Facility	No. of Tests	Radial Temperature Gradient (°C/m) Frozen Zone	Unfrozen Zone	Ratio of Radial Heat Flow to Vertical Heat Flow (x 100%) Frozen Zone	Unfrozen Zone
CR	3	10	15	15	22
SRU	2	12	16	18	24
PFC	6	2	10	3	15

Note: The vertical temperature gradient is 67°C/m in all units.

Figure 6. Temperature fluctuations.



different subzero temperatures. After completing a period of between 2 and 32 h at the lower temperature, the specimen is allowed to warm naturally to the higher temperature, at which it is maintained by the controller for the remainder of the time interval before the cycle is repeated. Controller 3 can be used in conjunction with a guard ring that contains two 19-W Peltier units so that the guard-ring temperature can also be cycled.

Temperature measurements are made using copper constantan thermocouples in conjunction with a reference oven that gives a system accurate to ±0.1°C. The thermocouples are connected to a 70-channel data logger with a punched tape output that permits continual scanning at intervals as long as 2 h.

Test Procedure

The specimen is compacted first by vibrating hammer (3 s on each of three layers), then by static compaction. Thermocouples are positioned as required, and the apparatus set up as described previously. The specimen is left to equilibriate in the refrigerator at +4°C for 24 h.

The controller is then switched on to initiate freezing. In the standard test, both the controller and the guard-ring system are adjusted to give -6°C. This value was chosen as typical of the top-of-specimen temperatures achieved in the cold room and SRU. The full current of 6 A is available for cooling as necessary. In the retarded test, on the other hand, the maximum available current is stepped manually, 0.5 A every 4 h, eventually reaching 6 A. This gives a much slower rate of penetration. Daily readings of temperature and water level are taken.

In both types of test, it was frequently found that all heave had ceased before 250 h had elapsed. Tests were terminated when the heaving rate became negligible (<0.1 mm/day), i.e., after five days in the series of tests described below.

RESULTS AND DISCUSSION

Temperature Control

Concrete dummy specimens, 102 mm in diameter and 152 mm high, in which thermocouples had been inserted in predrilled holes at the positions indicated in Figure 5, were used to investigate fluctuations in temperature. The thermocouples were bedded in plasticine to ensure good thermal contact and stable positioning. Concrete specimens were used because (a) they do not change significantly between tests, (b) they are not subject to heave that would change the elevation of the thermocouples, and (c) freezing has relatively little influence on the thermal properties of concrete.

Typical temperature gradients achieved in the various facilities are shown in Figure 5 and Table 1. The values in Table 1 are the results of readings taken every hour throughout the test. Spurious readings obtained during the passage of the zero isotherm through the thermocouple position have been ignored. The readings for radial heat flow as a percentage of the vertical flow indicate how nearly the condition of unidirectional flow is approached. The PFC is better than the other units, and within the frozen zone the radial heat flow is very small.

Individual temperature gradients in the frozen zone in the PFC were within ±0.1°C/m of the mean and the other individual radial gradients were within ±1°C/m of the mean. The improved performance of the PFC compared to the other units is presumably due to its being operated in a +4°C environment. Conversely, the very cold air circulating in the gap between the inner box and the tank walls is the most likely cause of the relatively high radial flow noted in the SRU. Filling this gap with insulating material may give some improvement.

In all the units the radial heat flow in the unfrozen zone is much higher than in the frozen zone, which probably reflects the influence of the copper specimen carriers. Substituting plastic carriers and lowering the staging to reduce the air gap might be advisable in the PFC, particularly when it is used to verify mathematical models. Although such changes would reduce the similarity of conditions in the PFC to those currently specified in the TRRL test, the benefits would appear to outweigh this disadvantage.

Typical temperature fluctuations are shown in Figure 6. Although the SRU top and bottom temperatures for the single specimen are both within the ±0.5°C specified for the water bath (26), the much better performance of the PFC is obvious. Furthermore, the bottom-of-specimen temperature in the SRU averages slightly below +4°C because of temperature gradients through

Figure 7. Penetration of zero isotherm.

