Aspects of the tensile strength of brick-mortar joints.

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ASPECTS OF THE TENSILE STRENGTH OF BRICK-MORTAR JOINTS

by

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PREFACE

The author graduated from Manchester University in 1975. After working for one year for the South Western Road Construction Unit in Exeter, he returned to Manchester University to carry out structural engineering research for which he received a MSc. degree. In 1980 the author was appointed as a research assistant at Sheffield City Polytechnic to work on the tensile strength of brickwork. Research was carried out in the Department of Building until November 1982.

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No portion of the work referred to in this thesis has been submitted in support of an application for another degree or qualification of this or any other academic body.

Sheffield. January 1984.

ABSTRACT

Aspects of the Tensile Strength of Brick-mortar Joints.

S.J. White.

The main purpose of this work is to assess the factors which affect the tensile bond strength of brick-mortar joints and to verify their relative importance, both by reference to the literature, and by experimentation. From these investigations the most important aspects are seen to be the absorption of water from the mortar by the brick, and the grade of the mortar.

Almost one thousand tensile bond couplets were tested using a newly devised apparatus which has several advantages over existing test methods. Four experimental programmes were carried out, each of which was designed to investigate one or more of the factors which were judged either to be of particular importance, or to be inconclusive, or both.

Arising out of the main section of the work was the tensile strength hypothesis. This is capable of showing, in a qualitative way, how the tensile strength and mode of failure of a brick-mortar joint can be related to the properties of the mortar and the brick. The hypothesis draws upon concepts from other disciplines, such as soil physics, in order to describe the physical processes which are important. Accordingly, it is the way that a brick absorbs water from the mortar that will have the most profound effect on the subsequent processes of hydration and strength development within the mortar.

In order to provide some evidence in favour of the hypothesis, pilot studies were carried out to determine the moisture characteristics of mortar and to furnish data on the hydration products within the joint. Whilst these pilot studies had their limitations, the results were encouraging.

Recommendations are made regarding future developments of the hypothesis from a theoretical and a practical viewpoint.

CONTENTS

1. INTRODUCTION

Brick masonry is one of the oldest forms of construction which is still in common use today, and is traditionally based on small manageable masonry units in combination with a simple binder/filler in order to produce monolithic structures built essentially by hand. During the early part of this century it became apparent that the behaviour of brickwork depends in a very complex way on properties of the components and on the nature of their interaction. Historically, the design philosophy of structural masonry was such that tensile stresses were not permitted to occur and so the tensile strength of brickwork was not considered. Nowadays, however, economics plays an increasingly important role in the design and construction of buildings which tend to be taller and more slender. Consequently it has become essential to develop a sound understanding of the tensile and flexural behaviour of brickwork.

In response, much valuable work has been done over the last fifty years in identifying the most important factors affecting the tensile and flexural strength of brickwork (1-5). The contributions of these and other workers will be presented in detail in the next section. It will be shown that opinions have often been conflicting and that the present level of knowledge is not adequate.

It is indicative of the state of the art that the recent code of practice, (Structural use of Masonry, BS5628; Part 1:1978) deals only briefly with the question of the tensile strength. Clause 24.1 states

> "In general, no direct tension should be allowed in masonry. However, at the designer's discretion half the values in table 3 may be allowed in direct tension when suction forces arising from wind loads on roof structures are transmitted to masonry walls, or when the probable effects of misuse or accidental damage are being considered."

This gives characteristic tensile strengths (N/mm^2) shown below, which were obtained by dividing the characteristic flexural strengths given in BS5628, table 3 by 2.

Mortar designation	(i)	(ii), (iii)	(iv)
Clay bricks having water			
absorption <7%	0.35	0.25	0.20
7%-12%	0.25	0.20	0.175
>12%	0.20	0.15	0.125

It is not clear from BS5628 why tensile stresses of this magnitude are allowed without regard to many factors of critical importance. Indeed, recent unconfirmed undergraduate work has shown that tensile strengths may be as low as 20% of the flexural strength (6).

Clearly there is a need for a better understanding of the mechanisms involved in the development of tensile strength in a brickwork joint, and it is for this reason that the present research project was initiated.

2. REVIEW OF LITERATURE ON THE FACTORS AFFECTING BOND STRENGTH.

Many factors have been reported in the literature as being of importance and it seems that they interact in a complex way. The following sections deal individually with the main factors and summarise the opinions of various workers on the effect that they have on the bond strength. Attention is confined to tensile tests except where conclusions of particular importance have been obtained from flexural or other forms of test.

2.1. Suction Rate of Brick.

Almost all workers have realised that probably the most important property involved is the suction rate or initial rate of absorption of the brick, which is defined as the mass of water absorbed vertically by unit area of the bed face of a brick in one minute. Palmer and Parsons (1) concluded that bond strength increases from a very low suction rate to a maximum at about 1 kg/m^2 min and then decreases, with the rate of decrease depending on the retentivity of the mortar. Collin (7) was in general agreement although comparative values for suction rate are not available due to Collin's method of measurement. His "rate of capillary absorption" measured the height of the water line on the brick at particular times. He stated that bricks of medium absorption rate gave the highest bond strengths and that bricks of high absorption rate gave low bond strengths, although the latter could be improved substantially by wetting the bricks before use. Parsons (8) reported that high suction rate would give poor extent of bond and that an optimum value lies in the range 0.3-1.1kg/m^2 min, although his conclusions were based on flexural, rather than direct tensile tests. These results were later contested by Whittemore and Dear (9) who pointed out that although bond strength tends to decrease with increasing suction rate, this relationship depends upon the type of brick and any conclusions drawn may not be applicable in a different situation.

Forkner et al (10) and Johnston et al (11) confirmed the general trend of decreasing strength with increased suction rate but Habib and Leeds (12) made some important observations on the way in which the rate of absorption changes with time. They considered not the one minute suction rate, but the instantaneous absorption rate in grammes per second. Their method required the weight of absorbed water to be determined at various short intervals of time, up to several minutes. From these results, the amount of absorbed water was plotted against time for all bricks, the slope of the graph giving the instantaneous absorption rate. Bricks were then chosen in pairs and from the absorption graphs of each, the pre-wetting time was determined so that the initial absorption rate was the required value, ranging from 0.4g/sec to 2.0g/sec. An optimum value was found to be about 1.2g/sec, which corresponds to a suction rate of approximately 1-2kg/m^2 min according to their published absorption curves. However, their results were erratic and later work by Philip (13) shows that the water absorption behaviour, even from a free water source, depends strongly upon the characteristics of the dry brick and upon its moisture content and not simply upon the instantaneous rate of absorption.

In a comprehensive review of the literature, Youl and Coats (14) concluded that the optimum suction rate is about 1.0-1.2kg/m^2 min although Kampf (3) suggested about half that value and Ritchie and Davison (15) give 0.5-1.0 kg/m^2 min as the optimum. The general trend of increases in suction rate giving reductions in bond strength was confirmed by Albrecht and Schneider (16) and by Fishburn (17).

By collecting data from previous workers, Grimm (5) has formulated an expression for the bond strength as follows:

$$f_b = 0.005\left[1.8+(F-105)^{0.5}\right](40-A)(124-t_m)$$

in which f_b is the cross-brick couplet bond strength in pounds per square inch; F is the initial flow of the mortar as measured by the flow table test described in BS4551:1980; A is the percentage air content of the mortar by volume; and t_m is the mortar exposure time in seconds. Suction rate however, is not a variable in this expression and Grimm merely states that this parameter should be in the range 0.1-1.0kg/m^2 min.

Morgan (18) pointed out that the long-term effects of brick suction are equally as important as the short-term, because if too much water is removed at a later date the mortar may become dehydrated and hydration will be inhibited. Morgan also pointed out that for optimum behaviour there must be compatibility between the suction rate of the brick and the retentivity of the mortar. This idea is also put forward by Sneck (19) who says that the characteristics of water absorption from a bed of mortar may not be directly related to the absorption from a free water surface.

This and the earlier theoretical work of Philip (13) on water absorption shows that brick suction is a complex property whose effect is not independent of other factors. Pearson (2) recognised this when he concluded that bricks of the same suction rate may not produce the same stiffening effect in the mortar because of the presence of unknown variables.

2.2. Brick Type and Texture.

The importance of brick type and texture has been reported by some workers to be as great as the importance of the suction rate. For instance, Palmer and Hall (20) reported that smooth dry-pressed clay bricks of high absorption give higher bond strengths than rough side-cut stiff-mud clay or shale bricks of low water absorption.

Evidence is quite often conflicting and reports, even by the same authors, may contradict one another. Whittemore and Dear (9) concluded that bond strength was highest for smooth bricks, but later, Johnston, Dear and Whittemore (11) stated that roughness seems to have no effect and that shale bricks are stronger than clay in bond. The same year, Forkner, Hagerman, Dear and Whittemore (10) reported that stiff-mud clay gives the highest strength and that the effect of roughness cannot be considered separately from the effects of brick composition, although they conclude that generally, better bond is achieved with rough bricks.

According to Thornton (21) the extent of bond is impaired by the use of rough, scored or sanded bricks because water is drawn away from the contact zone by capillarity.

Kampf (3) attributed the difference in performance of wire-cut and moulded bricks to differences in their surface texture. The difference is less for bricks of low suction rate, he stated, because these bricks have been burned to a higher temperature at which differences in surface texture disappear.

According to Hogberg (22) and Morgan (18) calcium silicate bricks do not behave in the same way as clay bricks. Their absorption-time relationships indicate that they exert suction forces over a prolonged period whilst having only a moderate initial rate of absorption.

The effect of brick perforations seems to be in some doubt. Forkner et al (10) and Kampf (3) stated that cored bricks exhibit similar bond strengths to solid bricks, although Ritchie and Davison (15) reported that the latter are superior, at least for low suction rate bricks.

Habib and Leeds (12) and Waters (23) suggest that the microtexture of the brick surface could have some bearing on the bond strength and reported that transfer of fine cement particles takes place, their penetration into the brick depending upon the relationship between the cement particle size and the brick pore entry diameter.

2.3. Sand.

Sand constitutes about two thirds of the volume of mortar and might be expected to have a significant influence on the properties. A review by Youl and Coats (14) summarises the effects of sand composition, particle shape and grading on workability and water requirement, and reaches the conclusion that the best results are obtained using rounded, rather than sharp, sand grains. Bloem (24) points out that the ASTM grading limits do not give a definitive indication of usefulness and that some sands, which lie outside the limits, are perfectly adequate in practice. In particular, sands beyond the fine limit behaved well. He goes on to show that water demand depends upon the grading of a particular sand that has been regraded, but that different sands of identical gradings may show quite dissimilar behaviour.

Hogberg (22) reports that the sand grading affects volume of voids and the ratio of water to binder (cement + lime), and that well-graded sands give a lower volume of voids and a lower water/binder ratio. Sneck (19) reports that fine sands give higher bond strengths than coarse or standard sands, using clay bricks with a suction rate of 3-4kg/m^2 min.

2.4. Cement Content of Mortar.

The compressive and tensile strengths of mortar are simply related to the cement content, but the situation is more complex with respect to the bond strength between bricks and mortar. Palmer and Hall (20) report that a 1:3 mix gives about 50% higher bond strength than 1:1:6.

Palmer and Parsons (1) later added that high cement mortars give higher bond strength, but with a good deal of scatter, and if high suction rate bricks are used the bond may be poor with the same mortar. Forkner et al (10), however, concluded that for stiff-mud shale bricks of moderate suction rate (0.5-1.0kg/m^2 min), 1:1:6 and 1:2:9 mortars gave the best results, with 1:$\frac{1}{4}$:3 considerably weaker. At higher consistency, however, the differences were not so marked.

Copeland and Saxer (25) agree that strength increases with cement content but Fishburn (17) was more cautious, stating only that the "intensity" of bond depends indirectly on the cement content.

Hogberg (22) found that generally, bond strength increases with cement content, although on a very porous base, 1:6 is better than 1:3. He recommends a binder/sand ratio of 1:5-6.

A multiple regression analysis has been carried out by Huizer (26) to discover the relative importance of various factors with respect to the flexural bond strength. In this investigation there appears to be a linear correlation between flexural bond strength and sand/cement ratio using a pressed clay brick with a suction rate of 3.3kg/m^2 min.

2.5. Lime Content of Mortar.

The variation of lime content is closely connected with the cement content as it is usual to maintain a constant binder/sand ratio, by volume. It is apparent, however, that some of the effects on the mortar properties are due to the addition of more lime, rather than the reduction of cement. Kampf (3) quotes these effects as being an improvement in water retentivity and workability and a reduction in shrinkage. He also states that a greater proportion of lime improves bond on high suction rate bricks but has the opposite effect on others.

2.6. Mortar Consistence and Workability.

Consistence is a measure of the rheological properties of mortar and is determined by the dropping ball test described in BS4551:1980. Workability is a more subjective property describing the ease with which a high quality joint can be formed.

It has generally been found that mortar should be used with the consistence as high as is convenient, particularly when high suction rate bricks are used (for example Parsons (8), Habib and Leeds (12), Ritchie and Davison (15) and Hogberg (22)). According to Whittemore and Dear (9) the effect of higher consitence is to improve the bond efficiency (ratio of bond strength to mortar tensile strength) and to give rise to a higher percentage of failures in the mortar itself. Grimm (5) points out that in order to achieve good bond the mortar should have the ability to flow into the surface voids of the brick. His expression for the bond strength (given in full in section 2.1.) includes the factor $[1.8+(F-105)^{0.5}]$, where F is the flow of the mortar as a percentage. It can easily be seen that a small increase in flow will, if the expression is valid, produce a larger proportional increase in bond strength. There are, however, dangers involved in artificially increasing the workability by the use of plasticizers, as this can be detrimental to bond (Thomas (27)).

Closely allied to the properties of consistence and workability is the water/cement ratio. It is well known that in concrete practice, strength reduces as the water/cement ratio increases. This is also true, according to Boynton and Gutschick (28), in the case of mortar tensile and flexural strengths. However, in brickwork, the situation is more complex because of the effect of brick suction. Hogberg (4,22) and Sneck (19) claim that the bond strength depends on the water/cement ratio after suction, as this is more relevent to the hydration reactions than is the initial water content.

It is obvious that a higher initial water content will result, after suction, in a higher final water content in the mortar. If the tensile strength of the mortar within a brickwork joint depends inversely on the water/cement ratio then, the mortar with the highest initial water content should be the weakest. However, the workers mentioned above concluded that high consistence mortars give higher bond strengths, which may be due to better brick to mortar contact of the wetter mortar. This would also account for the observations of Whittemore and Dear (9) that the location of the failure surface in a tensile bond test seems to be close to the interface for lower consistence mortars and away from the interface for wetter mortars.

2.7. Consistence Retentivity of Mortar.

The properties of consistence retentivity and water retentivity as described in BS4551:1980 are closely related and will affect bond strength in the same general way. Indeed, most workers do not distinguish between the two, and simply use the term retentivity.

Palmer and Parsons (1) and Parsons (8) concluded that bond strength is improved by increased retentivity and that the effect is more marked if bricks of high suction rate are used. Thornton (21), Ritchie and Davison (15) and Ryder (29) confirmed the general opinion that higher retentivity is beneficial to bond. Doubts have been raised, however, beginning-with Hogberg (22) who suggested that high suction rate bricks perform best with a low retentivity mortar having a high initial water content. Morgan (18) arrived at the same conclusion for calcium silicate bricks. Hogberg (22) also reported that because of the stiffening effect of brick suction, the properties of the lower brick are of greater importance than those of the upper brick. These conflicting conclusions again demonstrate the complex nature of the problem and show that the property of retentivity is of some importance despite the results of Huizer (26) who calculated that retentivity is the least significant of the variables he studied.

