Use of Recycled Materials in Subbase Layers

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Research was conducted on the reuse of construction waste, particularly as aggregate for use in the subbase layer in road pavement construction. Although Britain is relatively rich in natural aggregate reserves, planning approvals to develop new quarries are running at about half the rate of extraction. This means that in the future the rate of production of natural aggregate will be too slow to meet the demands of the construction industry. The use of secondary materials is not likely to create a major source of aggregate, but if recycled aggregate was used in less demanding situations the need for natural aggregate would be reduced. The research focused on the properties of crushed concrete (aggregate obtained from the break-up, crushing, and screening of concrete slabs from road pavements) and demolition debris (aggregate obtained from the recycling of general demolition debris). The performance of these materials was compared, mainly on the basis of laboratory testing, with that of limestone, which is commonly used as subbase aggregate in Britain. The tests on the aggregates included California bearing ratio, compaction, and frost susceptibility tests. In most of the tests, the recycled aggregates performed as well as limestone; it is therefore concluded that recycled aggregates could be used as alternative subbase aggregates. However, some proper guidelines on the production and quality of recycled materials are needed.

Recycling of demolition rubble is not a new idea; some reported cases of recycling demolition waste date back to World War II. In several countries, it is an important process that produces a useful source of aggregate for the construction industry. Britain has been slow to adopt recycling on a large scale because it possesses substantial mineral reserves. However, planning approvals to develop new quarries are running at only half the rate of aggregate extraction, which means that in the future the rate of production of crushed rock will be too slow to meet the aggregate demand of the construction industry. The use of secondary materials may not completely remove the problem of the resulting shortage of aggregate, but it could alleviate it. The more successful cases of recycling are those where the recycling plant is located in a large city and where there is likely to be sufficient demolition to provide a consistent supply of rubble.

The research project progressed into a detailed examination of the properties of two recycled materials: crushed concrete and demolition debris. The crushed concrete was a clean, well-graded aggregate, obtained from the break-up, crushing, and screening of concrete slabs during repair work on the M25 motorway in London. The demolition debris was an aggregate obtained from the recycling of demolition rubble and therefore included wood, plaster, brick, and block. These aggregates were compared with a carboniferous limestone from a quarry in southwest England.

Results were obtained from compaction, California bearing ratio (CBR), shear strength, and frost heave tests on the aggregates, particularly with a view to using the recycled aggregates as Type 1 and Type 2 granular subbase material, as defined by the British Specification for Highway Works (*1*). Type 1 subbase material can be used in less demanding circumstances; the specification therefore includes natural sands and gravels in this category.

Although some recycled materials are allowed to be used for certain purposes in Britain, no standard includes definitions of these materials or the levels of acceptable contamination. The main aim of the research project was to examine the properties of recycled materials; it was expected that the conclusions would be a basis from which to develop the production of a standard for recycled aggregates.

COMPACTION TESTS

Compaction tests were carried out on limestone and demolition debris following the procedure of the compactability test for aggregates (*2*). This test involves compacting aggregate in a mold with a vibrating hammer hung from a frame, under a standard surcharge. This test method was found to be capable of producing densities similar to those obtained in the field. Also, because the test was not dependent on the operator, the results were more repeatable than for compaction tests used previously (*3*). Samples of aggregate at a range of moisture contents were tested to determine the relationship between moisture content and dry density.

The main disadvantage of the test is that the mold with a diameter of 150 mm limits the maximum size of particle to be tested to 37.5 mm, although 15 percent of particles in an aggregate for use as road subbase are allowed to be larger than 37.5 mm (*1*).

When the limestone and crushed concrete aggregates were obtained from the suppliers, they contained very few particles larger than 37.5 mm. However, about 10 percent of the demolition debris particles were too large to be tested by the standard test (*2*). This finding suggested that the compaction test might not simulate the compaction of demolition debris in the field because of the difference in particle grading. To investigate whether the density would change if the grading was altered, another apparatus and test were devised.

A steel mold with an internal diameter of 300 mm was used. Holes 5 mm in diameter were drilled in its end to allow excess

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water to drain away during compaction. A 3.2-mm layer of filter fiber, known as vion, sandwiched between two perforated plates was used as the filter assembly; it was positioned at the bottom of the mold supported on a 20-mm-thick spiral spacer so that excess water could drain from the samples. A steel plate, with the vibrating hammer fitted in an indent in its top face, was placed on the sample.

