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Testing aggregates

Part 124: Method for determination of frost heave

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Foreword

Publishing information

This part of BS 812 is published by BSI and came into effect on 30 April 2009. It was prepared by Subcommittee B/502/6, *Test methods*, under the authority of Technical Committee B/502, *Aggregates*. A list of organizations represented on this committee can be obtained on request to its secretary.

Supersession

This part of BS 812 supersedes BS 812-124:1989, which is withdrawn.

Presentational conventions

The provisions of this standard are presented in roman (i.e. upright) type. Its methods are expressed as a set of instructions, a description, or in sentences in which the principal auxiliary verb is "shall".

Commentary, explanation and general informative material is presented in smaller italic type, and does not constitute a normative element.

Contractual and legal considerations

This publication does not purport to include all the necessary provisions of a contract. Users are responsible for its correct application.

Compliance with a British Standard cannot confer immunity from legal obligations.

1 Scope

This British Standard describes a test procedure for the determination of the frost resistance of unbound aggregate mixtures that have been compacted to form a cylindrical specimen with a predetermined water content and density.

It is applicable to unbound aggregate mixtures used in the construction of roads and other paved areas at a depth that might experience frost penetration.

NOTE This method can be used to assess hydraulically bound aggregate mixtures. However, acceptable values of frost heave might differ from those used to assess unbound mixtures.

This British Standard includes an option for the use of comparator specimens to confirm that the test chamber is working correctly. The method for the use of comparator specimens is given in Annex B.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

BS EN 932-1, *Tests for general properties of aggregates – Part 1: Methods for sampling*

BS EN 932-2, *Tests for general properties of aggregates – Part 2: Methods for reducing laboratory samples*

BS EN 932-5, *Tests for general properties of aggregates – Part 5: Measurement and calibration systems*

BS EN 933-1, *Tests for geometrical properties of aggregates – Part 1: Determination of particle size distribution – Sieving method*

BS EN 933-2, *Tests for geometrical properties of aggregates – Part 2: Determination of particle size distribution – Test sieves, nominal size of apertures*

BS EN 1097-5, *Tests for mechanical and physical properties of aggregates – Part 5: Determination of the water content by drying in a ventilated oven*

BS EN 13286-4, *Unbound and hydraulically bound mixtures – Test methods for laboratory dry density and water content – Part 4: Vibrating hammer*

BS EN 60584-2, *Thermocouples – Part 2: Tolerances*

3 Terms and definitions

For the purposes of this British Standard, the following terms and definitions apply.

3.1 constant mass

mass achieved by successive weighings after drying at least 1 hour apart not differing by more than 0.1%

*NOTE In many cases constant mass can be achieved after a test portion has been dried for a predetermined period in a specified oven (see **6.3.13**) at (110 ± 5) °C. Test laboratories may determine the time required to achieve constant mass for specific types and sizes of sample, dependent upon the drying capacity of the oven used.*

3.2 frost heave
maximum increase in the height of a test specimen during the freezing period

3.3 laboratory sample
reduced sample derived from a bulk sample for laboratory testing

3.4 test specimen
sample used in a single determination when a test method requires more than one determination of a property

4 Principle

Cylindrical specimens of unbound aggregate mixtures, compacted at a predetermined water content and density, are placed in a self-refrigerated unit (SRU).

The SRU subjects the upper surface of each test specimen to freezing air at –17 °C whilst their lower ends have access to water maintained at +4 °C. Comparator specimens can be used to confirm that the SRU is operating correctly.

The temperature gradient in the SRU causes water to be drawn into the freezing zone and might lead to the formation of ice lenses that increase the height of the specimens. The change in height is measured at intervals over a period of 96 h. The maximum increase is recorded and is used to calculate the frost heave of the mixture.

5 Sampling and sample reduction

Take the laboratory sample of unbound aggregate mixture to be sent to the laboratory in accordance with BS EN 932-1.

The mass of the laboratory sample shall be at least twice the quantity estimated as being necessary for the tests to be carried out. The minimum amount required for each test shall conform to Table 1.

When required, divide and reduce the size of the laboratory sample in accordance with BS EN 932-2.

NOTE The values in Table 1 are calculated using a loose bulk density of 2.0 Mg/m^3.

Table 1 **Minimum mass of test portion**

Test method		**Minimum mass of test portion**
		kg
BS EN 933-1	Particle size distribution (0/32 mm size mixture)	10
BS EN 13286-4	Dry density and water content by vibrating hammer	40
BS 812-124	Determination of frost heave	36

6 Apparatus

6.1 Particle size apparatus

The apparatus for the determination of the particle size distribution shall be as specified in BS EN 933-1.

6.2 Dry density and water content relation apparatus

The apparatus for determining the relationship between the dry density and water content of the unbound aggregate mixture shall be as specified in BS EN 13286-4.

6.3 Frost test apparatus

6.3.1 The apparatus for determining the frost resistance of the material shall be as specified in **6.3.2** to **6.3.15**. Unless otherwise stated, all apparatus shall conform to BS EN 932-5.

6.3.2 *Self-refrigerated unit (SRU)*, as described in Annex A.

6.3.3 *Balance(s)*, of suitable capacity, readable to 0.1% of the mass of the test portion.

6.3.4 *Container*, of suitable capacity, for the controlled addition of water to the test specimens.

6.3.5 *Mixing bowl and suitable spatula or trowel*.

NOTE Alternative methods of mixing may be used providing they are effective in distributing the added water evenly through the specimen.

6.3.6 *Containers*, at least nine, that can each hold 15 kg of mixture and are closeable.

6.3.7 *Low carbon steel mould and end plugs*, for specimen preparation, as shown in Figure 1.

6.3.8 *Hand-held steel tamper*, weighing 1 100 g to 1 200 g.

NOTE A suitable design is shown in Figure 2.

6.3.9 *Electrically powered vibrating hammer*, as described in BS EN 13286-4.

6.3.10 *Steel tamper*, with a circular foot of 100 mm diameter, to fit the vibrating hammer.

NOTE A suitable design is shown in Figure 3. The shank is a force-fit into the disc.

6.3.11 *Depth gauge*, capable of reading depths up to 250 mm and readable to 1 mm.

6.3.12 *Jacking device*, for ejecting the compacted specimen from the mould.

NOTE 1 A compression testing machine with suitable extension extruders has been found suitable.

NOTE 2 The apparatus used at the extrusion stage is illustrated in Figure 4, Figure 5 and Figure 6.

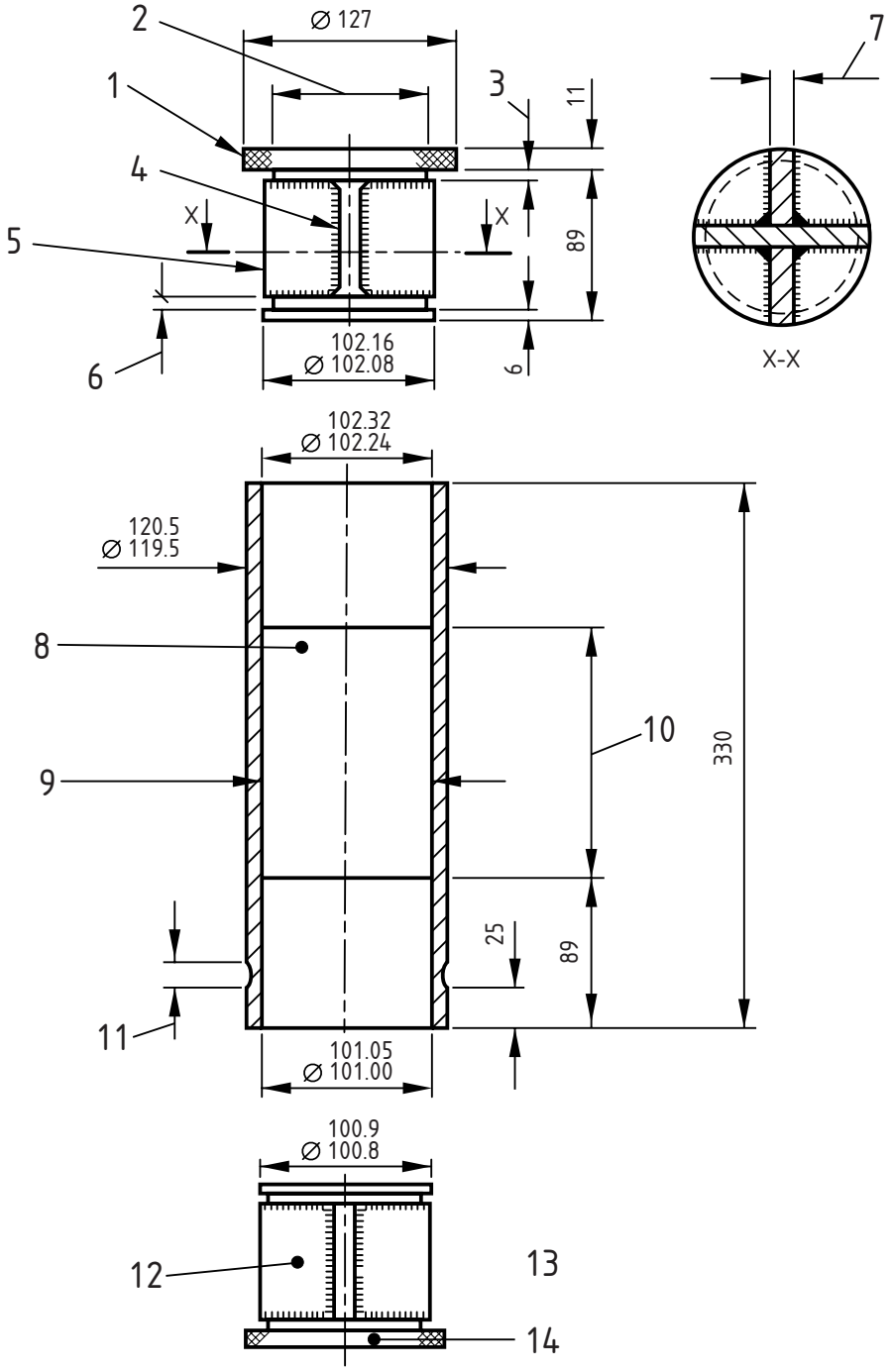
6.3.13 *Ventilated oven*, thermostatically controlled to maintain a temperature of (110 $\pm$ 5) °C.

6.3.14 *Test sieve*, 40 mm size, as specified in BS EN 933-2.

6.3.15 *A supply of distilled or demineralized water*.

Figure 1 **Mould and end plugs for the preparation of frost-heave test specimens**

Material: Low carbon steel. Dimensions in millimetres.