2.8. Air Content of Mortar.

Whilst the effects of retentivity have been studied for many years, it is only comparitively recently that the significance of the air content of mortar has been realised. Air in mortar is known to affect the workability and retentivity in a way, according to Kampf (3), similar to lime, and that a high air content reduces bond strength for low suction bricks and increases bond strength for high suction bricks. Although higher air contents give improvements in workability and retentivity, it is the unanimous opinion of Copeland and Saxer (25), Hogberg (22), Grimm (5), Huizer (26) and Beningfield (30) that bond strength is reduced as a result.

2.9. Suction Rate Adjustment of Bricks.

Another method of counteracting the effects of a high suction brick is by pre-wetting in order to reduce the absorptive forces. The result most often quoted is that wetting high suction rate bricks will improve the bond, whereas wetting low or medium suction rate bricks could decrease the bond strength, for example, Palmer and Hall (20), Collin (7), Kampf (3), Albrecht and Schneider (16). Wetting must not be overdone, however, or a film of water may form on the surface of the brick, which would be detrimental to the bond strength. Forkner et al (10) and Hogberg (22) point out that the bond strength obtained using wetted high suction rate bricks will not be as high as with bricks having an originally low suction rate. This behaviour would account for the scatter in the results of Habib and Leeds (12), who wetted bricks of different initial absorption rates by amounts necessary to reduce the absorption rates down to some chosen value.

Ryder (29) states that bond strength with high retentivity mortars is reduced when bricks are wetted and with low retentivity mortars wetting improves the bond. Hogberg (22), on the other hand, reports that using a 1:3 mix, an improvement in bond is obtained by wetting, but no such improvement occurs with a 1:6 mix (which presumably has a lower retentivity). This response was found when using calcium silicate bricks, however, which are known to differ from clay bricks in their behaviour (18).

2.10. Mortar Strength.

The strength of mortar is affected significantly by the cement content so it would seem reasonable to conclude that the relationship between cement content and bond strength is similar to that between mortar strength and bond strength. This seems to be partly true and most authors agree that bond strength increases with mortar strength. For highly retentive mortars, Palmer and Parsons (1) state that mortar strength is the most important factor. Pearson (2), however, concludes that there is no relationship between bond strength and the compressive strength of mortar.

2.11. Curing Conditions.

Even when good contact has been achieved between brick and mortar it is important that conditions are right for the full development of strength. Grimm (5) notes that hydration will cease if the relative humidity within the joint drops below 70-80%. It has been found generally that damp curing conditions will produce the highest strength. This is particularly important during the early stages of curing, according to Hogberg (22).

In practical terms, drying out of mortar is mainly a summer problem. In winter, freezing of brickwork is a major source of trouble. There has been a lot of experimental work carried out to assess the effects of freezing. Kampf (3), Ryder (29) and Hogberg (22) all suggest that freezing can be detrimental to bond, particularly in the early stages. Sneck (19) has offered some important thoughts on frost damage. He points out that damage may be caused by freezing unless either the water content has been lowered sufficiently by suction, or the mortar has hardened enough before freezing, or the mortar freezes immediately whilst still structureless. He does not recommend the last option, however, because of the sudden lack of stiffness of the mortar on thawing.

2.12. Other Factors.

The ease with which the top brick may be laid depends upon the condition of the mortar at the time of laying. In addition to the properties already discussed, this will be influenced by the time between spreading the bed of mortar and laying the top brick. According to Kampf (3), Ritchie and Davison (15) and Grimm (5) the effect of delay is a reduction in bond strength, particularly where high suction bricks are used.

The time between mixing the mortar and its use may also be of importance. Due to evaporation and hydration, mortar will become less workable and so it is common practice to retemper the mix with extra water. This seems to have little effect on the final strength for mortar which is not more than two hours old, according to Ritchie and Davison (15).

2.13. Summary.

The following conclusions represent the general opinions reviewed in the preceding sections and are in broad agreement with the conclusions of Goodwin and West (31).

(i) Maximum bond strength is obtained when the suction rate of the brick is in the range $0.5-1.2 kg/m^2$ min.

(ii) There is no fixed optimum suction rate; the relationship depends upon the brick type and the retentivity of the mortar.

(iii) The suction rate of the lower brick has a more significant effect than the suction rate of the upper brick.

(iv) The brick type is important, but there is a lack of agreement as to which is best.

(v) Generally, smooth bricks give a higher bond strength than rough bricks.

(vi) Well-graded sands with rounded grains give the highest bond strength.

(vii) Fine sands are best when used with high suction rate bricks.

(viii) Sands from different sources which have identical gradings will not usually exhibit the same behaviour.

(ix) Bond strength does not necessarily increase with cement content; high lime mortars are often superior for use with stiff-mud shale bricks.

(x) High lime mortars show improved workability and retentivity and less shrinkage.

(xi) Mortar consistence should be as high as practicable, particularly when high suction rate bricks are used.

(xii) Higher consistence increases the ratio of bond strength to mortar tensile strength and induces failure to occur in the body of the mortar, rather than at the interface.

(xiii) High suction rate bricks generally require mortars with high retentivity.

(xiv) Bond strength is usually reduced by the use of plasticizers and air entraining agents.

(xv) Pre-wetting high suction rate bricks will increase bond strength.

(xvi) Pre-wetting low or medium suction rate bricks could reduce bond strength.

(xvii) Dry bricks of a particular suction rate will give higher bond strength than bricks of a higher suction rate that have been wetted down to that level.

(xviii) Damp curing conditions improve bond strength.

(xix) Freezing can be detrimental to bond.

(xx) Delay between placing mortar and top brick will reduce bond strength, particularly for high suction rate bricks.

(xxi) Retempering of mortar to restore workability has little effect if the mortar is less than two hours old.

3. A REVIEW OF THE EXPERIMENTAL DETERMINATION OF BOND STRENGTH.

Tests to determine bond strength can be divided into two classes; direct tensile in which stresses are uniform, and flexural in which there is a linear variation of tensile stress and, in some forms of test, a shear component.

Much useful work has been carried out using a variety of test methods. The simplest is probably the flexural test performed on a stack bonded pier (fig.3.1), which has been carried out as a standard site test in Australia for many years (32). Pearson (2) has examined this form of test, but was of the opinion that for scientific work the large number of bricks required would be too expensive, particularly if some of the bricks were hand picked for the required properties. Another objection raised by Pearson is that the pressure of tapping necessary to manufacture the specimens would be virtually indeterminable. Also the self weight of the bricks would apply a compressive load to the joints during manufacture, which would not be the same for all joints in the pier.

A similar type of test, which attempts to remove these difficulties, is the cantilever test, in which only two bricks are used, one of which is clamped to a fixed surface and a lever arm is attached to the second brick (fig.3.2). There are several variants of this test. Anderegg (33) formed his couplets with both bricks in line and attached the lever arm to the side faces of the bricks, whereas Pearson (2) offset the bricks by a small amount to provide edge bearing strips for the lever arm. Because one brick of these couplets is clamped to a vertical surface and loading is by gravity, there will be a small shear stress applied to the specimen. In spite of this, Pearson (2) reports that the maximum tensile stresses developed are well in excess of the direct tensile bond strength. Other objections to this form of test are that the stresses on the two interfaces will not be the same because of the difference in the lever arms, and that only the mortar at the point of maximum tensile stress will be contributing significantly to the bond, so any lack of contact at the edge will be critical. Copeland and Saxer (25) use a similar configuration for the testing of concrete blocks bonded together, although their system is rotated through 90° whilst retaining the vertical application of load (fig.3.3).

Pearson has also investigated the wall test, in which bricks were levered from a wall (fig.3.4) which was built to take several rows of bricks and was known, because of its appearance, as an altar. The method gave consistent results, but suffered from the same inherent disadvantages as other flexural tests. In addition, once a set of bricks have been levered off the wall, the top surfaces of the bricks forming the wall will not be in the same condition as they were originally and could not be expected to behave in the same way again. The change in performance may not be important, but it is a factor which should be taken into account.

A new approach has been adopted by Jain (34) in which a force is applied to split apart a joint (fig.3.5). This method gives results which follow the well-known failure patterns for rich mortars of rupture close to the interface and for weak mortars of an ill-defined failure plane. It is, however, difficult to justify this type of test as either a simple, uniform stress system for materials research, or as a model of a practical situation for structural assessment. Recently Taylor and Taylor-Firth (35) have developed a successful shear/flexural system for testing brick couplets under various levels of precompression (fig.3.6). Their method, using only 1½ bricks per test, provides probably the most valid representation of in-plane behaviour yet devised.

The critical problem with direct tension testing of brickwork samples is that of achieving a uniform stress field within the specimen. The most popular test over the last half-century has been the crossed-brick couplet (2,7, 9,10,11,12,36). This test (fig.3.7) has the advantages that the manufacture of specimens is a simple and well-controlled procedure, and that testing can be carried out using any standard compression testing machine. Most test methods use a three-point bearing system in order to achieve the required stress distribution, although Habib and Leeds (12) have developed a novel four-point system with two of the bearings connected together and pinned to the support (fig.3.8). To take account of any lack of alignment of the upper and lower surfaces of the specimen, a spherical bearing is usually included in the test set up.

This may not, however, allow much freedom of rotation when under high loads. Kuenning (37) has calculated that the system of loading will cause the bricks to bend, producing tensile strains in the mortar of about 120×10^{-6} for a typical sample under a stress of 0.5N/mm^2. This bending action will induce failure at the edges of the mortar at levels of load which will underestimate the true tensile strength of the joint. A further objection which could be raised is that a typical failure load of about 3-4kN would be well below the normal operating range of most compression testing machines and unless a suitable load cell was incorporated into the system, results could include significant errors.

There have been several versions of bonded-plate test beginning with Johnston, Dear and Whittemore (11), who attached a perforated disc to the top face of a mortar bed in order to determine its bond strength to concrete block (fig.3.9). Load was applied in direct tension through a universal joint. There is also Hinderson's method (fig.3.10) used by Hogberg (22), who reports that strengths obtained by this method can be up to three times the crossed-brick strengths. The procedure is essentially a refinement of that used by Johnston et al in that a circular groove is routed in the mortar bed which isolates an 80mm diameter section of mortar to which is bonded an aluminium disc. This disc is then pulled off hydraulically. Both these tests have two disadvantages. It would be difficult to ensure that the forces applied are perpendicular to the mortar bed, and also the test is designed to test the bond strength of a mortar bed placed in isolation upon a brick or block. This is obviously a situation which would not occur in practice and the system may not necessarily behave in the same way as a normal brickwork joint.

Samples consisting of two half-bricks bonded together have been tested using the bonded-plate method by Kuenning (37) and by Sinha and Hendry (38). In these tests plates are bonded to the top brick (and in the case of Sinha and Hendry, to the bottom brick also) and the bricks are pulled apart in direct tension. The main difficulty with this test is to ensure that the tensile stresses are uniform. It also suffers from the disadvantage that extra time and effort are needed to prepare the sample for testing because of the necessity to bond the plates to the bricks. Also, several sets of plates would be required in order to test a batch of several specimens.

A closer step towards a truly axial test has been taken by Ritchie (39) and by Tytherleigh and Youl (40). Ritchie has devised a clamping system in which rigid frames are bolted to the bottom and second-to-bottom bricks of a stack (fig.3.11). The clamping bolts have swivelling bearing pads to give good contact and plywood or leather packing pieces are placed between the bearing pads and the brick. The clamping frames are positioned using special spacers which ensure that the frames will be parallel. Hanger bars are placed under the top frame with a ball and socket joint to the testing machine. The bottom frame is held rigid. This method seems to represent a more uniform axial mode, but great care must be taken to ensure that the frames are placed exactly parallel and no movement takes place when the eight bolts on each frame are tightened. Bond strengths up to about 0.7N/mm^2 can be obtained with this system, but for lower strengths (up to 0.2N/mm^2), a simpler clamping frame with only two bolts per side, bearing directly onto the brick, has been used.

Tytherleigh and Youl used small brick units, approximately 50mm square, having a slight taper. They are bonded together in pairs and tested using a standard Hounsfield Tension Testing Machine (fig.3.12). A difficulty with this form of test is that a high degree of accuracy would be necessary during manufacture because of the smallness of the sample.

The requirement for true axiality is of vital importance because any eccentricity of loading, or any small lateral load will give rise to additional tensile stresses at some point within the mortar joint causing tensile failure to occur prematurely. The ideal form of tensile test then should have the following characteristics:

(i) Specimens should consist of a pair of bricks only, so that laying conditions may be controlled to reduce variations between joints.

(ii) The bonded area should be as large as possible in order to reduce the significance of random variations in brick surface, mortar quality and brick/mortar contact from point to point.

(iii) Specimen manufacture should be closely controlled by some form of jig which is simple to use but which gives joint dimensions that are uniform and reproducible.

(iv) The mechanical device for applying load to the specimen should be simple and quick to fit and should be fully adjustable in order to eliminate any non-uniformity in stress distribution and any non-axiality within the system.

(v) The testing machine should have a selection of operating ranges with maximum loads up to about 10kN, and should provide a permanent record of load and deflection throughout the test.

It was felt that none of the test methods described in this chapter possess the five characteristics listed above to an acceptable degree and that a new design was desirable.

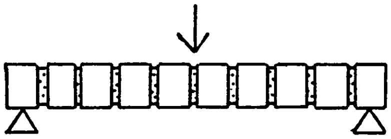


Figure 3.1. Australian site test (32).

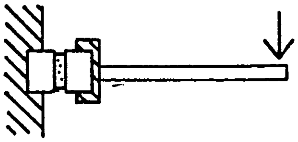


Figure 3.2. Anderegg (33).

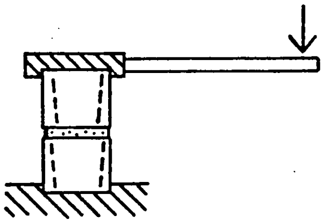


Figure 3.3. Copeland and Saxer (25).

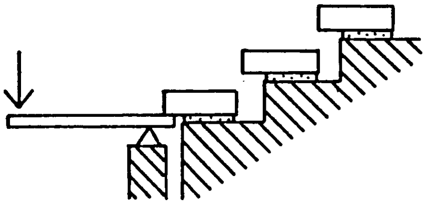


Figure 3.4. Pearson (2).

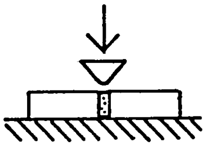


Figure 3.5. Jain (34).

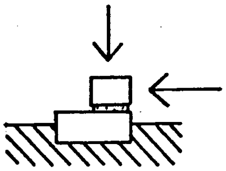


Figure 3.6. Taylor and Taylor-Firth (35).

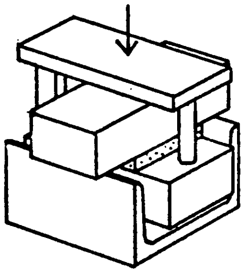


Figure 3.7. Crossed-brick couplet.

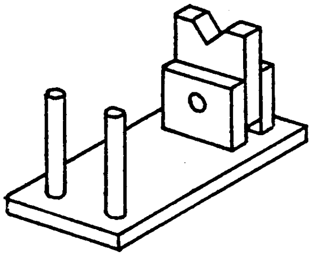


Figure 3.8. Habib and Leeds (12).

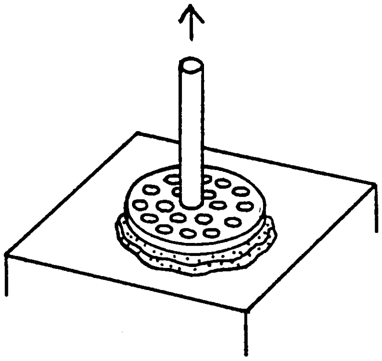


Figure 3.9. Johnston, Dear, Whittemore (11).

