Appendix A Physical properties of rammed earth

A.1 General

The level and extent of testing rammed earth materials depends on specific application and novelty of the material in use. Where a proven material is to be used then confidence in its qualities improves and the level of uncertainty and associated risk reduces.

For in-situ rammed earth, compliance tests are mostly undertaken on cylinders especially prepared for that purpose. In loadbearing applications it is usual to undertake soil classification, moisture–density (heavy manual compaction) testing, unconfined compressive strength and drying shrinkage assessment. Resistance to erosion and abrasion, flexural tensile and shear strength tests may also be carried out as necessary.

The rate at which materials are to be sampled for compliance testing should reflect the application and experience with the materials in use. Guidance for test procedures and the rate of testing are outlined in this appendix. Test conditions for specimens should as much as possible reflect the ambient or worst-case in-service conditions.

Pre-fabrication of rammed earth, in the form of either panels or blocks, enables some quality-control testing to be undertaken on the fabricated elements prior to their installation.

A.2 Compliance tests

Details and requirements for quality-control compliance testing of materials should be set out in the specification, as appropriate to the project, and agreed with all parties prior to commencement. The minimum performance specifications will vary with projects. Examples of appropriate specifications are given in Table A1. Suggested test methods for a range of parameters are set out in this appendix. Additional tests appropriate to the specification may also be used after mutual agreement amongst the parties involved.

Table A1 Typical minimum performance specifications for rammed earth

Parameter	Specification
Soil composition	Meet recommended and agreed specifications for grading, plasticity, shrinkage, chemical composition, mineralogy, colour, texture, organic matter content, and soluble salt contents
Minimum dry density	98% of heavy manual compaction test maximum dry density
Compaction moisture content	±1–2% of optimum moisture content
Unconfined compressive strength	1.0 N/mm^2 (general) 2.0 N/mm^2 (loadbearing)
Finish	Boniness, efflorescence, colour variation, etc, to be agreed in advance In general no cracks wider than 3 mm and longer than 75 mm
Erosion resistance	Erosion rate not greater than 1 mm/min
Surface abrasion	No general specification
Maximum drying shrinkage	Not greater than 0.5% (composite loadbearing) Not greater than 1.0% (other)

Physical property testing of in-situ placed rammed earth can be more problematic than other (prefabricated) materials and this needs to be addressed in any specification. Assessment of built walls is generally limited to aesthetic compliance. Surface hardness testing, using rebound hammers, has been used in the past, but results can prove variable and unreliable. Direct in-situ testing of density, such as sand-replacement or coring, is also problematic owing to low strength and relative slenderness of the elements. Indirect density tests, such as nuclear density testing used widely in other construction fields, may prove suitable for rammed earth in the future. Drying shrinkage measurements may be undertaken directly and reliably on walls, though the rate of drying needs to be considered; it may take many months for walls to dry out or reach relatively stable conditions. Therefore most compliance testing of rammed earth relies on preparation of cylinders for density and unconfined strength testing. Compliance testing, including moisture content and grading, can also be undertaken on samples of loose material during construction.

Extent of compliance testing will depend on the complexity of the project. The sampling rates and extent of testing need to be appropriate to the project. In some circumstances all assessment can be undertaken without laboratory testing, though in many cases some limited testing of materials will be necessary during initial selection of materials and for quality assurance during construction. Details of recommended field and laboratory testing procedures for materials and components are outlined in Table A2.

Table A2 Possible sampling rates for compliance testing during construction

Parameter	Sampling
Soil composition	Assessment during initial soil selection and delivery of each batch of material to site
Compaction moisture content	One representative sample per section of walling or one sample every 2 m^3
Unconfined compressive strength and minimum dry density	During initial material selection and 1 cylinder every 5–25 m^3 (depending on project specifications)
Finish	Test wall and on completion of construction and drying after specified period
Erosion resistance (optional)	During initial material selection
Surface abrasion (optional)	During initial material selection
Maximum drying shrinkage	During initial material selection and direct wall measurements after construction

A.3 Test methods

A.3.1 Test specimens

The test procedures set out below in general use small cylindrical or prism specimens. In preparation, particles greater than 19 mm are to be screened out. Inclusion of large particles in small specimens has a detrimental effect on performance.

Where a significant proportion of material is screened out the specimen test may no longer be representative, achieving greater compressive strengths than those achieved with the larger size particles included. Therefore, for soils containing a significant proportion (20–30%) of material greater than 19 mm, testing of larger-size specimens, such as 300 mm cubes or 300 mm diameter cylinders, is recommended. Test procedures should otherwise, however, follow those set out below.