Compaction was conducted using the vibrating hammer, which was hand-held during the 3-minute vibration time allotted to each layer. The vibration time was decided on after a series of trial tests. After compaction, the density of the material was calculated using the measured height of the sample and its weight.

The optimum moisture content at which peak density was achieved in the tests on limestone was 4 percent. The results for two gradings of demolition debris are shown in Figure 1; one test contained particles measuring less than 37.5 mm, and the other had particles up to 75 mm in size. At low-moisture contents, the effect of friction on the sides of the molds is evident. There was little difference in the results for the two gradings. It can be concluded therefore that the removal of particles greater than 37.5 mm did not significantly affect the density of the aggregate.

The results of some of these tests on recycled materials yielded densities close to or to the right of the zero air voids line. The measurements of specific gravity may not have been accurate because of the variation in content of the recycled materials, and the measurements of moisture content may not have been exact. The tests used to determine specific gravity were carried out several times because of variations in the results, particularly for demolition debris that contained assorted materials. These materials also had various water absorption values. In a demolition debris sample, the constituents would not be dispersed equally throughout the material. Therefore one sample of aggregate, when dried, could be found to have a higher moisture content if a large proportion of the material had the ability to absorb a large quantity of water.

The opportunity arose for part of the research to be carried out on site. A field trial was performed to observe the differences between using Type 1 graded demolition debris and Type 1 limestone in the capping layer of two lengths of road. When the densities of the materials obtained on site were compared with those obtained in the laboratory, it was found that compaction on site was more effective for both materials.

CALIFORNIA BEARING RATIO TESTS

The CBR test is a penetration test that can estimate the bearing capacity of subbases and subgrades. It is a crude test at large strains, and much doubt exists about the test's relevance and usefulness because of the difficulty in producing a sample in a mold with a 152-mm diameter at the same conditions expected in the field. Some engineers prefer to use a site test such as the plate bearing test, a field CBR test, or the Clegg impact soil tester so that the full grading of aggregate is tested in actual site conditions. However, the plate bearing and CBR tests exert stresses on the aggregate statistically while road pavements are generally loaded dynamically.

CBR tests were conducted on demolition debris and crushed concrete, and the results were compared with those of limestone to investigate the bearing capacity of the recycled materials. Some tests were carried out at optimum moisture content (OMC) and peak dry density ($\rho_{d,\mathrm{peak}}$), but the CBR of the aggregates was also examined at the same range of moisture contents and dry density conditions that were obtained from the compaction tests previously listed.

Figure 2 indicates that limestone achieved its highest CBR value close to OMC and $\rho_{d,\mathrm{peak}}$. Some iso-CBR contours were drawn by interpolation on the plot. If a full investigation was conducted, including tests executed at lower densities, the CBR for any condition in the field could be estimated. However, because the specification (*1*) requires that aggregate to be used as subbase material should be compacted to a high density, samples at lower densities were not tested.

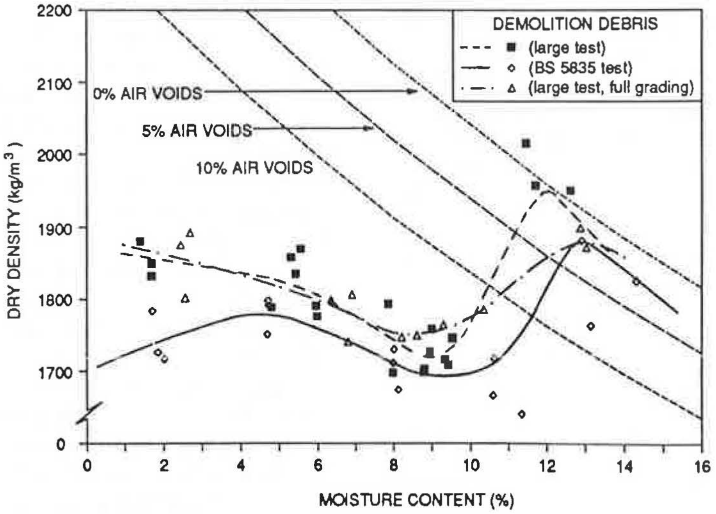

FIGURE 1 Relationship between moisture content and density for demolition debris.