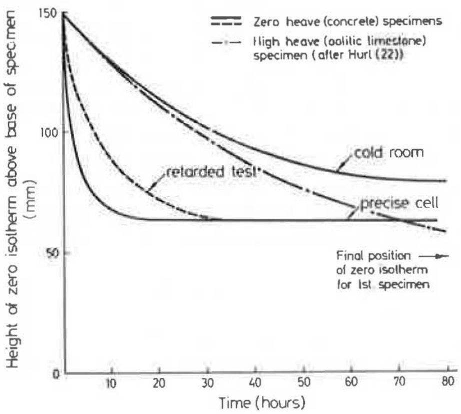


Figure 8. Grading curves.

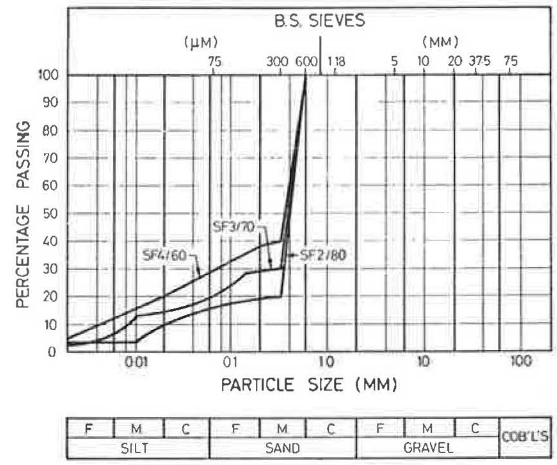
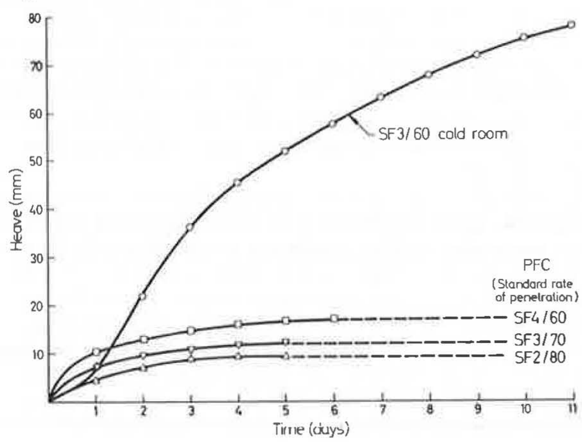


Table 2. Heave of sand and limestone filler mixtures.

		Cold Room and SRU Tests			PFC Tests				
Material	Facility	No. of Tests	Mean Heave, H_T (mm)	SD (mm)	Rate of Penetration	No. of Tests	Mean Heave, H_p (mm)	SD (mm)	H_p/H_T (x 100%)
SF 2/80	Both	39	20.1	2.4	S	10	6.7	1.1	33.3
					R	7	9.3	0.8	
SF 3/70	CR	3	44.2	6.4	S	8	13.9	1.0	31.4
SF 3/60	CR	9	76.7	6.7					(24.5)
SF 4/60					S	8	18.8	2.4	

Note: SF is sand and limestone filler mixture; S is standard; R is retarded rate of penetration. SF 3/60 and SF 4/60 have the same proportions and nominal grading but are derived from different batches of filler. Their frost susceptibilities may be slightly different.

Figure 9. Curves for heave versus time.



the porous disk. The PFC system is adjusted to give +4°C at the base of the specimen. Figure 7 shows that rate of penetration of the zero isotherm even in the retarded test is much faster in the PFC than in the cold-room test. The implications of this will be discussed in the next section.

Heave Tests

A series of tests was performed on sand-limestone filler mixtures. Standard Leighton Buzzard sand in the size range of 600-300 μm was mixed with limestone filler in various proportions to give the gradings shown in Figure 8. Specimens of the sand and limestone filler mixtures (SF) were compacted to the maximum dry density at the optimum moisture content (38) are given below.