A.3.2 Moisture–density relationship

A.3.2.1 Background

The dry density of rammed earth material is primarily dependent on soil type, moisture content at compaction and compactive effort or energy. In order to achieve maximum density, it is important that the optimum moisture content, appropriate to the method of compaction, is used when ramming. However, the compactive energies of both pneumatic ramming and manual ramming are difficult to establish as they vary between operatives. The heavy manual compaction test and the 'drop' test are two commonly used procedures for establishing the optimum moisture content for rammed earth materials. These are both outlined below. The heavy manual compaction test should normally be undertaken in accordance with procedure outlined in BS 1377-4:1990[17].

A.3.2.2 Compaction test procedure

In this test a soil sample of known moisture content is compacted in a 1 litre (115 mm high × 105 mm diameter) cylindrical mould. Compaction is carried out in five layers of equal thickness by a 4.5 kg dropping weight falling 27 times on each layer from 450 mm. When the cylinder has been compacted to its full height within the standard mould, its wet weight is recorded to establish its bulk density. A sample of material is then taken for oven drying to establish the soil moisture content. At least five specimens at various moisture contents are prepared the same way and their bulk densities and moisture contents are recorded. After drying, the moisture contents and dry densities are calculated and plotted on a graph (of dry density and soil moisture content, see Figure 35). From the resultant curve, it is possible to determine the optimum moisture content for which the soil experiences its maximum dry density for the given compactive effort. The compactive energy of the heavy manual compaction test is widely believed to be lower than typical pneumatic works.

A.3.2.3 Drop test procedure

The 'drop test' is widely believed to provide a good approximation of the optimum moisture content. A ball of moist soil, approximately 40–50 mm diameter, is compacted by hand. The soil ball is dropped onto a hard flat surface from a height of approximately 1.5 m. When the soil is too dry the ball breaks into many pieces. When enough water has been added so that the ball breaks into only a few pieces, the soil is very close to its optimum moisture content. If the ball remains in one piece then the soil is too wet. The test is widely used as a means of controlling soil moisture content during construction. The drop test has a tendency to over-estimate optimum moisture contents, especially as the soil plasticity increases.

A.3.3 Unconfined compressive strength

A.3.3.1 Background

Compressive strength represents a basic quality-control measure for rammed earth, in the same way that cube testing does for concrete. The test to determine unconfined compressive strength of rammed earth is normally undertaken on cylinders prepared for that purpose. The cylinders are placed in a compression-testing device and loaded in uniform uniaxial compression until failure. Compressive strength is obtained from maximum applied loading and initial cross-sectional area.

Unconfined compressive strength is obtained by testing cylinders having a height to diameter ratio of 2. Alternatively the approximate unconfined strength of compaction test size cylinders (115 mm high × 105 mm diameter) may be established by factoring the test value by 0.7.

Cylinders are normally tested following drying to a stable moisture content under ambient conditions or curing for a specified period, such as 28 days.

A.3.3.2 Test procedure

Prepare five identical cylinders 200 mm high × 100 mm diameter or 300 mm high × 150 mm diameter. The material should be compacted at its optimum or, if different, the as-used moisture content, using the specified reproducible compactive effort. Compactive effort is usually the heavy manual compaction test, using a 4.5 kg hammer, though pneumatic ramming may also be specified. The maximum aggregate size should not exceed one-sixth of the cylinder diameter. Where more than 20–30% of material is screened out this change in grading may have a significant influence on recorded strength, and a larger more representative specimen should be used (see A.3.1).

After compaction, the cylinders should be stored for drying or curing. Rammed earth specimens may be dried at 15–20 °C and 40–60% RH until there is no further loss of moisture. Specimens containing cement or another stabilising additive should normally be cured under appropriate conditions for the specified period (eg 28 days) and then tested after laboratory oven drying.

Cylinders should be capped after drying and before testing to provide two opposing parallel and flat surfaces. The capping material may be dental plaster or similar material and should not exceed 5 mm in thickness at either end. Before capping, measure and weigh each cylinder to establish material bulk density.

Ensure that the end surfaces are clean and place the cylinder between the compression testing platens. The load is to be applied without shock and increased continuously until failure.

In strain-controlled devices the moving head should travel at a rate of 1.0 mm/m strain per minute. In load-controlled devices, the load should be applied at a constant rate equivalent to a specimen stress of 0.2 N/mm^2 per minute. Record the maximum load and mode of failure. If required, set aside representative samples of material from each test cylinder to determine moisture content at testing.