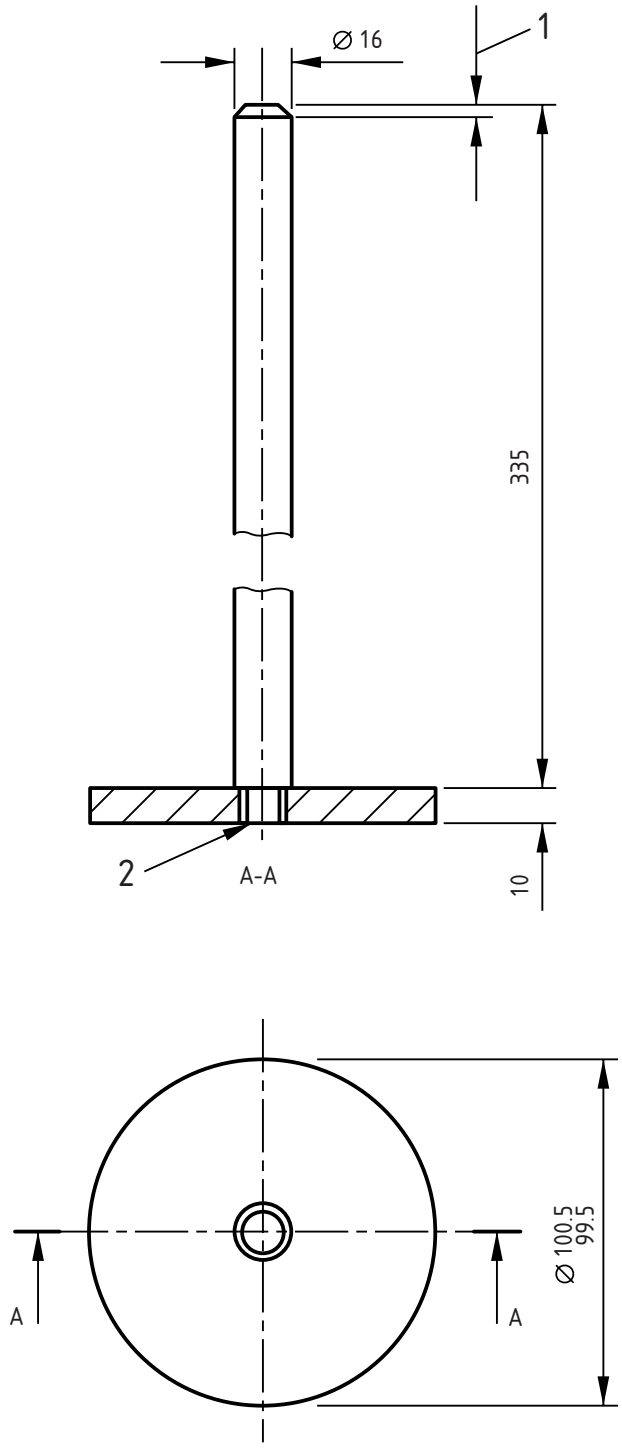


Key

1	Medium diamond knurl	8	Mould
2	Undercut Ø 95 (typical)	9	Straight polished taper
3	Undercut: 3.0	10	Length of taper: 152.4
4	All welds 5 mm continuous fillet	11	Identification groove 12 wide × 0.3 deep to denote smaller bore and paint
5	End plug (large)	12	End plug (small)
6	Undercut: 6.0	13	Other dimensions as end plug (large)
7	Webs: 13	14	Paint surface for identification

Figure 2 **Hand-held tamper**

Material: Low carbon steel. Dimensions in millimetres.



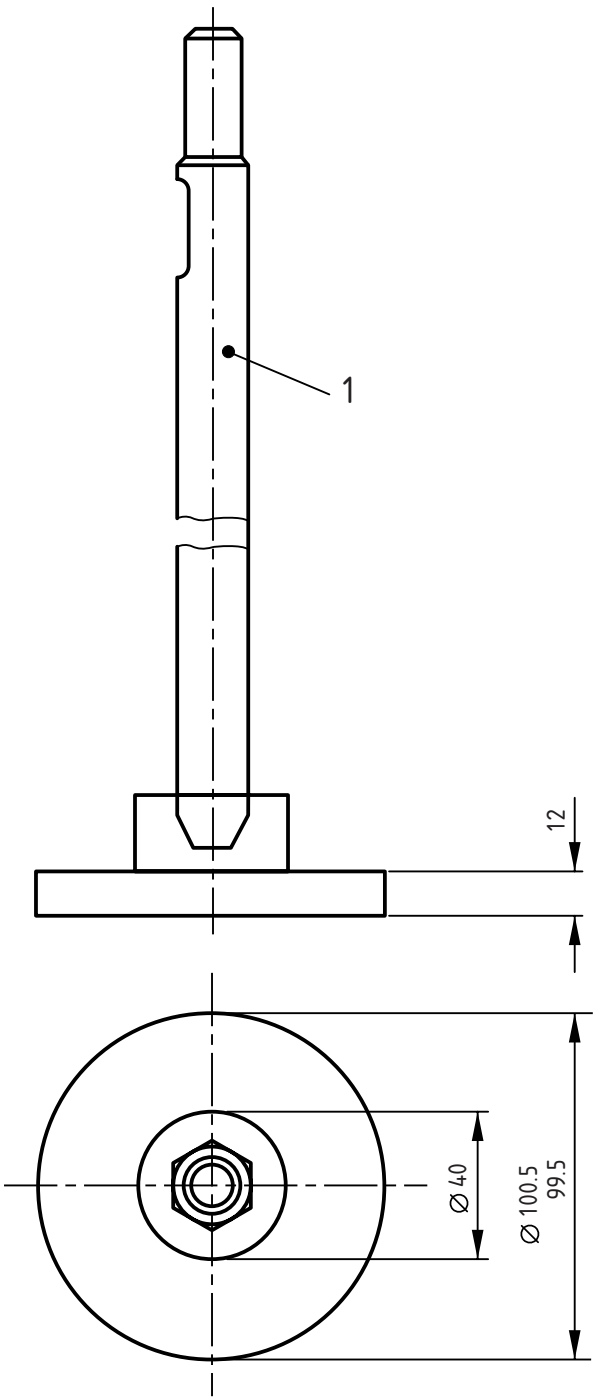
Key

1 Chamfer 1.5 × 45°

2 Thread M10 and machine flush with end face on assembly; finally, secure with an industrial adhesive

Figure 3 **100 mm tamping foot for vibrating hammer**

Material: Low carbon steel. Dimensions in millimetres.



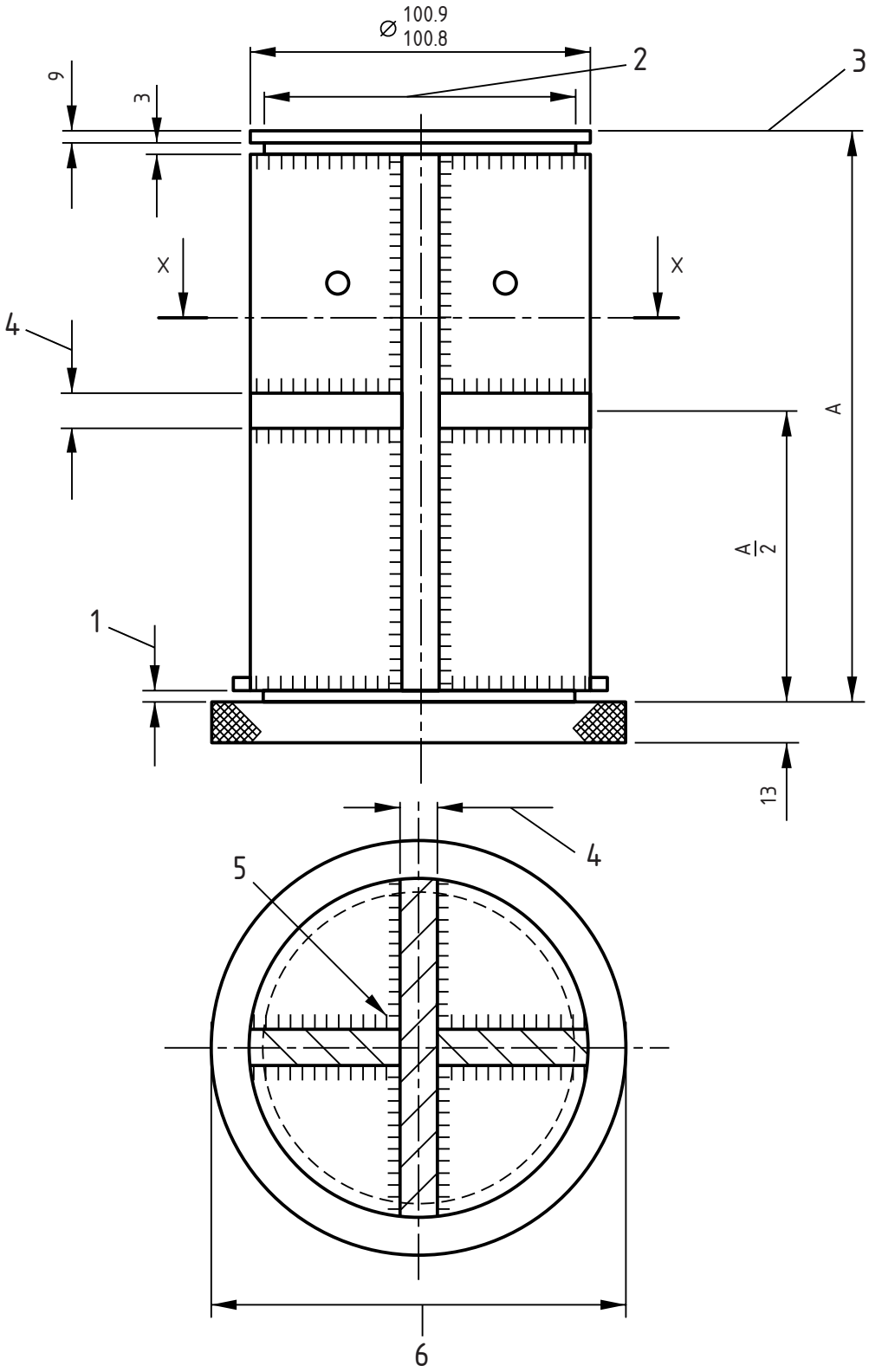
Key

1 Shank design to suit vibrating hammer
Mass of tamper not to exceed 3 kg.

NOTE This design has been found satisfactory, but alternative design may be employed provided that the essential requirements are fulfilled.

Figure 4 **Specimen extruder**

Material: Low carbon steel. Dimensions in millimetres.