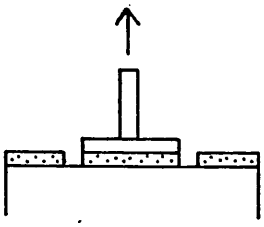


Figure 3.10. Hinderson's method.

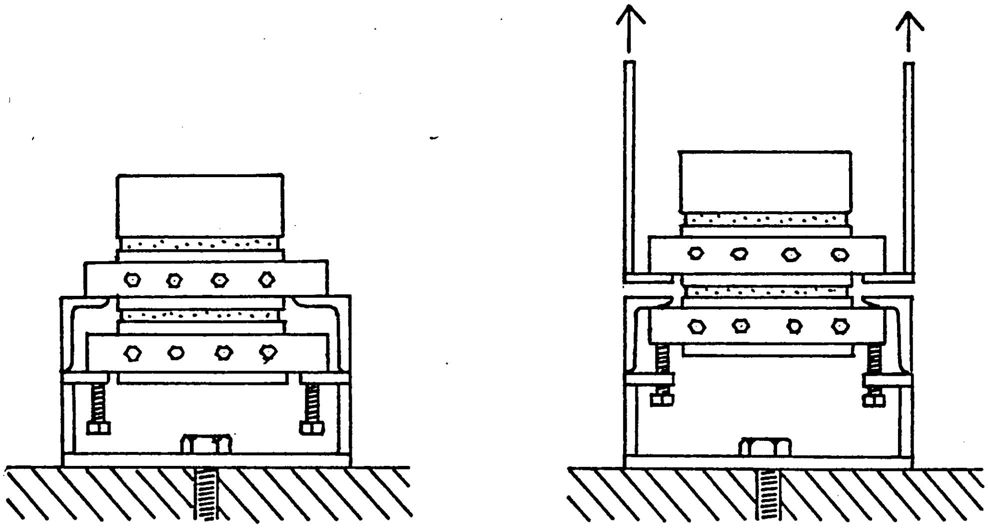


Figure 3.11. Ritchie (39).

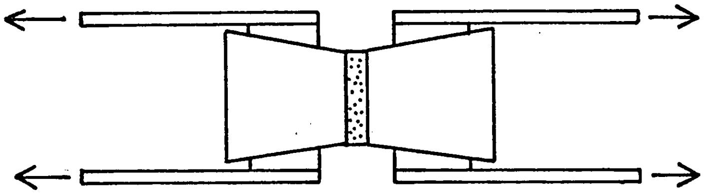


Figure 3.12. Tytherleigh and Youl (40).

4. RESULTING TENSILE TEST APPARATUS.

After careful consideration of the test requirements listed in the previous chapter, a new form of apparatus was designed and built with a high degree of flexibility at all joints to allow for irregularities in specimen dimensions and to ensure axiality.

The apparatus, shown in figure 4.1, accepts a couplet consisting of parallel bricks bonded together over an area of approximately 100mm x 150mm. This area is about 50% larger than the bonded area of a standard crossed-brick couplet. Load is applied to the specimen, via four fully adjustable slings and two load-transfer plates, using a variable range Monsanto tensometer. Between five and ten specimens could be tested in one hour.

The reliability of the apparatus was assessed using electrical resistance strain gauges. Readings were taken of the strains in each vertical hanger rod for a selection of the most badly shaped specimens, in order to test the effectiveness of the system in giving uniform stresses.

Figure 4.2 shows a typical set of results from the gauges on the top four hanger rods during the testing of a specimen using Funton stock bricks. These bricks were of poor shape and it was felt that the better shape and uniformity of the other two types of brick used (Southwater engineering and Holbrook facing) would give much better results.

The dotted line shows the average tensile strain calculated from the recorded ultimate load for this sample. The figure shows that the maximum error in

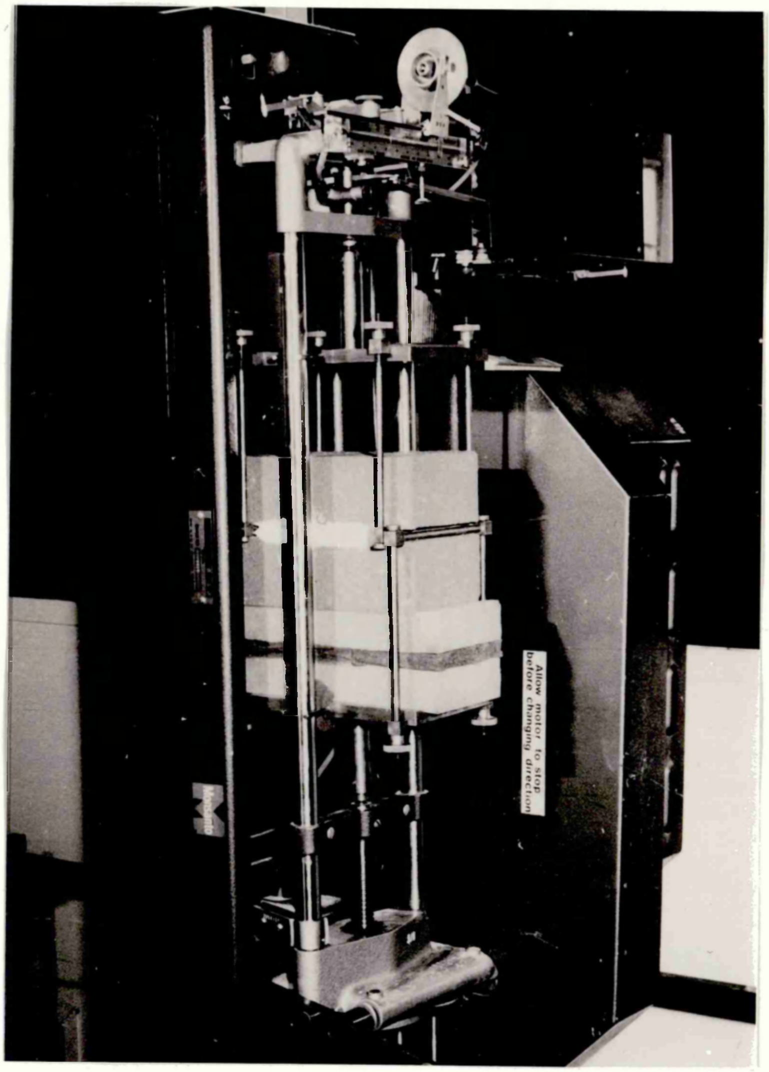


Figure 4.1. Tensile test apparatus.

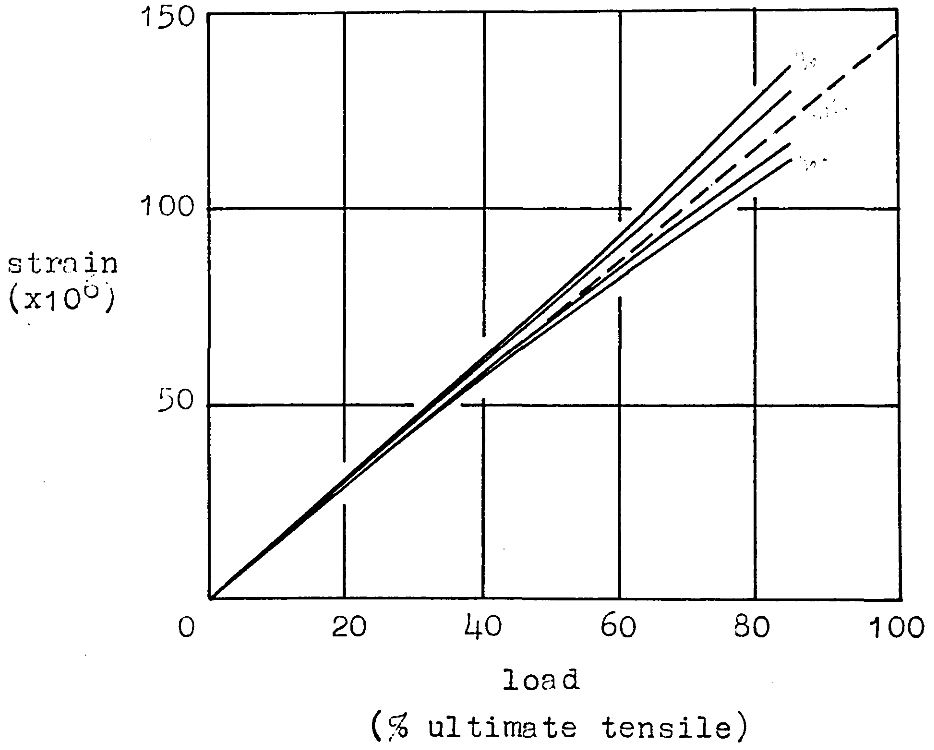


Figure 4.2. Typical strain gauge readings from top four hanger rods.

tensile stress is about 10% at 85% of ultimate load, for this specimen.

The use of strain gauges also presented an opportunity to assess whether or not creep had taken place during loading. After the strains had been recorded on all gauges, the first reading was checked. During the period of about two minutes in which the readings were taken, the strain registered by the first gauges had not changed by more than about 2 to 4×10^{-6}. It can therefore be concluded that over the duration of the test no significant reduction in load had taken place due to creep.

In all, about 1000 couplets have been successfully tested on this apparatus, the purpose and results of which will be described in sections 6 and 9.

5. PROPERTIES OF MATERIALS USED.

For the manufacture of the brick couplets for tensile bond strength testing, the following materials were chosen:

Bricks: Southwater engineering (double frog)
Holbrook facing (23 perforations)
Funton stock
supplied by Redland Brick Co. Ltd.

Sand: Auckley washed building sand
supplied by ARC Ltd.

Cement: OPC
supplied by Ketton Portland Cement Co. Ltd.

Lime: Limbux hydrated lime
supplied by ICI (Buxton) plc.

The following subsections describe the relevant properties of these materials.

5.1. Brick Suction Rate.

Suction rates were determined for ten Southwater, Holbrook and Funton bricks by measuring the weight of water absorbed per unit area of the bed face in one minute.

In each case the net area of the bed face was used, allowance being made for frogs and perforations, although the use of the net area of a perforated brick may lead to an overestimate of the suction rate (41).

A Southwater brick with a deep crack was tested and was found to have a suction rate of 0.98kg/m^{2}min. This result has not been used in the calculation of the mean value given on the following page.

Brick Type	Mean Suction Rate (kg/m^2min)	Range (kg/m^2min)
Southwater	0.13	0.06-0.18
Holbrook	0.25	0.21-0.28
Funton	3.04	1.36-5.45

5.2. Brick Suction Rate After Adjustment.

As a part of the experimental test programme, some of the Southwater and Holbrook bricks were suction rate adjusted, by dunking for one minute, followed by 30 - 45 minutes drain. The sample batch used in section 5.1 was treated in this way and the resulting suction rates were determined.

Brick Type	Mean Adjusted Suction Rate (kg/m^2min)	Range (kg/m^2min)
Southwater	0.066	0.056-0.074
Holbrook	0.079	0.027-0.103

5.3. Brick Water Absorption.

The percentage water absorptions were determined by the five hour boiling method on ten samples of each brick type, in accordance with BS3921, "Clay Bricks and Blocks".

Brick Type	Water Absorption (%)	Range (%)
Southwater	1.7	1.4-2.4
Holbrook	4.5	3.0-5.2
Funton	25.0	17.1-34.4

5.4. Particle Size Analysis.

Figure 5.1 shows the particle size analysis of the materials used in the mortar. (Data from Ketton Cement and ICI Buxton for cement and lime).

5.5. Mortar Strength.

In this section the mortar strengths are the mean values for each grade of mortar, for which the range of consistence was approximately 8-14mm (dropping ball penetration). The complete results will be given in section 9.1. Each value is the mean of 18 specimens. Cube strengths are based on 75mm cubes and flexural strengths on 100x25x25mm prisms. All specimens were cured for 28 days in purpose-built cabinets as shown in figure 7.7.

Mortar Designation	Cube Strength (N/mm^2)	Flexural Strength ($N/mm2$)	BS5628 Requirement (N/mm^2)
(i) 1:¼:3	24.0	5.7	16.0
(ii) 1:½:4½	13.7	4.1	6.5
(iii) 1:1:6	6.2	2.9	3.6
(iv) 1:2:9	2.8	1.5	1.5

The last column gives the required cube crushing strengths for laboratory tests, given in BS5628: Part 1: 1978. It can be seen that the mortar strengths are considerably higher than the minimum requirements.

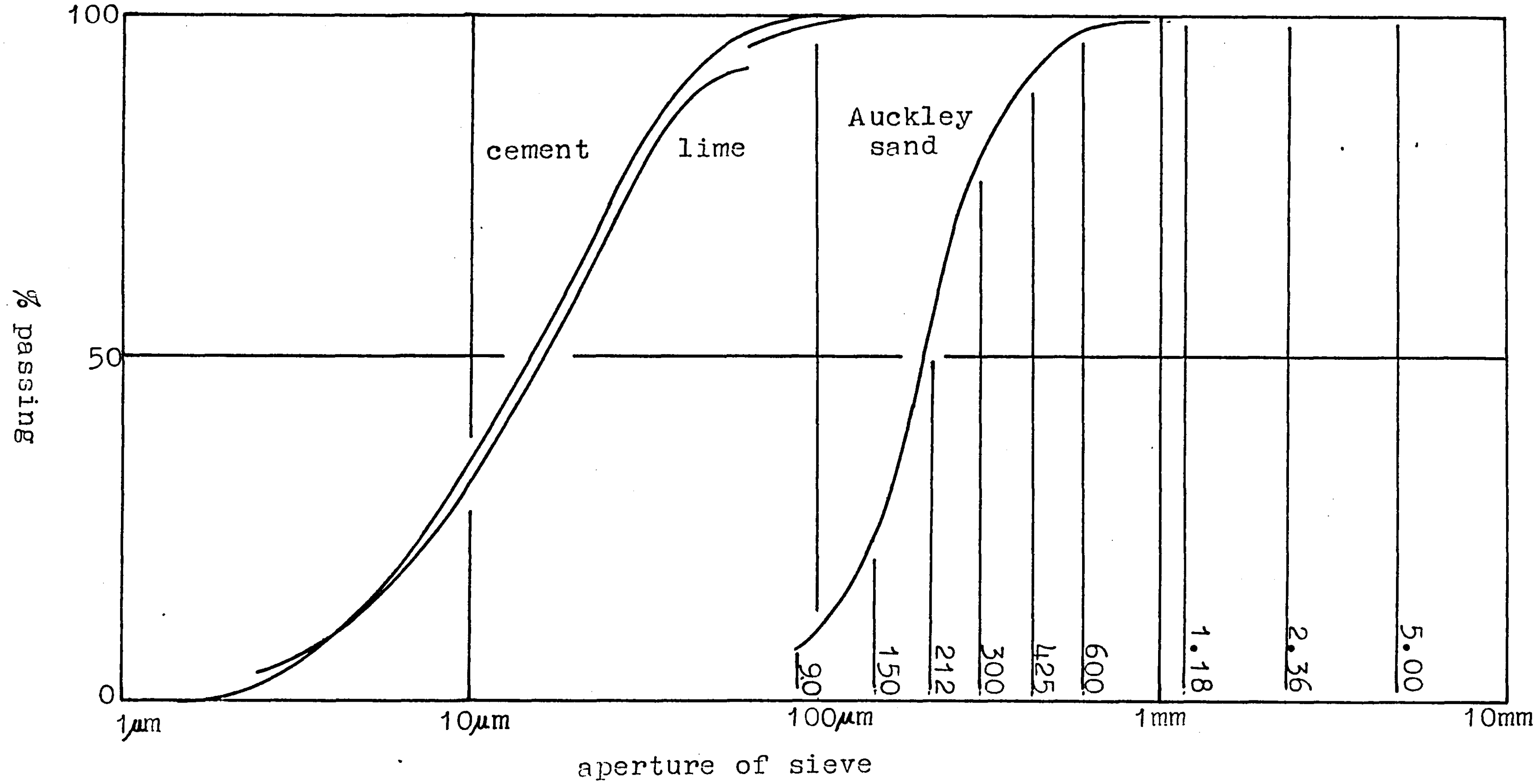


Figure 5.1. Particle size analysis of cement, lime and sand.