For cylinders of height to diameter ratio of 2, the unconfined compressive strength of each specimen is equal to its maximum load divided by initial cross-sectional area. The characteristic unconfined compressive strength is given by:

$$f_c = f_a - 1.65\sigma_{n-1}$$

where: f_c = characteristic unconfined compressive strength of test sample
f_a = average unconfined compressive strength of test sample
σ_{n-1} = standard deviation of test sample

The test report should include:

- Specimen dimensions
- Moisture content at compaction
- Compactive effort
- Percentage of material screened out during preparation
- Drying conditions
- Capping material
- Moisture content at testing
- Cylinder dry density
- Average and characteristic unconfined compressive strength

A.3.4 Drying shrinkage

A.3.4.1 Background

The test is a measure of how much rammed earth materials shrink linearly on drying following compaction. Atmospheric conditions (temperature, relative humidity) will determine both the rate and final drying shrinkage of rammed earth. Drying shrinkage tests are recommended where the differential shrinkage of rammed earth may have significant influence on loadbearing walls. Tests may be undertaken on cylinders prepared for unconfined compressive strength testing (A.3.3). Where more than 20–30% of material is screened out, the proportionally greater fines content of the cylinders may overestimate actual material shrinkage. Proportion of materials screened out in preparation should be reported.

A.3.4.2 Test procedure
Five cylindrical specimens should be prepared for compressive strength testing. Following compaction the cylinders should be allowed to dry out under controlled temperature and RH conditions. Recommended test conditions should remain constant and within the ranges 15–20 °C and 40–60% RH, though these may be varied to suit specific applications.

Determination of linear shrinkage relies on measurement of total or relative changes in length of the cylindrical samples. Measurements may be made directly using total length, before and after drying, or more precisely using surface-mounted strain devices such as a DEMEC gauge. Initial measurements should be taken immediately following compaction and demoulding of the cylinders and thereafter periodically during drying. Shrinkage measurements cease when they no longer change with time and when the cylinder mass remains constant.
Change in moisture content may be determined from an additional specimen prepared for that purpose and subject to the same test conditions.

Cylinder shrinkage is expressed as the ratio of change in length to original datum length. The test report should include:

- Average drying shrinkage of the cylinders
- Compactive effort
- Proportion of material screened out
- The initial (compaction) moisture content
- Final moisture content
- Period of time for shrinkage to occur
- Test conditions during drying
- Method of measuring shrinkage

A.3.5 Flexural tensile strength

There is no recognised test procedure for flexural tensile or bending strength testing of rammed earth. In most applications knowledge of flexural strength is not required. However, when considered necessary, tests should normally seek to determine flexural strength perpendicular to the horizontal compaction layers.

The test specimen should allow application of flexural tensile stress in bending perpendicular to compaction layer bedding. The specimen should be of sufficient size to allow a number of identical compaction layers to be tested under conditions of increasing uniform bending moment. The specimens should be prepared under the heavy manual compaction test or other specified and reproducible compactive effort. After compaction the specimens should be dried or cured and dried under agreed conditions, such as those specified for compressive strength testing (A.3.3). If more than 20–30% of material is screened out this change in grading may have a significant influence on recorded strength, and a larger more representative specimen should be used.

Flexural tensile stress may be applied to test specimens either as a four-point load beam test or using a bond wrench[22] or similar device. The influence of self weight should be taken into account when determining flexural tensile strength. The load should be applied to the test specimens without shock at a uniform rate until failure. Testing should normally be complete within 60–120 seconds of applying the load. The flexural tensile strength of each specimen should be calculated based on gross cross-sectional properties.

The test report should normally include:

- Size of test specimen
- Compactive effort details
- Proportion of material screened out
- Details of soil preparation
- Rammed earth moisture content at compaction and testing
- Curing and drying conditions
- Details of test set-up, including loading rate
- Individual specimen results
- Average and characteristic flexural tensile strength

A.3.6 Shear strength

Knowledge of shear strength may be required in design to assess racking shear resistance of (non-loadbearing) rammed earth walls. Shear strength may be determined using large-scale (ie 300 mm × 300 mm) shear box testing or direct tests on prototype walls (Figure A1). Preparation of materials and specimens should replicate likely site conditions.