Key

1 Undercut: 3

2 Undercut Ø 95 (typical)

3 Dimension A:
Long extruder: 330
Short extruder: 174

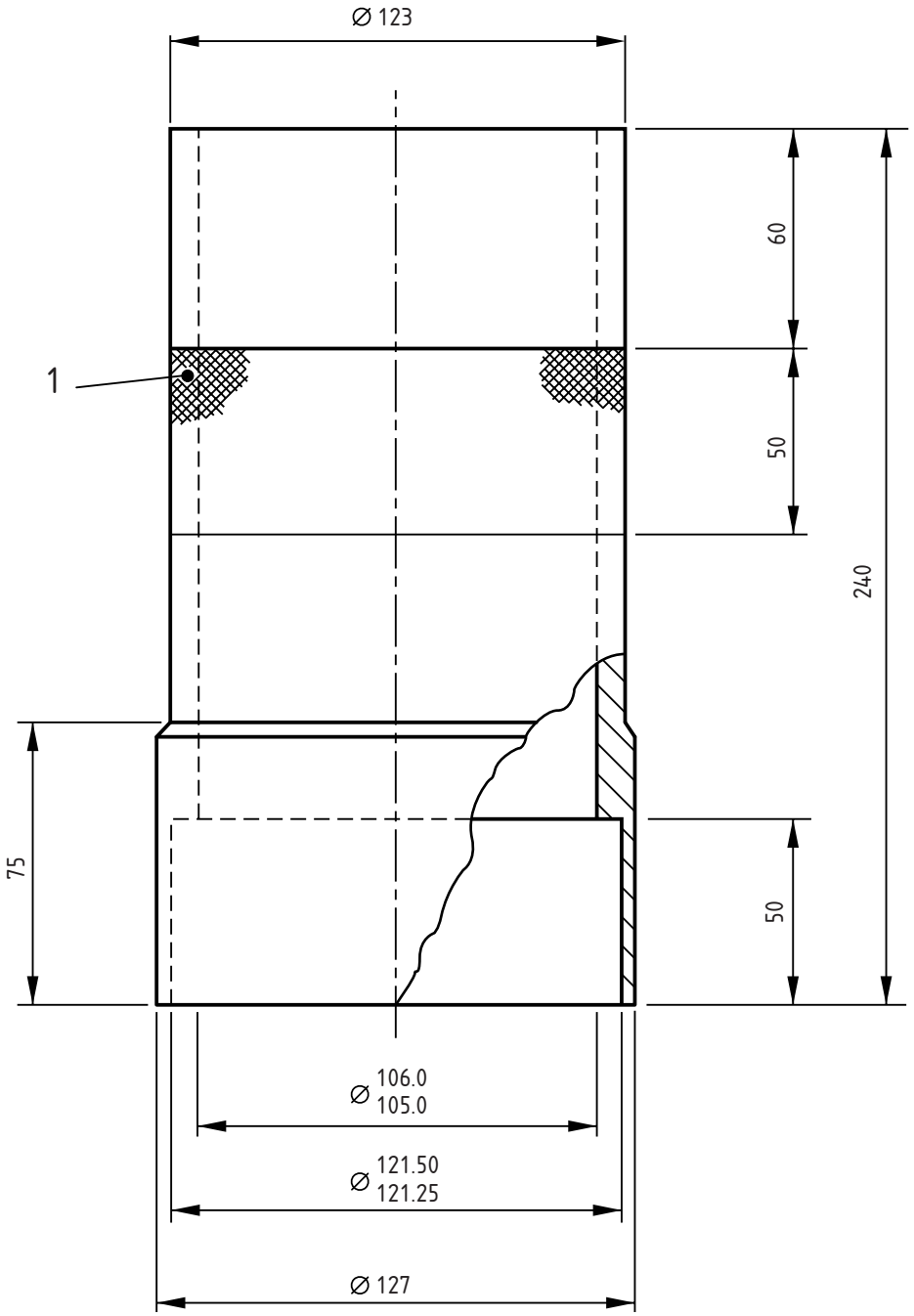
4 Webs: 13

5 All welds 5 mm continuous fillet

6 Medium diamond knurl Ø 127

Figure 5 **Extrusion cylinder**

Dimensions in millimetres.

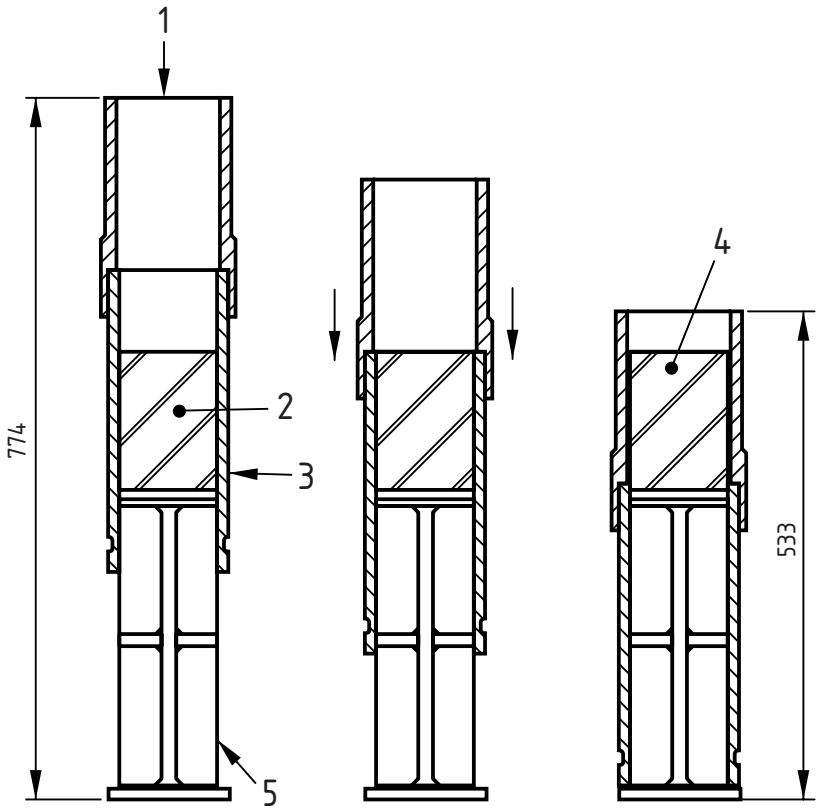


Key

1 Medium diamond knurl

Figure 6 **Extrusion process**

Dimensions in millimetres.



Key

1 Extrusion cylinder
2 Specimen
3 Mould (see Figure 1)
4 Extruded specimen
5 Long extruder (see Figure 4)

7 Preliminary testing procedure

7.1 Particle-size distribution

Determine the particle-size distribution of a test portion taken from the laboratory sample in accordance with BS EN 933-1.

NOTE 1 Before proceeding with further testing, the determined particle size distribution should be checked to confirm that it is typical of the routine production from the source. For some unbound mixtures, this might involve comparison with the supplier declared value for grading. If there is a discrepancy, a more representative sample should be obtained before continuing.

NOTE 2 Typical particle size distribution results are normally available from the supplier of the unbound mixture.

7.2 Water content and dry density

7.2.1 Stage 1

If values are not nominated from previous tests (see Note 1), determine the optimum water content and maximum dry density of test specimens taken from the laboratory sample in accordance with BS EN 13286-4 (see Note 2). Use these values for the initial preparation of a frost heave test specimen, as described in **7.2.2**.

NOTE 1 The water content and density at which test specimens are to be prepared may be nominated before testing, on the basis of earlier tests.

NOTE 2 The primary requirement when choosing suitable values of water content and dry density is that the test specimens should be stable.

7.2.2 Stage 2

Prepare a test specimen from the laboratory sample with a mass of not less than 5 kg. Dry the test specimen by heating at a temperature of (110 $\pm$ 5) °C to constant mass. Allow it to cool, pass through the 40 mm size test sieve (**6.3.14**) and remove any particles retained on the sieve.

Use the dried and sieved test specimen to prepare a frost heave test specimen using the water content (w, expressed as a percentage by weight) and dry density (ρ_d Mg/m^3) chosen in Stage 1 (see **7.2.1**). Use a mass of dry aggregate equal to 1 360 × [ρ_d (in grams)] and a mass of water equal to 13.6 × [$w\rho_d$ (in grams)].

Place the dried aggregate in the mixing bowl (**6.3.5**), add the water and thoroughly mix.

Use this mixture to prepare and extrude a trial frost heave test specimen, using the procedures in **8.4**.

If, immediately after extrusion, the specimen cannot stand on the extruder without collapsing, adjust the dry density and/or water content values to achieve a specimen that is sufficiently stable but has not been subjected to such a degree of compaction that undue crushing of the individual particles has occurred.

NOTE 1 Adjustment should be achieved systematically by trial and error, until a stable specimen has been made.

*NOTE 2 The values of water content and dry density used to prepare the stable specimen are used to prepare the test specimens in Clause **8**.*

When a stable specimen has been prepared, transfer the test specimen to a suitable tray and break it up. Determine the moisture content of the test specimen in accordance with BS EN 1097-5 and the particle size distribution of the test specimen in accordance with BS EN 933-1.

8 Preparation of test specimens

8.1 General

The test procedure described in Clause **9** uses three frost heave test specimens for each test on an unbound aggregate mixture.

NOTE The SRU can accommodate nine specimens. This means that three different unbound mixtures can be tested at one time. If three comparator specimens (Annex B) are used, two unbound mixtures can be tested at one time.

8.2 Test portions

Reduce the laboratory sample to a mass of at least 15 kg for use as a subsample for the frost heave test. Dry this subsample by heating at a temperature of (110 ± 5) °C to constant mass. Allow it to cool and remove any particles retained on the 40 mm size test sieve.

Use the dried and sieved aggregate to prepare three frost heave test specimens, as described in **8.4**. Retain the remainder of the laboratory sample, in case it is needed for repeat tests.

8.3 Mixing

Use the values of water content (w, expressed as a percentage by weight) and dry density (ρ_d Mg/m^3) chosen to give a stable test specimen (**7.2.2**) to calculate the mass of dry aggregate and water needed to prepare enough unbound mixture for three frost heave test specimens.

Use a mass of dry aggregate equal to 4 080 × [ρ_d (in grams)] and a mass of water equal to 40.8 × [$w\rho_d$ (in grams)]. Place the dried aggregate in the mixing bowl (**6.3.5**), add the water and thoroughly mix.

*NOTE If it is not possible to mix enough unbound mixture for the three test specimens at the same time, individual specimens can be prepared using the mass of aggregate and water in **7.2.2**.*

Store the mixture in a sealed container (**6.3.6**) for a minimum of 16 h before starting the compaction stage (**8.4.1**).

8.4 Method for preparing a single test specimen

8.4.1 Compaction into the mould

Weigh out mixture from the sealed container (**8.3**) to give a mass, M, equal to ⅓ of the mass required for one frost heave test specimen, to the nearest 2 g.

