Developments in the British Approach to Prevention of Frost Heave in Pavements

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In Britain, frost heave (and also thaw weakening) is prevented by ensuring that all materials within 450 mm of the road surface are non-frost susceptible as defined by the Transport and Road Research Laboratory test, the latest version of which is known as the SR829 test. Materials are not frost susceptible if their mean heave in valid SR829 tests is not greater than 12 mm. For materials close to the borderline, tests are required at three different laboratories to define the mean heave. The test, which now has improved reproducibility, is to be included in British Standard Specification 812. In this paper the evolution of the test is summarized and the implications of the revisions and of other factors in design, such as depth of frost penetration and the availability of water, are examined critically. Results of a series of tests are presented that show that the British frost-susceptible materials correlate with the "highly frost-susceptible" classification in the United States and French systems. Particle size distribution and saturation moisture content are shown to be poor indicators of the frost susceptibility of aggregates, because neither can reflect the contribution of between-particle and within-particle pore size distributions. Suction characteristics, determined by an osmotic technique, overcome this shortcoming and correlate well with the frost susceptibility of the materials tested.

For almost 20 years British specifications have required that all material within 450 mm of the road surface be non-frost susceptible on the basis of the Transport and Road Research Laboratory (TRRL) test. Both the test and the limits have evolved during that period; the latest version being SR829 *(1)*. This approach, which automatically controls thaw weakening, implies that

1. Frost-susceptible materials can be identified by the TRRL test and hence both reproducibility of the test and the classification applied to the results are adequate.
2. There is a strong probability that frost will penetrate to a depth of 450 mm during the design life of the road.
3. A supply of water to feed the freezing frost is readily available.

These implications are discussed in the light of recent developments. The correlation between the British classification system and those used in both the United States and France is then examined on the basis of experimental results. Finally, the physical properties of aggregates that render them frost susceptible are considered and guidance is given on the best way of using borderline materials.

THE TRRL FROST-SUSCEPTIBILITY TEST

The test has its origins in early work in the United States *(2, 3)*. By the 1950s procedure was standardized within the then-titled Road Research Laboratory (RRL) *(4)* and was essentially that described in LR90 *(5)*.

The test's introduction into compliance testing began with the publication of the 1965 edition of Road Note 29 *(6)* and was completed with the issue of the fourth edition of the *Specification for Road and Bridgeworks* in 1969 *(7)*. Following difficulties with poor reproducibility, both the test and its interpretation have been revised in the last 15 years. TRRL reports SR318 *(8)*, MM64 *(9)*, and SR829 *(1)*, together with advice and instructions issued by the Department of Transport (DTp), the Scottish Development Department (SDD), and the Welsh Office, and also new editions of the *Specification for Road and Bridgeworks* issued in 1975 and 1986, detail these changes.

The SR829 Test in Relation to Its Predecessors

The SR829 test is undertaken on 102-mm dia × 152-mm high specimens compacted with a vibrating hammer to the maximum dry density at optimum moisture content. Particles larger than 37.5 mm are removed before compaction.

Nine such specimens, encircled in waxed paper, are placed on porous stones in contact with water (at + 4° ± 0.5°C) in a self-refrigerated unit (SRU) in which the water level is maintained automatically *(10)*.

The space between the specimens is filled with loose dry sand so that the specimens are frozen vertically downwards for 4 days when the air temperature above them is lowered to −17° ± 1°C. Before freezing, the specimens are allowed to temper (that is, imbibe water) for 5 days. During freezing, the air, water, and specimen boundary temperatures are measured routinely at selected points and the heave of individual specimens is measured daily.

Normally, specimens are tested in sets of three. For an initial test to be valid, the temperature should be within specified limits; the mean heave should not be suspiciously low (<2 mm); and, if the mean heave is less than 18 mm, the range of individual results should not be more than 5 mm. If a wide spread is obtained, the test is repeated using six specimens. Materials are immediately classified if the mean heave, in a valid test, is either less than 9 mm or more than 15 mm as non-frost susceptible and frost susceptible, respectively. If the mean heave is between 9.1 and 14.9 mm, further tests are required at two other laboratories. The material is then classified as non-frost susceptible if the grand average heave is less than 12 mm.