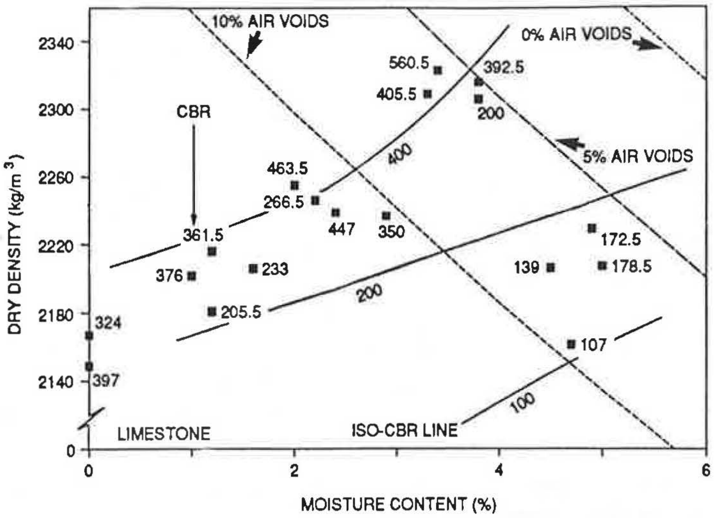

FIGURE 2 CBR values of limestone in relation to dry density and moisture content.

Plots for demolition debris and crushed concrete are shown in Figures 3 and 4, respectively. Figure 3 shows that the CBR did not decrease close to saturation. When the standard compaction test (*1*) was conducted on demolition debris, an OMC of 13 percent was determined. However, it appeared in the CBR series that an OMC of 15 percent was achieved. This difference was possibly caused by the variation in content of demolition debris. If tests were conducted at moisture contents higher than those shown in Figure 3, it is likely that the CBR would decrease. The data in Figure 4, which shows the CBR results of crushed concrete, are much more useful for plotting iso-CBR contours than those in Figures 2 and 3.

SHEAR BOX TESTS

The shear box tests were conducted in a 300-mm by 300-mm by 179-mm shear box. The arrangement of the box was similar to that of the standard Casagrande 60-mm shear box. The top and bottom platens were ridged, and the areas of the platens were slightly smaller than the area of the shear box. The flat top of the top platen allowed a load cell to be placed on it.

Two series of shear box tests were conducted on limestone and the recycled materials. The first series was conducted at a vertical stress of 50 kN/m^2 at varying density. The second set of tests was conducted at similar density but at vertical stresses varying from 50 to 200 kN/m^2. Figure 5 indicates that although the recycled materials had lower dry densities, because of their lower specific gravities, the friction angles of the materials were as high as that of limestone. These recycled materials could be classed as lightweight and would be useful in situations where high-quality natural gravel is currently used. Figure 6 indicates that vertical stress had little influence on the friction angles of the materials over the range of stress applied.

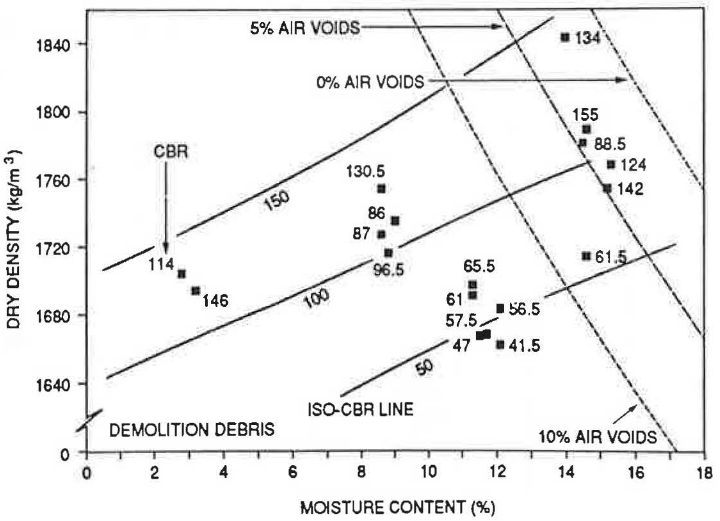

FIGURE 3 CBR values of demolition debris in relation to dry density and moisture content.