6. DETAILS OF ENGINEERING TEST PROGRAMMES.

Using the materials specified in section 5, the following four experimental programmes were devised to investigate some of the most important factors which influence bond strength.

From section 2.13 it can be seen that a comprehensive experimental programme to study all the major variables would be a formidable task. Consequently, some compromises have proved necessary. The following programmes have been devised to examine some of the more important points in section 2.13, or those about which there is some disagreement in the literature and for which the conclusions are unclear (in particular, points iv, v, ix, xvi and xix).

6.1. Mortar Programme.

Designed to investigate:

Effect of pre-wetting bricks of low suction rate.

Effect of mortar type.

Effect of water content of mortar.

Variables studied:

Brick type	2
Suction rate adjustment	2
Mortar grade	4
Water content of mortar	6
Number of couplets per test	5
Total number of couplets	480

The bricks used were Southwater engineering and Holbrook facing.

The two suction rate adjustment cases refer to unadjusted and dunked as specified in section 5.2.

Mortar grades were as specified in section 5.5 using the mix proportions given in table 6 of BS4551:1980, and reproduced in section 7.

Six water contents were used, in steps of 0.5% by weight of dry constituents.

6.2. Sand Grading Programme.

Designed to investigate:

Effect of sand grading.

Effect of pre-wetting bricks.

Variables studied:

Brick type	2
Sand gradings	7
Suction rate adjustment	2
Number of couplets per test	10
Total number of couplets	280

The brick types and suction rate adjustment were the same as in the mortar programme .

Mortar grade (ii) with 19½% water was chosen for the Holbrook facing bricks and mortar grade (iii) with 21% water was chosen for the Southwater engineering bricks as the most suitable mix in each case, based on the results of the mortar programme.

Mortar grade (ii) was chosen in preference to grade (i) because it was felt that the coarser sands used in this programme would require a higher lime content in the mortar to give adequate workability.

6.3. Suction Rate Programme.

Designed to investigate:

Effect of brick suction rate.

Variables studied:

Brick suction rate	6
Number of couplets per test	10
Total number of couplets	60

In order to give a wide range of suction rates, a Funton , stock brick was used. The one minute suction rates were determined for almost 400 bricks and from these, 20 were chosen in each of the following suction rate bands:

0.00 - 0.75	kg/m^2 min
0.76 - 1.50	"
1.51 - 2.25	"
2.26 - 3.00	"
3.01 - 3.75	"
3.76 - 4.50	"

Mortar grade (iii) was used. It was hoped that all mixes would be identical, but it was found that the water content of the mortar had to be increased for the higher suction rate bricks in order to counteract the rapid stiffening of the mortar during laying.

6.4. Curing Programme.

Designed to investigate:

Effect of various curing conditions.

Variables studied:

Brick type	2
Curing conditions	5
Number of couplets per test	10
Total number of couplets	100

The bricks were the same type as used in the mortar programme.

Mortar grade (i) with 19% water was used for the Holbrook facing bricks and mortar grade (iii) with 20% water for the Southwater engineering bricks. These mixes were chosen, on the basis of results from the mortar programme, to give the greatest bond strength and optimum mortar consistence.

Bricks were not suction rate adjusted.

The curing conditions were as follows:

a) Cabinet	Sealed in curing cabinets for 28 days. Temperature and humidity monitored.
b) Wet/dry	Submerged in water (18.5°C) for 24 hours on days 2,9,16 and 23. Otherwise uncovered in laboratory.
c) Freeze/thaw	In freezer from day 2 - day 27 on 24 hour cycle -4°C to 10°C. 10hr. freeze down, 14 hr. thaw.
d) Mist room	Day 2 - day 28 100% relative humidity, 18°C.
e) Const. temp-humidity	Day 2 - day 28 60% relative humidity, 20°C.

7. METHOD OF SPECIMEN MANUFACTURE.

All mortar mixes were prepared in accordance with BS4551:1980 "Methods of testing mortars, screeds and plasters", using weigh batching proportions as shown below.

Mortar designation	Approximate Volume Proportions	Percentages by Weight		
		Cement	Lime	Dry Sand
as specified in BS5628: Part 1: 1978		from table 6, BS4551: 1980		
(i)	$1:\frac{1}{4}:3$	22.9	1.5	75.6
(ii)	$1:\frac{1}{2}:4\frac{1}{2}$	17.0	3.1	79.9
(iii)	1:1:6	13.6	5.1	81.3
(iv)	1:2:9	9.0	6.4	84.6

The total mass of dry constituents used was 10kg per mix. This amount was found to be sufficient to manufacture ten couplets. In order to provide quality control, three 75mm cubes and three flexural prisms were made for each batch of mortar produced. The dropping ball penetration test was used to measure the mortar consistence prior to and shortly after the manufacture of the couplets.

The couplet forming equipment shown in figure 7.1 was designed to produce a 10mm joint between two full-size building bricks. The bonded length was 150mm with a gap at each end of about 25mm in which the testing slings were placed. After the brick had been placed in the mortar former (fig. 7.2) the mortar guides were rotated into position. These guides ensured that a mortar bed of length 130mm and thickness 15mm was placed centrally on

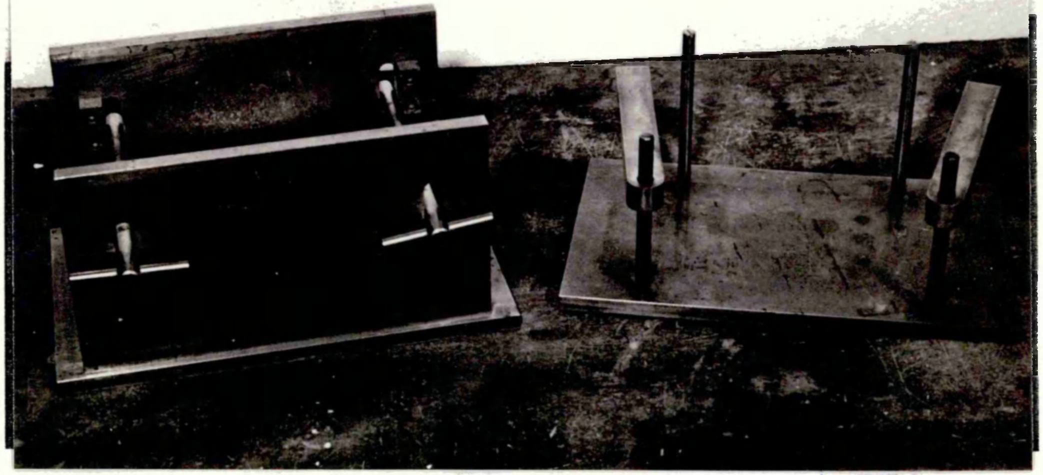


Figure 7.1. Specimen forming equipment.

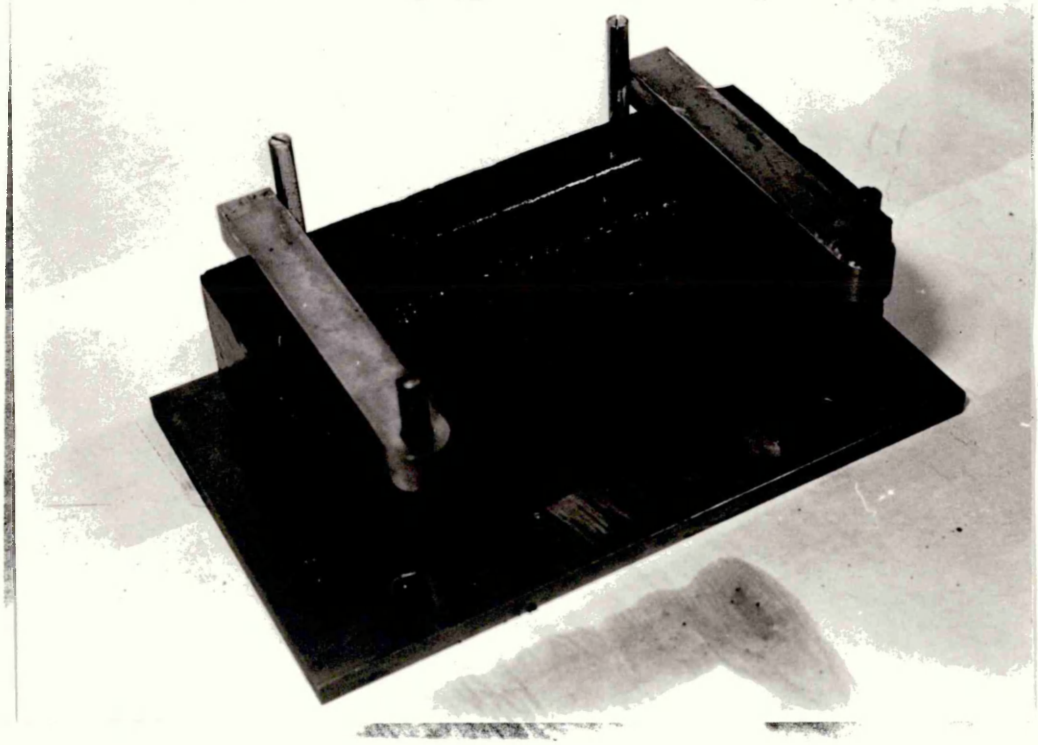


Figure 7.2. Brick in place.

the brick prior to placing the top brick (fig.7.3). The guides were rotated away (fig.7.4) and the brick was transferred to the joint former. Brass rods of 10mm diameter and 150mm apart rest on the brick as shown in figure 7.5. The top brick was placed on the mortar bed and pressed or tapped downwards until contact with the brass rods was achieved. The rods were then removed with a twisting action which ensured that the joint was adequately tooled at the ends. Finally the couplet was lifted out and the sides of the joint tooled with a small trowel (fig.7.6). Occasionally, if the consistence of the mortar was very high, tooling was delayed for approximately 30 minutes in order to minimise disturbance to the couplets.

The length of time taken to manufacture the ten samples was recorded for each of the 90 mixes. On only one occasion was the manufacture time less than 20 minutes and on only three occasions did the manufacture time exceed 40 minutes. The mean manufacture time was 29 minutes for ten couplets.

With the exception of the special curing conditions used in the curing programme, all samples were placed in sealed cabinets for 28 days prior to testing (fig.7.7). The transparent polythene covers were arranged in such a way that once sealed, the specimens would not be exposed or disturbed by the placement of the next batch.

During May and June 1982, readings of temperature and humidity were taken in the sealed cabinets whilst specimens were being cured in them. The mean temperature was found to be 19.4^{o}C and the mean relative humidity was 89%.

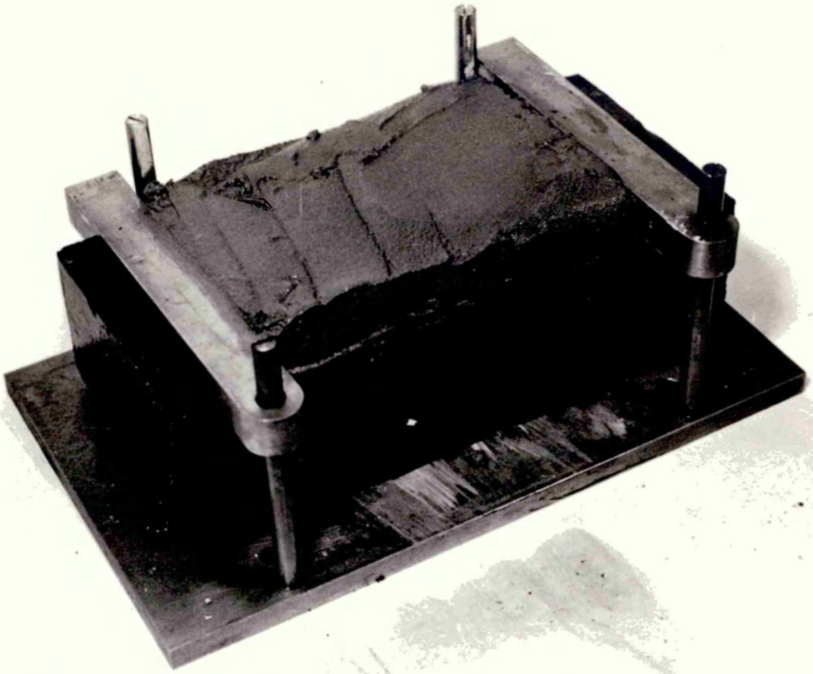


Figure 7.3. Mortar spread to level of formers.

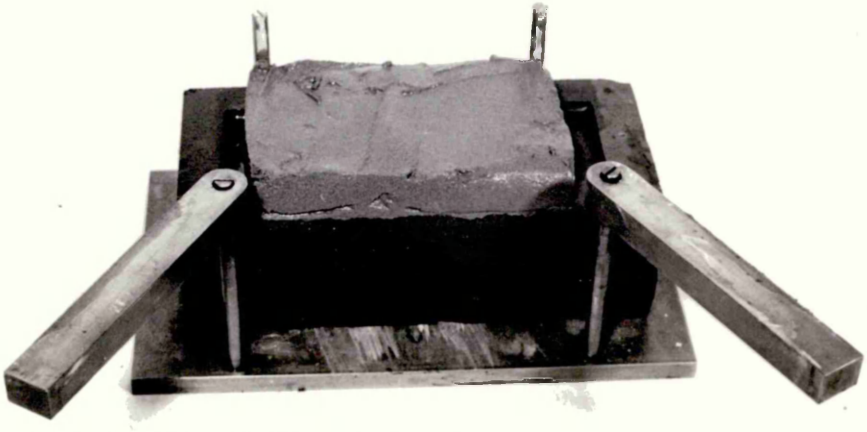


Figure 7.4. Formers removed.