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The evolution of the test from LR90 to SR829 is summarized in Table 1. Significant developments include

- The introduction of SRUs,
- The change to vibratory compaction,
- Shortening the freezing period (from 250 to 96 hr),
- Lengthening the tempering period (from 24 to 115 hr), and
- The possible involvement of several laboratories to classify a single material.

The reduction in the freezing period has been suggested by many previous investigators. The increase in tempering time was introduced following indications, from a series of tests on sand/limestone filler specimens, that it would result in improved repeatability *(11)*. Subsequently, a few tests on real aggregates indicated a marginal improvement in repeatability that was accompanied by a slightly increased heave. An unwelcome side effect of this change is the loss of an early warning of probable noncompliance that was particularly useful to contractors during the tendering period. It is too early to evaluate the effects of the possible need to test at three laboratories before classification, but concern has been expressed about both the time and costs involved. Currently there are some three dozen SRUs in Britain, although not all are in independent test houses.

As far as the test is concerned, there has been a marked improvement in reproducibility, which is quantified as the value below which the absolute difference between two single test results obtained by the same method, in different laboratories with different operators, may be expected to be within a probability of 95 percent. A study on the same batches of materials indicated a reproducibility value of 6 at a mean heave of 12 mm *(1)*. This estimate was based on trials with both sand/limestone filler mixes and a hoggin (gravel-sand-fines). A later trial with a flint gravel *(12)* gave a reproducibility of 9 on a mean heave of 13.5 mm. These trials have attempted to measure the precision of the test and do not include sampling error or variations in target density and moisture content. However, the inherent variability of specimens [which may be high, particularly for a flint gravel *(10)*], is included. Further work is being considered to obtain a more reliable estimate of the precision of the test over a greater range of materials.

The new procedure is intended to be applied to a source rather than a routine control. The importance of proper sampling cannot be overemphasized. In particular, sampling and testing of recovered material from compacted subbases is at best problematical *(13)*.

Background on the British Classification Limits

The upper limit of 13 mm (after 250 hr of freezing) for non-frost susceptibility (given in LR90) was based on a limited amount of field evidence, some of which was obtained from subgrades rather than subbases, dating back to the 1940s *(14)*. Because the subbase effectively replaced subgrade when thicker pavements were introduced, the same limits were thought appropriate *(5)*. Croney *(4)* summarized a few more recent failures including the Preston By-Pass in 1958 and the 1962/1963 incidents at Maidstone By-Pass (M20) and the Ross Spur (M50). A common feature was the use of frost-susceptible material with little more than 300 mm cover.

Preston is particularly interesting because the wet-mix limestone base, having a 250-hr heave of up to 15 mm and a cover of only 85 mm of surfacing, did not appear to heave significantly. The problem was with the compacted colliery shale subbase (which had a 250-hr heave of up to 65 mm). Subsequently, the 250-hr limit of 13 mm was maintained in England and Wales. However, after 1972, for well drained roads with impermeable surfaces, a 250-hr limit of 18 mm was applied in Scotland, where all the testing was undertaken in a single laboratory.

For 96-hr freezing tests, the limit set at 10 mm for the MM64 procedure was increased to 12 mm in SR829. For tests with 1-day tempering, the direct equivalence was probably nearer 10 mm. However, the effects of increased tempering time, backed by engineering judgment based on the known performance of, say, carboniferous limestone over many years, suggest that the limit of 12 mm for the SR829 procedure is appropriate. These developments should obviate the need for special consideration for Scotland.

DEPTH OF FROST PENETRATION

The general use of 450 mm of frost penetration for design has been reexamined recently *(15)*.

The mean annual freezing index was obtained for nearly 50 meteorological stations throughout Britain for the period 1959 to 1979 (Figure 1). The maximum freezing index for a single winter was 302 (for 1962/1963, the coldest winter for nearly 200 yr). The grand mean was 50°C days, which corresponds to a frost penetration somewhat in excess of 250 mm. For three sites a freezing index exceeding 50 was not recorded in the study period, and for a further five this figure was only exceeded in 1962/1963. It would appear that the appropriate design depth for frost penetration should vary within the range 200 to 450 mm, depending on the location. A more detailed study of 1959 to 1981 data was undertaken for seven sites. However, still further research, particularly into the effects of bridging periods (intervals of, say, up to 3 days during which the temperature does not rise above +1°C) is needed before appropriate design depths can be assigned with confidence. The same quality of non-frost susceptible material will be required within the design depth but savings may be achieved by using poorer materials beneath.

