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RILEM TC 127-MS: TESTS FOR MASONRY MATERIALS AND STRUCTURES

Recommendations

FOREWORD:
The texts presented hereunder are drafts for general consideration. Comments should be sent to the editor:
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MS-B.4 Determination of shear strength index for masonry unit/mortar junction

B.4.0. CONTENTS

B.4.1 SCOPE

This recommendation specifies a method of measuring an index of the shear strength of the interface between masonry unit and mortar using specimens made of 3 units bonded together with mortar. The method is suitable for all the normal masonry mortar types and both thick and thin joints. Guidance is given on the number of tests required, preparation of the specimens, the apparatus, the test procedure, the method of calculation, and the contents of the test report.

B.4.2 SPECIMENS (Size, shape, numbers)

Basically, all masonry units are suitable for tests. Randomly sample 5 masonry units for determining the moisture content. Additionally, for tests with no preload, randomly sample a further 15 masonry units for the construction of the specimens and, for tests with preload, randomly sample a further 15 masonry units per preload value for the construction of the specimens. A minimum of 3 preload values are recommended, which will require 45 masonry units.

The specimens in the form of stack bonded triplets shall be built by normal bricklaying methods using masonry mortar with a consistence (slump approx. 170 mm) ensuring a good workability or following manufacturers' instructions for thin joint mortars. Normally, 5 specimens shall be tested per preload value including zero preload.

B.4.3 PREPARATION OF SPECIMENS

The face sides of the masonry units where the load is applied (Fig. 1) shall be plane and perpendicular to the

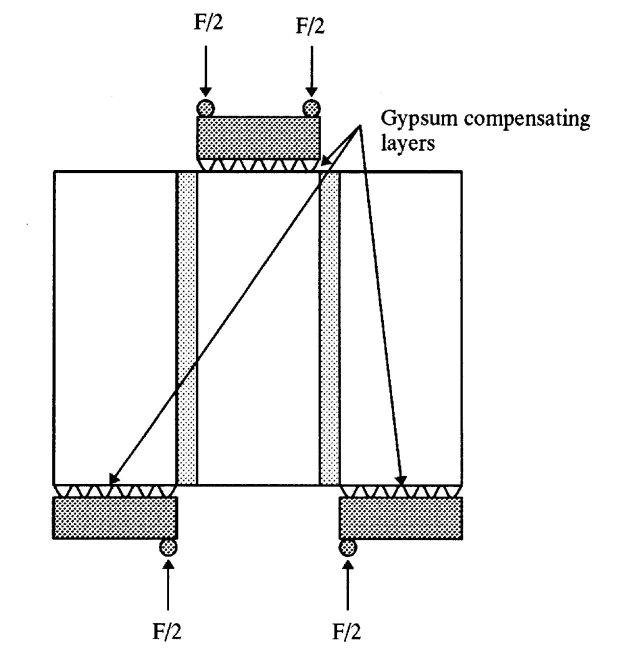

Fig. 1 – Specimen for procedure (a) with no normal preload.

bearing surface. If necessary, they shall be ground or made plane with capping. Alternatively, gypsum compensating layer material may be placed between the face side of the unit and the support (Fig. 1). Where the moisture content of the masonry units, at the time of constructing the specimens, is required to be within a certain range, store the units under appropriate conditions. During the storing of the masonry units, sufficient air space between the units shall be provided. When storing under humid conditions, the units should be stored in air for about one day prior to laying in mortar. Units may be dipped in water and drained prior to laying, if specified. In any case, the moisture contents of 5 masonry units shall be determined at the time of laying in mortar.

The bearing surfaces of masonry units shall be cleaned of adhesive dust, *e.g.* by lightly wiping. The lower unit shall be laid on a horizontal area. For normal thickness joints, a metal jig should be used, comprising a clamp-on frame which is pretreated with mould oil, having dimensions on all sides of 5 mm greater than the face side of the unit or the type specified for test LUM B.1. This should be set in such a manner that a layer thickness of $T_d + 3 \pm 1$mm is attained when filled with mortar (where T_d is the design joint thickness). Where a shell-bedded specimen is required, a strip of $T_d + 3$ mm thick, easily-compressible plastic foam of the specified width should be laid down the centre of the frame.

The mortar is filled in the center of the bearing surface and distributed laterally in such a manner that no voids occur in the horizontal joint. The mortar shall be struck off with a trowel or straight-edge, flush with the frame. The frame/jig rails should then cautiously be removed and the next unit laid on the mortar layer flush with the lower unit. By tapping gently on the upper unit with a trowel, the thickness of the horizontal mortar joint shall be adjusted to $T_d \pm 1$ mm. The upper unit shall be brought into good parallel, vertical, and linear alignment to the lower one, using a try square and a machinery level. Excess mortar shall be immediately skimmed off with the trowel. After sufficient hardening of the first joint mortar, the third unit shall be put on top using the same procedure.

Normal masonry mortar should be used within half an hour of mixing. Air lime, retarded ready-to-use and thin joint mortars should be used within the working time specified by the manufacturer. For thin joint masonry, follow the manufacturers' instructions for laying technique.

B.4.4 CONDITIONS OF SPECIMENS

Prior to testing, the specimens shall be stored at a temperature of 20 ± 2°C and not less than 90% r.h. for a period of 1 day. For hydraulic cement mortars, this treatment should be continued for a further 20 days, followed by laboratory conditions of 20 ± 10°C and uncontrolled relative humidity for the final 7 days. Mortars made from air lime binder should be cured in air at 20 ± 10°C and 50% ± 10% r.h for a further 90 days. For thin joint masonry, follow the manufacturers' instructions for curing conditions. The specimens shall be protected from vibration and shocks especially within the first 3 days.

B.4.5 APPARATUS

Tests shall be carried out in a testing machine that complies with the requirements given in Table 1. Where an axial preload is required, these specifications also apply to the preloading device.

Table 1 – Requirements for testing machines

Measuring error (% of true force)	Repeatability (% of true force)	Zero error (% of scale maximum)
2.0	2.0	0.4

The testing machine shall have adequate capacity, but the scale used shall be such that the ultimate load on the specimen exceeds one fifth of the full scale reading. The machine shall be be provided with a load pacer or equivalent means to enable the load to be applied at the rates specified in Clause 4.6. The test machine shall be equipped with two steel bearing platens. The stiffness of the platens and the manner of load transfer shall be such that the deflection of the platen surfaces at ultimate load shall be less than 0.1 mm measured over 250 mm. The platens shall be either through-hardened or the faces case-hardened. Where the testing faces are case-hardened they shall have a Vickers hardness of at least 600 HV when tested in accordance with ISO 6507.

The upper and lower platens of the machine shall be plane parallel non-tilting blocks and the bearing faces shall be larger than the size of the specimens. The bearing surfaces of the platens shall not depart from a plane by more than 0.05mm.

B.4.6 PROCEDURE

B.4.6.1 Procedure (a) - with no preload

Following Fig. 1, the specimen shall be inserted into the testing machine in such a manner that the load acts parallel to the mortar joint. It is advisable to move the point of load application to as near the joint as possible, to minimise the bending moment, using rollers or knife edges as shown. Apply the load at a constant rate, such that the test is completed in 1 to 2 minutes, and record the maximum force.

B.4.6.2 Procedure (b) - with axial preload

Following Fig. 2, the specimen shall be inserted into a frame having an actuator to apply a force and a load cell to measure the force, such that an axial load normal to the plane of the joint can be applied. Apply a set preload and test 5 randomly-selected triplet specimens by loading parallel to the mortar joint. It is advisable to move the point of load application to as near the joint as possible, to minimise the bending moment, using rollers or knife edges as shown. Apply the load at a constant rate, such that the test is completed in 1 to 2 minutes, and record the maximum force.