Material	Optimum Moisture Content (%)	Maximum Dry Density (Mg/m^3)
SF 2/80	9.0	2.00
SF 3/70	9.5	2.01
SF 4/60	9.9	2.03

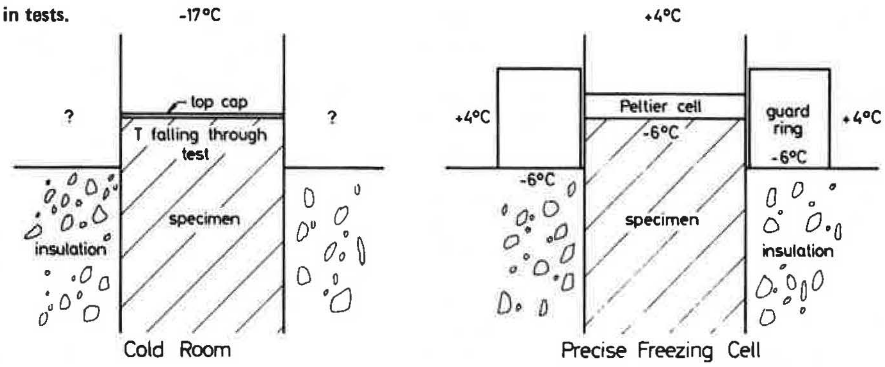
As previous investigators have found (28, 30), the heaves obtained in the cold room and SRU were not significantly different (39); either can be used as a reference against which the PFC results can be judged. The results obtained are summarized in the table below. Details of individual PFC results are given in Table 2, and typical curves for heave versus time are shown in Figure 9.

Heave (mm)

SF 2/80		SF 3/70	SF 4/60
Standard	Retarded	Standard	Standard
8.0	9.5	14.5	16.5
8.0	9.1	14.8	16.9
6.7	10.7	14.1	18.3
4.8	9.0	11.8	21.9
7.0	9.7	13.9	17.0
5.0	8.7	14.4	17.1
6.5	8.0	14.2	20.8
7.2		13.7	22.3
6.8			
7.1			

The striking feature of these results is the much lower heaves obtained in the PFC than in the other units. Furthermore, the ratio of PFC heave to CR-

Figure 10. Boundary conditions in tests.



SRU heave decreases with increasing heave. Since the sidewall conditions are similar, friction and adfreezing can be discounted as possible explanations. The surcharge from the pressure of the Peltier unit (1 kPa) is also much too small to account for the effect.

More probable explanations are to be found in differences in (a) the rate of penetration of the zero isotherm and (b) the application of the boundary conditions. It was postulated earlier that ice segregation occurs when the suction is too low and the temperature is correspondingly too high to permit ice penetration. Thus, during the penetration isotherm (PI) stage, a slow rate of heat extraction favors the growth of intermediate ice lenses. A fast penetration of the zero isotherm, on the other hand, yields high heaving rates (40) associated with maximum suction (22). The high rates, however, occur for a limited time, so that the total heave observed is less than with a lower heaving rate extending over a longer period.

Intermediate ice lenses (rhythmic ice banding) are associated with the PI stage. As equilibrium approaches, the isotherms cease to penetrate and may even recede slightly. In this nonpenetrating isotherm (NPI) stage, the terminal lens will continue to grow until the heat input and output are balanced. In general, a terminal lens will commence under PI conditions and end with NPI conditions. With rapid heat extraction, the PI stage will be short, which will lead to low overall heave. The greater heave experienced in the retarded penetration test (Table 2) affirms this explanation.

Closer examination of the temperature boundary conditions applied in the PFC compared with those in the cold room (Figure 10) indicates a significant difference. Essentially, in the PFC the constant temperature is applied to a moving boundary, while in the cold room the constant temperature is specified and maintained at the level of the top of the trolleys. Immediately above the specimens, the temperature tends to be raised somewhat higher by heat conducted from below.

The temperatures in the SRU are intended to be similar to those in the cold room. Thus, in both units a high-heaving specimen experiences considerable additional cooling from its sides as it protrudes above the sand insulation. Consequently, the final position of the zero isotherm becomes lower as the heave (after 250 h) increases (Figure 7). In practice, the TRRL test condition appears to approximate a constant boundary temperature at the level of the original top surface of the specimens. It is arguable that the PFC more nearly reflects field conditions.

While the very wide range of heave values experienced in CR and SRU tests should make for easier classification, this advantage is offset by the greater scatter obtained with high-heave specimens. The above interpretation suggests that particular attention should be given to obtaining uniform air temperatures in the CR and SRU within the zone into which specimens heave.

Further Work

The comparison between the performance of the PFC and those of the other facilities needs to be extended to other materials, including subbase aggregates. Also, we intend to test specimens of rock cores that have been split horizontally. The feedback thermistor will be placed in the split so that an ice lens can be formed at that level. The results will be compared with those from compacted aggregate specimens on identical rock. Thus we hope to gain further insight into the relative contributions that within-particle and between-particle pore systems (13) make to frost heaving of aggregates. Pilot studies in the cold room have indicated that this technique is feasible.