AVAILABILITY OF WATER

The dramatic reduction of frost heave because of a low water table or an impermeable subgrade has been demonstrated by tests at TRRL in which full-scale freezing of road structures was simulated in 1.5-m deep test pits *(16–18)*. On average, lowering the water table depth from 0.6 m to 1.4 m reduced the surface heave from about 70 mm to less than 10 mm.

The number of subbase/subgrade combinations that can be investigated at full scale in a pit is limited. To provide further information, a series of TRRL frost-susceptibility tests was undertaken on composite specimens in which the bottom portion was subgrade soil and the remainder represented

TABLE 1 EVOLUTION OF THE TRRL TEST

	LR90 (1967)	SR318 (1977)	MM64 (1981)	SR829 (1984)
PRELIMINARY				
Sample Size		200 Kg (64 Kg for FH)	200 Kg (60 Kg for FS)	500 Kg (100 + 200 Kg for FS)
Grading		Representative	Nearest average (Must comply with D.Tp. Spec.)	Truly representative & BS812: Pt102: 1984
D_{100}/mm	50	37.5	37.5	37.5
MDD + OMC	Test 12 (BS1377)	as LR90	Test 14 BS1377 or MVHT (BS5835)	BS5835 Pt 1: 1980 or Test 14 BS 1377:1975
SPECIMEN PREP				
No. of Specimens			3 (then 9 if needed)	3 (plus 6 if needed; then 3 or 6 at different lab (4))
Mixing			Machine (after 16 hours tempering)	Machine (after 16 hrs tempering)
Compaction	Rodding + Static (>300kN)	Tamping (3 layers) + static (>400 kN) (Gap <2mm)	Tamping + vibrating hammer (3 layers) Gap $\not>$2mm	Tamping + vibrating hammer (3 layers) Gap $\not>$ 4mm
FREEZING				
Facility	CR	CR (/SRU)	SRU	SRU
Temperatures - Water	+4°C	+4 ± 0.5°C	+3.5 to +4.5°C (3)	+3.0 to +4.5°C (3)
Air	-17°C	-17 ± 1.0°C	-16 to -18°C (3)	-16 to -18°C (3)
Monitoring			10 Thermocouples	10 Thermocouples
Test duration				
Tempering /days	1	1	5	5
Freezing /days	10	10	4	4
Criteria for validity of test (assuming temperatures OK)			Range (of 3) > 5 mm s.d. (of 9) > 3 mm	1) Range $\not>$ 5mm (for 2<H <18mm) 2) H > 18mm 3) Repeat if H < 2mm or if >2 No. (from 9). specimens show heave drop > 1mm.
REPORTING		H_1 H_2 H_3; H	H_1 H_2 H_3 ...; H ρ_d + w PSD bulk PSD trial specimen	H_1 H_2 H_3 ...; H. ρ_d + w PSD bulk PSD trial specimen
UPPER LIMIT OF HEAVE/mm FOR NFS (1)	13 (2)	13	10	12

SYMBOLS: H_1 H_2 etc = heave of individual specimens H = average of set. CR = Cold Room.

NOTES (1) Limit for SR318 and MM64 test specified separately by D.Tp. Based on 'grand average' heave of valid tests. NFS = non frost susceptible. (2) Metric equivalent. (3) Subject to more detailed requirements (see Appendix 2 of MM 64 or SR829 respectively.) (4) Tests at different labs if first lab obtains average between 9.1 and 15mm.

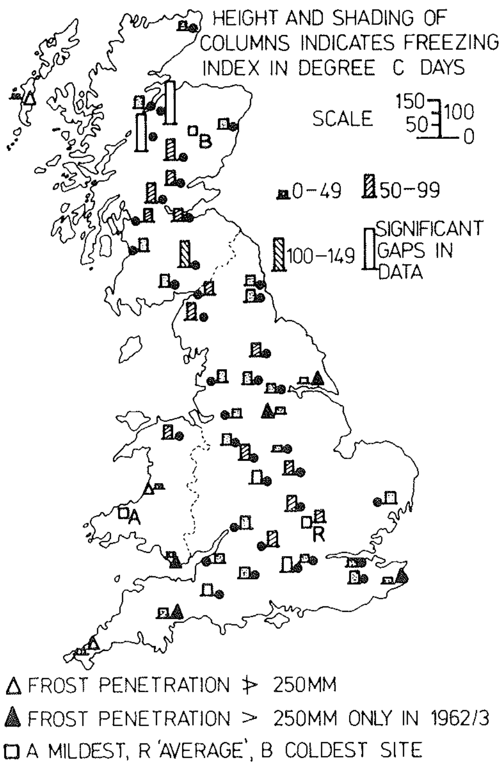

FIGURE 1 Mean yearly freezing index (1959 to 1979) for sites studied [after Sherwood and Roe *(15)*].