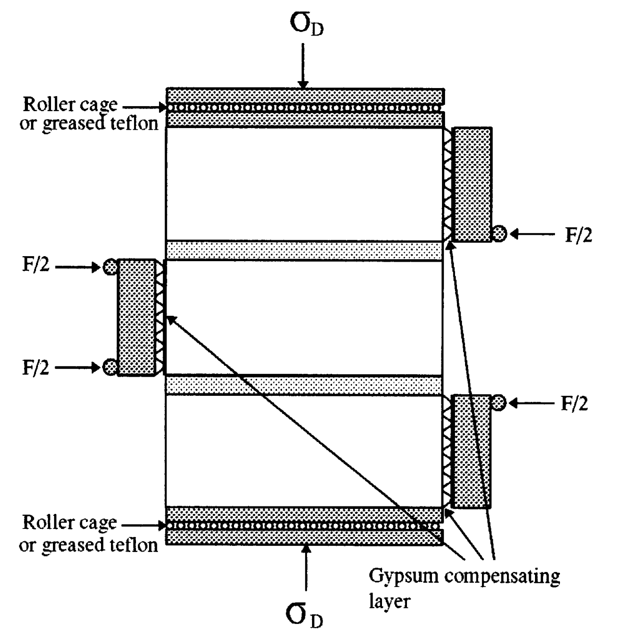

Fig. 2 – Specimen for procedure (b) with normal preload.

B.4.6.2a Preload values

For units with compressive strengths greater than 10 N/mm^2, use precompression loads that give approximately 0.2 N/mm^2, 0.6 N/mm^2 and 1.0 N/mm^2. For units with compressive strengths less than or equal to 10 N/mm^2, use precompression loads that give approximately 0.1 N/mm^2, 0.3 N/mm^2 and 0.5 N/mm^2. The precompression loads should be kept within ± 2% of the initial value.

B.4.7 TEST RESULTS

B.4.7.1 Test results using procedure (a)

The adhesive shear strength τ_0 is determined in the absence of normal stresses perpendicular to the mortar joint. The following relationship may be applied:

$$\tau_0 = F / (A_1 + A_2)$$

where:
F is the maximum force applied by the test machine,
A_1 is the area of the upper joint, and
A_2 is the area of the lower joint.

The adhesive shear strength shall be determined as the arithmetic mean of all successful individual tests. A test shall be regarded as not successful if the specimen crushes during the test or if the shear strength is lower than 0.03 N/mm^2. Both single values and arithmetic mean shall be rounded to the nearest 0.01 N/mm^2. Additionally, the coefficient of variation in % shall be determined to the nearest 0.1%. The test shall be repeated if more than 2 individual determinations are not successful. In this case, all successful test results from the first and repeated tests shall be considered.

B.4.7.2 Test Results using procedure (b)

A minimum of three sets of data (15 specimens) will be available, where for each specimen:
F is the maximum force applied by the test machine,
τ_a is the total shear stress which is equal to $F / (A_1 + A_2)$ for each replicate, and
σ_D is the applied preload normal to the bed joint.

Carry out a normal linear regression analysis[1] of the data in which τ_a is the dependent (Y) variable and the applied preload, σ_D, is the controlled (X) variable. Determine the value of the adhesive shear strength (τ_0) and the coefficient of friction (μ) from the regression equation:

$$\tau_a = \tau_0 + \mu \cdot \sigma_D$$

The adhesive shear strength, τ_0, shall be determined as the intercept on the Y axis and the coefficient of friction (μ) as the slope. Fig. 3 illustrates such a determination using three sets of five test specimens.

A test shall be regarded as not successful if the specimen crushes during application of the preload or during the test, or if the shear strength is lower than 0.03 N/mm^2. Both single values and arithmetic mean shall be rounded to the nearest 0.01 N/mm^2. The test shall be repeated if more than 2 individual determinations at each preload are not successful. In this case, all successful

(1) Simple linear regression is normally available on most graphics handling packages and spreadsheets for personal computers.

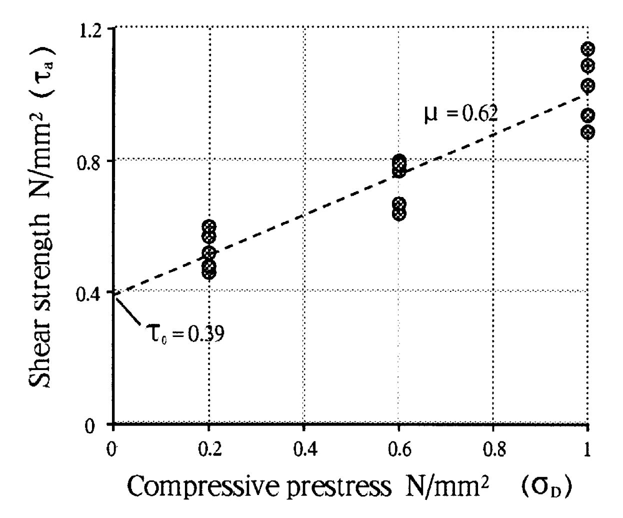

Fig. 3 – Typical plot of τ_a versus σ_D showing derivation of τ_0 and μ.

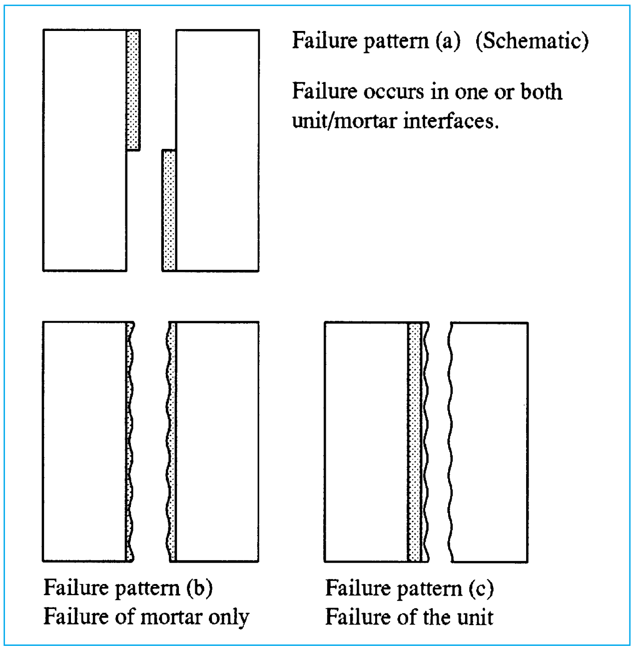

Fig. 4 – Failure modes for shear specimens.

test results from the first and repeated tests shall be used in the regression.

B.4.7.3 Failure patterns

The characteristic failure patterns shown in Fig. 4 may be recorded. Also intermediate patterns are possible. Failure occurs in the unit/mortar interface, being distributed either on one or on two sides of the unit. If failure is predominantly of type (c), the parameter measured is the shear strength of the unit material and this should be reported with the results.

B.4.8 TEST REPORT

1) A reference to this test method and which procedure was used.
2) A description of the test specimens, including their overall size, shape, bonding, tooling and joint thickness.
3) The method of sampling of the masonry units including site or place of sampling.
4) The properties of the masonry units including strength and, where appropriate, water absorption, IRA, and density.
5) The composition and strength of the mortar used.
6) The date of preparation of the specimens and the date of the test.
7) The conditions of storage.
8) All individual failure loads in Newtons and relevant dimensions in mm and, where relevant, normal compressive stress.
9) The position of all the cracks in each failed specimen. It is particularly important to record the type of failure and whether it is predominantly at the upper or lower masonry unit/mortar interface or through the mortar.
10) For procedure (a), all individual values of bond shear strength calculated as specified together with the sample mean, standard deviation, and coefficient of variation.
11) For procedure (b), the derived values of adhesive shear strength and the coefficient of friction together with the statistical parameters R, the regression coefficient and S_{x-y}, the standard deviation for the regression.

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MS-D.1 Measurement of mechanical pulse velocity for masonry

D.1.0 CONTENTS

D.1.1 SCOPE

This recommendation specifies a method for determining the velocity of low frequency mechanical pulses induced in existing masonry. Details regarding the principles involved, the apparatus, the method of test, the method of calculation, and the contents of the test report are provided. The pulses (stress waves) are induced by striking the masonry with an instrumented hammer.

D.1.2 SPECIMENS (Size, shape, numbers)

Test locations are dictated by engineering objectives; however an attempt should be made to measure the variation in material quality or condition throughout the structure. The number of tests required is dependent on the accuracy and resolution desired in the evaluation. A quick survey of material uniformity may require only a few tests in each area of interest, whereas an in-depth analysis will require a dense gridwork of tests. Generally, a large number of replications are required to provide an adequate statistical data base. The level of replication required depends on the variability of the test results. Mechanical pulse velocity may be measured in the plane of the masonry or through masonry in a direction perpendicular to the surface.