M is calculated using the equation:

$$M = 4.12 \times [\rho_d]\ (100 + w)\ \text{(in grams)}$$

where ρ_d and w are as defined for the stable test specimen in **8.3**.

Fit the bottom (smaller) end plug to the mould (**6.3.7**) and carefully transfer the weighed material into it. Level the mixture in the mould with a suitable spatula (**6.3.5**). Hold the tamper (**6.3.8**) inside the mould with the upper surface of its base level with the top. Allow the tamper to drop freely under its own weight, taking care that the foot is level when it strikes the mixture. Repeat this manual tamping until 25 drops have been completed.

Compact the material using the vibrating hammer (**6.3.9**), fitted with the 100 mm diameter tamping foot (**6.3.10**). Hold the hammer in an upright position. Check the depth from the top edge of the mould to the upper surface of the compacted mixture using a depth gauge (**6.3.11**). Stop compaction when the reading is in the range 183 mm to 189 mm, measured at the centre of the compacted mixture.

Score the top surface of the compacted mixture with a spatula, to assist with the bond between the layers.

Weigh out a second mass, M, of the mixture. Transfer it to the mould, level and tamp 25 times as before. Use the vibrating hammer fitted

with the tamping foot to compact the material in the mould. Stop compaction when the reading is in the range 133 mm to 139 mm, measured at the centre of the compacted mixture.

Weigh out a third mass, *M*, of the mixture. Transfer it to the mould, level and tamp 25 times as before. Carefully wipe clean the inside of the mould above the tamped material and insert the top (larger) end plug into the mould (**6.3.7**). Apply the vibrating hammer to the top plug until the specimen is fully compacted (see Note). The specimen is considered fully compacted when the gap between the top of the mould and the bottom of the knurl part of the end plug is not more than 4 mm.

NOTE For some granular mixtures, the last layer might not be fully compacted after 60 s of compaction. In such cases, invert the mould assembly and apply the hammer to the bottom plug. Do not apply the hammer to either end for more than 1 min at a time. With very coarse mixtures it might be necessary to remove one of the plugs and apply the vibrating hammer directly onto the surface of the mixture to complete the compaction stage.

8.4.2 Extrusion from the mould

Remove both end plugs.

NOTE 1 Normally one or two clockwise and anticlockwise rotations will loosen the top plug in the mould and allow it to be lifted off. The mould can then be lifted from the bottom plug in a similar way.

NOTE 2 If the end plugs cannot be removed by hand, the mould assembly should be left to stand for 5 min to 10 min before a further attempt is made. This allows excess water, which might form a seal around the plugs, to drain away. It is important not to strike the mould or plugs with a heavy object since this is likely to damage them. If, however, after 10 min standing the plugs still cannot be removed, gentle tapping with a rubber-faced mallet or similar light, non-metallic object can be used. If the plugs become persistently difficult to remove, the mould and plugs should be checked for damage and their dimensions checked. A mould can become distorted during use.

Extrude the specimen from the mould using a jacking device (**6.3.12**), e.g. a compression machine.

EXAMPLE
Place the narrow end of the mould over the short extruder and then place both the mould and the extruder on the platen of the compression machine. Start the extrusion process on the machine and remove the mould and extruder from the machine when the extrusion can proceed no further. Complete the final extrusion by hand using the long extruder.

NOTE 3 Other methods using compression machines or hydraulic-jack extruders can be used if they can be shown to be effective and smooth in operation.

NOTE 4 If final hand-extrusion proves difficult, the following procedure is recommended when the compression machine has space of at least 720 mm between the platens. The sample is extruded using a cylinder which fits over the top of the mould. The mould and cylinder are then placed on the long extruder of the compression machine and extrusion completed on the machine. Where the machine has a space of 780 mm between the platens, the extrusion can be effected using the long extruder only. This extrusion process is illustrated in Figure 6.

8.4.3 Completion

Immediately after extrusion, wrap a waxed-paper sheet (**A.4.6**) around the curved face of the specimen and secure it with a short piece of adhesive tape. Do not encircle the specimen with the adhesive tape. Ensure that the lower edge of the paper is in line with the bottom of the specimen, to leave an upstand of approximately 50 mm above the upper face of the compacted test specimen. Place a rigid disc made of cotton reinforced phenolic paper (**A.4.7**, hereafter referred to as "rigid disc"), with the recess uppermost, on top of the test specimen.

Carefully place the test specimen on a porous disc (**A.4.8**) and position the specimen and porous disc in a copper specimen carrier (**A.4.9**). The specimen assembly is then ready to be placed in the SRU.

NOTE Positioning of the copper specimen carrier can be made easier if the carrier is placed over a cylinder slightly taller than the carrier and of slightly smaller diameter than the hole in the bottom of the carrier. The porous disc can then be placed on top of the cylinder and the carrier lifted gently into place. This avoids the difficult operation of inverting the specimen.

Remove the mould from the extruder. Clean and dry the mould, both plugs and the extruder so they can be used again.

9 Procedure for the determination of frost heave

9.1 Loading test specimens into the self-refrigerated unit

9.1.1 Number the specimen positions as shown in Figure 7. If comparator specimens are not used, load the three test specimens for the first unbound mixture in positions 1 to 3, for the second unbound mixture in positions 4 to 6 and for the third unbound mixture in positions 7 to 9.

If comparator test specimens are used, load the test specimens in the sequence given in **B.4**.

9.1.2 Locate a thermocouple (**A.3.5**) between the bottom of the porous disc under the test specimen and the copper specimen carrier in positions 1, 3, 5, 7 and 9. Ensure that the tip of the thermocouple is not in contact with the copper carrier, is 5 mm to 10 mm into the water bath when the carrier is loaded with specimens, and is as central as possible in each specimen position.

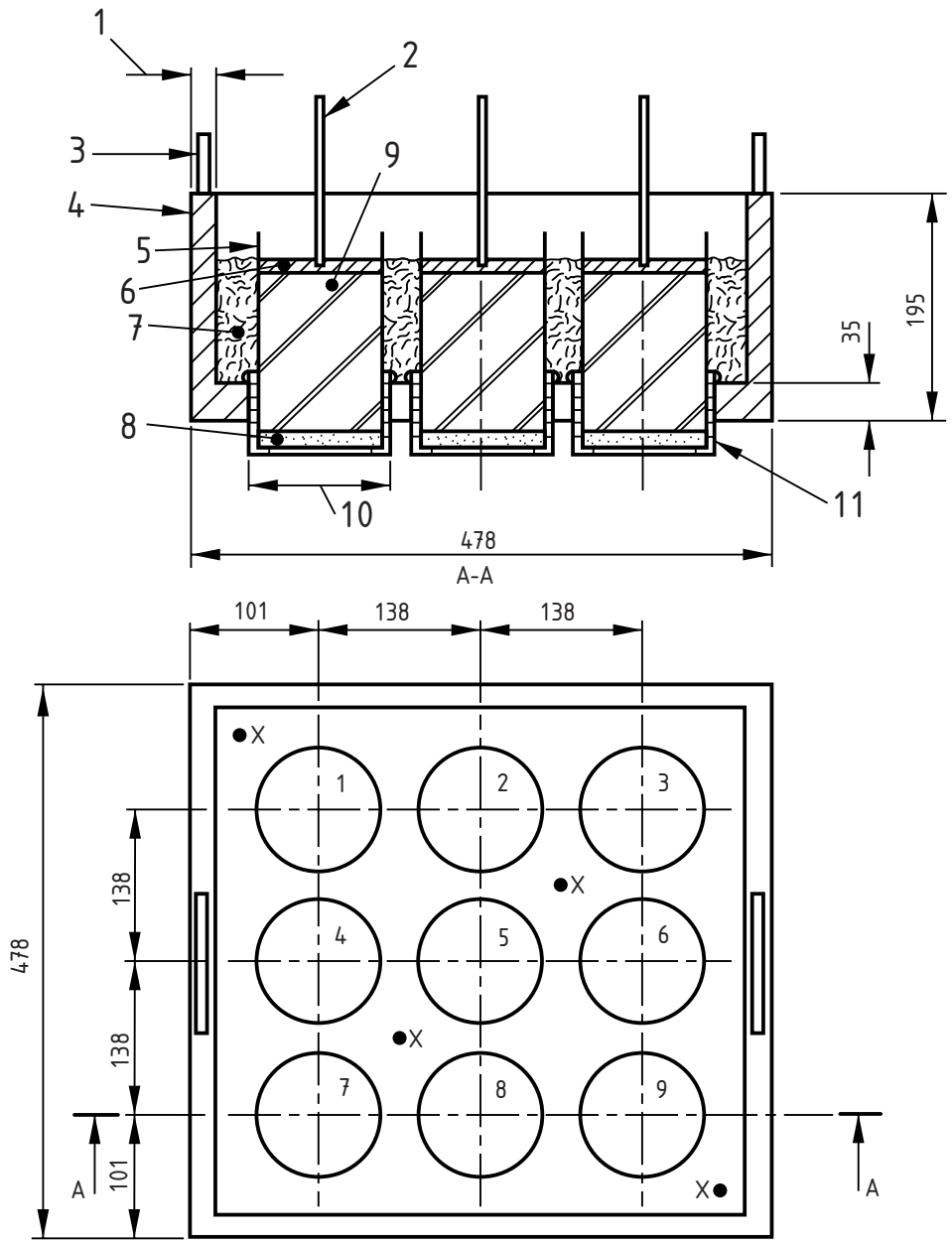
Fix another thermocouple under the rigid disc on top of the test specimen in position 5, so that the junction is exposed at the centre of the disc and in contact with the upper surface of the test specimen.

If fewer than nine specimens are to be tested, fill the vacant positions with dummy specimens.

*NOTE If SRU tuning procedures are to be carried out during the test run, see **A.6**.*

Figure 7 **Specimen cradle showing specimen position numbers**

Material: Marine-quality plywood, waterproof finish. Dimensions in millimetres.



Key

1 Typical: 19
2 Brass rod Ø 6.0 × 750 long
3 Handle
4 Specimen cradle
5 Waxed paper
6 Rigid disc
7 Coarse sand fill
8 Porous disc
9 Specimen
10 Typical hole size: Ø 112
11 Specimen carrier (see Figure A.2)

"X" indicates the positions of four thermocouples in the air.

9.1.3 When nine test specimens are in position, locate four more thermocouples so that there is one above each of the spots marked "X" on the floor of the cradle in Figure 7, at a level 250 mm above the plane containing the lower faces of the specimens.

NOTE This can be achieved by attaching each thermocouple to a 6 mm diameter wooden dowel approximately 300 mm long so that the junction is exposed (205 ± 2) mm from the lower end of the dowel. Position the four dowels on the floor of the cradle. Support the dowels either by drilling holes of the correct diameter or by using flexible tubing placed on the dowel ends which are then pushed onto preset studs on the floor of the cradle.