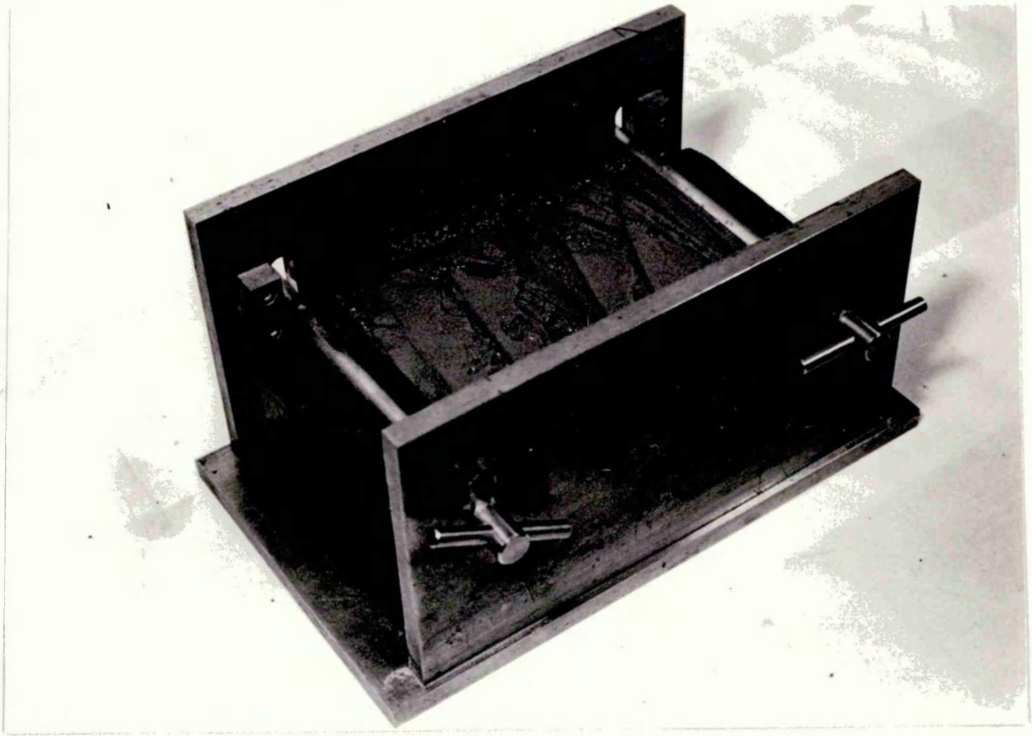


Figure 7.5. Spacer rods in place.

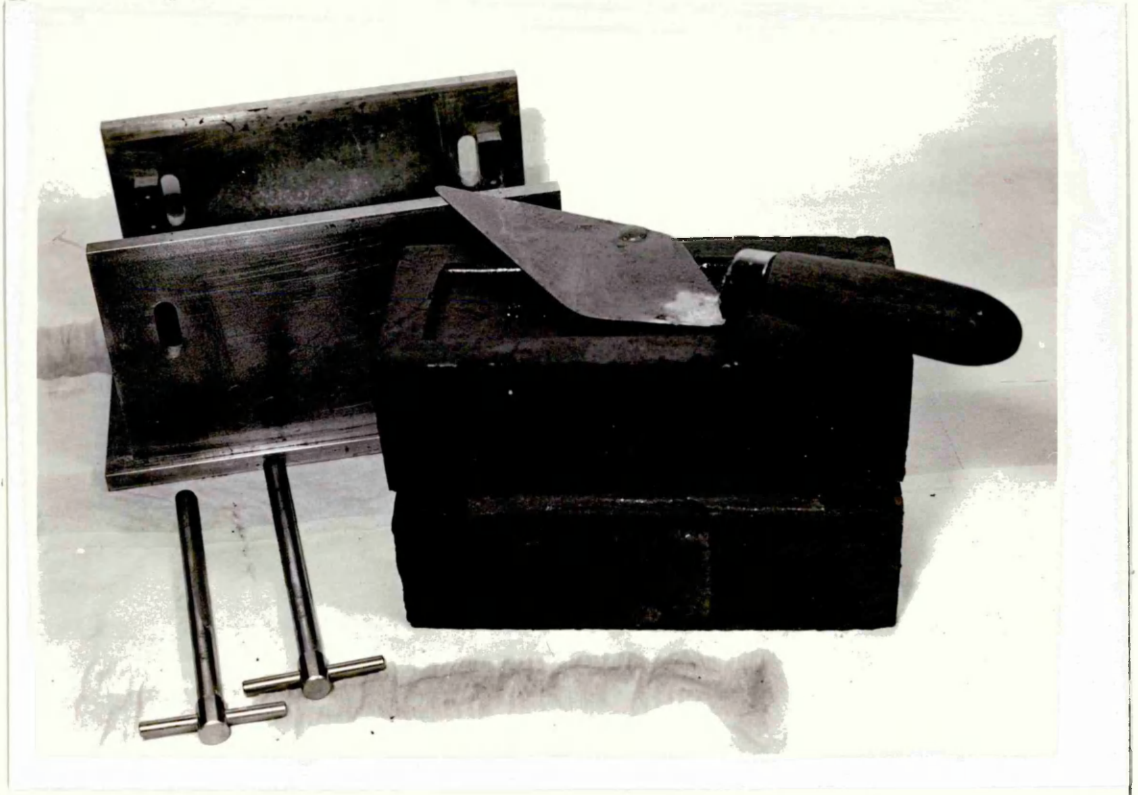


Figure 7.6. Specimen completed.

Figure 7.7. Curing cabinets.

8. METHOD OF TESTING SPECIMENS.

The tensile testing apparatus has already been described in detail in section 4 and was used as follows.

The specimen to be tested was placed on top of an appropriate thickness of flexible packing so that it was located centrally between the loading plates. The top hangers were located and adjusted, followed by the bottom hangers. Finally, all eight adjusting screws were checked to ensure that all hangers were making an even contact with the bricks without being either overtightened or loose. Figure 8.1 shows the specimen set up and ready for testing. The load was applied manually, as shown in figure 8.2, and was recorded on heat-sensitive paper which was located on the drum shown in the top right of figure 8.2. Figures 8.3 and 8.4 show a typical failed sample and figure 8.5 shows the recorded load-deflection data for a typical batch of couplets. The non-linearity of the output graphs is due to the fact that the recording stylus is pivoted at one end and moves in an arc. This can be seen more clearly at the point of failure when the stylus drops back to its zero load position (shown dotted in figure 8.5 for clarity).

From this output failure can be characterised as brittle, and there is no evidence of cracking prior to failure, or of creep having taken place.

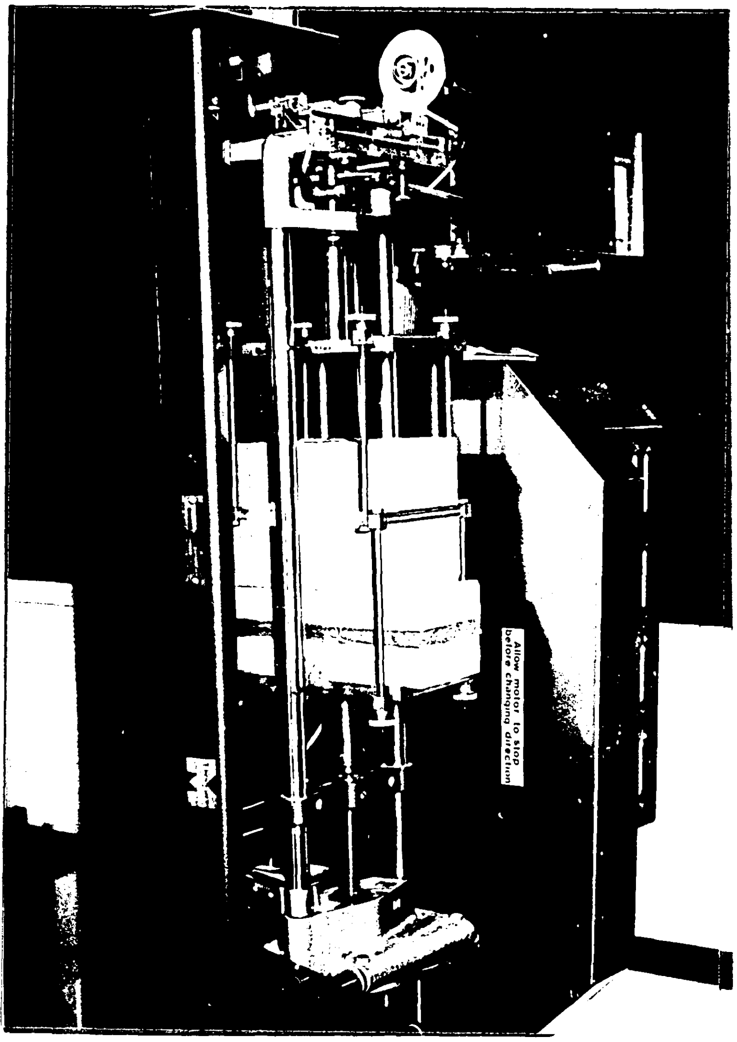


Figure 8.1. Couplet in place in Monsanto tensometer.

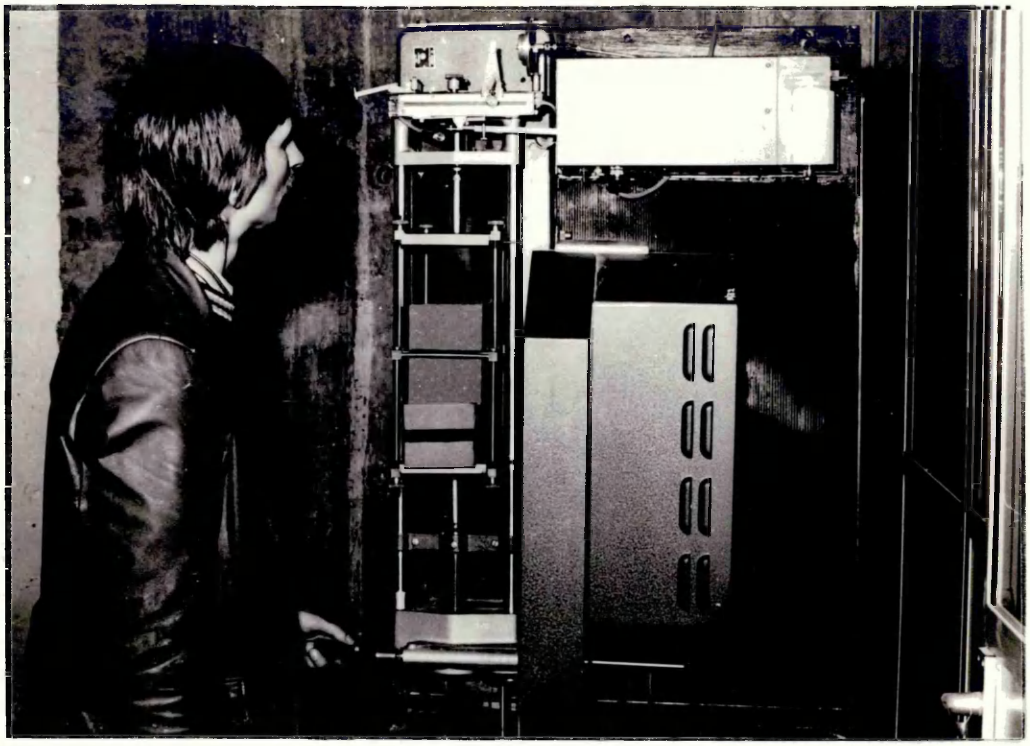


Figure 8.2. Manual application of load.

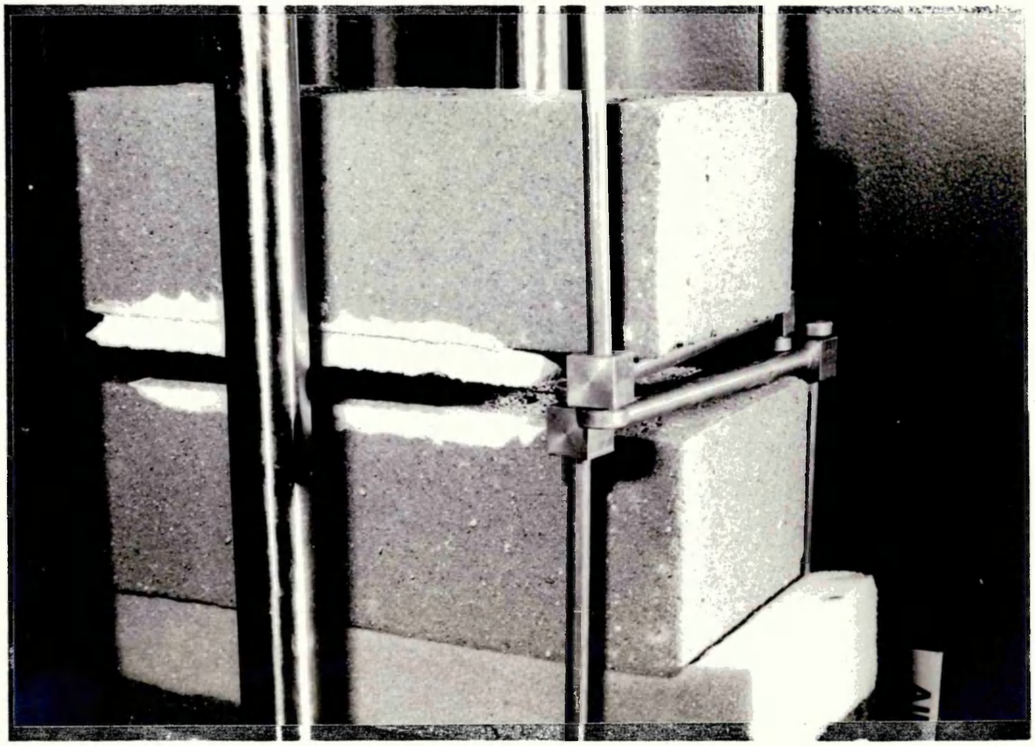


Figure 8.3. Failed couplet in tensometer.

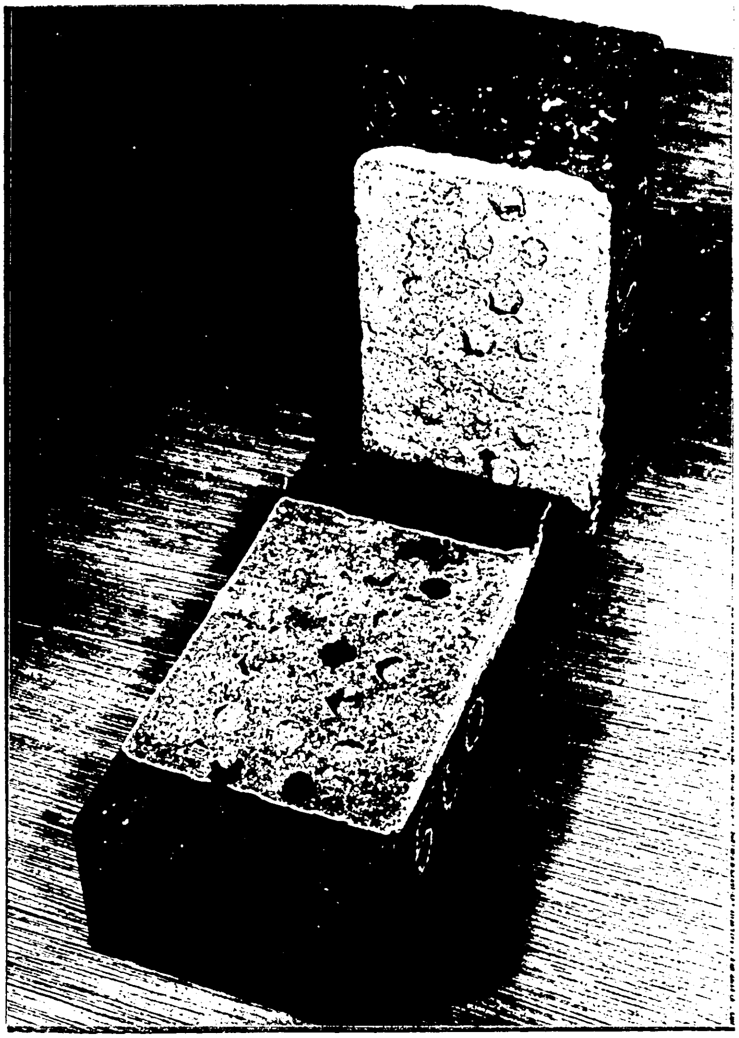


Figure 8.4. Typical tensile failure.