D.1.3 PRINCIPLES OF THE TEST

The travel time and waveform characteristics of a low frequency (in the range of 1 to 5 kHz) stress wave may be used to obtain an estimate of relative masonry quality. The high energy content and long wavelength of the input wave provide a robust signal, which lends itself particularly well to evaluation of large expanses of older masonry. The frequency content of the input wave is very important, because a relation exists between the minimum detectable flaw size and the primary frequency of the input wave. A flaw will not be detected if the wavelength of the input wave is equal to or longer than the flaw size and hence the mechanical pulse system is unable to detect flaws or delaminations which may be very small. However, this technique is sensitive enough to detect larger flaws that are of interest in a structural evaluation.

The mechanical pulse technique is best suited to the task of locating flaws and discontinuities such as deteriorated or missing mortar joints and large cracks or voids, using the three techniques illustrated in Fig. 1. Direct tests are used to locate flaws and voids in the middle wythes, whereas semi-direct and indirect tests are useful for determining the average velocity through a single outer wythe of masonry.

A typical wave record of both the hammer input and received pulse is shown in Fig. 2. With the path length and transit time of the stress wave known, the average velocity can be calculated. Variations in pulse velocity may indicate: the presence of flaws in the form cracks and voids; delamination-type flaws between the mortar and masonry unit; variations in density; or changes in unit and mortar strength. Waveform characteristics such as frequency content and amplitude may provide additional information.

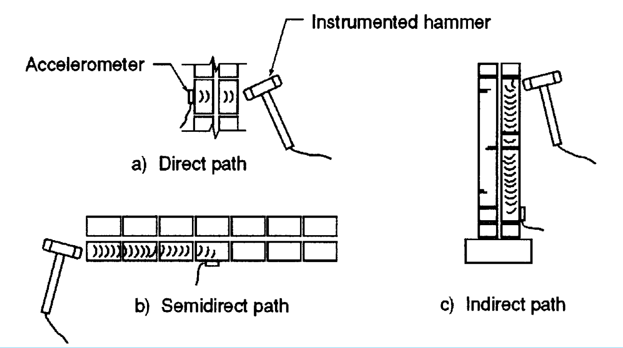

Fig. 1 – Three different types of tests normally conducted to determine mechanical pulse velocity.

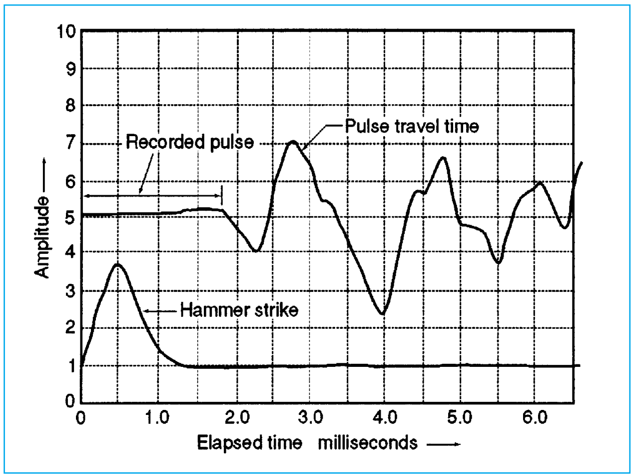

Fig. 2 – Recorded waveforms, showing both the input hammer pulse and the received pulse.

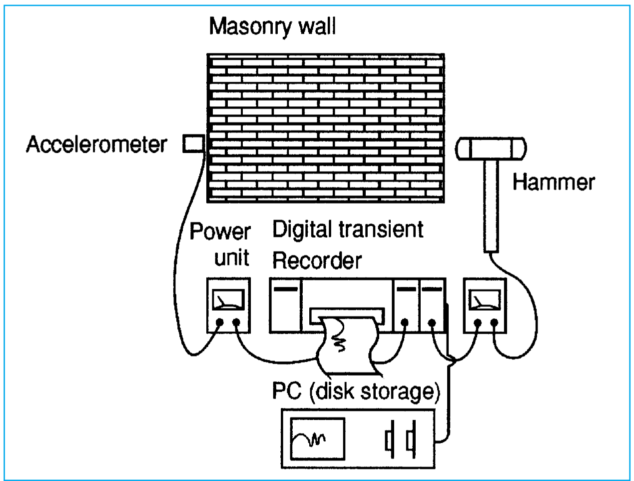

Fig. 3 – Equipment used for determination of mechanical pulse velocity.

The method has proven to be reasonably accurate for predicting masonry compressive strength, using empirical relationships derived under carefully controlled laboratory conditions. However, strength predictions can only be justified if a calibration of pulse velocity with masonry strength is made for the specific structure under consideration, and then only if the conditions of testing can be carefully controlled. The empirical relationship between mechanical pulse velocity and masonry compressive strength must, in effect, be established for every structure evaluated.

D.1.4 CONDITIONS OF TESTING

Tests are to be conducted under ambient conditions; however the work shall not be carried out in heavy rain or other conditions likely to cause serious fluctuations in the state of the specimens or the instrumentation. Moisture content of the masonry will have a direct effect on pulse velocity: a high saturation level may conceal otherwise significant flaws within the masonry.

D.1.5 APPARATUS

Mechanical pulse velocity equipment may be obtained from any of several different manufacturers. The general set-up, shown in Fig. 3, consists of a stress wave generator, a hammer or a calibrated impactor, receiving accelerometer, and a recording device, which records the input pulse and received waveform.

The stress wave is generated by a small, modally tuned hammer/impactor with an attached accelerator to record the input pulse. A more consistent pulse is possible if a steel plate is resin-bonded to the impact point. The frequency and energy content of the input pulse are governed by characteristics of the hammer. A hard hammer head will provide a high amplitude, short duration signal, suitable for transmission through large expanses of masonry, whereas a softer rubber head may be used to avoid damage to fragile masonry. The mass of the hammer determines the initial energy content of the input stress wave. Accelerometers are used to record the waveform after it passes through the masonry. A sensitivity of between 100 mV/g and 1000 mV/g is sufficient for most work. The received signal is recorded and /or displayed on an external device such as an oscilloscope or digital waveform recorder.

D.1.6 PROCEDURE

Three types of tests are conducted: (1) direct (or through-wall) tests in which the hammer hit and accelerometers are in line with one another on opposite sides of the masonry element, (2) semi-direct tests in which the hammer hit and accelerometers are on surfaces at a right angle to each other, and (3) indirect tests in which the hammer strike point and accelerometer are both located on the same face of the wall in a vertical or horizontal line. These test configurations are illustrated in Fig. 1.

The objective of the mechanical pulse tests is to locate flaws and voids in the masonry, or to measure material uniformity. Towards this end, a gridwork of test locations shall be laid out on each test element. The shortest direct path between hammer strike point and accelerometer location for each test position shall be measured to an accuracy of 0.5% of the path length and recorded.

At each test point in succession, an accelerometer is fixed to the receiving point using an adhesive, and the input pulse is generated by a hammer blow at the marked input point. The oscilloscope or transient recorder is set up to trigger at the beginning of the input hammer pulse, and to record both input and output channels for later analysis.

The time between the generation of the pulse and its first arrival at the receiving transducer, *i.e.* the stress wave travel time, is determined by measuring elapsed time off the recorded waveform. The travel time is defined as the elapsed time between the onset of the hammer pulse and the first arrival recorded by the receiving accelerometer, as shown in Fig. 2.

Interpretation of mechanical pulse velocity results can be difficult - for this reason, it is recommended that pulse velocity techniques be used in conjunction with companion *in-situ* or destructive tests, such as the flatjack test to verify the deformability and strength of the masonry. If a correlation between pulse velocity and material properties is desired, it will be necessary to develop a relationship between pulse velocity and strength for each individual structure. A minimum of four such tests are suggested for each structural element in question. In the absence of such tests, however, pulse velocity techniques are still suited for identification of areas where material quality may represent a significant departure from the norm throughout the structure. The pulse velocity techniques can provide a map of material uniformity in the structure, as well as locating major flaws.

The velocity will be affected by the presence of moisture in the masonry, and it is thus advisable to measure the moisture content using a reliable site technique, such as weight loss on drying of drilled powder specimens. A description of the technique is given in Annex 1. This method is fairly accurate for damp masonry but will underestimate moisture content in wet or saturated masonry.