subbase aggregate. The results of all the tests known to the author are summarized in Table 2. The subgrade was a 20-, 30-, or 38-mm thick layer of London clay, gault (both heavy clays), Keuper marl (a silty clay), or Attenborough silt (nonplastic). The subbases consisted of whin (a basalt), dene (a carboniferous limestone), and two surrogate materials (a limestone filler and a limestone filler/sand mix). Most of the values quoted in Table 2 are the mean of three tests *(19, 20)*, and Thompson, private communication. Also included are two TRRL tests *(5)*.

The heave of the composite specimen was always less than that of the "subbase," with very considerable decreases occurring for the highest heaving "subbases." Roughly 75 percent of the results showed the composite to have an even lower heave than the subgrade, with the remaining composites having a heave intermediate between those of the individual components.

The observed heave is a product of the suction gradient and the permeability. The freezing front was always within the subbase, which would be expected to exert a lower suction than the finer-grained subgrades. Permeability, on the other hand, may decrease with suction, particularly if the bubbling point is exceeded. Thus the heave of the composite may be greater or less than that of the subgrade.

The important point is that, if there is restricted access to water, frost heave will be reduced. In the actual highway however, water can enter from the top (through hair cracks, joints, and so on), or possibly from the sides, and may form a perched water table. Often, subbases excavated for reconstruction have been found to be saturated. In general, there is a conflict between constructing a stiff well-graded subbase and a less stiff one with an open grading that will permit drainage. This is a matter of current research and debate; but meanwhile the possibility of a perched water table is difficult to discount in design.

TABLE 2 RESULTS OF TESTS ON COMPOSITE SPECIMENS

SUB-BASE	SUBGRADE THICKNESS/mm					SUBGRADE					Source Ref.
	0(1)	20	30	38	152(2)	Type	LL	PL	PI	Class	
Silty Clay	40	-	-	13	10	London Clay	78	24	54	CV	(5)
Chalk	182	-	-	33	10	- do -	78	24	54	CV	(5)
Lst, Filler (LF)	102	-	-	2	11	- do -		31			(19)
SF3/60	47	-	-	5	12	- do -		31			(19)
SF60	45	9	4	2	11	- do -	59	26	33	CH	(20)
Whin	22	9	6	7	11	- do -	59	26	33	CH	(20)
Dene	5	2	-	2	11	- do -	59	26	33	CH	(20)
SF3/60	47	-	-	7	12	Gault		27			(19)
Lst Filler (LF)	102			18	16	Keuper Marl		18			(19)
SF3/60	47	-	-	23	16	- do -		18			(19)
SF60	45	9	12	5	23	- do -	31	16	15	CL	(20)
Whin	22	11	11	14	23	- do -	31	16	15	CL	(20)
Dene	5	2	-	2	23	- do -	31	16	15	CL	(20)
SF60	45	43	31	35	31	Attenborough silt	33	NP	-	NP	(20)
Whin	22	22	16	15	31	- do -	33	NP	-	NP	(20)
Dene	5	2	-	2	31	- do -	33	NP	-	NP	(20)

(1) heave of sub-base alone (2) heave of sub-grade alone

COMPARISON OF THE BRITISH, UNITED STATES, AND FRENCH CLASSIFICATIONS

In both the Cold Regions Research and Engineering Laboratory (CRREL) test in the United States *(21)* and the French Laboratoire des Ponts et Chaussées (LCPC) test *(22)*, cylindrical specimens are subject to unidirectional freezing with open access to water from below. The diameter of the specimens is 152 mm in the CRREL test but only 76 mm in the LCPC test (which precludes its use with aggregates). The CRREL specimens carry a surcharge of 3.5 kPa and are subjected to a constant rate of frost penetration of 13 mm/day.