9.1.4 Place coarse sand (**A.4.2**) carefully in the space around the specimens (and around the vertical dowels if these are used) until the sand is level with the tops of the specimens. Take care to remove any sand particles accidentally spilt on the rigid discs, particularly in the recesses.

NOTE 1 Care should be taken to ensure that the particles of sand do not get under the dowels, thus raising the thermocouples.

NOTE 2 When the sand is in place, the waxed paper around each test specimen should stand approximately 50 mm above the level of the sand.

9.1.5 Check the positions of the thermocouples and any control sensors and then close the lid of the test chamber. Locate the support (datum) frame on the SRU (Figure A.1). Pass the brass rods (**A.4.1**) through the holes in the frame and in the chamber lid, and locate each one in the central recess of the corresponding rigid disc on top of the test specimen. Start the constant-level device (**A.3.1**) by opening the outlet tap, O (see Figure 8), to allow water to flow into the water-bath and restore the correct level. The water level is controlled automatically for the remainder of the test.

9.1.6 Complete the loading of the SRU within one working day.

9.1.7 Leave the loaded SRU undisturbed for (115 ± 5) h from the time that the last specimen was inserted in the cradle before proceeding. Use the temperature recorder to monitor the temperatures in the test chamber during this period. Do not activate the refrigeration function at this stage.

9.2 Freezing the specimens and measuring frost resistance

9.2.1 After (115 ± 5) h (**9.1.7**), check the location of the brass rods. Use surgery wool or similar absorbent material (**A.4.5**) to plug the gaps between each rod and the hole in the test-chamber lid through which it passes.

NOTE 1 The surgery wool prevents any water that condenses on the rods from running into the test chamber.

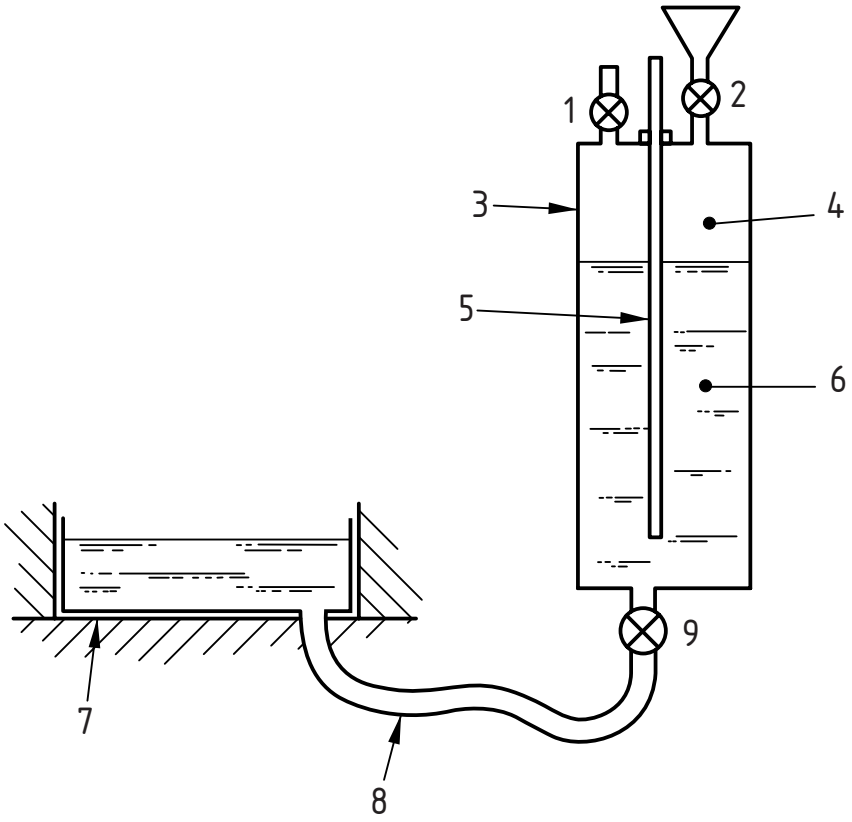
NOTE 2 The surgery wool should not be packed too tightly into the holes. This could disturb the location of the brass rods.

9.2.2 For each brass rod, record the distance between the top of the rod and the top of the support (datum) frame to the nearest 0.5 mm.

9.2.3 Record the temperature of each thermocouple.

9.2.4 Switch on the SRU to start the freezing process. Record the time. Ensure the operating temperatures specified in **A.6** are reached in a time between 4 h and 14 h from switching on the SRU. Maintain these operating temperatures for the duration of the test.

Figure 8 **Principle of a constant level device to control water supply to frost resistance specimens**



Key

1 Vent tap "V"
2 Filler tap "F"
3 Air-tight vessel capacity 6–8 L
4 Vacuum
5 Capillary tube, inside diameter approx 3.0 mm
6 Water
7 Water bath
8 Flexible connection
9 Outlet tap "O"

9.2.5 Measure the frost heave after a period of (24 ± 2) h from the time of switching on the refrigeration using the following procedure.

a) Rotate the brass rods to ensure that they have not stuck. Check the surgery wool and replace if necessary.

b) For each brass rod, record the distance between the top of the rod and the top of the support (datum) frame to the nearest 0.5 mm.

c) Calculate the value of any heave that has occurred by subtraction. Record this value as the "frost heave".

9.2.6 Continue to record the frost heave as described in **9.2.5** at intervals of (24 ± 2) h until at least 96 h has elapsed from the time of switching on the SRU.

9.3 Monitoring the temperature conditions

9.3.1 Employ the procedure described in **9.3.2** to **9.3.4** during every test.

NOTE Although it is not necessary to carry out a detailed tuning check of the SRU before or during every test, it is important to ensure that the equipment continues to operate correctly.

9.3.2 At least daily, record the temperature at each thermocouple sequentially at intervals not exceeding 5 s. Calculate the instantaneous water temperature [defined in **A.6.1.2.2** a, Note] and the instantaneous air temperature [defined in **A.6.1.2.2** d, Note].

9.3.3 If the instantaneous water temperature is outside the range 3.0 °C to 4.5 °C, or if the instantaneous air temperature is outside the range –18 °C to –16 °C, then determine the mean temperatures in the air and the water by the method given in **A.6.2** (see Note).

NOTE If this procedure has to be followed more than once during a test, even though the results are within the required range, this means that the SRU is operating close to the limits allowed and it should therefore be retuned before the next test.

If the mean water temperature is outside the range 3.0 °C to 4.5 °C, or the mean air temperature is outside the range –18 °C to –16 °C, abandon the test and retune the SRU (**A.6.1**). Determine the mean temperature at least once during every test.

9.3.4 Inspect the temperature recorder at least daily to check whether any sudden changes in temperature have occurred while the equipment has been unattended (for example, a power cut). If the temperature recorder shows that a sudden change in temperature of more than 0.5 °C in the water or more than 1 °C in the air and for more than 1 h duration has occurred, abandon the test.

9.4 Unloading the self-refrigerated unit

9.4.1 After at least 96 h, or earlier if it has been decided to abandon the test, unload the SRU using the procedures in **9.4.2** to **9.4.8**.

9.4.2 Switch off the refrigeration system.

NOTE The water-bath circulation/heating system should still be running at this stage, to prevent the water temperature falling too far while it is exposed to the very cold air in the test chamber.

9.4.3 Remove the surgery wool from the holes in the test-chamber lid and discard. Remove the brass rods and allow them to return to room temperature. Remove the support (datum) frame and open the test-chamber lid.

9.4.4 Carefully remove the thermocouples in the air above the specimens.

9.4.5 Remove the coarse sand (a vacuum cleaner may be used).

*NOTE The sand may be dried and sieved to allow it to be re-used (see Note to **A.5.2**). The sand should not be used again until it has returned to room temperature.*

9.4.6 Remove the test specimens from the cradle, taking care not to damage any thermocouples as they are detached.

Discard the test specimens and the waxed paper around them. Clean and dry the rigid discs, porous discs and copper specimen carriers.

Check that the porous discs have not become blocked, particularly when fine-grained materials have been tested. If any are found to be no longer permeable, replace them before future tests.

NOTE Porous discs can be cleaned by boiling in water or soaking in an ultrasonic bath.

9.4.7 Remove the wooden cradle. Allow it to return to room temperature, clean and dry.

9.4.8 Leave the SRU with the lid open until the air in the test chamber has warmed to above 0 °C. Switch off the water-bath controls and completely drain both the bath and the constant-level device. Discard the waste water.

Defrost the SRU and the test chamber (including the water-bath) and thoroughly clean and dry. Do not use the SRU for another test until it has returned to room temperature.

NOTE Signs of condensation on the walls of the chilled tank indicate that room temperature has not been reached. Leaving the SRU overnight after defrosting and cleaning is usually adequate.

10 Calculation and expression of results

10.1 Review the calculated values of frost heave for each of the nine test specimens taken in **9.2.5** over the test period.

If the values show that the frost heave of two or more of the nine test specimens has fallen by more than 1 mm, consider the test run to be invalid. Do not report the result and repeat the test using new test specimens.

10.2 For each test specimen, determine the maximum value of frost heave observed during the test period. For each set of three test specimens, calculate the mean of the maximum values, to the nearest 0.1 mm.

10.3 If comparator test specimens have not been used, use the mean value calculated in **10.2** as the frost heave value for the mixture, subject to the following conditions.

a) If the maximum value of frost heave of all nine specimens is less than 2.0 mm, the results are suspiciously low. Repeat the test unless the results are consistent with previous experience for that mixture.

b) If the mean value of frost heave for a set of three test specimens is less than 18.0 mm, calculate the range (i.e. highest – lowest) of the maximum values for the three test specimens. If the range for the set of three exceeds 6.0 mm, consider the test run to be invalid. Repeat the test using new test specimens.

c) If the mean value of frost heave is 18.0 mm or greater, the test result is valid. No further testing is required.

10.4 If the test was carried out using comparator specimens (see Annex B), use the mean value calculated in **10.2** as the frost heave value for the mixture, subject to the following conditions.

a) The mean value of frost heave for the three comparator specimens is in the range (13.6 $\pm$ 4.0) mm.

b) The range (i.e. highest – lowest) of the maximum values for the three sets of test specimens does not exceed 6 mm.

If either of these conditions is not satisfied, consider the test run to be invalid. Repeat the test using new test specimens.

NOTE The operating procedure and equipment should be examined and adjusted as necessary, to ensure that the requirements for the range and mean of the standard sand and filler specimens are satisfied.

11 Test report

11.1 Test report

For each unbound aggregate mixture, the test report shall state that the frost heave was determined in accordance with this part of BS 812 [1)] and the information in **11.2** and **11.3**. The test report shall also state whether or not a copy of a certificate of sampling is available. If available, a copy of the certificate of sampling shall be provided.