D.1.7 TEST RESULTS

The simplest way to utilize mechanical pulse wave transmission data is to simply record the arrival time and the path length and calculate an average velocity, V, for the pulse: $V=l/t$,

where: 1 = pulse path length,
t = pulse travel time.

Further analysis may yield modified data in the form of X-Y plots, or contour maps. These forms of data are described below:

X-Y plots. The simplest way to interpret data from indirect tests is to plot the data directly on an X-Y plot with the path length on the ordinate and the pulse travel time on the abscissa. When data measured along a single vertical or horizontal line is plotted in this way, the slope of a regression line through the points represents the average pulse velocity along the line, (assuming that the plotted points may be accurately represented by a linear function). An apparent break or change of slope in the line indicates some change in the pulse velocity at a point or within a specific area, and is often indicative of a change in material properties or the existence of a flaw or discontinuity.

Contour maps of arrival time. Through wall (direct) tests can not be represented graphically in the same way as indirect tests. These data are more effectively presented in the form of a contour plot (or a 3-D surface plot) over the area of the tests. The contours may represent either pulse velocity or, if the path length is a constant, the pulse travel time. In this way, areas with different pulse velocities are highlighted as "hills" and "valleys" on the contour plot.

D.1.8 TEST REPORT

1) A reference of this RILEM standard.
2) The date of the test.
3) Description of the testing conditions, *e.g.* site, geographical location, environmental conditions, temperature, building identification, date of construction (if available), and name of the technician conducting the test. Include details of the type and quality of construction.
4) Type and model of equipment used, including date of most recent calibration.
5) Identification and description of the specific test locations in the structure, including a diagram of the structural element being tested, adjacent masonry, and all pertinent dimensions.
6) For each test location, information concerning the location of the point, the path length, the pulse arrival time, the calculated pulse velocity and a copy of the time signal on paper and/or magnetic disk.
7) Test results compiled in the form of individual X-Y or contour plots, if desired.
8) A tabulation of the mean and standard deviation of the mechanical pulse velocity as determined for the entire structure. Locations which show a significant deviation from the mean value shall be noted.
9) Results from any companion destructive or *in-situ* tests which were conducted, including any correlations between compressive strength and ultrasonic pulse velocity.

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MS.D.1 – ANNEX 1, MEASUREMENT OF MOISTURE CONTENT BY DRILLING

Scope/Principle

Small quantities of dust and debris are removed from the specimen (structure or material) by drilling. The dust is weighed then dried to constant weight in an oven at 100°C. The weight loss represents the weight of water or any other volatile compound absorbed in the pore structure of the specimen.

Limitations

1) The technique normally assumes that the only volatile component is water and any significant contamination by other volatile compounds would invalidate the test.

2) There will be a substantial reduction in accuracy for very high water contents due to loss of free water as the solid material is broken down.

3) There will be a reduction in accuracy for very hard materials where heating of the drill bit will result in evaporation.

Specimens

At least two, and preferably five or more, replicate drillings should be taken to represent a given material or zone of a structure. The variation of moisture content with depth may be obtained by separating the drilling dust into multiple samples representing increments of depth of the drill.

Apparatus

A power drill (normal or percussive) with a selectable speed of 1200 ± 100 rpm. Sharp 8 mm diameter (= 5/16"), 150 mm long (= 6") tungsten carbide tipped drill bits. A collecting device which is either held in place or temporarily attached just beneath the drill hole. A balance accurate to 0.01 g. An oven.

Procedure

Hold or attach the dust collector to the specimen within 25mm below position selected for the the hole. Starting with the drill-bit at room temperature, drill a hole horizontally to a sufficient depth to give a representative sample. The drill should be hand held and sufficient pressure should be applied to attain a depth of 100 mm in 45-60 seconds. Allow the drill bit to cool between each measurement or cool it by dipping into methylated spirits to speed up the process. Change the collector at set depth intervals if a depth profile is required. Weigh each specimen of dust, then dry to constant weight in the oven. Fig. 4 illustrates the specimen gathering process.

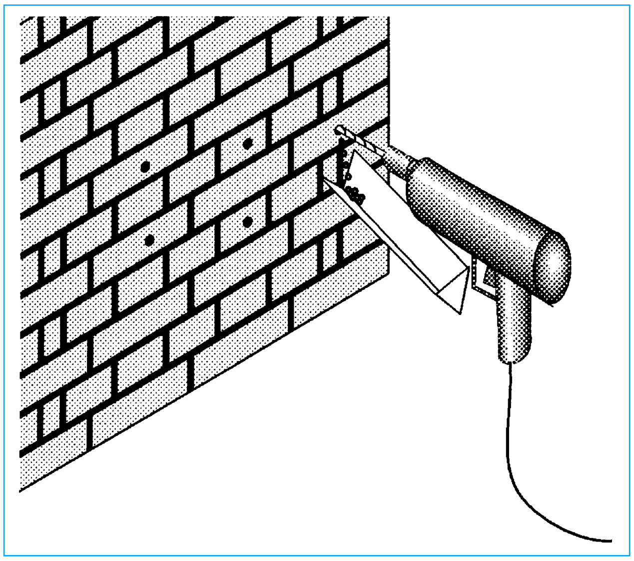

Fig. 4 – Typical drilling / collection procedure.

Test results

For each individual determination report the percentage moisture content by mass as the weight change on drying divided by the dry weight multiplied by 100. Calculate the mean of replicate specimens.

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MS-D.5 – Measurement of ultrasonic pulse velocity for masonry units and wallettes

D.5.0 CONTENTS

D.5.1 SCOPE

This recommendation specifies a method for determining the ultrasonic pulse velocity of masonry units, mortar specimens and wallettes. The method is typical for non-destructive measuring of a quality parameter and its variation related to the density, the isotropic/anisotropic characteristics and the presence of cracks and flaws (voids and fissures). Since the properties expressed by one quality parameter can/will change over time, *e.g.* crack/flaw propagation and deterioration of masonry units and mortar, the method may be suitable for measuring qualitative changes caused by cyclic decay mechanisms, *e.g.* crystallization stresses, freeze/thaw cycles).

The method becomes useless if pores, cracks and/or flaws (voids and fissures) are partly or completely filled with ice, salt crystals or other solid materials.

D.5.2 SPECIMENS (size, shape and numbers)

Specimens are a sample of masonry or pavement units and mortar bars prepared for testing, as well as representative wallettes. Since an overall quality parameter is measured, the number of specimens for units or bars depends on the variation in material quality or condition throughout the structure. Generally, the minimum sample size is 20 specimens. In the case of wallettes, the quality variation may be larger; however, the aim of testing is not to establish an absolute quality measure, but to investigate quality dispersion within a wallette and quality differences between wallette specimens. The minimum number depends on purpose; generally, a minimum of 10 wallettes is required. A wallette specimen can be considered as a representative part of a real wall or pavement. This means that it is composed of the same units and mortar made under the same conditions as in the real world. The minimum dimensions are:

length: 2 full units, and at least one horizontal layer with 2 vertical joints;

height: 3 horizontal layers and thus 2 bed joints;

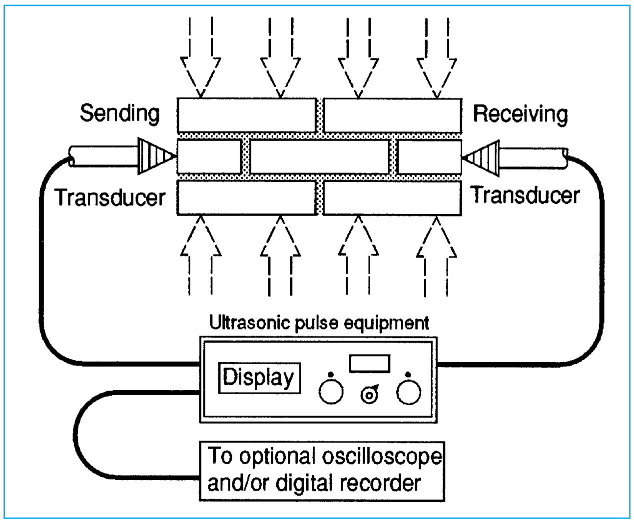

Fig. 1 – Example of a minimum sized wallette and the measurement set-up.

width: in accordance with real wall thickness. The minimum sized wallette is shown in Fig. 1.