The PFC, with its close control of temperature and water level, offers considerable benefit in the study of many variables such as suction, suction gradient, heat, and water flow required in the development of mathematical models. The apparatus can be adapted to measure thermal conductivity in the vertical direction; this is an alternative to the radial measurement obtained in the line source method (41). However, its major value is likely to be in verifying the predictions made with mathematical models. We hope that the cycling facility, yet to be evaluated, will enable the effects of diurnal temperature variations to be modeled.

For most of these applications, which are essentially of a research nature, the temperature stability of the present cold room and SRU are inadequate. We anticipate, however, that the continued development of techniques will enable routine testing in the foreseeable future to be undertaken in the SRU.

CONCLUSIONS

1. A precise freezing cell (PFC) has been constructed in which freezing is achieved in an open system by the application of constant boundary temperatures controlled to ±0.1°C. The temperature stability of the PFC is much better than that of the cold rooms and self-refrigerated units currently being used for routine testing in the U.K.
2. The radial heat flow in the frozen zone (3 percent of the vertical flow) is small, so a close approximation of unidirectional flow is achieved. Conditions are less satisfactory in the unfrozen zone, and modifications to improve this situation are proposed.
3. In two years' operation, the PFCs have proved quite reliable and less prone to minor faults than the other facilities.
4. For identical specimens, the heave achieved in

the PFC is much less than that in a cold room or SRU. The ratio of PFC to SRU heave decreases as heave increases.

5. The reduction in heave is due partly to the greater heat extraction rate and partly to constant boundary temperatures being applied to a moving level rather than to a fixed level.

6. For the present, routine testing in Great Britain is likely to continue in cold rooms and SRUs because the capital cost per specimen is only about a third of that for the PFC. Nevertheless, the PFC has a useful role in highlighting areas where modifications might be made to the standard test to give improved reproducibility.

7. Some form of precise cell is considered essential for research purposes, particularly for the development and verification of mathematical models. The apparatus described appears well suited for this purpose.