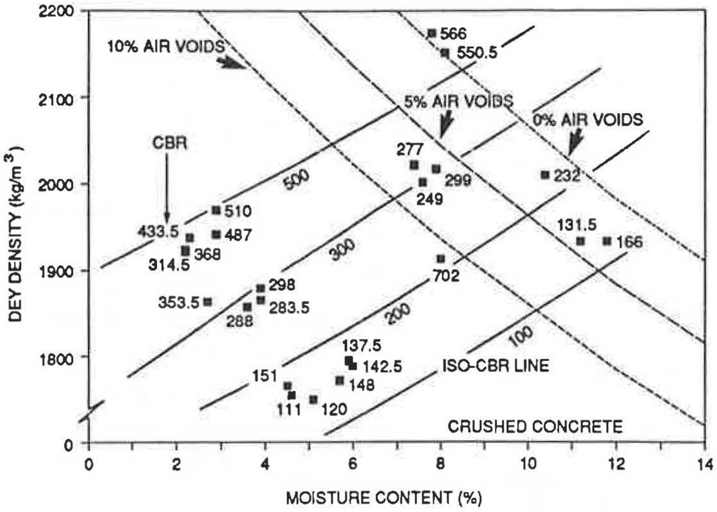

FIGURE 4 CBR values of crushed concrete in relation to dry density and moisture content.

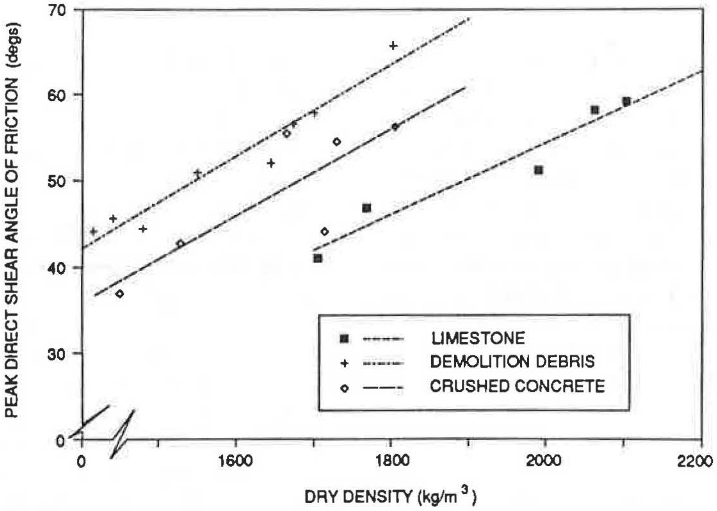

FIGURE 5 Influence of dry density on peak direct shear angle of friction.

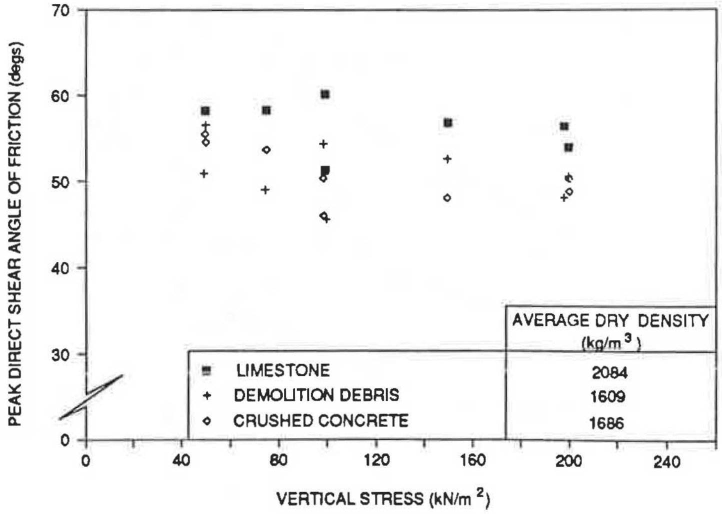

FIGURE 6 Influence of vertical stress on peak direct shear angle of friction.