The ultrasonic pulse technique uses an electro-acoustic transducer to pass a high frequency stress wave through a test specimen. By means of a receiver at the opposite side of a test specimen, the pulse travel time from transducer or receiver can be measured. The longitudinal waves between transducer and receiver form a wave train with the highest velocity and, consequently, the shortest pulse travel time through a specimen.

D.5.3 PRINCIPLES OF THE TEST

Since dispersion by transversely passing waves is negligible in this case, the pulse velocity is independent of the wave frequency. In testing practice, a frequency range of 10 to 200 kHz is being used. The higher the frequency, the more accurate the measurement of the pulse travel time will be. However, the lower the frequency, the smaller the signal attenuation of the waves which travel *via* a relatively long path from transducer to receiver. Therefore the optimum frequency is, in this case, 40-50 kHz.

With the path length and transit time of the ultrasonic wave, an average velocity can be calculated. Measurements between chosen points on both sides of a given path can be repeated as many times as required for the calculation of the accuracy (standard error).

Measurements can be obtained for every path and on every direction of interest, *e.g.* in the X, Y and Z direction of specimens. In this way, variations in density and in structure (isotropic/anisotropic) can be investigated, as well as the detection of cracks and flaws (voids and fissures) in the materials and in the composites. A 3-dimensional quality image can eventually be obtained. In addition to measurements of the pulse travel time, a waveform analysis can be useful or even required for a more effective interpretation of the results. An example of such a record is shown in Fig. 2.

The method has proven to be accurate for the classification of masonry units, mortar and pavers with respect to changes of density, modulus of elasticity and strength under the condition that the material structure (fabric) is isotropic. For anisotropically structured masonry materials and composites, like wall or wallettes, the dispersion is higher accordingly. An accurate prediction of, *e.g.* the strength of a wall, can only be justified if a calibration of pulse velocity with wallette strength is made for the specification structure under consideration. The ultrasonic pulse velocity technique is most useful for durability testing, that is, for measuring decay with time or with the number of stress cycles (freeze/thaw, thermal shocks, wetting/drying processes, acid rain cycles, vibration cycles by wind or traffic, etc.). In this case, the first measurement of each specimen represents an individual value which reflects the initial quality. The latter is used as a reference for conditional changes with time or with the number of stress cycles.

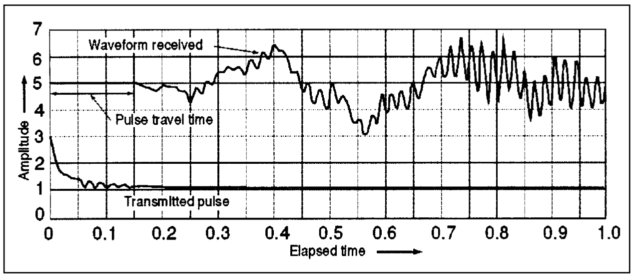

Fig. 2 – Wave record, showing both transmitted and recorded ultrasonic pulses.

D.5.4. CONDITIONS OF TESTING

Tests are to be conducted under the conditions as desired for the purposes under consideration. The ultrasonic pulse velocity depends strongly on the moisture content of the specimens. This implies that the moisture content of all specimens must be identical and kept constant during testing. The pulse velocity is higher accordingly as the moisture content is higher and attains, for a given specimen, a maximum value at complete saturation (achieved under vacuum or by immersion in boiling water). The lowest value is obtained when a given specimen is dry (zero moisture content). Testing of dry specimens is recommended. In the case of moist or wet specimens, an even moisture distribution is required.

Measure the moisture content using a reliable site technique such as weight loss on drying of drilled powder specimens. This method is fairly accurate for damp masonry, but will underestimate moisture content in wet or saturated masonry. The method is described in Annex 1.

D.5.5 APPARATUS

Ultrasonic pulse velocity equipment may be obtained from any of several different manufacturers. The general set-up consists of ultrasonic pulse velocity equipment and a measuring table which is adjustable to the dimensions of a given specimen.

The sending and receiving transducers are (mechanically, electrically, physically) identical. Their metal heads have a conical shape with a rounded top. Each device is placed in an adjustable rod (steel pipe) in line with one another on opposite sides of the specimen on the measuring table. Both devices are spring-loaded in view of free movements in their rods and to ensure that a specimen becomes wedged between the sending and receiving devices. The springboard is adjusted to purpose and then kept constant. Good and reproducible results are achieved with a constant spring-load of 10 N. Then a positive connection between the heads and a specimen is secured without the application of any couplant at the interfaces.

The transmitter should have an adjustable resonant frequency of between 10 - 200 kHz. The apparatus should be capable of measuring pulse travel times between 0.1 s and 1000 s, to an accuracy of 0.1 s or better. A digital display of the pulse travel time is desirable. Furthermore, a connection to an oscilloscope and/or a digital recorder is desirable to analyse the waveform in more detail.

A standard reference block, provided by the manufacturer and calibrated to a known standard, should be used periodically to establish the accuracy of the ultrasonic pulse velocity equipment.

D.5.6 PROCEDURE

Bring specimens to the right condition as far as moisture content is concerned. Zero moisture content is recommended, but any other condition between fully dry and fully immersed is possible if the moisture is evenly distributed throughout each specimen. The moisture content must be kept constant during testing.

Each specimen is placed on a 2 mm rubber mat on the adjusted table of the apparatus, and at the right place, wedged with a load of 10 N between the transducer and receiver heads.

When the transmitter is triggered, an ultrasonic wave of, preferably, 40 kHz is induced into the specimen. After passing through, the pulse is picked up by the receiving transducer and converted to an electrical signal. The time delay between the generation of the pulse and its first arrival at the receiving transducer is measured internally by the recording device and displayed on a digital display. Record this time in s to an accuracy of 0.1 s as the pulse travel time of the wave.

Alternatively, a true facsimile of both transmitted and received pulses may be obtained through an oscilloscope output. Then the pulse travel time may be determined graphically. The pulse travel time is defined as the elapsed time between the onset of the transmitter pulse and the first arrival recorded by the receiving transducer, as shown in Fig. 2.

Since this test is non-destructive, measurements on each specimen can be repeated until reproducible results are obtained. At the same time, the standard error can be established. As an example, for solid bricks with an isotropic structure, a coefficient of variation of less than 0.01 for pulse travel time data is achievable.

Interpretation of pulse travel times results in terms of relative quality between separate units in a sample or between samples. In the case of durability testing, the first measurement is the reference value followed by a number of subsequent measurements as the test proceeds. The method is also suitable to investigate the anisotropy of structures, which are shown by different velocities when the pulse is sent subsequently through the X, Y, and Z direction of specimen. In this way it is also possible to locate flaws in wallettes, and particularly in mortar joints.

D.5.7 TEST RESULTS

Record the pulse travel time and the associated path length through the specimen from transducer to receiver for each test location. Then the ultrasonic pulse velocity, V, can easily calculated: $V = l/t$,
where:
l = pulse path length in mm to an accuracy of 0.5 mm;
t = pulse travel time (in s to an accuracy of 0.1 s);
V = ultrasonic pulse velocity (in km/s rounded off to one decimal).

It is noted that for homogeneous materials with an isotropic structure, there is a perfect linear relationship between l and t, represented by a straight line in a X-Y plot. The slope of the l-t plot may be used to judge consistency of quality between successive specimens. However, the dispersion becomes large when the path length is shorter than the 50 mm by which the minimum dimension of a specimen is determined. Internal damping of ultrasonic waves (rapid signal attenuation) can occur when the path is too long, which is indicated by a deviation from the linear relationship. This phenomenon is not expected for testing masonry units and wallettes.

D.5.8 TEST REPORT

1) A reference to this RILEM standard.
2) The date of the test.
3) Description of the testing conditions, *e.g.* site, laboratory, preparation of specimens, and the name of the technician conducting the test. Include all relevant information.
4) Type and model of pulse velocity equipment, and data of most recent calibration.
5) Testing objectives.
6) Testing results in the form desired. It is noted that ultrasonic pulse velocity measurements can be part of another test, *e.g.* freeze/thaw cyclic testing.

D.5.9 BIBLIOGRAPHY

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[7] Noland, J.L., Atkinson, R.H. and Baur, J.C., 'An investigation into methods of nondestructive evaluation of masonry structures', Report to the National Science Foundation, National Technical Information Service Report No. PB 82218074, Springfield, Virginia, 1982.