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REFERENCES

1. E. Penner. Frost Heaving in Soils. Proc., 1st International Conference on Permafrost. Purdue Univ., West Lafayette, IN, 1963, pp. 197-202.
2. D.H. Everett and J.M. Haynes. Capillary Properties of Some Model Pore Systems with Special Reference to Frost Damage. International Union of Testing and Research Laboratories Materials and Structures, Paris, Bull. New Series 27, 1965, pp. 31-38.
3. P.J. Williams. Properties and Behaviour of Freezing Soils. Norwegian Geotechnical Institute, Oslo, Publication 72, 1967.
4. H.B. Sutherland and P.N. Gaskin. Pore Pressure and Heaving Pressures Developed in Partially Frozen Soils. Proc., 2nd International Conference on Permafrost, Yakutsk, Yakutsk Autonomous Soviet Socialist Republic, National Academy of Sciences, Washington, DC, 1973, pp. 409-419.
5. S. Taber. Freezing and Thawing of Soils as Factors in the Destruction of Road Pavements. Public Roads, Vol. 11, No. 6, 1930, pp. 113-132.
6. J.F. Haley and C.W. Kaplar. Cold Room Studies of Frost Action in Soils. HRB, Special Rept. 2, 1952, pp. 246-247.
7. K.A. Linell and C.W. Kaplar. The Factor of Soil and Material Type in Frost Action. HRB, Bull. 225, 1959, pp. 81-126.
8. C.W. Kaplar. A Laboratory Freezing Test to Determine the Relative Frost Susceptibility of Soils. Cold Regions Research and Engineering Laboratory, Hanover, NH, CRREL Technical Note, 1965.
9. D. Croney and J.C. Jacobs. The Frost Susceptibility of Soils and Road Materials. British Road Research Laboratory, Crowthorne, England, LR Rept. 90, 1967.
10. H.B. Sutherland and P.N. Gaskin. A Comparison of the TRRL and CRREL Tests for Frost Susceptibility of Soils. Canadian Geotechnical Journal, Vol. 10, No. 3, 1973, pp. 553-555.
11. S.F. Obermeier. Frost Heave Susceptibility Research. Proc., Symposium on Frost Action in Roads, Organization for Economic Cooperation and Development, Paris, 1973, Vol. 1, pp. 251-266.
12. D.L. Townsend and T.I. Csathy. A Complication of Frost Susceptibility Criteria Up to 1961. Queens Univ., Kingston, Ontario, Rept. 14, 1961.
13. R.H. Jones and K.G. Hurt. An Osmotic Method for Determining Rock and Aggregate Suction Characteristics with Applications to Frost Heave Studies. Quarterly Journal of Engineering Geology, Vol. 11, No. 3, 1978, pp. 245-252.
14. R.H. Jones. Frost Damage and Its Prevention. In Developments in Highway Pavement Engineering (P.S. Pell, ed.), Applied Science Publishers, Barking Essex, 1978.
15. K.A. Linell, F.B. Hennion, and E.F. Lobacz. Corps of Engineers' Pavement Design in Areas of Seasonal Frost. HRB, Highway Research Record 33, 1963, pp. 76-128.
16. R.L. Harlan. Analysis of Coupled Heat-Fluid Transport in Partially Frozen Soils. Water Resources Research, Vol. 9, No. 5, 1973, pp. 1314-1323.
17. S. Outcalt. A Numerical Model of Ice Lensing in Freezing Soils. Proc., 2nd Conference on Soil-Water Problems in Cold Regions, Edmonton, Alberta, 1976, pp. 63-74.
18. G.S. Taylor and J.N. Luthin. Numerical Results of Coupled Heat-Mass Flow During Freezing and Thawing. Proc., 2nd Conference on Soil-Water Problems in Cold Regions, Edmonton, Alberta, 1976, pp. 155-172.
19. J. Aguirre-Puente, M. Fremond, and J.M. Menot. Gel dans les Milieux Poreux Permeabilite Variable et Mouvements d'Eau dans la Partie a Temperature Negative. Proc., International Symposium on Frost Action in Soils, Lulea, Sweden, 1977, Vol. 1, pp. 5-28.
20. R.L. Berg, K.E. Gartner, and G.L. Guymon. A Mathematical Model to Predict Frost Heave. Proc., International Symposium on Frost Action in Soils, Lulea, Sweden, 1977, Vol. 2, pp. 92-109.
21. E. Penner. Discussion. Proc., International Symposium on Frost Action in Soils. Lulea, Sweden, 1977, Vol. 2, p. 46.
22. K.G. Hurt. The Prediction of the Frost Susceptibility of Limestone Aggregates with Reference to Road Construction. Univ. of Nottingham, Ph.D. thesis, 1976.
23. A. Onalp. Calculation of Water Transport in the LR 90 Test. Proc., Colloquium on Frost Heave Testing and Research (R.H. Jones, ed.), Univ. of Nottingham, 1977, pp. 115-126.
24. Annual Report. U.K. Transport and Road Research Laboratory, Crowthorne, England, 1971, p. 83.
25. R.H. Jones and K.G. Hurt. Improving the Repeatability of Frost Heave Tests. Highways and Road Construction, Vol. 43, No. 1787-8, 1975, pp. 8-13.
26. The LR 90 Frost Heave Test—Interim Specification for Use with Granular Materials. U.K. Transport and Road Research Laboratory, Crowthorne, England, Supplementary Rept. 318, 1977.
27. Research on the Frost Susceptibility of Road Making Materials. U.K. Transport and Road Research