The test report for shear testing will normally include:

- Details of specimen preparation, including materials
- Details of test set-up and rate of loading
- Shear strength
- Coefficient of friction (when testing under increasing normal stress such as the shear box)

A.3.7 Accelerated erosion test

A.3.7.1 Background

At present there is no simple or reliable test to predict the erosion resistance of rammed earth materials. Test methodologies including water-spray, water-drip or wet–dry tests may be used to compare relative performance of different materials. The accelerated erosion test, as set out in *The Australian earth building handbook*[3], is recommended to determine relative erosion resistance of rammed earth panels. Specimens are subject to a continuous jet of water spray for

Figure A1 Shear testing of rammed earth wall panel

60 minutes or until the water has completely penetrated the specimen. Performance, in terms of erosion rate, is determined on the basis of pitting depth or time taken to penetrate the specimen completely.

A.3.7.2 Test procedure

Normally three identical rammed earth specimens should be prepared for the erosion test. The specimens should measure 300 mm × 300 mm (test face area) and normally be at least 100 mm thick. Thickness should be adequate to allow a representative material grading in testing. The specimens shall be compacted using the heavy manual compaction procedure or another specified and reproducible compactive effort. The rammed earth layers shall be compacted in equal layers across the length and thickness of the specimen. Each specimen will be allowed to dry out and protective coatings applied as required in preparation for testing.

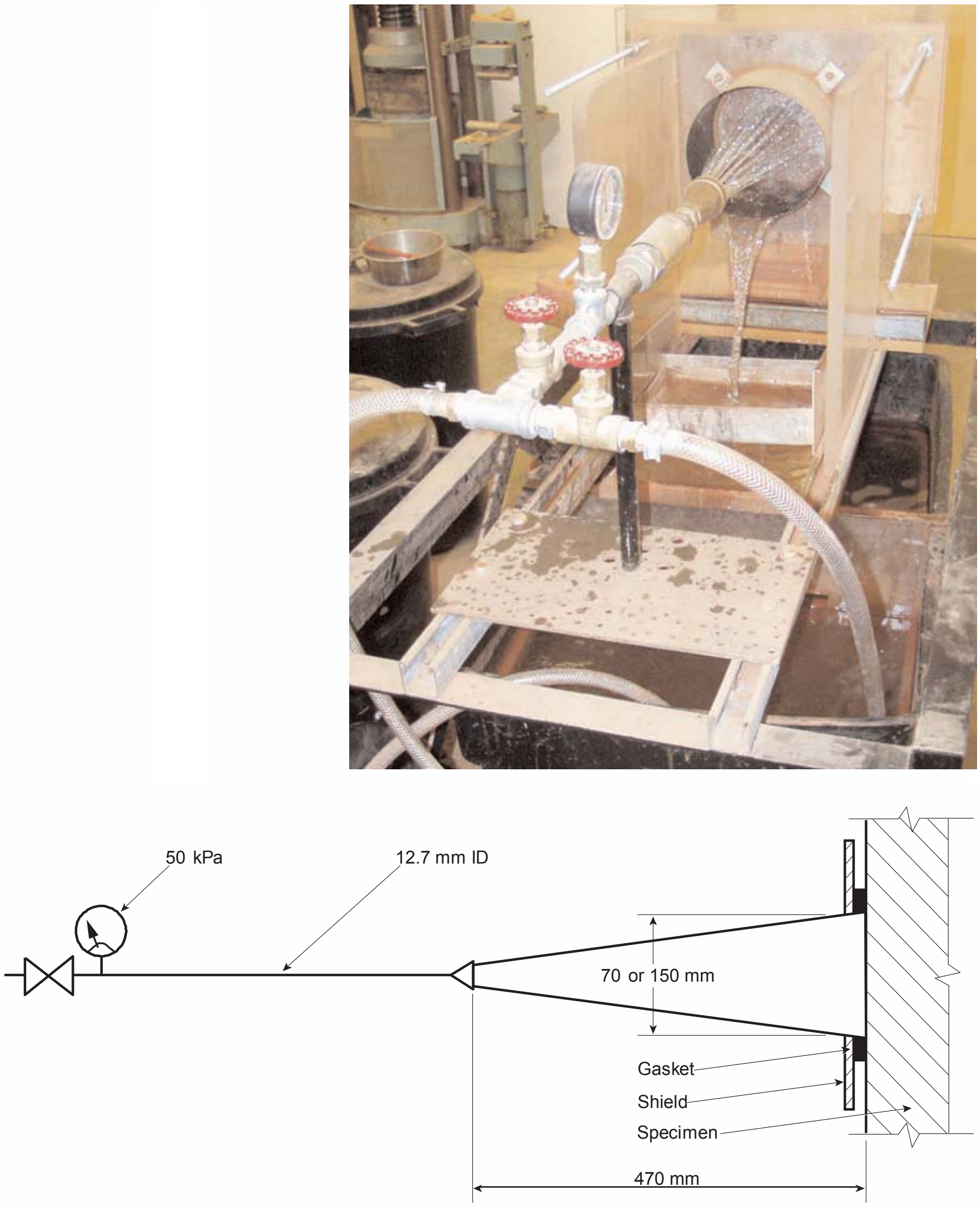

Photo: Vasilios

Figure A2 Spray erosion test

The specialised apparatus required for the test is shown in Figure A2. The test includes a 50 mm spray nozzle mounted in front of the specimen, a water pump and pressure gauge, settlement tank, filtration screen to remove particulate matter, and mountings for the specimen, including a screen and gasket.