MS-D.5 – ANNEX 1, MEASUREMENT OF MOISTURE CONTENT BY DRILLING

Scope/Principle

Small quantities of dust and debris are removed from the specimen (structure or material) by drilling. The dust is weighed, then dried to constant weight in an oven at 100 °C. The weight loss represents the weight of water or any other volatile compound absorbed in the pore structure of the specimen.

Limitations

1) The technique normally assumes that the only volatile component is water and any significant contamination by other volatile compounds would invalidate the test.
2) There will be a substantial reduction in accuracy for very high water contents, due to loss of free water as the solid material is broken down.
3) There will be a reduction in accuracy for very hard materials where heating of the drill bit will result in evaporation.

Specimens

At least two, and preferably five or more, replicate drillings should be taken to represent a given material or zone of a structure. The variation of moisture content with depth may be obtained by separating the drilling dust into multiple samples representing increments of depth of the drill.

Apparatus

A power drill (normal or percussive) with a selectable speed of 1200 ± 100 rpm. Sharp 8 mm diameter (= 5/16"), 150 mm long (= 6") tungsten carbide tipped drill bits. A collecting device which is either held in place or temporarily attached just beneath the drill hole. A balance accurate to 0.01 g. An oven.

Procedure

Hold or attach the dust collector to the specimen within 25 mm below the position selected for the hole. Starting with the drill-bit at room temperature, drill a hole horizontally to a sufficient depth to give a representative sample. The drill should be hand held and sufficient pressure should be applied to attain a depth of 100 mm in 45-60 seconds. Allow the drill bit to cool between each measurement or cool it by dipping into methylated spirits to speed up the process. Change the collector at set depth intervals if a depth profile is required. Weigh each specimen of dust, then dry to constant weight in the oven. Fig. 3 illustrates the specimen gathering process.

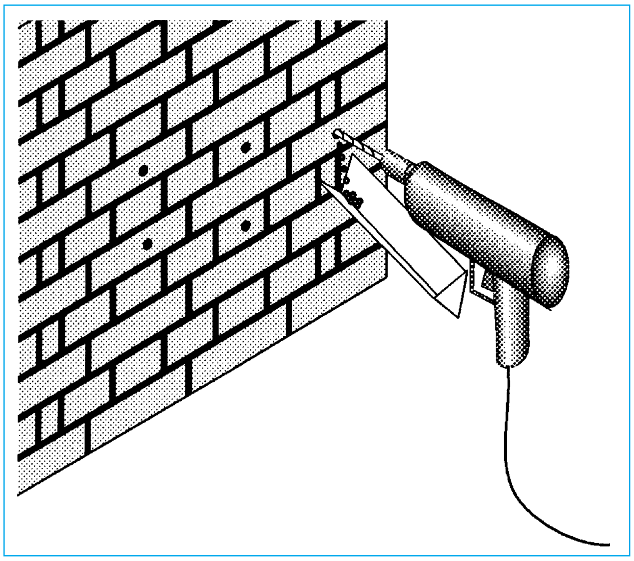

Fig. 3 – Typical drilling / collection procedure.

Test results

For each individual determination, report the percentage moisture content by mass as the weight change on drying, divided by the dry weight multiplied by 100. Calculate the mean of replicate specimens.

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MS-D.6 – In situ measurement of masonry bed joint shear strength

D.6.0 CONTENTS

D.6.1. SCOPE

This standard covers methods of the determination of the average bed joint shear strength in existing unreinforced solid-unit and ungrouted hollow-unit masonry built with clay or concrete units. Two methods are provided:

Method A – For determining bed joint shear strength when the state of vertical compressive stress at the test site is controlled during the test, using the flatjack method described in RILEM LUM D.2. Horizontal displacements of the test unit are monitored throughout the test. The test setup for this method is shown in Fig. 1.

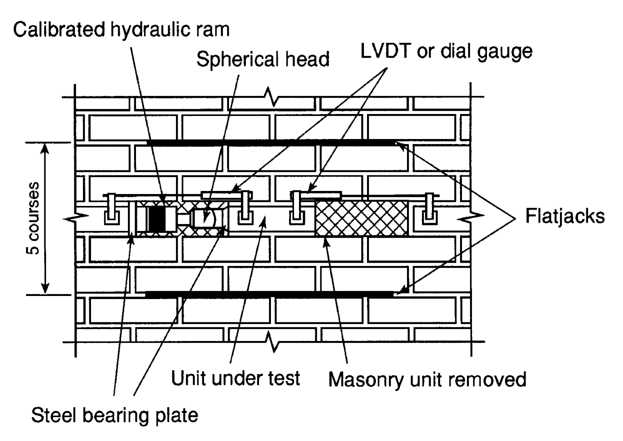

Fig. 1 – Test setup - Method A.

Method B - For determining bed joint shear strength using an estimate of the vertical compressive stress at the location of the test site, as shown in Fig. 2. Monitoring of the horizontal displacement of the test unit during this procedure is optional.

D.6.2 SPECIMENS (size, shape, numbers)

This test is performed *in-situ* in masonry as-is. It is advisable to carry out at least 3, and preferably 5 or more, measurements at different locations in nominally the same material.

D.6.3 PRINCIPLES OF THE TEST

The in-place shear test is used to measure the *in-situ* horizontal shear resistance of bed joints in unreinforced masonry. A single masonry unit and a head joint are removed from opposite sides of the chosen test unit, as shown in Fig. 2. The test unit is then displaced horizontally relative to the surrounding masonry using a hydraulic jack. The horizontal force required to cause first visible movement of the test unit, or the change in slope of the load-displacement curve, provides a measure of the bed joint shear strength.

D.6.4 SIGNIFICANCE AND USE

4.1 – Shear strength is measured only on the bed joints adjacent to the unit being tested, and is calculated based upon the gross area of the bed joint, assuming the unit to be fully bedded in the mortar joint. In the case of multi-wythe masonry, joint shear strength is estimated only in the wythe in which the test unit is located. Joint shear strength at other locations and in other wythes may be different.

4.2 – The contribution of the collar joint in multi-wythe walls to the horizontal shear strength of the unit is neglected. This may lead to an overestimate of the initial shear strength. The collar joint may be removed with considerable experimental difficulty, if necessary.

4.3 – The test procedure listed for Method A may be conducted as an extension of a normal series of flatjack tests. The single flatjack test described in Standard C 1196 reveals the *in-situ* state of normal stress at the test joint, and thus provides essential data for determining the expected joint shear strength in the area of the test. The two-flatjack test, conducted in accordance with RILEM LUM D.2, then provides half of the required set-up for the modified in-place shear test. At the completion of the test, the relationship between the expected joint shear strength and normal stress, the measured normal stress and the deformability of the masonry at the test location will be known.

D.6.5 APPARATUS

5.1 – The following equipment is required for both Method A and Method B:

5.1.1 – Use a hydraulic jack with an appropriate working pressure range to load the test unit. The force output of the jack throughout the working pressure range should be known, to facilitate conversion between hydraulic pressure and force applied to the masonry. As an alternative to a conventional cylinder jack, a small flat-jack with an area equal to that of the head joint may be used.

5.1.2 – Use steel bearing plates at each end of the test jack to distribute the load uniformly across the end of the test unit and the reaction unit as shown in Fig. 1.

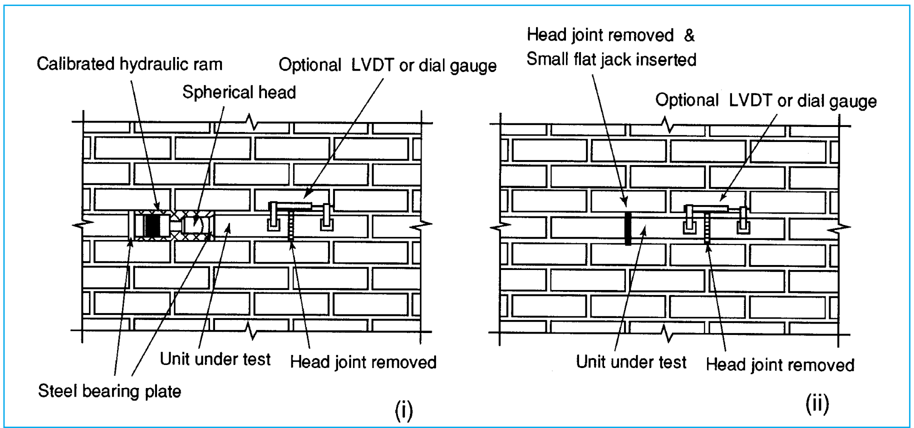

Fig. 2 – Test setup - Method B
(i) using a hydraulic ram
(ii) using a mini-flat jack.