Laboratory, Crowthorne, England, Leaflet 611, April 1976.
28. G.R. Nellist. An Apparatus for Testing the Resistance of Road Making Materials to Frost Damage. Journal of Scientific Instruments, Vol. 44, 1967, pp. 553-555.
29. A. Onalp. The Mechanisms of Frost Heave in Soils with Particular Reference to Chemical Stabilization. Univ. of Newcastle upon Tyne, Ph.D. thesis, 1970.
30. R.J. Kettle and R.I.T. Williams. The Development of Frost Testing Equipment. International Union of Testing and Research Laboratories Materials and Structures, Paris, Vol. 6, No. 34, 1973, pp. 299-305.
31. Frost and Susceptibility of Materials. Highway and Traffic Engineering, June 1971, pp. 23-24.
32. J. Hill. Self Refrigerating Units: Frost Cabinet Temperature Distribution. Proc., Colloquium on Frost Heave Testing and Research (R.H. Jones, ed.), Univ. of Nottingham, 1977, pp. 23-27.
33. W. Lechner. Peltier Cooling. Philips Technical Review, Vol. 27, No. 5, 1966, pp. 113-130.
34. P. Hoekstra, E. Chamberlain, and T. Frate. Frost Heaving Pressures. HRB, Highway Research Record 101, 1965, pp. 28-38.
35. P.J. Williams. Thermoelectric Cooling for Precise Temperature Control of Frozen and Unfrozen Soils. Canadian Geotechnical Journal, Vol. 5, No. 4, 1968, pp. 265-267.
36. R.J. Kettle and R.I.T. Williams. Frost Heave and Heaving Pressure Measurements in Colliery Shales. Canadian Geotechnical Journal, Vol. 13, No. 2, 1976, pp. 128-138.
37. C.W. Kaplar. New Experiments to Simplify Frost Susceptibility Testing of Soils. HRB, Highway Research Record 215, 1968, pp. 48-58.
38. Methods of Tests for Soils for Civil Engineering Purposes. British Standards Institution, London, BS:1377, 1975.
39. S.J-M. Dudek. A Preliminary Assessment of the Design and Performance of Frost Susceptibility Testing Facilities. Proc., Colloquium on Frost Heave Testing and Research (R.H. Jones, ed.), Univ. of Nottingham, 1977, pp. 13-21.
40. C.W. Kaplar. Phenomenon and Mechanism of Frost Heaving. HRB, Highway Research Record 304, 1970, pp. 1-13.
41. R. McGaw. Thermal Conductivity of Compacted Sand/Ice Mixtures. HRB, Highway Research Record 215, 1968, pp. 35-47.

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Subdrainage with a Sand Backfill as a Positive Influence on Pavement Performance

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Expansive soils are an estimated $4 billion-a-year problem in the United States. They cause severe distortion in many human works, including highways. Subdrainage has been used extensively in attempts to intercept or remove excess moisture from expansive clays. Minimizing moisture change is seen as a way of reducing surface distortion and improving pavement performance. Underdrains have been used on many highways to remove excess subsurface water, and one Texas study revealed that their use in expansive soils results in a mixed pattern. The effectiveness of deep underdrains with sand backfill is now being examined. The sand is used to provide a moisture reservoir and stabilizer for the expansive clay and the underdrain will remove the moisture the sand cannot hold. A field test of an Israeli experiment is being conducted on a roadway section, which has resisted considerable previous attention, on US-90 west of D'Hanis and Hondo, Texas. This section cuts through a limestone crust into a clay and has had repeated level-up courses of asphalt. Lime had been placed in holes 45 cm (18 in) in diameter, 1.5 m (5 ft) deep, and on centers. In this test 381 m (1250 ft) of 15.24-cm (6-in) slotted underdrain pipe was placed 2.4 m (8 ft) deep; the sand backfill was placed along the south roadway crown line. Observations indicate that maximum movements are taking place on the nonunderdrained side in 9 of the 12 sections and are averaging three times the movement on the underdrained side. Expansive soil movement under existing pavements probably can be reduced by sand-backfilled underdrains.

Swelling soils cause an estimated $4 billion a year in damages in the United States. More than half of this occurs in our transportation facilities: highways, railroads, airport runways, sidewalks, bikeways, and canals. Even this estimate is probably conservative.

The original $2 billion a year (1) estimated in 1973 reflected the lower side of industry estimates. Pavements damaged by these soils are usually repaired with asphalt products or other equally energy-intensive materials. As long as the price of a barrel of oil rises and other energy sources rise sympathetically, even extending cost increases makes the latest estimate lower than it actually should be.

What can be done about damaged transportation facilities? The roadways that represent half of the damages offer several possibilities. First, we can build them differently in the future and avoid expansive clay areas or remove a significant amount of it, treat it deeply with lime, pond it, or seal off the zones of activity with asphalt, lime, or fabric. All are worthy suggestions. However, some of these concepts do not adapt well to the existing roadway, runway, sidewalk, bikeway, or canal. Their remedy is the asphalt patch, asphalt level-ups, or total replacement.