A report was produced (*4*) to describe a shear box test for the examination of the stability of granular subbases. The report also made recommendations that the test could be used as a standard test for aggregates and suggested that the test should be included in the British Standard for aggregate testing. A classification system for aggregates was established by comparing the results of a series of shear box tests with trafficking trials conducted on several aggregates. In the trafficking trials (*4*), a 150-mm layer of each aggregate was placed on a 250-mm capping layer (a coarsely graded layer placed over the subgrade) to provide a strip 5 m wide. The lorries used for trafficking were restricted to channeled wheel paths. The peak stress ratio values $(\tau/\sigma_v)_p$, (where τ is the shear stress and σ_v is the vertical stress) from the shear box tests, which were conducted on the same materials in similar conditions, were plotted against the surface deformation caused by 1,000 standard axles in the trials. From this plot the following classification system for aggregates was produced (*4*):

- Low strength—$(\tau/\sigma_v)_p$ less than 1.9. Materials in this category would not be suitable in subbase layers but might be stable enough to be used as capping layer materials.
- Medium strength—$(\tau/\sigma_v)_p$ between 1.9 and 2.8. Materials achieving these values may be stable in favorable conditions, but their performance should be checked by a preliminary trafficking trial designed to simulate real conditions of service.
- High strength—$(\tau/\sigma_v)_p$ above 2.8. Materials achieving these values should produce satisfactory subbases under normal construction traffic.

For this shear box test (*4*), the aggregate was placed in a shear box between 96 and 98 percent of $\rho_{d,\mathrm{peak}}$, where $\rho_{d,\mathrm{peak}}$ was determined by the standard compactibility test (*2*). The vertical stress (σ_v) exerted on the material during the test was 10 kN/m^2, which represented the surcharge expected to be placed on a subbase on site. The rate of shear specified for the test was 1.0 mm per minute (*4*). Under these test conditions, $(\tau/\sigma_v)_p$ was reached rapidly; one of the major advantages of the test is that it is quick and the quality of an aggregate can be determined in a few hours. The mean of two tests is taken as the final result if the difference between the two is less than 0.3.

This test was performed on limestone, crushed concrete, and demolition debris to determine whether they could be used as satisfactory subbase materials with regard to the classification system. The results are given as follows:

Aggregate type	$(\tau/\sigma_v)_p$
Limestone	3.2
Demolition debris	2.5
Crushed concrete	1.9

The result for crushed concrete was lower than that for demolition debris, but both materials were in the medium-strength category. Limestone, as expected, would provide a high-strength subbase. With regard to stability, the recycled aggregates could be used as road subbase material, provided that a preliminary trafficking trial was carried out in conditions similar to those expected on site.

FROST HEAVE TESTS

All materials placed within 450 mm of any road surface in Britain should not be susceptible to frost, as defined by the Transport and Road Research Laboratory test (*5*). Although long periods of freezing are uncommon in the British climate, severe winters do occur.

The frost heave test (*5*) is a laboratory test simulating frost heave in the field. In this research, the frost heave of limestone and recycled aggregates was examined because their potential use within 450 mm of a road surface would require them to be not susceptible to frost (*1*).

The layers in a road pavement most susceptible to frost heave are the subbase and the subgrade. The pore spaces in these layers are generally large enough to accommodate the expansion of the water they contain when freezing starts. However, during freezing, more water rises from the unfrozen material by capillary action. The pore spaces do not have the capacity to hold this extra water when it expands on freezing. Clean granular materials do not have the potential to hold enough water to cause frost heave (*6*). Although clays are capable of retaining large quantities of water, frost heave is inhibited because of clay's low permeability.

The frost heave tests involved placing compacted specimens of material in a chamber with the bottom ends of the specimens in contact with water. The temperature of the water was maintained at 4°C but the air temperature was reduced well below freezing, to −17°C. The resulting heave of the aggregate was measured after 96 hours. The procedure for preparing the specimens is described in a Transport and Road Research Laboratory report (*5*).

It was stated earlier that frost heave depends on the flow of water from below. However, it was decided to test the three aggregates at OMC and two other moisture contents, one below and one above OMC, to establish whether frost heave was also influenced by the moisture content at which the material was placed. To examine a wide range of moisture contents, it was initially decided that tests should be carried out at 0.5 OMC and 1.5 OMC, which were considered to be the limits of moisture content that might be obtained in the field. Three samples at each test condition were tested.