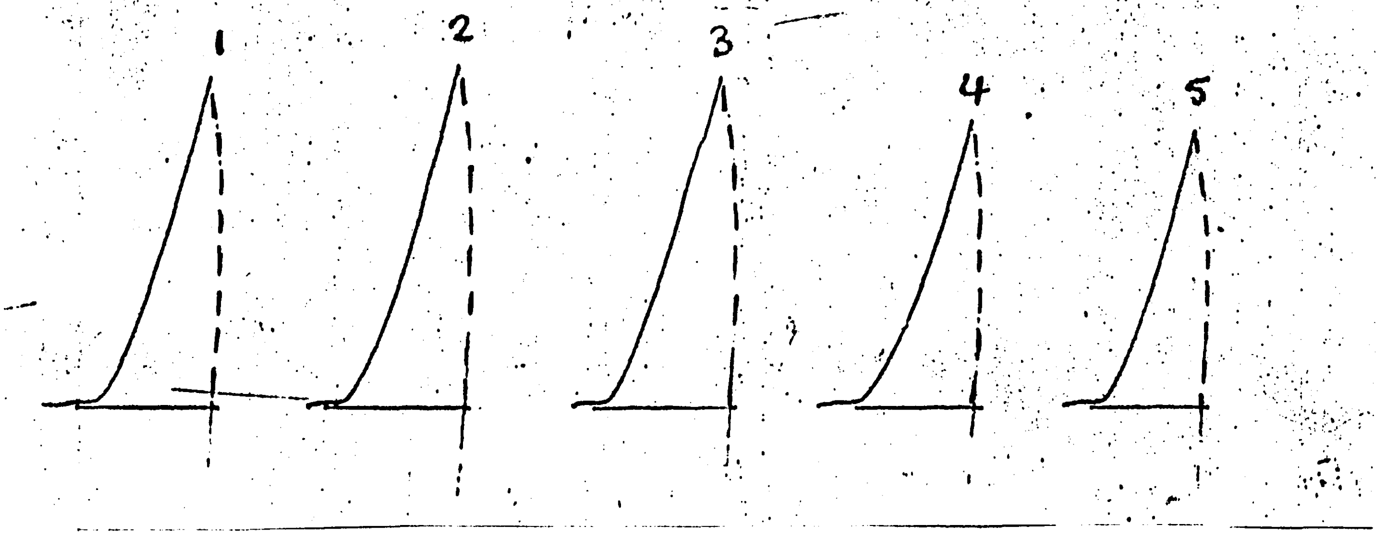


Figure 8.5. Typical load-deflection output from Monsanto tensometer.

9. RESULTS OF THE EXPERIMENTAL PROGRAMMES.

The details of the properties of the materials used and of each test programme are given in sections 5 and 6 respectively.

Each programme has been devised to examine and verify some of the conclusions listed in section 2.13.

The full details of each individual test are given in appendix 1, so the following sections contain information summarised from appendix 1.

9.1. Mortar Programme Results.

The properties of the mortar which are relevent to this programme are given in table 9.1. The water contents quoted refer to the percentage, by mass, of the dry constituents. All mixes contain 10kg of dry material, with between 1.75kg and 2.25kg of water.

Figure 9.1 shows the mortar consistence, as determined by the dropping ball penetration method. It can be seen that ball penetration increases with the water content of the mortar and, except for a small overlap between 1:½:4½ and 1:1:6, with the cement content also.

The variation of consistence with cement/lime ratio may be due to the different particle shapes and the early chemical behaviour in water. Particle size is not thought to account for the behaviour since the grading curves of cement and lime are very similar (figure 5.1).

Table 9.1 also shows that mortar cube and flexural strengths (using 75mm cubes and 25x25x100mm prisms) are independent of the consistence of the mortar. The highest strengths were obtained with 1:¼:3 and the lowest with

DROPPING BALL PENETRATION (mm)

WATER CONTENT (%)	MORTAR GRADE (i)	(ii)	(iii)	(iv)
17½	6.4			
18	7.2			
18½	8.1	7.6		
19	9.2	7.8	8.4	
19½	10.2	8.4	8.8	
20	12.8	10.0	9.4	8.1
20½		11.1	10.5	9.2
21		12.8	12.4	10.1
21½			13.5	10.0
22			14.7	10.7
22½				12.5

MORTAR CUBE STRENGTH AT 28 DAYS (N/mm^2)

WATER CONTENT (%)	MORTAR GRADE (i)	(ii)	(iii)	(iv)
17½	24.4			
18	24.8			
18½	24.9	14.9		
19	25.2	14.3		
19½	24.0	13.2	6.9	
20	20.9	13.6	6.4	2.8
20½		13.4	5.8	3.1
21		12.7	6.8	2.8
21½			6.0	3.2
22			5.6	2.6
22½				2.2

MORTAR FLEXURAL STRENGTH AT 28 DAYS (N/mm^2)

WATER CONTENT (%)	MORTAR GRADE (i)	(ii)	(iii)	(iv)
17½	5.6			
18	6.5			
18½	5.5	4.3		
19	5.2	4.2		
19½	5.7	3.7	3.3	
20	5.6	3.9	3.2	1.5
20½			2.6	1.6
21			2.7	1.7
21½			3.1	1.5
22			2.6	1.4
22½				1.3

CUBE ÷ FLEXURAL STRENGTH

WATER CONTENT (%)	MORTAR GRADE (i)	(ii)	(iii)	(iv)
17½	4.4			
18	3.8			
18½	4.5	3.5		
19	4.8	3.4		
19½	4.2	3.6	2.1	
20	3.7	3.5	2.0	1.9
20½		3.1	2.2	1.9
21		3.1	2.5	1.6
21½			1.9	2.1
22			2.2	1.9
22½				1.7

Table 9.1. Mortar Properties.

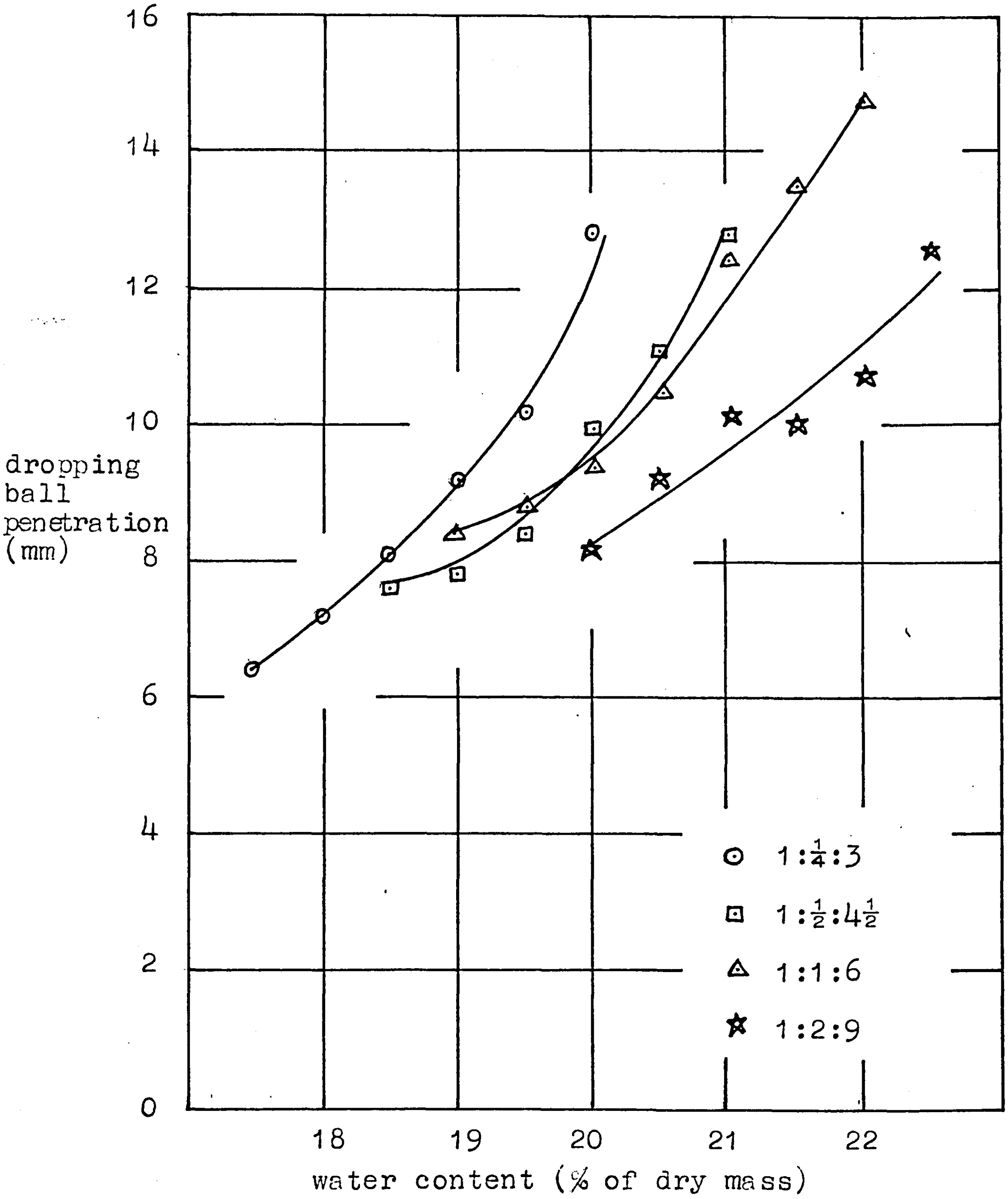


Figure 9.1. Variation of mortar consistency with water content.

1:2:9 mortar. The ratio of compressive to flexural strength can be seen to vary according to the mortar grade, from about 2 for 1:2:9 to almost 5 for 1:¼:3 mortar. A possible reason for this behaviour is that high-cement mortars tend to be more brittle in nature, which would be more critical in the flexural than the compressive mode.

The mean joint thickness for all the couplets in the mortar programme was 10.17mm. The mean values for each section of the programme were as follows,

Holbrook	Dry	10.44mm
Holbrook	Wet	10.39mm
Southwater	Dry	10.02mm
Southwater	Wet	9.82mm .

It can be seen that consolidation of the mortar in the joint during manufacture is greater for wetted bricks and greater for the smooth, heavier Southwater engineering bricks.

The bond strength results from this programme are given in table 9.2 and are plotted in figures 9.2-9.6. To plot the mortar grade in these figures, the volume of cement as a proportion of the total volume of cement plus lime was used, giving cement contents of 80%, 67%, 50% and 33% for the four grades. For this reason the spacings of the grades on figures 9.2-9.6 are not all equal. From the results the following conclusions may be drawn.

(i) Holbrook facing bricks give higher bond strength than Southwater engineering bricks.

(ii) For Holbrook facing bricks, 1:¼:3 mortar gives the highest bond strength.

(iii) For Southwater engineering bricks, 1:1:6 mortar

HOLBROOK FACING - DRY

WATER CONTENT (%)	MORTAR GRADE			
	(i)	(ii)	(iii)	(iv)
17½	0.33			
18	0.39			
18½	0.38	0.30		
19	0.37	0.33		
19½	0.38	0.29	0.27	
20	0.40	0.34	0.28	0.22
20½		0.36	0.27	0.21
21		0.34	0.22	0.23
21½			0.30	0.22
22			0.30	0.22
22½				0.23

HOLBROOK FACING - WET

WATER CONTENT (%)	MORTAR GRADE			
	(i)	(ii)	(iii)	(iv)
17½	0.35			
18	0.36			
18½	0.37	0.28		
19	0.32	0.29		
19½	0.35	0.27	0.23	
20	0.36	0.28	0.28	0.20
20½		0.28	0.20	0.19
21		0.24	0.23	0.21
21½			0.22	0.16
22			0.26	0.18
22½				0.20

SOUTHWATER ENGINEERING-DRY

WATER CONTENT (%)	MORTAR GRADE			
	(i)	(ii)	(iii)	(iv)
17½	0.11			
18	0.13			
18½	0.14	0.12		
19	0.13	0.16	0.18	
19½	0.15	0.16	0.21	
20	0.18	0.18	0.18	0.12
20½		0.21	0.15	0.15
21		0.17	0.25	0.16
21½			0.18	0.12
22				0.13
22½				0.15

SOUTHWATER ENGINEERING-WET

WATER CONTENT (%)	MORTAR GRADE			
	(i)	(ii)	(iii)	(iv)
17½	0.10			
18	0.11			
18½	0.09	0.13		
19	0.11	0.13	0.16	
19½	0.10	0.13	0.13	
20	0.13	0.12	0.14	0.14
20½		0.14	0.12	0.13
21		0.13	0.12	0.10
21½			0.16	0.10
22				0.11
22½				0.13

Table 9.2. Couplet Bond Strength at 28 Days from Mortar Programme. (N/mm^2)

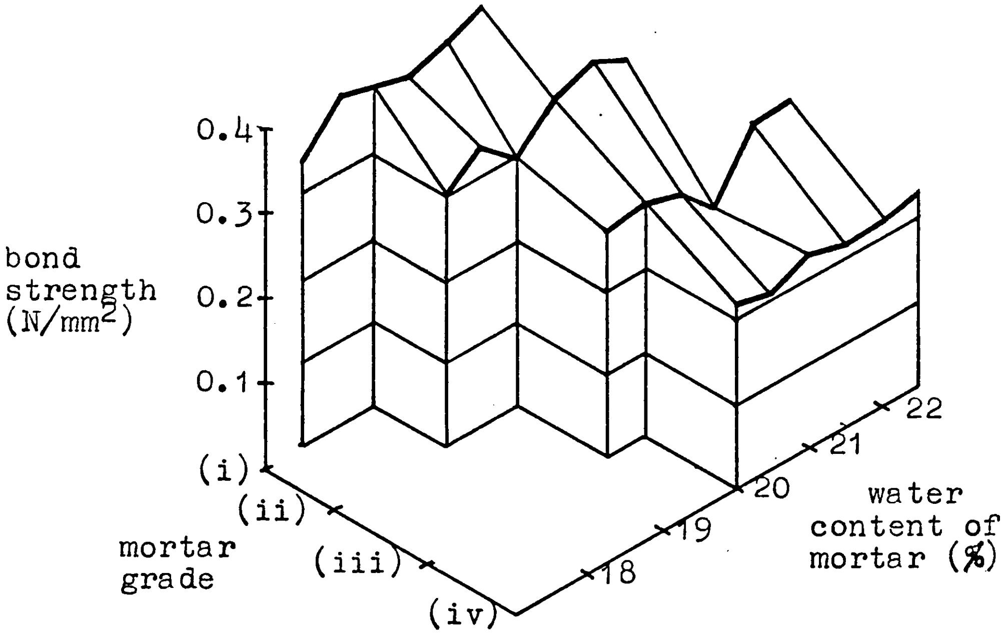


Figure 9.2. Bond strength using dry Holbrook facing bricks.