The bearing plates shall have a minimum thickness equal to 1/8 the maximum dimension in a vertical cross section. The bearing plates shall have dimensions in the vertical plane 1/8 inch less than the dimensions of the unit and the plate shall be centred on the end of the unit. A 2-inch diameter spherical seat between the jack and the steel bearing plate nearest the test unit is suggested to avoid eccentricities of load. Bearing plates should be replaced by shim-plates when flat jacks are used.

5.1.3 – An electrically or manually operated hydraulic pump with hydraulic hoses is required to pressurize the loading jack. Measure pressure using gauges calibrated to a traceable standard having both an accuracy of 1% of full hydraulic scale and an appropriate operating range. The pressure gauge shall have a slave pointer to indicate the maximum hydraulic pressure attained during specimen loading. The hydraulic system shall be capable of maintaining constant pressure within 1% of full scale for at least 5 minutes.

5.1.4 – Alternatively, a small load cell may be used to measure the force applied by the hydraulic jack. Verification of load measurement shall be conducted in accordance with Method E 4. The load cell should be placed between the spherical seat and the bearing plate nearest the test unit.

5.1.5 – Instrument the test unit with mechanical extensometers or electronic devices to allow measurement of horizontal displacements of the unit. The method or device used to measure deformations shall be capable of deformation measurements up to 6 mm (0.25 inch). Deformation measurements shall have an accuracy of at least 0.005% of gauge length. Fasten brackets or other attachment devices securely to the surface of the masonry using a rigid adhesive and/or screws and plugs. This is optional for method B, but recommended particularly if a flat jack is used to apply the force.

5.2 – The following additional apparatus is required for method A:

5.2.1 – Flatjacks and associated equipment required to measure the state of compressive stress are described in RILEM LUM D.2 and LUM D.3 and Standard C 1195. Standard C 1197 describes apparatus necessary to apply a known state of vertical compressive stress to the masonry at the test site using flatjacks.

D.6.6 PROCEDURE

D.6.6.1 Measurement of the state of vertical compressive stress

The magnitude of vertical compressive stress will have a direct effect on the measured joint shear strength and must be determined beforehand.

Method A - Apply compression using flatjacks. A flatjack shall be placed two courses above and shall be centred directly over the test unit. Prepare another slot 5 courses below this flatjack and insert a flatjack into the slot. A single brick unit, located on the centreline midway between the two flatjacks, is the unit to be tested for measurement of joint shear strength. The slots and flatjack installation shall be in accordance with ASTM C 1196 or C 1197. Where mini-flatjacks are used, it is only necessary to cut the two head joints on either side of the unit to be tested, thus introducing less error due to ambient stress.

Method B - Estimate the average vertical compressive stress on the unit based upon the location of the test unit in the structure and the estimated dead and permanent live loads. Record the magnitude of the calculated vertical compressive stress on the test unit. Mini-flatjacks may also be used for this measurement with advantage.

D.6.6.2 Preparation of test site

The location at which joint shear strength is measured is dictated by engineering objectives. Areas in which the bed joints appear to be non-parallel should be avoided. In addition, the unit to be tested should be in the stretcher position, with stretcher courses directly above and below the test unit. The test site should be located a sufficient distance from wall openings or ends such that the loading jack bears against a sufficient mass of masonry to resist forces generated during loading of the test unit. The basic arrangement is illustrated in Fig. 1 for Method A, and in Fig. 2 for Method B. At the desired location the following steps should be taken to prepare the site for testing:

For very soft mortars, the test needs either a correction term of the order of 15%, due to the compression of adjacent perpend joints or, for accurate results without applying a correction term, these joints must be cleaned out and packed with steel shims.

Method A - Provide a space for the loading jack by removing a unit on one side of the test unit. Drill out all mortar in the joints around these units to facilitate removal, being careful not to disturb the mortar directly above and below the test unit or the test unit itself. Set the removed unit aside, to be replaced later if required. Clean out any remaining mortar from this space. Remove the unit on the other side of the test unit to isolate the joints being investigated. At this point, the mortar in the joints above and below the test specimen should be flush with the vertical ends of the unit being tested.

Method B - Either remove a unit on one side of the test unit and the head joint on the opposite end of the test unit (as in Fig. 2(i)), or remove head joints at both ends of the unit (as in Fig. 2(ii)). At this point, the mortar in the joints above and below the test specimen should be flush with the vertical ends of the unit being tested.

Both Methods - Measure the top and bottom dimensions of the test unit directly adjacent to the bed joints being tested, to an accuracy of 0.5 mm (1/32 inch). The gross area of the bed joints being tested is the summation of the area of the upper and lower joints.

D.6.6.3 Test procedure

Method A -

Instrument the test unit by attaching a mechanical or electronic displacement transducer between the centre of the test unit and the centre of the unit directly opposite the loading jack. Place the loading jack, spherical seat, and bearing plates into the space next to the test unit or pack the mini-flatjack into the headjoint with steel shims. Shim the jack to provide a properly centred horizontal force on the test unit. Set the pressure in the two flatjacks equal to 0.7 bar (=0.07 N/mm^2 or 10 psi) or less, and close the valve. Increase pressure in the horizontal loading jack gradually, recording deformation of the unit at small increments of horizontal load. Monitor the flatjack pressure during loading and adjust the internal pressure, if necessary, to provide a constant vertical stress. When the bond between the unit and mortar joints is broken, the unit will begin to displace continually under a constant horizontal load. This represents the maximum horizontal load for this level of vertical compressive stress.

Increase the pressure in the flatjacks to the next desired level of vertical stress, and repeat the process of horizontal loading until the maximum horizontal load for this level of vertical stress is reached. Continue repeating the sequence in this manner, to determine the bed joint shear at various levels of vertical compressive stress.

The horizontal jack may be transferred to the cavity on the opposite side of the test unit, the displacement instrumentation reversed, and the test sequence repeated in the opposite direction to investigate the effect of shear force reversal on the *in situ* shear strength, if desired.

Release pressure in the horizontal jack after the final displacement measurement has been taken and remove the loading jack. Release pressure in the flatjacks and remove the flatjacks and displacement measurement devices. Any voids or slots created during site preparation may be filled using the original units and a mortar, or other suitable material of a colour and strength similar to the original mortar.

Method B -

Place the loading jack, spherical seat (if used), and bearing plates into the space next to the test unit or pack the mini-flatjack into the headjoint with steel shims. Shim the jack to provide a centred horizontal force on the unit. Increase pressure in the hydraulic jack gradually until the test unit begins to displace continually under a constant level of horizontal load. Record the maximum load indicated by the pressure gauge or load cell.

Optionally, instrument the test unit by attaching a mechanical or electronic displacement transducer between the centre of the test unit and the centre of the unit directly opposite the loading jack, as shown in Figs. 1 and 2. Increase pressure in the hydraulic jack gradually and record jack pressure versus displacement. Determine the static shear bond strength from the change in slope of the load versus displacement curve as shown in Fig. 3, taking into account any vertical stress.

Release the pressure from the loading jack and remove the jack. Replace the original masonry unit and/or the removed head joint, using mortar or other suitable material of a colour and strength similar to the original mortar.

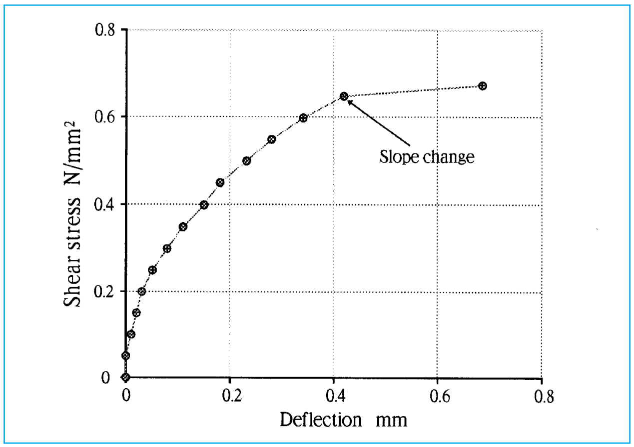

Fig. 3 – Shear stress versus displacement plot using Method B (ii).