The particle gradings of the materials tested for frost susceptibility are shown in Figure 7. The target density and moisture content for sample L2 (L = limestone, see Table 1) were $\rho_{d,\mathrm{peak}}$ and OMC. Although samples L1 and L3 were prepared at different moisture contents, the target density remained at $\rho_{d,\mathrm{peak}}$ so that stable samples could be obtained (L1, L2, and L3 are the test reference numbers). However, it was clear during compaction that this density could not be achieved for these two test conditions. Compaction of these samples was continued until an increase in compaction time did not change the volume of the material. When this stage had been reached, the specimens were extruded. Because they remained stable, it was decided to use these samples in the frost heave test.

Initially, the choice of test conditions for demolition debris was similar to that for limestone. The demolition debris had a water absorption of 8 percent, which was much higher than the value of 0.45 percent for limestone; consequently, the moisture contents of the samples for the frost heave tests on demolition debris were also higher. However, it was difficult to obtain stable samples at a moisture content of 0.5 OMC. The OMC for demolition debris was found to be 13 percent using the standard compaction test (*2*); consequently 0.5 OMC was lower than the water absorption value. Therefore, not enough water was present in these samples to bind the ag-

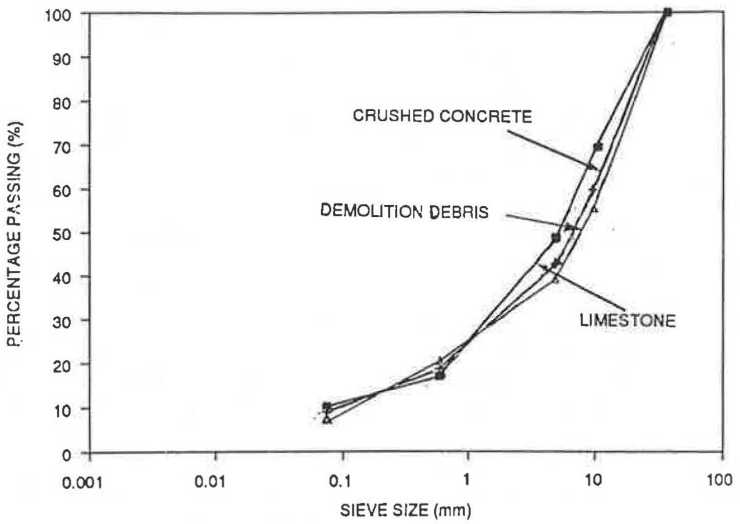

FIGURE 7 Particle gradings of materials.

gregate together. It was also impossible to obtain stable samples of the material at a moisture content of 1.5 OMC. To rectify this situation, new target moisture contents were calculated as follows:

Low moisture content = OMC − (OMC − W_a)/2

High moisture content = OMC + (OMC − W_a)/2

where W_a was the water absorption of the aggregate. Stable samples could be obtained when these moisture contents were used.

Crushed concrete had a water absorption value lower than 0.5 OMC so the same approach as that for limestone was adopted, i.e., the target moisture content values were 0.5 OMC, OMC, and 1.5 OMC. When the trial specimens were prepared, it was concluded after several attempts that the target density of $\rho_{d,\text{peak}}$ for sample C3 (C = crushed concrete, see Table 1) was too high. Therefore the target value for C3 was changed to the maximum density that could be obtained for this test condition in the trial samples.

The self-refrigerating unit (SRU), in which freezing was carried out, consisted of a large insulated box with internal dimensions of 600 mm by 600 mm by 550 mm. Nine specimens were placed on supports above a water bath at the bottom of the chamber. The height of water in the water bath at the bottom of the chamber was maintained level with a constant level device located at the side of the SRU. The test procedure (*5*) required that the water be maintained at a level so that the top of the porous disc under each specimen was not covered with water but was damp, i.e., the water level was about 1 mm below the top of the porous disc. The specimens were surrounded by coarse sand to simulate the field conditions. The temperatures of the water and air surrounding the samples were monitored using thermocouples.

To measure the heave of the specimens, brass rods were passed through a datum frame on top of the SRU and through its lid until the ends were located in the central recesses of the Tufnol discs on top of the specimens. Small pieces of cotton wool were placed loosely in the gaps between the rods and the lid to prevent ice formation around the rods.