Classification is based on the rate of heaving in the CRREL test and on the slope, p, of the heave versus FI graph in the French test. FI, the freezing index, is the area under the negative temperature-time graph.

An idea of how the TRRL classification relates to the CRREL and LCPC systems was obtained from TRRL tests in which additional monitoring of internal temperatures was undertaken. Some such tests were included in an extensive testing program undertaken at Nottingham University during the development work associated with the revision of the TRRL test. The results are included in Table 3. The materials tested included both sandy gravels and crushed-rock aggregates. The "as dug" or "crusher run" materials were washed, screened, and recombined to achieve reproducible gradings. This procedure tended to produce gradings that had rather less fines than the targets (see Figure 2) but this was unimportant provided that all the gradings within a set were consistent. Tests were undertaken on both Type 1 (essentially those with C to F1 gradings) and Type 2 aggregates (essentially those with F1 to F2 gradings) *(7)*. In addition, some tests were undertaken on mixtures of sand and limestone filler designated SF4/80 (see grading curve, Figure 2).

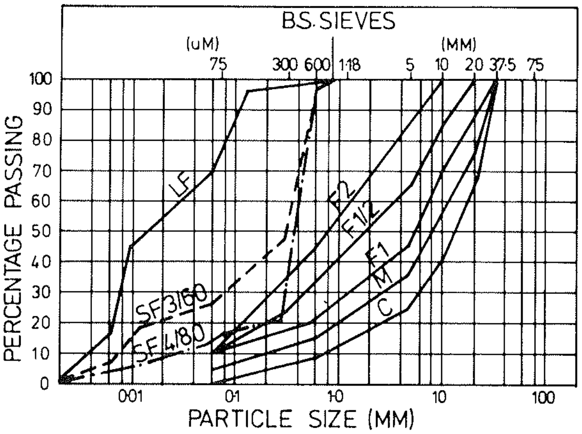

FIGURE 2 Grading curves.

The test procedure was generally similar to SR829 except that tempering was for 1 day only. Series H tests were undertaken in a cold room rather than an SRU but the two facilities have been shown to give similar results *(10)*.

Measurements showed that the frost penetration rate decreased continuously in the TRRL tests. In several tests on three materials (whin 2, OOL2, and concrete) an "instantaneous" value of 13 mm/day was recorded at times ranging from 16 to 30 hr, with an average of 24. Because the heaves of these three materials cover the main range of interest, it is reasonable to assume that the heave rate at 24 hr, $\dot{H}_{24}$, in the TRRL test will approximate that imposed throughout the CRREL test. The relationship between $\dot{H}_{24}$ and the 96 hr's heave H_{96} is shown in Figure 3.

For all the TRRL tests in which sufficient data had been recorded, the slope P, of the heave versus $(FI)^{1/2}$ was deter-

TABLE 3 PROPERTIES OF MATERIALS AND FROST HEAVE RESULTS

1 Material	2 Description	3 Grading	4 <20µ %	5 SMC %	6 MDD Mg/m³	7 OMC %	8 $\theta_{2.5}$ %	9 N	10 H_{96} mm	11 $\dot{H}_{24}$ mm/d	12 P
SANDY GRAVELS											
Ashton Keynes (102)	Lst (Jurassic)	M	1.0	4.0	2.11	7.3	9.5	9	11.7	4.5	
Spencers Farm (103)	Flint hoggin	M	0.5	2.7	2.14	6.6	7.2	9	4.8	1.7	
Stanley Ferry (106)	Gritstone	M	0.5	4.0	2.12	7.5	8.7	9	4.2	2.1	
Woodhall Spa (114)	Sandy hoggin	F1	0	3.4	2.13	6.9	10.6	9	15.1	6.5	0.54
	with chalk	F1/2	0	2.9	2.04	7.9	-	9	14.7	5.8	0.50
	and flints	F2	0	2.4	1.96	8.9	9.3	9	11.3	5.1	
CRUSHED ROCKS											
Croft (105)	Granite	M	0.5	1.6	2.15	6.9	4.3	9	1.6	1.0	0.08
Dene (119)	Carb. Lst	M	1.0	2.1	2.17	5.4	5.8	3	3.8	1.4	
	" "	C	1.0	2.1	2.05	6.7	-	9	3.1	1.5	0.10
Whin 2 (B)	Dolerite	M	2.5	2.8	2.22	8.0	9.6	9	13.3	4.9	0.50
OOL 2 (B)	Shelly mudstone	M	-	4.1	2.05	7.4	12.5	9	12.7	3.8	0.71
OOL 1 (H)	Oolitic Lst	M		5.4	2.10	9.0	20.0	12	29.5	8.4	1.30
	" "	F1		5.4	2.11	9.0	21.3	4	25.5	6.8	
DOL (H)	Dolomitic Lst	M		4.2	2.23	7.5	13.4	12	7.6	3.5	0.45
	" "	F1		4.2	2.25	7.8	14.7	4	12.6	4.1	
MIC (H)	Microcellulitic	M		13.9	1.85	13.5	25.9	12	16.2	7.6	
	Calc/dolomite	F1		13.9	1.87	14.5	23.6	4	23.5	7.4	
CAL (H)	Dolomitic Lst	M		4.6	2.20	7.5	15.4	12	25.6	7.9	
	" "	F1		4.6	2.21	8.0	17.3		25.1	6.7	
SILTY SAND											
SF4/80	Sand/Lst filler	-	1.0	-	2.00	9.00	12.8	18	17.5		