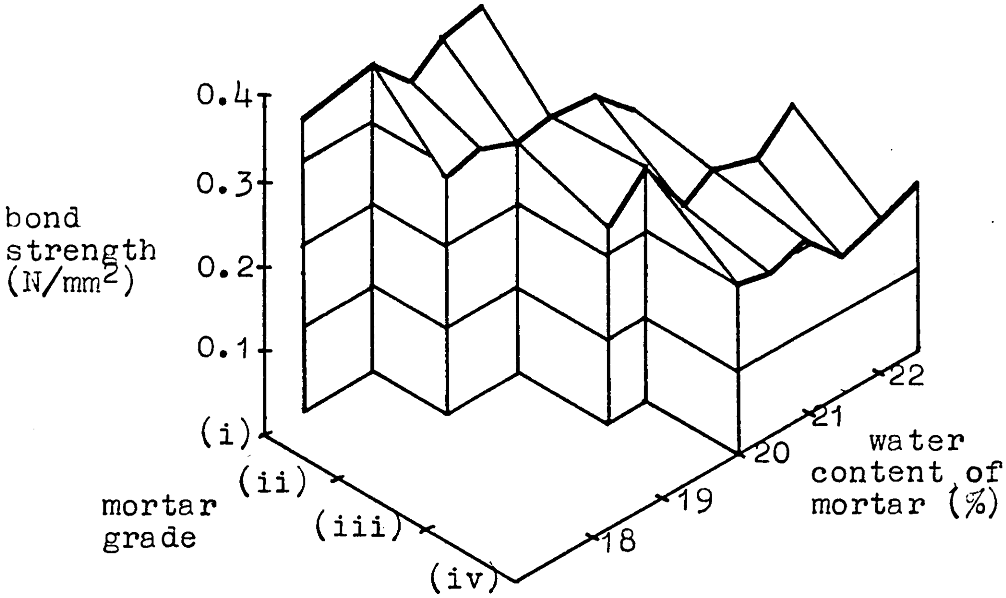


Figure 9.3. Bond strength using suction rate adjusted Holbrook facing bricks.

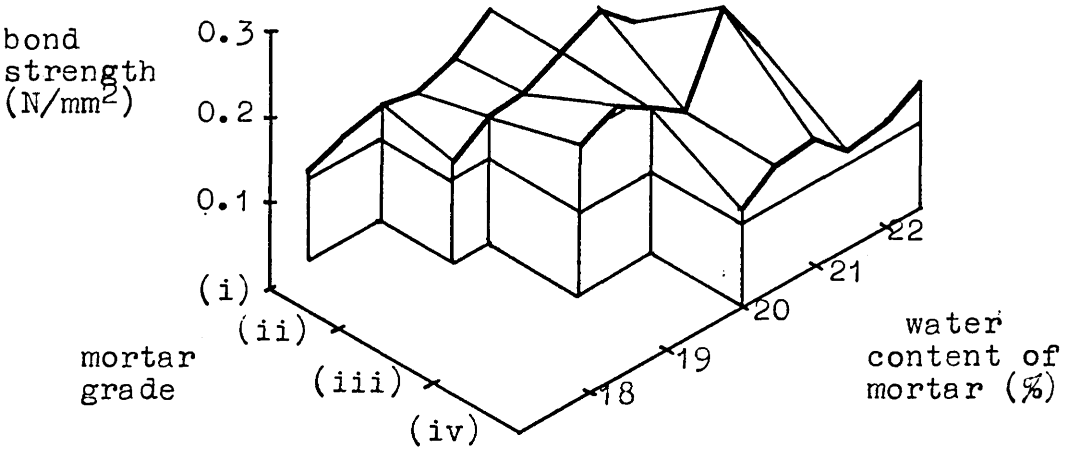


Figure 9.4. Bond strength using dry Southwater engineering bricks.

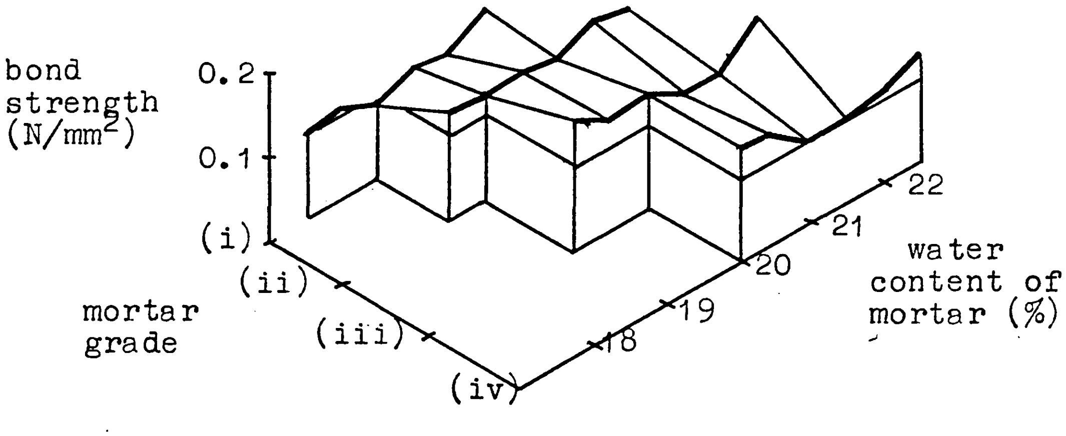


Figure 9.5. Bond strength using suction rate adjusted Southwater engineering bricks.

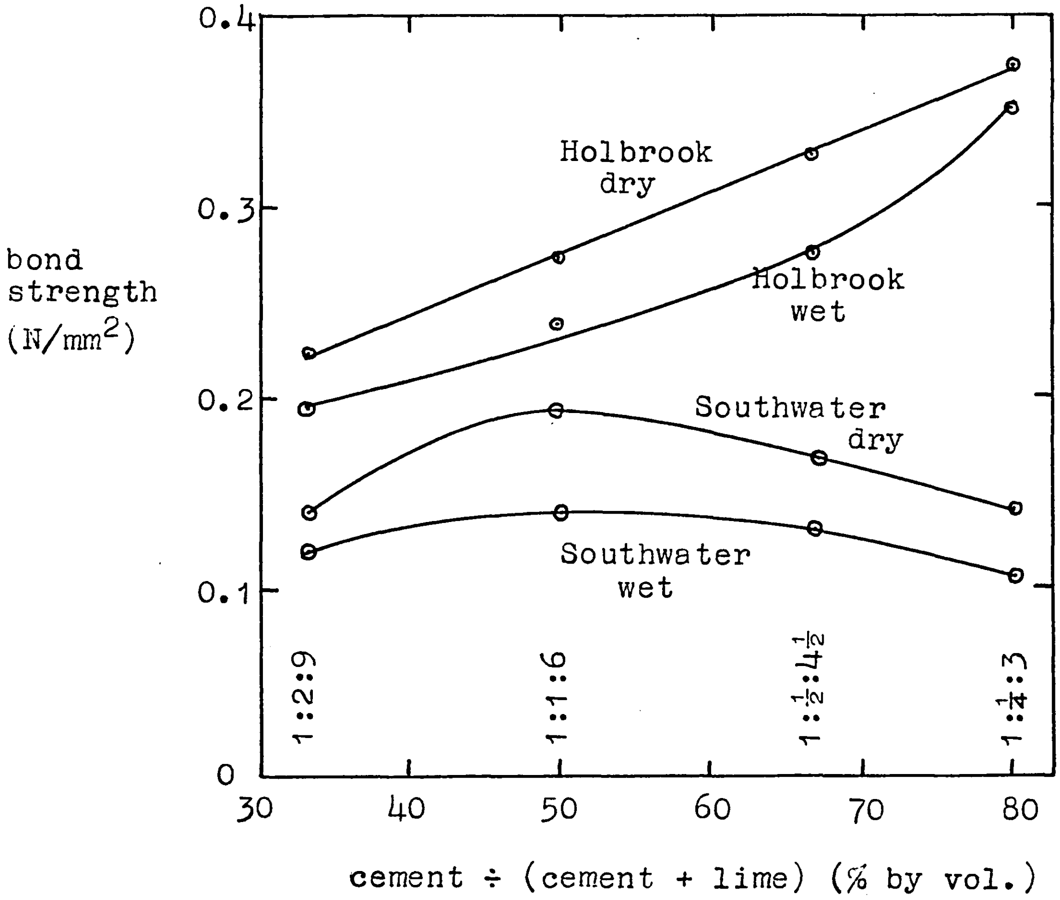


Figure 9.6. Couplet bond strength (30 specimens per point).

gives the highest bond strength.

(iv) For Holbrook facing bricks, bond strength increses with the cement content of the mortar.

(v) Generally, the water content of the particular mortar grade being investigated does not significantly affect the bond strength (see appendix 2).

(vi) Both brick types show a highly significant reduction in bond strength due to pre-wetting (fig.9.6).

The coefficients of variation have been calculated for each group of five couplets, from which the mean values for each of the four combinations of brick type and suction rate adjustment have been determined. These values, given below, show that Southwater bricks have a higher variation than Holbrook bricks and that pre-wetting increases the coefficient of variation. A possible explanation of this behaviour will be given in section 10.

Holbrook	Dry	9.7%
Holbrook	Wet	11.7%
Southwater	Dry	14.5%
Southwater	Wet	18.6%

In tables A1.1-A1.16 of appendix 1, the failure modes of each couplet are given. The designations T, M and B refer to failures which are top-plane, mortar and bottom-plane respectively. In this context a mortar failure is defined as a failure within the joint leaving mortar attached to both top and bottom bricks. Some couplets exhibit a failure mode which is a combination of more than one of the above.

An analysis of the data given in appendix 1 on the failure modes of the couplets reveals the following facts.

(i) Increasing the lime content of the mortar causes failure to occur more often in the body of the mortar.

(ii) Pre-wetting bricks increases the incidence of failures at the brick-mortar interface.

(iii) Holbrook bricks show a higher incidence of mortar failures than Southwater bricks.

(iv) Top-plane failures are more common than bottom-plane failures, except where dry Holbrook bricks are used.

Under a uniform load a mortar joint will fail at the point where the tensile strength is first exceeded by the tensile stress. Clearly different failure modes will occur because there is a distribution of tensile strength across the joint. The above conclusions suggest that in general, such a distribution will be influenced by the characteristics of the brick and mortar and that with each combination of factors there will be associated a "weakest point" at which (with random variations) failure will occur. This concept will be discussed fully in section 13.

9.2. Sand Grading Programme Results.

This programme was designed to examine the effect of changing the grading of a particular sand on the strength of the bond with Holbrook and Southwater bricks of a low suction rate.

The normal Auckley sand was close to the fine end of the BS1200:1976 grading requirements, so it was decided that most of the regraded sands should be obtained by removing fine material.

Sand N is the normal Auckley sand, as delivered. Sands 1C, 2C, 3C, 4C and 5C were prepared by mechanical shaking, for 5 minutes, of sand N on the 90μm, 150μm, 212μm, 300μm and 425μm sieves respectively, and discarding any material which passed through.

Sand F was prepared by using only that sand which passed through a 300μm sieve.

After the sands had been prepared, samples were taken from each and subjected to a rigorous sieve analysis in accordance with BS812:Part 1 (table 6). This table gives the maximum mass of sand which should be retained on each particular sieve, with the exception of the 90μm sieve. In order to be consistent with table 6 of BS812 the requirement for this size of sieve was taken as being 40g.

The results of the sieve analyses are given in table 9.3. It can be seen that for the five coarse sands, some of the fine material remained, despite being nominally removed by the sieving process. This meant that the resulting sands were well-graded and did not show an unrealistic cut-off at a particular grain size. It is unfortunate that the sieving process resulted in some misordering of the gradings, particularly with respect to the fine fractions of sand 4C compared with sands 1C, 2C and 3C.

Following the detailed sieve analyses, samples of each sized fraction were examined microscopically at magnifications up to 160x. It was noted that the grains of

SAND	F	N	1C	2C	3C	4C	5C
NOMINAL RANGE	<300μm	normal	>90μm	>150μm	>212μm	>300μm	>425μm
SIEVE	% PASSING (BY MASS)						
5.00mm	100.0	99.7	100.0	100.0	100.0	100.0	99.7
2.36mm	100.0	99.4	99.8	99.8	99.6	99.5	98.2
1.18mm	100.0	99.1	99.5	99.4	99.0	98.9	95.6
600μm	100.0	98.1	98.5	98.2	97.4	97.1	87.8
425μm	100.0	91.4	91.9	92.0	89.9	88.1	51.4
300μm	100.0	78.6	74.9	72.8	65.4	58.3	29.9
212μm	66.6	49.6	42.8	37.6	21.3	29.4	15.4
150μm	33.2	24.7	18.0	8.7	6.4	13.0	6.4
90μm	9.1	7.5	2.2	1.5	1.4	3.1	1.6

Table 9.3. Sand Grading Characteristics.

each fraction were of approximately the same size with no smaller particles adhering to them. This demonstrates the effectiveness of the sieve analysis procedure recommended in BS812. Figures 9.7 and 9.8 show samples of the 300-425μm and the 150-212μm fractions at magnifications of 17x and 38x respectively.

Table 9.4 shows the results of the sand grading programme. The bond strength results for the Holbrook facing brick couplets have been highlighted for clarity. No couplets were manufactured using Southwater engineering bricks and sand 5C mortar because the combined effect of the heavier brick and the high consistence mortar was such that mortar was squashed out from the joint on removal of the brass spacer rods (see section 7, figures 7.5 and 7.6).

The effect of sand grading has been studied by Bessey (42) who proposed a classification system based on the median grain size and a sorting coefficient. The median grain size D_{50}, is defined as the diameter of particle below which 50% of the mass of the sand occurs. The sorting coefficient is a measure of the breadth of grading and is equal to $\sqrt{(D_{75}/D_{25})}$, where D_{75} and D_{25} are the upper and lower quartiles defined in a similar way to D_{50} above. Hence any grading curve can be approximately described by two numbers which can be treated as cartesian coordinates. Bessey plotted these points on a diagram which he divided into three regions showing the suitability of the sand for mortar, according to which the sands in the present programme may be classified.