11.2 General

a) Reference to this British Standard [1)].

b) Identification of the sample.

c) Identification of the laboratory.

d) Date.

e) Maximum dry density, to the nearest 0.01 Mg/m^3 (**7.2.1**).

f) Optimum water content to the nearest 0.5% (**7.2.1**).

g) The actual dry density at which the test specimens were prepared, to the nearest 0.01 Mg/m^3 (**7.2.2**).

h) The actual water content used to prepare the test specimens, to the nearest 0.5% (**7.2.2**).

i) The particle size distribution of the test portion (**7.1**).

j) The particle-size distribution of the stable test specimen (**7.2.2**).

k) The maximum frost heave observed in 96 h of each individual specimen, to the nearest 0.5 mm.

l) The mean value of frost heave, calculated to the nearest 0.1 mm.

If required, the test report shall also include the following optional information.

m) Name and location of the sample source.

n) Description of the material.

11.3 Standard sand and filler mixture (if used)

a) The maximum frost heave observed in 96 h of each individual specimen, to the nearest 0.5 mm.

b) The frost heave, calculated to the nearest 0.1 mm.

[1)] Marking BS 812-124:2009 on or in relation to a product represents a manufacturer's declaration of conformity, i.e. a claim by or on behalf of the manufacturer that the product meets the requirements of the standard. The accuracy of the claim is solely the claimant's responsibility. Such a declaration is not to be confused with third-party certification of conformity.

12 Precision

12.1 The precision data given in Table 2 were determined from an experiment conducted in 1984/5 involving 19 laboratories using well graded unbound flint gravel without comparator specimens.

Table 2 **Precision estimates, frost resistance**

Level	Average	r_1	R_1	R_2	$\sqrt{V_{r1}}$	$\sqrt{V_L}$	$\sqrt{V_S}$
	mm	mm	mm	mm	mm	mm	mm
Flint gravel	13.5	7.0	8.5	9.0	2.5	1.8	1.0

12.2 A further precision experiment included tests on unbound mixtures (Type 1) made with crushed limestones and on sand/filler mixes. The reproducibility value (R_2) of the frost resistance of the crushed limestones was 11.3 mm.

The use of comparator sand/filler mixes to exclude tests where the frost resistance of the sand/filler mix deviated by more than 4.0 mm from the target value for the mixture reduced the reproducibility value (R_2) to 7.1 mm.

NOTE Precision data is not available for hydraulically bound mixtures.

Annex A (normative) Self-refrigeration unit

A.1 General description

The SRU used in this test shall be a self-contained unit and shall have the following features:

- a test chamber (**A.2**) and associated refrigeration and control equipment (**A.3**);
- adjustable legs so that the equipment can be levelled.

A.2 The test chamber

A.2.1 The principal features and dimensions of the test chamber are shown in Figure 7 and Figure A.1.

The tolerances on the dimensions given in Figure 7 and Figure A.1, subject to the compatibility of parts, shall be:

- dimensions in excess of 100 mm: ± 10 mm;
- dimensions in excess of 25 mm: ± 5 mm;
- other dimensions: ±1 mm.

NOTE The dimensions of the support frame and brass rods are nominal, and can be altered to suit the equipment.

A.2.2 The test chamber shall have the following features:

- a chilled tank with smooth stainless-steel sides;
- a water-bath, let into the floor of the chilled tank, provided with an overflow tube (**A.3.1**) and fitted with a separate drain-cock;
- a thermally insulating medium which does not absorb water and which connects the sides of the water-bath to the sides of the tank;
- a wooden cradle capable of holding nine test specimens, located centrally over the water-bath, made of marine-quality plywood, waterproof finish;
- a cooling system applied to the tank sides, located above the specimen cradle;
- a hinged lid with a stainless-steel underside and an interior light fitted to the underside, with nine holes of not less than 10 mm and not more than 15 mm in diameter, at the same centres as the holes in the specimen cradle to allow brass rods (**A.4.1**) to be located.

A.3 Associated refrigeration and control equipment

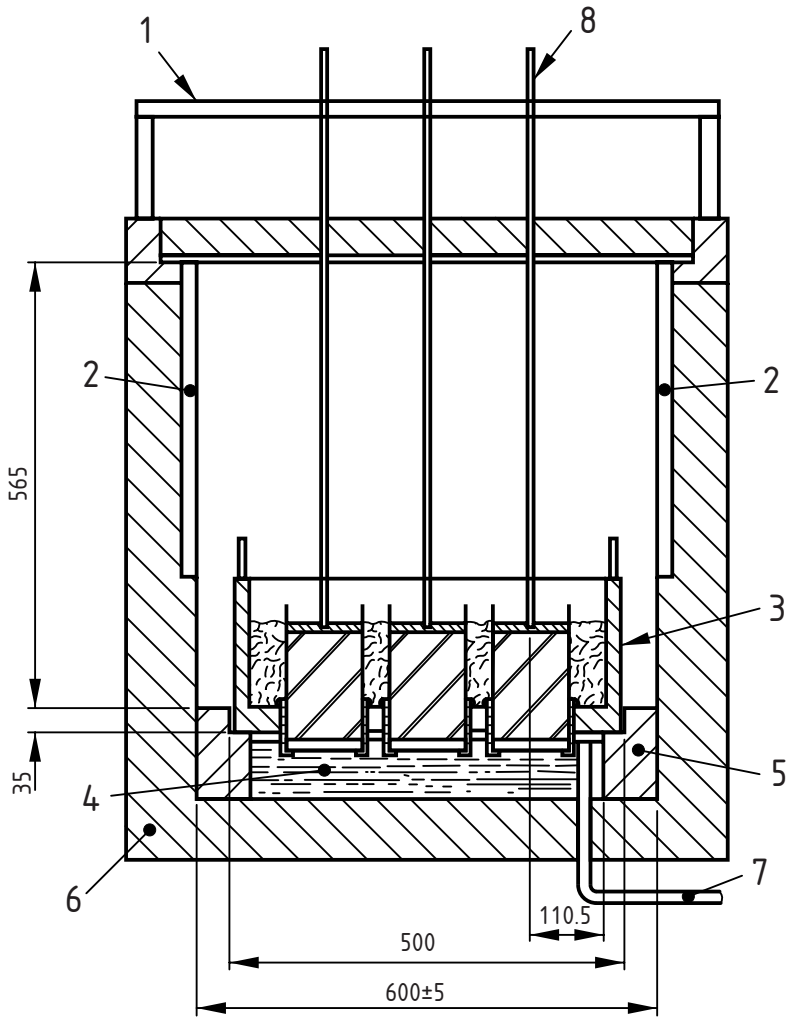
A.3.1 *A means of maintaining the water in the water-bath at a constant level between 8 mm and 11 mm from the underside of the specimen cradle* (i.e. as close as possible to the tops of the porous discs).

NOTE 1 The principle of a suitable device is illustrated in Figure 8 (see Note 2).

NOTE 2 The device shown in Figure 8 has been found to be a simple and convenient method of maintaining a constant level of water in the apparatus but it is permissible for other means of keeping the water level constant to be used if preferred.

Figure A.1 **Main features and dimensions of test chamber**

Dimensions in millimetres.



Key

1 Support frame 150 ± 25
2 Cooling coils
3 Specimen cradle (see Figure 7)
4 Water bath
5 Solid insulating material
6 Insulating material
7 Overflow pipe
8 Brass rod

A.3.2 *A device for gently circulating the water in the water-bath to maintain an even temperature distribution.*

A.3.3 *An air-cooling system*, which:

- provides a means of cooling the sides of the tank above the specimen cradle such that the operating temperatures for the air defined in **A.6** can be achieved and maintained;
- is capable of reducing the air temperature at the centre of the tank to (–20 ± 2) °C with the normal arrangement of specimens (Figure 7) in place and can achieve these temperatures between 4 h and 14 h from the time the system is switched on;
- is capable of operating at ambient temperatures of 15 °C to 25 °C.

A.3.4 *A water-cooling system*, which:

- provides a means of cooling the water in the water-bath such that the operating temperatures for the water defined in **A.6** can be achieved and maintained and can achieve these temperatures between 4 h and 14 h from the time the system is switched on;
- is capable of operating at ambient temperatures of 15 °C to 25 °C.

NOTE It is not essential to have a separate cooling system for the water-bath. A system utilizing heat-loss through the specimens and additional cooling from the system cooling the air above the specimen cradle, together with a heater mat to limit the minimum temperature, is acceptable provided that the operating temperature requirements are met.

A.3.5 *Temperature indicators*, conforming to BS EN 60584-2. At least five thermocouples in the water-bath and five in the air (see Note 1) above the specimen cradle, together with a compatible electronic thermometer with a resolution of at least 0.1 °C, and a selector switch to allow thermocouples to be tested in quick succession (see Note 2).

*NOTE 1 One of these five thermocouples will eventually be attached to the rigid disc covering the specimen in position 5 (see **9.1.2**).*

NOTE 2 If the electronic thermometer is mounted integrally within the console of the cabinet, it is essential that care be taken to prevent interference from electrical/magnetic components in the cabinet.

A.3.6 *A rigid detachable metal datum frame*, to support the brass rods (Figure A.1), which can be positively located above the lid of the test chamber and has horizontal bars with holes 6.5 mm diameter at the same centres as the holes in the specimen cradle and the test chamber lid. The upper surface of the datum frame shall be not less than 125 mm and not more than 175 mm above the top of the lid.

A.4 Additional equipment for use with the SRU

A.4.1 *Nine brass rods*, 750 mm long and 6.0 mm in diameter.

NOTE These are illustrated in their positions during the test in Figure A.1.

A.4.2 *A supply of clean and dry single-sized coarse silica sand* from either the 5 mm to 2.36 mm or the 2.36 mm to 1.18 mm fractions.

NOTE Approximately 30 kg is sufficient for one SRU.

A.4.3 *A steel rule* or other suitable means of measuring the displacement of the brass rods above the datum frame, readable and accurate to 0.5 mm.

A.4.4 *A temperature recorder*, to record continuously the air and water temperatures during the test.

NOTE It is recommended that the recorder be built into the SRU, although this is not essential provided that access is provided for the sensors.

A.4.5 *A supply of surgery wool* or similar absorbent material.

A.4.6 *Waxed paper sheets*, approximately 350 mm × 200 mm in size, of between 0.2 mm and 0.4 mm thickness; and *adhesive tape* of between 0.1 mm and 0.25 mm thickness.