Specimens are to be mounted in the test rig in the same orientation as that intended for the wall construction, ie with the compaction layers horizontal. The screen should be positioned such that a limited area of one face of the specimen is exposed to the spray. Each specimen is subjected to the water spray for 60 minutes or until the specimen has completely eroded through.

At the end of testing the depth of erosion is measured to the nearest millimetre using a 10 mm diameter flat-ended rod. The maximum depth measured for each specimen is taken as the rate of erosion (mm/hour). Where the specimen fails in less than 60 minutes the rate of erosion is determined from specimen thickness divided by the time (in hours) at which the test was stopped. The average test performance for the sample of three specimens is to be reported.

A.3.8 Abrasion resistance

A.3.8.1 Background

At present there is no universal recognised test for expression of abrasion resistance for earthen materials. Laboratory tests generally comprise wire-brush abrasion of surfaces under a specified pressure and measurement of material lost. Abrasion testing may be useful for comparing the performance of different materials or protective coatings, but is unlikely to provide a reliable predictive indication of future performance. Variations in surface finish of rammed earth, such as boniness, can lead to significant varying performance of an individual test panel. A simple test procedure, developed for compressed earth blocks, is outlined below[23]. Other methods, such as those developed by Minke[9], might also be used.

A.3.8.2 Test procedure

The basic objective of the test is to measure the resistance to abrasive damage of a rammed earth surface. The rammed earth test panel is subject to abrasive action of a metal wire brush, at constant vertical pressure, for a given number of cycles. The rammed earth panel surface should be prepared to be representative of the proposed or actual wall construction. The specimen should measure 300 mm × 300 mm × up to 100 mm thick. The abrasion resistance is measured as loss of material (mass) over the test surface area.

The test uses a standard wire brush. To maintain a constant vertical pressure a mass of 3 kg is fixed to the brush (Figure A3). In preparation for testing the specimen(s) should be dried to constant mass under specified conditions. The specimen should be capable of being laid flat for testing. The specimen is initially weighed. The test face is then subject to wire-brush abrasion, which comprises 60 complete backward and forward cycles in 1 minute. No further vertical pressure should be applied during

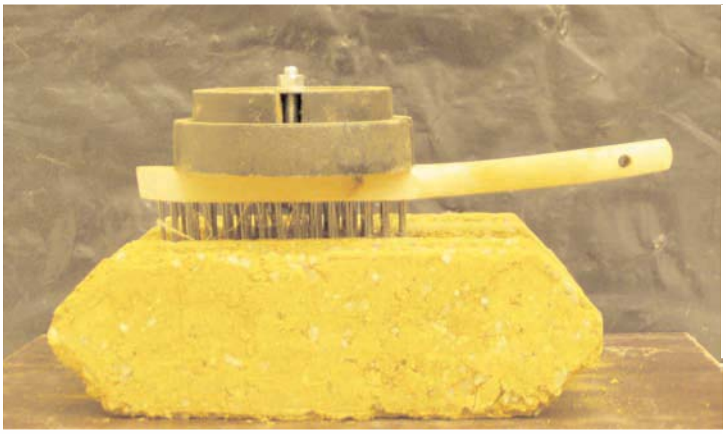

Photo: Vasilios

Figure A3 Abrasion test

testing. The width of the brushed area should not exceed the width of the brush by more than 2 mm. The brushing should be along the full 300 mm length of the panel and throughout brushing at least half the surface of the brush should remain in contact with the test surface. On completion of brushing lightly remove any remaining loose material and re-weigh the panel. Report the abrasion resistance of the test panel as the area of the brushed surface divided by the mass reduction caused by brushing (m^2/kg). The direction of brushing may be parallel or perpendicular to the direction of the compaction layers. Normally more than one test may be undertaken on both sides of each specimen.

The test report will normally include:

- Details of specimen preparation, including protective coatings
- Specimen density and moisture content
- Average abrasion resistance of each specimen
- Average abrasion resistance of sample
- Direction of brushing relative to compaction layers