NOTES: 1. Reference code in parenthesis, 2. Lst = Limestone:Hoggin = gravel, sand & clay, 3. See Fig. 2. 4. Test 7C BS1377:1975. 5. Saturation moisture content of particles, 6-7. Maximum dry density and optimum moisture content, Test 14 BS1377:1975, 8. See text, 9. Number of specimens tested, 10. Heave at 96 hours, 11. Heave rate at 24 hours:mm/day, 12. Heave/(freezing index)$^{0.5}$:mm(°Chr)$^{-0.5}$

mined. The relationship between P and H_{96} is shown in Figure 4. P is a close analogue of p, which measured in the French test but is not identical to it because of differences in the testing regimes. There is some evidence *(23)* that the limits appropriate for P may be slightly higher than those for p, but any discrepancy appears quite small.

An approximate equivalence is demonstrated between the TRRL test and each of the other tests, especially if allowance is made for the 1 day's (rather than 5 days') tempering in these TRRL tests. Essentially, frost-susceptible materials in the United Kingdom correspond to those with high frost-susceptibility in the United States and France.

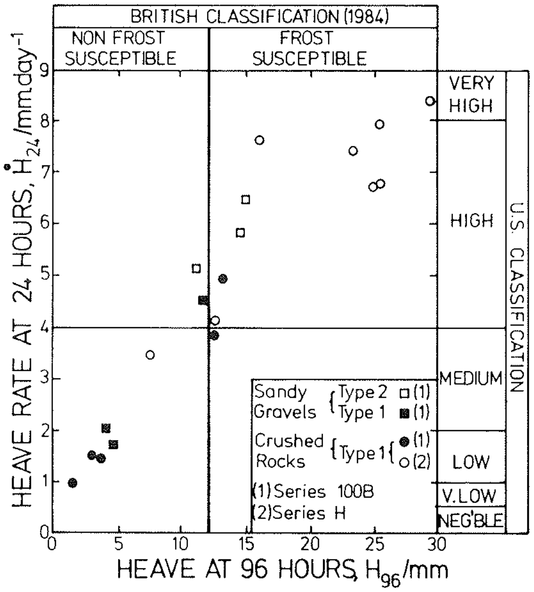

FIGURE 3 Approximate correlation between frost-susceptibility tests at the Transport and Road Research Laboratory in England and the Cold Regions Research Engineering Laboratory in the United States.

PHYSICAL FACTORS CONTROLLING THE FROST-SUSCEPTIBILITY OF AN AGGREGATE

Theory suggests that pore size distribution is a major determinant of frost susceptibility. Attempts have been made to use grading or saturation moisture content (SMC) criteria for frost susceptibility. Although the heaves shown in Table 3 are influenced by grading, all the aggregates have less than 3 percent of fines (< 20 μm) and would therefore be classified as non-frost susceptible by the Casagrande criteria *(21)*. In the TRRL tests, half of these materials proved to be frost susceptible. The criteria did however correctly classify the silty sand (SF4/80) as frost susceptible. Comparison of columns 5 and 10 in Table 3 shows that SMC also is an imperfect guide to frost susceptibility.