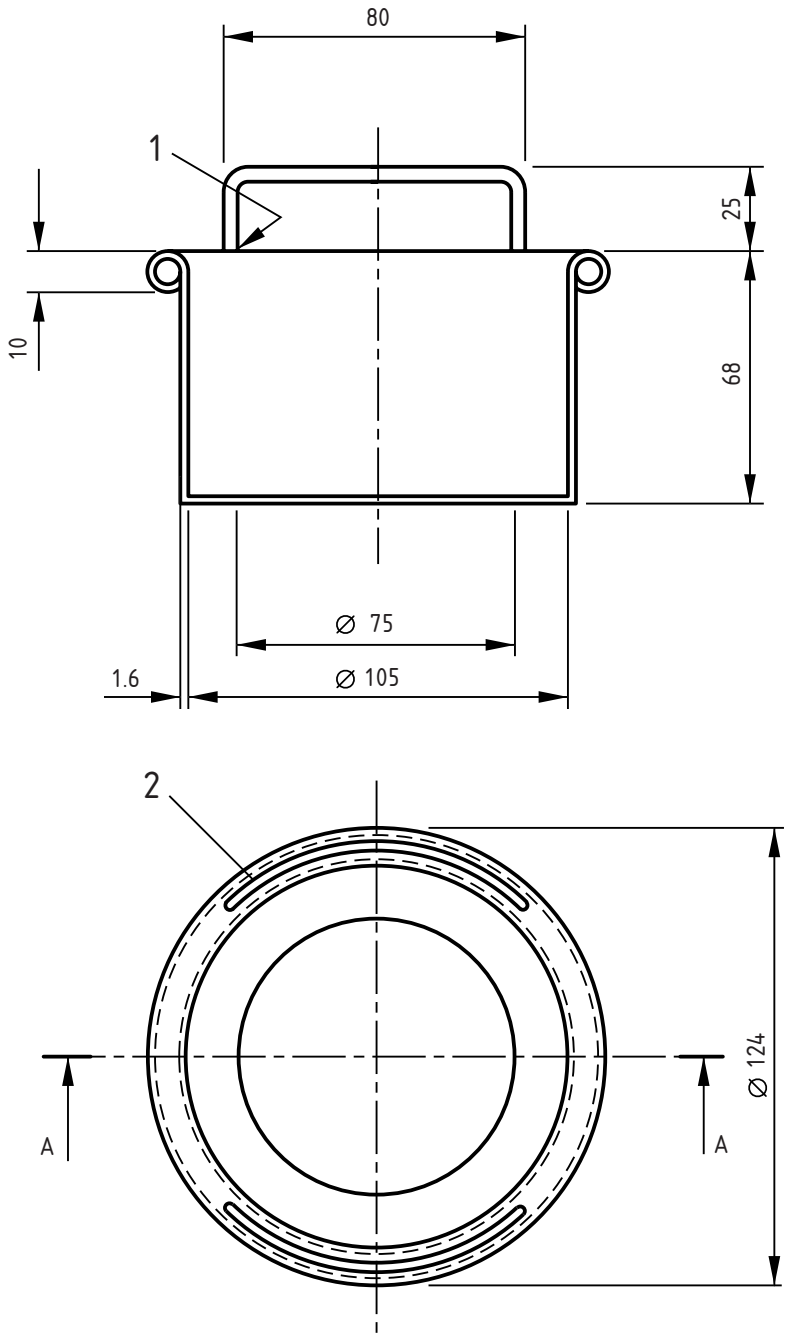
A.4.7 *Rigid discs made of cotton reinforced phenolic paper*, at least nine, 95.0 mm in diameter, 5.0 mm thick, with a central recess 10.0 mm diameter and 2.0 mm deep in one side.

A.4.8 *Porous ceramic discs*, at least nine, 13.0 mm thick and 101.6 mm in diameter, of maximum pore size 110 µm.

A.4.9 *Copper specimen carriers*, at least nine, as shown in Figure A.2.

Figure A.2 **Specimen carriers**

Dimensions in millimetres.



Key

1 Silver solder

2 Two handles, Ø 3.0 brass rod

A.5 Setting up of the self-refrigerated unit

NOTE The following operations should be carried out before the test specimens are prepared.

A.5.1 If necessary, adjust the SRU so that it is level and ensure that the test chamber, including the water-bath and constant-level device, is clean, dry and at room temperature. Use a spirit level in the base of the specimen cradle when properly seated to level the apparatus.

A.5.2 Check that the coarse sand (**A.4.2**) for filling the space around the test specimens is clean, dry and at room temperature, and if necessary wash, re-sieve to the correct grading, and dry.

NOTE Because the sand can become contaminated with use, it should periodically be washed and re-sieved to maintain the correct grading.

A.5.3 Check the operation of all the thermocouples and repair or replace any that are broken.

A.5.4 Locate the wooden specimen cradle in its position within the test chamber.

NOTE It is useful at this stage to select the thermocouples from the water-bath which are to be used at the bottom of the porous discs, feed them through the respective holes in the cradle and temporarily secure them to it. This is much easier to do at this stage than when the bath is full and specimens are in the cradle.

A.5.5 Fill the constant-level device (CLD) and water-bath with distilled or demineralized water at (20 $\pm$ 5) °C.

A.5.6 Check the water-level setting by the following procedure.

Open taps F, V and O (Figure 8) of the CLD and close the drain-cock of the water-bath. Place a suitable receiver below the overflow-pipe outlet.

Place a specimen carrier in one of the holes in the wooden cradle.

Pour water into the water-bath until the bottom lip of the specimen carrier is just covered. Check that there is no airlock or blockage in the pipe connecting the CLD to the water-bath.

Adjust the level of the capillary in the CLD if necessary so that it is approximately 5 mm above the present water-level (see Note 1).

NOTE 1 It should not be necessary to adjust the level of the capillary once it has been set up correctly. The actual method of adjustment depends on the design of a particular vessel, but generally either means moving the capillary up or down within the vessel or, if it has a fixed capillary, moving the vessel itself.

Close tap O and fill the CLD through the filler tube. Air will be expelled through the vent pipe.

Close taps F and V. Place a second specimen carrier with a porous disc in place in one of the other holes in the cradle.

Open tap O. Air should bubble through the capillary tube as water flows into the water-bath. When the bubbling stops, adjust the water level in the bath (see Note 2) so that it is approximately 1 mm from the top of the porous disc, i.e. the surface of the disc appears wet but is not covered. If the level is too low, close tap O and raise the level of the capillary slightly. Re-open tap O and allow the water to find its new level (see Note 2). Repeat this process until the required setting has been achieved.

NOTE 2 If the porous disc is covered or water overflows before the bubbling stops, the capillary is set too high. In this case, close tap O and drain the water out of the bath to its original level, covering the lip of the specimen carrier before adjusting the capillary.

When the level has been set, close tap O. Drain off water from the bath until the water again just covers the lip of the specimen carrier.

Remove the specimen carriers and disc and dry them. Top up the CLD (taps V and F open, O closed) if necessary.

Check that all the taps are closed.

NOTE 3 The functioning of the CLD can be tested at the stage when the correct levels have been achieved, with the reservoir connected, but before specimens are put in place. This can be done as follows.

- *Using a 100 mL bulb pipette and suction bulb, withdraw water from the cabinet until a bubble separates from the constant head capillary. Measure the volume withdrawn by discharging the pipette into a 100 mL measuring cylinder.*
- *Allow the levels to come to equilibrium again (bubbling ceases) and repeat the measurement.*
- *Typical results are 62 mL, 56 mL, 52 mL; Mean 57 mL. This demonstrates that a drop in water-bath level of 0.23 mm is corrected by the CLD arrangement and represents an outside estimate of the differential over which the device works.*

A.5.7 Check the water circulating system to ensure that it is operating satisfactorily.

A.5.8 Set the SRU controls to the positions which give the correct operating temperatures when the unit is eventually switched on (see **A.6**).

A.6 Operating temperatures and self-refrigerated unit tuning procedures

*NOTE Because the temperature at a given point in the test chamber clearly depends on the location, the operating temperatures within the test chamber cannot be specified in terms of a single point and temperature. Also, the temperature within the chamber will vary continuously as a result of the cycling of the refrigeration system and, possibly, changing ambient conditions. **A.6.1** gives details of how the temperatures are to be measured and the SRU tuned to give the required values. **A.6.2** gives the actual values which are to be achieved. Subclause **12.1** gives details of the measurements normally made during a routine frost resistance test.*

A.6.1 Tuning procedure

NOTE This subclause describes the procedure to be followed to check whether the test chamber is correctly tuned. It should not be necessary to follow this procedure before every test, but the procedure should be carried out periodically or after any major adjustments to the control system.

A.6.1.1 Setting up the tuning test

A.6.1.1.1 Prepare the SRU and load as described in **9.1**. Use any typical well-graded granular material for the specimens, except for cement-bound specimens (see Note). Ensure that all the thermocouples are properly located and working correctly. When the SRU has been

prepared and loaded, leave it for at least 20 h to allow the initial temperature conditions to become steady.

NOTE Although cement-bound specimens cannot be used in tuning tests because they affect the heat transfer characteristics, they can be used for convenience in any preliminary trials to adjust thermostats.

A.6.1.1.2 After 20 h have elapsed, switch on the SRU and leave it for a further 20 h before any internal temperature measurements are made. Determine the length of the initial cooling period (see Note). The air and water should reach their operating temperatures between 4 h and 14 h from starting the SRU.

NOTE The initial cooling period can be estimated from the temperature recorder, or a special timing device can be fitted to the SRU for the purpose.

A.6.1.2 Determination of mean temperatures

A.6.1.2.1 Observe the control system of the SRU until the thermostat controlling the air temperature causes the refrigeration to be switched OFF. At this point, record in turn the temperatures indicated by each of the 10 thermocouples; all 10 should be recorded in not more than 50 s. Continue to record the temperatures of the ten thermocouples at equal intervals until at least 20 sets of readings and three complete refrigeration cycles (i.e. OFF–ON–OFF–ON–OFF–ON–OFF) have been observed (see Note).

NOTE If the refrigeration system completes three cycles in less than 1 h, continue taking measurements until the first occasion that the refrigeration switches OFF after the hour has elapsed.

A.6.1.2.2 When the measurements for a sampling period have been completed, calculate the following values.

NOTE An example of the calculations is given in Annex B.

a) For each set of readings, the instantaneous water temperature (IWT).

   NOTE This is the mean of the five thermocouples below the porous discs.

b) For each set of readings, the instantaneous water temperature range (IWR).

c) The mean water temperature (MWT) and the standard deviation.

   NOTE This is the mean of the IWTs from a).

d) For each set of readings, the instantaneous air temperature (IAT).

   NOTE This is the mean of the four thermocouples in the air above the specimens.

e) For each set of readings, the instantaneous air range (IAR).

f) The mean air temperature (MAT) and the standard deviation.

   NOTE This is the mean of the IATs from d).

g) The water temperature mean range (WMR).