D.6.7 TEST RESULTS

D.6.7.1 Calculation Method A

Calculate the average bed joint shear strength τ_i for each level of normal compressive stress, s_v, as:

$$\tau_i = P_{hi}/A_j$$

where:
P_{hi} = Maximum horizontal force resisted by the test unit at the ith level of normal compressive stress;
A_j = Gross area of upper and lower bed-joints in the case of solid-unit masonry or the net mortar-bedded area for the case of hollow-unit masonry.

Prepare the plot of joint shear strength t versus vertical compressive stress s_v (determination of vertical compressive stress on the test unit, as applied by flatjacks, is discussed in Annex A1.) Fig. 4 gives a typical graphical plot.

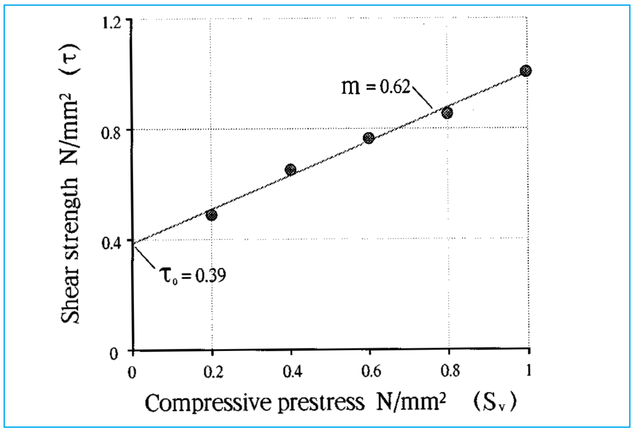

Fig. 4 – Shear strength versus compressive stress plot using Method A.

The shear friction of the masonry, m, is calculated as the slope of the best-fit line through these points. Estimates of joint shear strength at other levels of vertical compressive stress may be calculated using the relation

$$\tau = \tau_o + m(s_v)$$

where:
τ_o = joint shear strength at zero vertical compressive stress, or adhesion stress.

D.6.7.2 Calculation Method B

Calculate the average bed joint shear strength, t, as:

$$\tau = P_h/A_j$$

where:
P_h = Maximum horizontal force resisted by the test unit (or alternatively the point of change of slope of the load displacement curve);
A_j = Gross area of upper and lower bed joints.

The shear stress from the test (τ) is reduced to the value which would have been obtained under zero axial load (τ_o) using the relation:

$$\tau_o = \tau - m(s_v).$$

where:
m = coefficient of friction for the masonry[1];
s_v = estimated vertical compression stress at the test unit.

D.6.7.3 Precision and bias

Insufficient data exists to correlate the shear strength measured with the *in situ* test to the actual shear strength of the masonry. *In situ* measurement of bed joint shear strength and coefficient of friction may be affected by workmanship, the quality of the collar joint, and inaccuracies in determining vertical compressive stress, whether estimated or controlled during testing using flatjacks.

Laboratory studies have shown that the *in situ* bed joint shear test will generally overestimate the actual shear strength of a wall panel; however insufficient data currently exists to provide a reliable bias statement.

D.6.8 REPORT

1) Report each *in situ* bed joint shear strength determination, including the following information:

2) Description of the testing conditions, *e.g.* site, geographical location, environmental conditions, temperature, building identification, date of construction (if available) and name of the engineer/technician conducting the test. Include details of the type and quality of construction.

3) Identify and describe the specific test location in the structure and the reason for the test.

4) Description and sources (if possible) of the masonry materials at the test location, including a general condition statement, an elevation drawing and other pertinent material data.

5) Method used to determine joint shear strength, a diagram of the test unit, adjacent masonry, and location of the loading jack, including all pertinent dimensions.

6) Description and source of instrumentation, hydraulic system, and other pertinent information.

7) Magnitude of vertical compressive stress s_v and method used for determination, including calculations.

8) Magnitude of measured bed joint shear strength t, and shear strength calculated for zero vertical stress τ_o, and coefficient of friction m used for calculations.

9) Other observations.

10) Additional information is required if Method A has been used, including: all pertinent information regarding flatjack usage, as required by LUM D.2, D.3 and Standards C 1196 and C 1197; description of deformation measuring devices used, including locations; data sheets containing deformation measurements; joint shear strength for each level of vertical compressive stress; data and calculations for determination of coefficient of friction m.

(1) Laboratory studies have shown that the coefficient of friction between masonry units and mortar varies from 0.3 to 1.6, with a mean value of 1 and a coefficient of variation of between 30 and 50%.

D.6.9 BACKGROUND AND REFERENCES

D.6.9.1 Standards

RILEM LUM D.2 – In situ stress tests on masonry based on the flat jack, RILEM Technical recommendations for the testing and use of construction materials, (E&F.Spon, London, 1994) pp 503-505.
RILEM LUM D.3 – In situ strength/elasticity tests on masonry based on the flat jack, RILEM Technical recommendations for the testing and use of construction materials, (E&F.Spon, London, 1994) pp 506-508.
ASTM C1196 - 92 – In Situ Compressive Stress Within Solid Unit Masonry Estimated Using Flatjack Measurements.
ASTM C1197-92 – In Situ Measurement of Masonry Deformability Properties Estimated Using the Flatjack Method.
ASTM E4-94 – Practices for Force Verification of Testing Machines.
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D.6.9.2 Papers

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D.6.10 INFORMATIVE ANNEX (optional information)

A1. MAGNITUDE OF VERTICAL COMPRESSIVE STRESS APPLIED BY FLATJACKS

The procedure for Method A, described above, is intended to allow the magnitude of normal compressive stress on the test unit to be controlled during testing. Past practice has been to assume that the normal stress on the test unit is equivalent to the uniform stress imposed upon the masonry by the flatjacks; however, recent analyses have shown the actual stress distribution on the test unit to be significantly different.

Calculation of normal stress on test unit

It is necessary to modify the normal stress applied to the test unit by a factor j in order to convert the flatjack stress to normal stress on the test unit:

$$S_n = j(s_{fj})$$

where:
s_n = normal stress on the test unit,
j = modification factor,
s_{fj} = stress applied by the flatjacks to the masonry, computed in accordance with Standard C1196. For this analysis, l_{fj} = 480 mm, l_u = 210 mm and α = 45°.

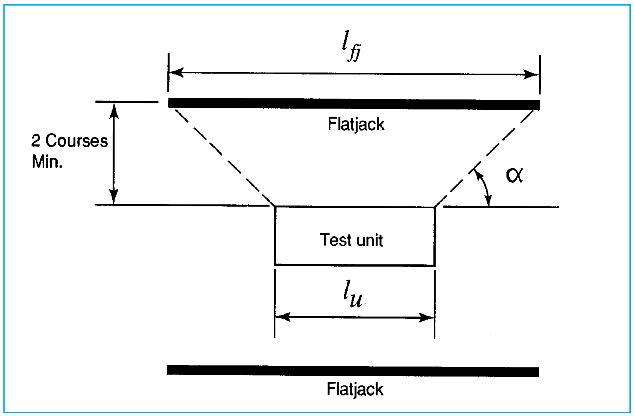

Fig. 5 – Geometrical configuration of analytical model.

A1.3 – Analytical models in the form of two and three-dimensional finite element models have been developed for the shear test described in method A, to determine the normal stress distribution on the test joints. Analysis of an *in situ* shear test on a two-wythe brick masonry wall set-up has shown that the distribution of normal stress on the test unit is non-uniform, with the average stress equivalent to 1.7 times the applied flatjacks stress. Hence, the modification factor j is equal to 1.7 for this case.

A1.4 – The value for j is unique for this particular configuration; however it is reasonable to assume that this factor may be applied in cases where the test configuration is proportional to the one shown in Fig. 5. The angle α, shown in Fig. 5, may be used to compare different test configurations. For the analysis described above, α equals approximately 45 degrees. Hence the modification factor j = 1.7 may be used if the angle α is equal to about 45 degrees. Further analysis would have to be conducted to determine the actual state of normal stress acting on the test unit for other geometries and test configurations.