The inadequacies of grading and SMC criteria are not surprising because the former reflects only the between-particle pore size distribution and the latter only the within-particle porosity. In principle, suction characteristics, which reflect the volumetric distribution of both pore systems, are likely to yield a more reliable indicator of frost susceptibility.

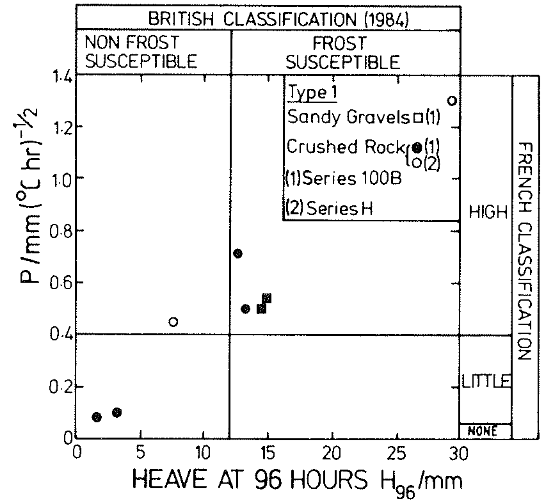

FIGURE 4 Approximate correlation between frost-susceptibility tests at the Transport and Road Research Laboratory in England, and the Laboratoire des Ponts et Chaussées in France.

Measurement of Suction Characteristics

A technique of obtaining suction characteristics of aggregates has been developed *(24)*. Briefly, aggregates at their optimum moisture content are compacted into a mold of plastic pipe, frozen and sliced with a diamond saw into disc-shaped specimens of 110 mm dia by 15 to 12 mm high. The specimens are flanked with semipermeable (dialysis) membranes in a cell that is then placed in a tank containing polyethylene glycol (carbowax) 6000 (see Figure 5). Water passes through the membrane so that the moisture content of the specimen equilibrates with the osmotic pressure of the carbowax (which has been determined by previous calibration). Seven days are allowed for equilibrium. A series of tests at different concentrations of carbowax enables the suction-moisture content curve to be determined over a range of pF 1.5 to 4.4 (4 to 2500 kPa). Capillary rise methods are used at lower suctions.

Relationship Between Suction Characteristics and Frost Heave

Inspection of Table 3 and the suction-moisture-content curves (Figure 6) revealed that the volumetric moisture content at a suction of pF 2.5 (31 kPa), $\theta_{2.5}$, ranked most of the materials in the same order as the frost heave. For $\theta_{2.5}$ less than 20 percent H_{96} increased with $\theta_{2.5}$, but there was a decrease thereafter (see Figure 7). It has been suggested *(24)* that for aggregates with an optimum moisture content of less than 10 percent, $\theta_{2.5}$ is associated with a characteristic suction in the frozen fringe. However, both this suggestion and any frost-susceptibility criterion developed from it, must be regarded as tentative until they are confirmed by tests on many more materials.

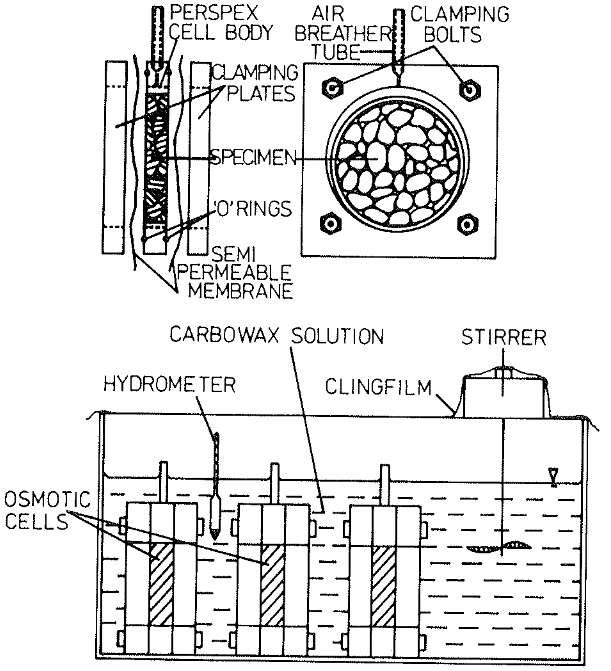

FIGURE 5 Osmotic suction apparatus.