   NOTE This is the mean of the IWRs found in b).

h) The air temperature mean range (AMR).

   NOTE This is the mean of the IARs found in e).

i) The mean value of the temperature below the central rigid disc for the sampling period.

A.6.1.3 Measurement of variations in mean temperature

If the first determinations of mean temperatures show that the equipment is set to operate within the temperature ranges given in **A.6.2**, make repeat measurements following the procedure given in **A.6.1.2** until six consecutive determinations of MAT and MWT have been made. Allow at least 3 h and not more than 20 h to elapse between successive determinations. If any mean temperature is outside its specified range, adjust the control system accordingly and allow at least 20 h to elapse before starting again from **A.6.1.2**.

The tuning test shall be completed within 250 h of switching on the SRU.

NOTE Allow at least 20 h to elapse after any alteration to the controls before attempting a sequence of six determinations of mean temperatures. If several adjustments are needed, it might be necessary to set up a new tuning test. In any case, the tuning test should be completed within 250 h of switching on the SRU.

A.6.2 Temperature values and tolerances

A.6.2.1 Mean water temperature

Any mean water temperature shall be in the range 3.0 °C to 4.5 °C. The range of the six successive determinations with at least 3 h and not more than 20 h between each determination shall not exceed 0.5 °C. The standard deviation of any individual determination of MWT shall not exceed 0.3 °C.

A.6.2.2 Mean air temperature

Any mean air temperature shall be in the range –18.0 °C to –16.0 °C. The range of the six successive determinations with at least 3 h and not more than 20 h between each determination shall not exceed 0.5 °C. The standard deviation of any individual determination shall not exceed 0.8 °C.

A.6.2.3 Temperature mean ranges

A.6.2.3.1 Any water temperature mean range shall not exceed 0.5 °C.

A.6.2.3.2 Any air temperature mean range shall not exceed 2.7 °C.

A.6.2.4 Temperature below central rigid disc

The mean temperature below the central rigid disc during any sampling period shall be in the range –2 °C to –8 °C (see Note).

NOTE In the case of coarse-grained materials, poor contact between the disc and the specimen could result in the temperature falling below –8 °C. This can be avoided by using fine sand to even out any roughness in the surface of the specimens.

Annex B (normative) Use of comparator specimens

B.1 General description

This Annex describes the use of comparator specimens in the SRU. Comparator specimens are included:

- when the SRU is tuned;
- in cases of dispute or for referee testing;
- when the test run includes specimens for product attestation;
- at the request of the client.

Data obtained on the comparator specimens shall be retained by the laboratory.

NOTE The data should be made available to the supplier of the comparator filler on request.

B.2 Materials

B.2.1 *Standard sand*: clean rounded silica sand for use in preparing comparator specimens, which:

- conforms to the grading requirements as follows: 100% passing the 0.600 mm sieve and 0% passing the 0.300 mm sieve;
- has not been used previously for any other test.

B.2.2 *Standard filler*: limestone filler for use in comparator specimens. [2)]

B.3 Preparation of comparator specimens

Take representative samples of the sand and filler. Oven-dry them separately to constant mass at 105 °C to 110 °C so that a mass of at least 7.5 kg of sand and 1.3 kg of filler is obtained. After drying, store the sand and filler separately in sealed containers (**6.3.6**) and allow to cool to room temperature.

Weigh out to the nearest 1 g representative portions of 2 338 g of sand and 412 g of filler and place both together in a suitable container (e.g. a plastic bag). Shake the contents of the container in the dry state for 30 s to ensure that the sand and filler are thoroughly mixed.

Place the sand filler mixture into the mixing bowl (**6.3.5**). Add 250 mL of distilled or demineralized water. Mix the sand, filler and water for 5 min. Store the mixed material in a sealed container for a minimum period of 16 h before proceeding with the tests.

Weigh out to the nearest 1 g, 2 562 g of the mixed material and prepare a frost resistance specimen as described in **8.4**. Repeat to prepare two further comparator specimens.

[2)] Information about the product known as standard filler can be obtained from Jacobs Laboratories, Doubleday House, St Michael's Close, Aylesford, Kent, ME20 7BU. This information is given for the convenience of users of this document and does not constitute an endorsement by BSI of the product. Equivalent products may be used if they can be shown to lead to the same results.

B.4 Loading comparator specimens into the SRU

Place the three comparator specimens into positions 3, 5 and 7 (see Figure 7). Fill the other six positions with specimens, a minimum of three for each material to be tested.

B.5 Example of temperature parameter calculations (informative)

Evaluation of the various parameters is facilitated by the use of specimen charts. Figure B.1 is a completed chart for the determination of mean water and air temperatures. In this example, the temperatures were recorded in sets of 10 at 4 min intervals. Columns are provided for recording instantaneous temperatures and ranges; the mean temperatures and standard deviation are recorded at the foot of each column.

Figure B.2 is a chart summarizing all the determinations made during a complete turning point. The data from Figure B.1 correspond to sampling period 3 on this chart.

Figure B.1 **SRU tuning, temperature recording chart**

	Water-bath							Air						Central rigid disc
Set number	Thermocouples (°C)					IWT (°C)	IWR (°C)	Thermocouples (°C)				IAT (°C)	IAR (°C)	Thermo-couples (°C)
	W1	W2	W3	W4	W5			A1	A2	A3	A4			
1	3.7	3.7	3.8	3.7	3.6	3.7	0.2	– 19.2	– 16.8	– 19.0	– 16.9	– 18.0	2.4	– 4.4
2	3.8	3.9	4.0	3.9	3.8	3.9	0.2	– 18.7	– 16.5	– 18.6	– 16.5	– 17.6	2.2	– 4.4
3	4.1	4.2	4.3	4.2	4.1	4.2	0.2	– 17.5	– 15.3	– 17.3	– 15.5	– 16.4	2.2	– 3.7
4	3.9	4.0	4.1	3.9	3.9	4.0	0.2	– 17.7	– 15.5	– 17.6	– 15.6	– 16.6	2.2	– 3.8
5	3.9	3.9	4.0	3.9	3.8	3.9	0.2	– 18.2	– 15.9	– 18.1	– 16.1	– 17.1	2.3	– 4.0
6	3.8	3.9	4.0	3.9	3.8	3.9	0.2	– 18.6	– 16.3	– 18.5	– 16.4	– 17.5	2.3	– 4.0
7	3.8	3.8	3.9	3.8	3.7	3.8	0.2	– 18.8	– 16.5	– 18.7	– 16.7	– 17.7	2.3	– 4.0
8	3.8	3.8	4.0	3.9	3.8	3.9	0.2	– 18.8	– 16.5	– 18.7	– 16.6	– 17.7	2.3	– 4.3
9	3.9	3.9	4.1	4.0	3.9	4.0	0.2	– 18.0	– 15.8	– 17.8	– 15.9	– 16.9	2.2	– 3.9
10	4.0	4.0	4.1	4.0	3.9	4.0	0.2	– 17.6	– 15.4	– 17.4	– 15.5	– 16.5	2.2	– 3.8
11	3.8	3.8	3.9	3.9	3.7	3.8	0.2	– 18.0	– 15.8	– 17.9	– 15.9	– 16.9	2.2	– 4.0
12	3.8	3.8	3.9	3.8	3.7	3.8	0.2	– 18.5	– 16.2	– 18.4	– 16.4	– 17.4	2.3	– 4.1
13	3.7	3.7	3.9	3.7	3.6	3.7	0.3	– 18.9	– 16.5	– 18.7	– 16.6	– 17.7	2.4	– 4.1
14	3.8	3.8	3.9	3.7	3.7	3.8	0.2	– 19.0	– 16.6	– 18.9	– 16.8	– 17.8	2.4	– 4.3
15	3.8	3.9	4.0	3.8	3.8	3.9	0.2	– 18.6	– 16.4	– 18.5	– 16.5	– 17.5	2.2	– 4.4
16	4.0	4.1	4.2	4.0	3.9	4.0	0.3	– 17.5	– 15.3	– 17.3	– 15.4	– 16.4	2.2	– 3.7
17	3.9	3.9	4.0	3.8	3.7	3.9	0.3	– 17.6	– 15.4	– 17.5	– 15.6	– 16.5	2.2	– 3.8
18	3.8	3.8	3.9	3.6	3.6	3.7	0.3	– 18.2	– 15.9	– 18.0	– 16.0	– 17.0	2.3	– 4.0
19	3.8	3.8	3.9	3.7	3.6	3.8	0.3	– 18.5	– 16.2	– 18.4	– 16.3	– 17.4	2.3	– 4.1
20	3.8	3.8	3.9	3.7	3.7	3.8	0.2	– 18.8	– 16.4	– 18.7	– 16.6	– 17.6	2.4	– 4.1
21	3.8	3.8	3.9	3.7	3.7	3.8	0.2	– 19.1	– 16.7	– 19.0	– 16.9	– 17.9	2.4	– 4.2
22														
23														
24														
25														
26														
27														
28														
29														
30														
MEAN	—	—	—	—	—	3.87	0.22	—	—	—	—	– 17.24	2.28	– 4.05
Standard deviation			—	—	—	0.12	—	—	—	—	—	0.53	—	

Test number	Freezing started	
	at	on

Sampling period number	Sampling started	
	at	on
3		

Time interval between each set of readings
4 min

Ambient temperature
22 °C

Recorded by

Figure B.2 **SRU tuning, temperature parameter summary chart**

	Test number	SRU loading complete			Freezing started		Specimens material	
		at	on	by	at	on		

Sampling period number		Water bath			Air			Central rigid disc	Background information					
		MWT		WMR	MAT		MAR		Sampling started		Interval between sets of readings	Number of sets of readings in period	Ambient temp.	Data recorded by
		Value	Std Dev.		Value	Std Dev.		Mean value	at	on				
1		3.76	0.12	0.19	–17.22	0.51	2.25	–4.67			4	21	21	
2		3.74	1.10	0.24	–17.28	0.49	2.29	–4.19			4	20	21	
3		3.87	0.12	0.22	–17.24	0.53	2.28	–4.05			4	21	22	
4		3.90	0.12	0.20	–17.18	0.61	2.27	–4.06			4	21	21	
5		3.91	0.10	0.20	–17.28	0.49	2.26	–4.16			4	22	24	
6		3.87	0.09	0.18	–17.16	0.49	2.27	–4.00			4	21	22	
Maximum of six	actual	3.91	0.12	2.24	–17.16	0.61	2.29	–4.00						
	permitted	4.5	0.3	0.5	–16.0	0.8	2.7	–2						
Minimum of six	actual	3.74	—	—	–17.28	—	—	–4.67						
	permitted	3.0	—	—	–18.0	—	—	–8						
Range of six	actual	0.17	—	—	0.12	—	—	—						
	permitted	0.5	—	—	0.5	—	—	—						

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