TABLE 1 FROST HEAVE RESULTS FOR ALL MATERIALS

TEST REF. No.	MOISTURE CONTENT	SAMPLE 1 HEAVE (mm)	SAMPLE 2 HEAVE (mm)	SAMPLE 3 HEAVE (mm)	MEAN FROST HEAVE (mm)	STANDARD DEVIATION (mm)
L1	0.56 OMC	5.5	7	9	7.2	1.43
L2	0.96 OMC	5	2.5	3	3.5	1.08
L3	1.08 OMC	4	3.5	3	3.5	0.41
D1	0.84 OMC	12	12.5	13	12.5	0.41
D2	1 OMC	12	12	13	12.3	0.47
D3	1.12 OMC	10.5	10.5	11	10.7	0.48
C1	0.6 OMC	4	3.5	3.5	3.7	0.236
C2	0.8 OMC	10	10	13	11	1.414
C3	1.28 OMC	30	30	33	31	1.414

The SRU was left at room temperature for 115 hours so that the specimens could equilibrate. When this period had elapsed, the distances between the tops of the brass rods and the top of the lid were measured to the nearest 0.5 mm and the temperature of each thermocouple was recorded. The controls on the SRU for maintaining the correct water and air temperatures were switched on. The water was kept at a temperature between 3°C and 4.5°C, and the air temperature was maintained between -16°C and -18°C. The temperatures were continually monitored during the test using a chart recorder. If at any time the temperatures were found to be outside these limits, the test would be abandoned. Frost heave was recorded every 24 hours; the last set of readings was taken at 96 hours.

To determine whether material in a particular test condition is frost susceptible, the mean frost heave of three specimens should be calculated (*5*).

1. If the mean frost heave is less than 9 mm, the material is classified as not frost susceptible.
2. If the mean is greater than 15 mm, the material is classified as frost susceptible.
3. However, if the mean heave is in the range of 9.1 to 14.9 mm, the material is regarded as "not proven" (*5*).

If a material is classified in the last category, samples should be sent to two other laboratories for further testing. If the overall mean frost heave, determined by the three laboratories, is less than 12 mm the material can be classified as not frost susceptible.

The results for all tests are given in Table 1. L2, D2, and C2 were the samples closest to OMC and $\rho_{d,\text{peak}}$. The 3.5-mm frost heave of the L2 samples was very low, well below the 9-mm limit. Limestone therefore was classified as not frost susceptible. However, the mean frost heave of the demolition debris (D2) samples was 12.3 mm, which indicated that demolition debris was in the "not proven" range.

The moisture content of crushed concrete (C2) was 0.8 OMC, much lower than expected. To obtain an indication of the likely frost heave at OMC, the frost heave results of the tests conducted on crushed concrete were plotted against moisture content. There appeared to be a direct relationship between initial moisture content and frost heave for crushed concrete, as shown in Figure 8. By extrapolation of the results on the plot, a frost heave of 18 mm was obtained at OMC (10 percent), which implied that crushed concrete would be classified as frost susceptible.

Demolition debris should have been tested at two other laboratories to satisfy the test requirements (*5*), but financial restrictions for the research did not allow further testing.

The relationship between frost heave and moisture content is shown in Figure 8. At a high moisture content, the frost heave of crushed concrete was excessive in comparison with that of the other aggregates. High frost heave is associated with the flow of large quantities of water into a material from below. The C3 samples were in a saturated condition before the frost heave test commenced, and it does not seem likely that they would have been capable of taking in any more water. Therefore, in this case, it would appear that the voids in the compacted aggregate were not large enough to accommodate the expansion of water that they already contained. Frost heave might be dependent not only on the flow of water into the materials but also on its initial moisture content.

However, when the increase in height of the specimen caused by the expansion of the initial free water content was calculated, it was found to be insignificant compared with the frost heave of 31 mm that was recorded for C3 samples.

Moisture content did not appear to directly influence the frost heave of the other materials, but it is apparent that as the moisture content increased, the frost heave decreased slightly (see Figure 8). It can be seen, at OMC or greater, that the frost heave of limestone remained unchanged. A decrease in frost heave was exhibited for demolition debris as the moisture content increased. Unfortunately, the lowest frost heave of 10.7 mm was still above the 9-mm limit.