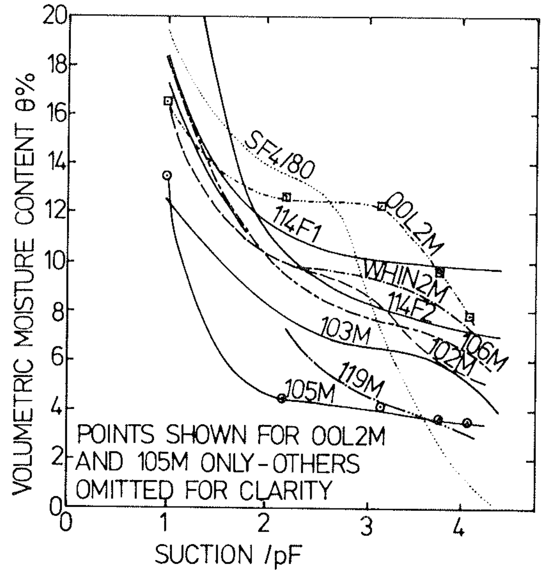

FIGURE 6 Suction characteristics.

Nevertheless, the relationship between $\theta_{2.5}$ and H_{96} is consistent with the applicability of the capillary theory to subbase aggregates.

The apparatus to measure $\theta_{2.5}$ is simpler, cheaper, and more easily duplicated than that for direct frost heave tests. The suction method could be a useful supplement, especially where only small quantities of material are available or where a large number of materials need to be processed simultaneously, for example at the preliminary investigation or tendering stages.

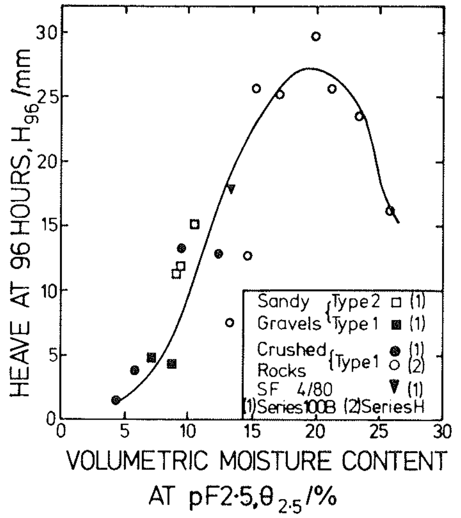

FIGURE 7 Correlation of frost susceptibility and aggregate suction $\theta_{2.5}$.

OPTIMIZING THE USE OF BORDERLINE MATERIALS

A borderline material is most likely to satisfy the frost-susceptibility criterion if it is produced at the coarsest permitted grading (this minimizes the effect of the between-particle pores). The contribution of within-particle pores may be reduced either by excluding suspect horizons at source or by mixing with better material. Experience suggests that careful testing is required to optimize any proposed mixing procedure.

Following the discussion in the earlier part of the paper, another use for borderline materials is in locations where the zero isotherm is unlikely to penetrate or where water is absent.

CONCLUSIONS

The following conclusions were reached:

1. Detailed changes to the TRRL test have improved reproducibility;
2. The design depth to which frost protection is required could safely be reduced below the presently specified 450 mm in the milder parts of lowland Britain, although further research is needed to quantify the depth appropriate to a particular site;
3. Even where relatively frost-susceptible aggregates are used within the depth of frost penetration, the surface heave will be much reduced if the supply of water is restricted by drainage or an impermeable subgrade. However, the potential improvement may be nullified if a perched water table exists;
4. Materials classified as frost susceptible in the United Kingdom are likely to be in the high frost-susceptibility categories in the United States and France;
5. Suction characteristics appear to be better indicators of frost susceptibility than grading or saturation moisture content. In particular, for a range of granular materials, frost heave and $\theta_{2.5}$ (the volumetric water content at a suction of pF 2.5,

equivalent to 31 kPa) were related by a single curve. However, any frost-susceptibility criterion based on suction characteristics must be regarded as tentative until supported by considerably more data; and

6. An understanding of the basic factors affecting frost heave enables the best use to be made of borderline materials. Lower-quality material may prove satisfactory if used at a coarse grading or placed where the probability of frost penetration or freely available water is low. There may also be some scope for improvement by mixing with better-quality materials.

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