Standard deviations for the frost heave data are given in Table 1. It is interesting to note that the results for demolition debris were the most consistent. It was expected that the frost heave of samples containing various constituents would vary more than that of more uniform materials. It is difficult enough

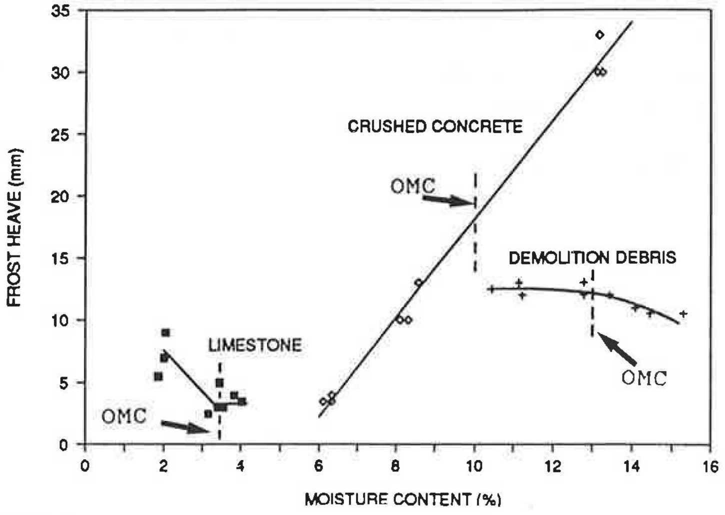

FIGURE 8 Influence of initial moisture content frost heave.

to prepare identical samples with regard to particle size without the additional problem of various constituents in the aggregate. The results for limestone and crushed concrete were not very consistent considering the uniformity of the aggregates. The particle grading of these well-graded materials encompassed a wide range of particle size. It was difficult to obtain similar samples in a mold with a 102-mm diameter when the material contained particles up to 37.5 mm in size.

The data suggest that crushed concrete should not be used as a subbase material until other factors contributing to its apparent susceptibility to frost have been determined.

The results of the frost heave tests presented earlier were both disappointing and confusing. The demolition debris was made up of various constituents but was less susceptible to frost than crushed concrete, which was a cleaner and more uniform material. The results for demolition debris were also more consistent than the frost heave results of the other materials. It was surprising that no direct relationship between moisture content and frost heave existed for demolition debris, similar to relationship noted for crushed concrete. It appears that water absorption did not play a major part in the frost heave process because demolition debris exhibited lower frost heave than crushed concrete but its water absorption was much higher.

It was found that the addition of cement to aggregates reduced frost heave (*6*). In a field trial (*7*), it was observed that crushed concrete and demolition debris, used as subbase materials in road pavements, exhibited better resistance to rutting 3 months after construction than when the material was first placed. It was apparent that recycled aggregates had a self-cementing effect (*7*). If further tests were conducted, this ability might also be found to influence frost heave.

CONCLUSIONS

The inclusion of particles larger than 37.5 mm did not appear to have a major influence on the density of demolition debris. However, it was found that site compaction was more effective than that produced by the standard compactibility test (*2*), contrary to the conclusion of the designers of the test (*3*). The CBR of crushed concrete was found to be similar to that of limestone, but the CBR of demolition debris was lower. However, all materials attained CBR values greater than the 30 percent value stipulated in the specification (*1*). It is difficult to interpret the significance of very high CBR values. A CBR greater than 100 percent can only mean that the material has a greater bearing capacity than natural crushed rock.

Although the recycled materials could be described as lightweight aggregates, their shear strength was found to be similar to that of limestone. The shear box test for subbase aggregates (*4*) was conducted on limestone and the recycled materials. It was concluded that demolition debris and crushed concrete would be classified as medium-strength subbase aggregates and limestone as a high-strength subbase aggregate.

No definite conclusion could be made on the frost susceptibility of demolition debris because further testing could not be conducted at other laboratories. Crushed concrete was found to be frost susceptible, and the data suggest that in most cases the frost heave results of recycled materials would fall in the inconclusive or the frost susceptible ranges. However, the self-cementing ability of recycled aggregates may mean that the susceptibility of these materials to frost would decrease with time.

ACKNOWLEDGMENTS

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