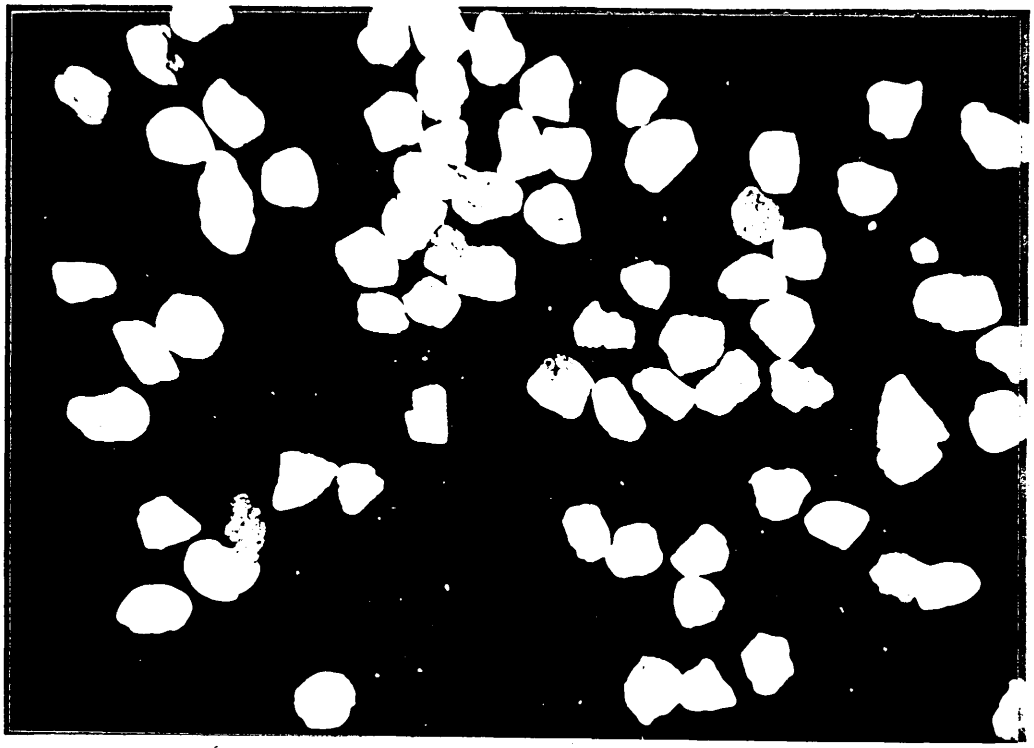


Figure 9.7. 300 - 425μm 17x

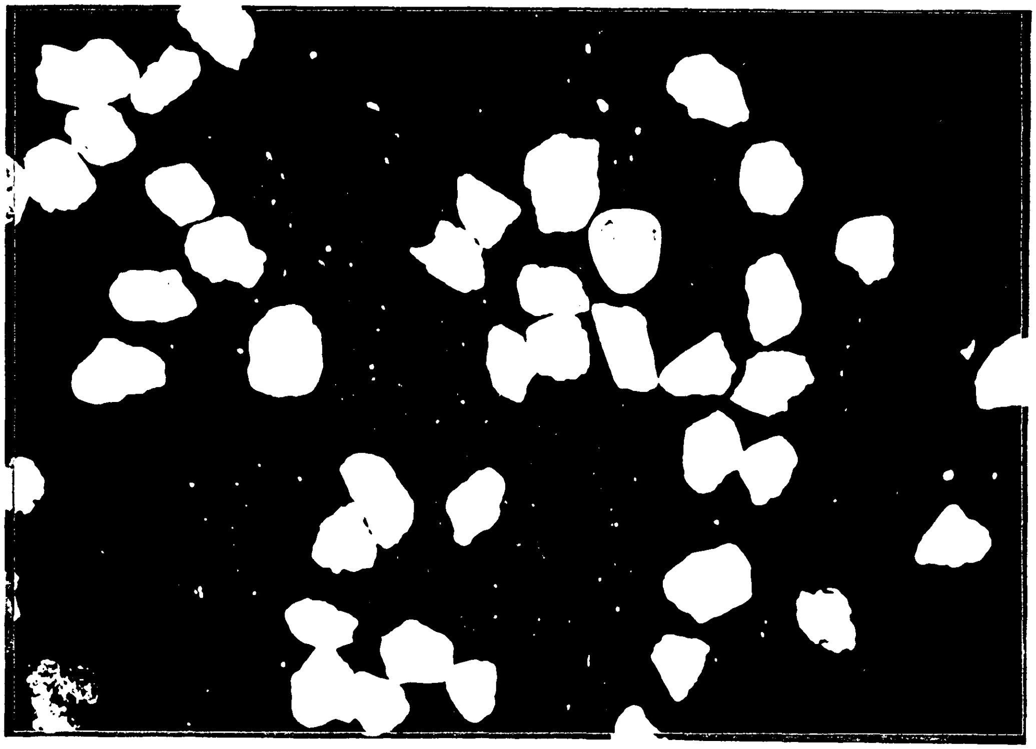


Figure 9.8. 150 - 212μm 38x

SAND CLASSIFICATION	TYPE OF BRICK	MIX PROPORTIONS	WATER CONTENT (%WT.)	D. BALL PENETR. (mm)	MORTAR CURING CONDITION	MORTAR STRENGTH		LAYING CONDITION	JOINT THICKNESS (mm)	BOND STRENGTH (N/mm^2)	LOCATION OF FAILURE PLANE		
						COMP. (N/mm^2)	FLEX. (N/mm^2)				TOP (%)	MORTAR (%)	BOTTOM (%)
F passing 300μm sieve	FACING	1:$\frac{1}{2}$:4$\frac{1}{2}$	19$\frac{1}{2}$	6.0	AIR	13.6	3.7	DRY	10.2	0.29	60	0	40
					WATER	10.5	3.5	WET	10.2	0.29	100	0	0
	ENG'RG	1:1:6	21	7.7	AIR	8.2	3.1	DRY	10.2	0.22	70	2	29
					WATER	6.6	2.4	WET	9.7	0.12	100	0	0
N normal as delivered	FACING	1:$\frac{1}{2}$:4$\frac{1}{2}$	19$\frac{1}{2}$	8.7	AIR	14.8	4.4	DRY	10.2	0.34	60	1	39
					WATER	11.8	3.5	WET	10.2	0.30	66	0	34
	ENG'RG	1:1:6	21	11.4	AIR	8.0	2.9	DRY	9.9	0.19	70	4	26
					WATER	6.5	2.4	WET	9.7	0.19	69	2	29
1C held on 90μm sieve	FACING	1:$\frac{1}{2}$:4$\frac{1}{2}$	19$\frac{1}{2}$	8.3	AIR	13.5	3.5	DRY	10.3	0.33	61	2	44
					WATER	11.4	3.4	WET	10.3	0.26	80	0	23
	ENG'RG	1:1:6	21	10.4	AIR	7.6	2.4	DRY	10.0	0.24	80	6	14
					WATER	6.4	2.3	WET	10.0	0.17	90	2	10
2C held on 150μm sieve	FACING	1:$\frac{1}{2}$:4$\frac{1}{2}$	19$\frac{1}{2}$	8.8	AIR	12.9	3.3	DRY	10.5	0.36	42	8	50
					WATER	11.3	3.4	WET	10.3	0.27	100	0	0
	ENG'RG	1:1:6	21	10.8	AIR	7.7	2.6	DRY	9.8	0.24	30	16	55
					WATER	6.3	2.1	WET	9.8	0.20	99	1	4
3C held on 212μm sieve	FACING	1:$\frac{1}{2}$:4$\frac{1}{2}$	19$\frac{1}{2}$	10.1	AIR	14.5	3.6	DRY	10.4	0.35	80	0	24
					WATER	12.1	3.5	WET	10.5	0.30	81	1	18
	ENG'RG	1:1:6	21	12.4	AIR	8.2	2.4	DRY	9.5	0.22	84	11	10
					WATER	7.0	2.4	WET	9.4	0.17	80	2	18
4C held on 300μm sieve	FACING	1:$\frac{1}{2}$:4$\frac{1}{2}$	19$\frac{1}{2}$	11.4	AIR	16.1	4.9	DRY	10.4	0.38	86	0	21
					WATER	11.8	4.0	WET	10.4	0.30	88	0	15
	ENG'RG	1:1:6	21	14.6	AIR	10.1	3.4	DRY	9.2	0.19	96	4	0
					WATER	6.3	2.5	WET	9.1	0.14	100	0	8
5C held on 425μm sieve	FACING	1:$\frac{1}{2}$:4$\frac{1}{2}$	19$\frac{1}{2}$	18.4	AIR	15.9	3.5	DRY	10.2	0.39	66	6	34
					WATER	15.5	4.0	WET	10.4	0.33	92	0	12
	ENG'RG	1:1:6	21	17.4	AIR	9.9	2.6	DRY	<7.0	-	-	-	-
					-	-	-	-	-	-	-	-	-

Table 9.4. Sand Grading Programme Results.

Sand	Median Size (mm)	Sorting Coefficient	Classification
F	0.179	1.354	unsuitable
N	0.213	1.379	"
1C	0.229	1.351	"
2C	0.240	1.309	"
3C	0.266	1.256	"
4C	0.272	1.375	moderate
5C	0.415	1.410	"

Table 9.5. Sand Classification according to Bessey (42).

From table 9.5 it can be seen that none of the sands are classified as "good" and the majority as "unsuitable", however all sands gave adequate bond strength (with the exception of 5C as described above). It seems that Bessey's considerations of the grading characteristics alone are insufficient and that other factors, such as silt content and particle shape, might be of greater importance.

Whilst the bond strength appears to be generally independent of the sand grading, mortar consistence clearly is not. The results in table 9.4 show that there is a definite increase in consistence as the grading becomes more coarse.

Ozol (43) has reviewed the work of others in this field, particularly Malhotra (44) and concluded that water demand is related to the number of points of contact between aggregate particles, which will be greater if the grains are more angular, or if the grading is finer. This behaviour is confirmed by the results of the present programme, and is in agreement with the findings of Bloem (24) already mentioned in section 2.3.

The coeffiecients of variation follow the same pattern as the previous programme and are as follows, with the values based on groups of 10 couplets.

Holbrook	Dry	8.9%
Holbrook	Wet	12.4%
Southwater	Dry	15.4%
Southwater	Wet	17.4%

From the experimental results the following conclusions may be drawn.

(i) Mortar consistence depends strongly upon the grading of the sand.

(ii) Bond strength is largely independent of sand grading.

(iii) For all of the sands, pre-wetting the bricks significantly reduced the bond strength.

Data on the failure modes of individual couplets are given in tables A1.17-A1.25 of appendix 1 and mean failure modes for groups of ten couplets summarised in table 9.4. For this programme the area of the failed surface has been estimated as a percentage of the total bonded area at each of the locations T, M and B as described in the previous section. For some of the couplets failure occured on both top and bottom plane, with a section of the mortar becoming detached. In these cases the sum of the failed areas will be greater than 100%. The following conclusions may be drawn.

(i) Top-plane failures occur about three times as often as bottom-plane failures.

(ii) Southwater bricks give more top-plane failures than Holbrook bricks.

(iii) Pre-wetted bricks give more top-plane failures than dry bricks.

(iv) Pre-wetting bricks reduces the interfacial bond strength relative to the tensile strength of the mortar in the joint, as indicated by the reduction in the number of mortar failures.

In general, it can be concluded from this programme that the effect of changing the grading of the particular sand is small compared to the effects of other factors.

9.3. Suction Rate Programme Results.

The purposes of this programme were to investigate the effect of brick suction rate on the bond strength and to highlight the difficulties associated with the use of high suction rate bricks. It was anticipated that the high suction rate bricks would cause some stiffening of the mortar during laying but the severity of this effect had not been expected.

For the test couplets a Funton stock brick was chosen, which had a wide range of suction rates. The one-minute suction rate was determined for each of 383 bricks in order to group the bricks into suction rate bands. Figure 9.9 shows the distribution of suction rates and the choice of bands. Couplets were manufactured using pairs of bricks selected from the same suction rate band. Bricks were laid bed-plane to bed-plane in order to eliminate the effect of the frog and because the suction rate data were obtained for the bed-planes. Ten couplets were tested from each suction rate band, having been stored in the curing cabinets described in section 7 for

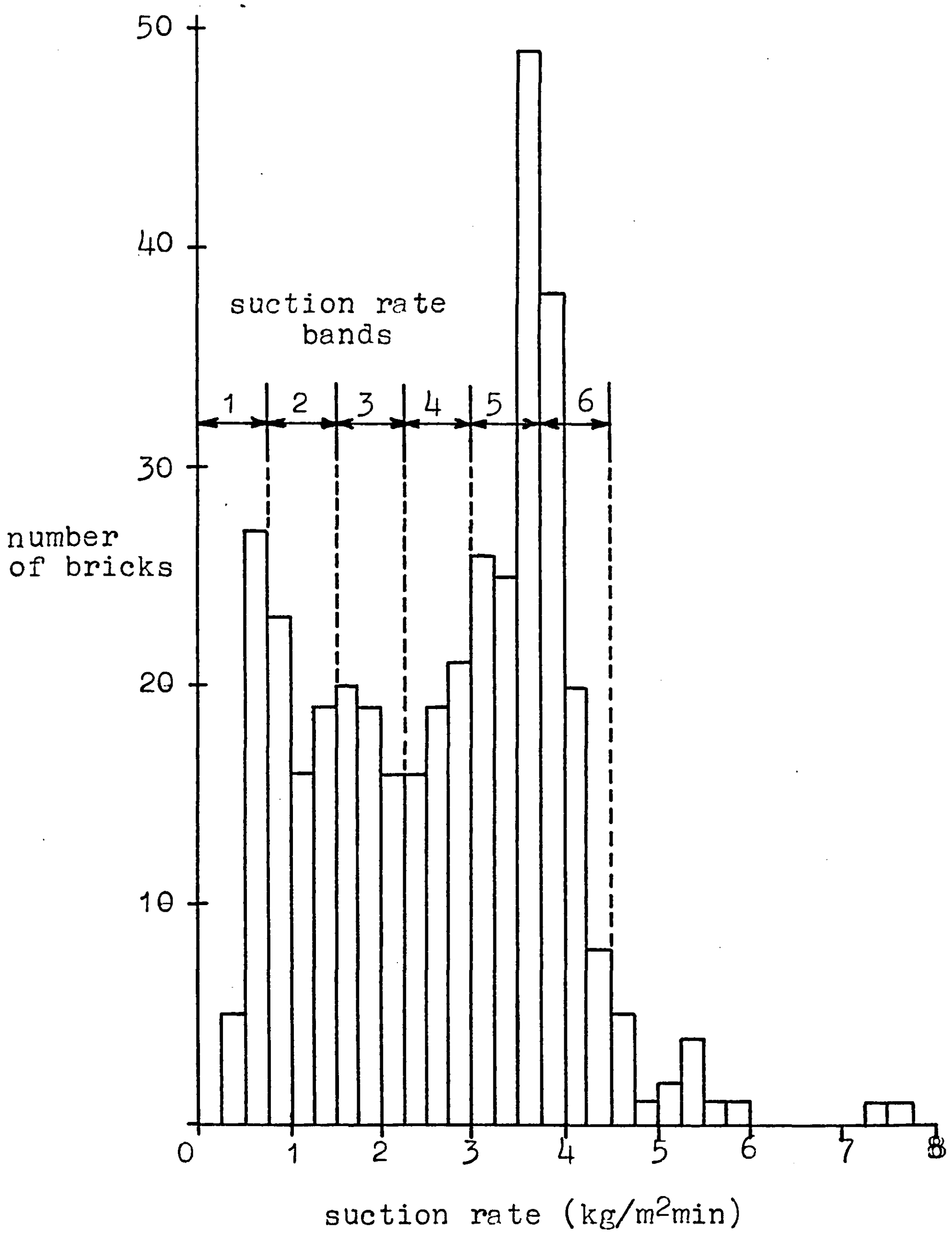


Figure 9.9. Histogram showing distribution of suction rate for Funton Stock bricks, and bands used for suction rate programme.

28 days.

A 1:1:6 mix was used with a water content which was greater for the high suction rate bricks. In the original planning of the experiment it was decided that the water content should remain constant throughout. However, it was found that the higher suction rate bricks caused the mortar to stiffen so rapidly that extra water had to be added to compensate.

It was apparent during the laying of the high suction rate bricks that the addition of extra water to the mortar would not completely compensate for the high brick suction. In order to facilitate laying and to give good contact, some pre-wetting of the bricks would have been necessary. Due to the shortage of time and materials (many of the bricks were of poor shape), this modification to the programme could not be implemented.

As a consequence, many of the couplets were found, after failure, to have incomplete contact between brick and mortar; the contact area generally decreased with increasing suction rate.

Table 9.6 summarises the results of the suction rate programme, which are given in full in tables A1.26 and A1.27 of appendix 1. It can be seen that the data on the location of the failure plane includes tensile failure of the bricks themselves. This manifested itself as small pieces of brick remaining attached to the mortar at failure and suggests that the bricks which were of high suction rate had a lower tensile strength.

The symbols describing the failure mode are as

SUCTION RATE BAND	SUCTION RATE RANGE (kg/m^{2}min)	AVERAGE SUC.RATE (kg/m^{2}min)	WATER CONTENT (%)	DROP.BALL PENETRATION (mm)	MORTAR STRENGTH COMPRESSIVE (N/mm^2)	MORTAR STRENGTH FLEXURAL (N/mm^2)
1	0.00-0.75	0.62	20	9.2	8.2	2.9
2	0.76-1.50	1.09	20	9.6	8.6	2.9
3	1.51-2.25	1.84	$20\frac{1}{2}$	10.9	7.2	3.0
4	2.26-3.00	2.64	21	11.2	6.9	2.6
5	3.01-3.75	3.49	$21\frac{1}{2}$	12.8	7.0	2.6
6	3.76-4.50	4.03	22	13.8	6.3	2.5

SUCTION RATE BAND	CONTACT AREA (%)	BOND STRENGTH (N/mm^2)	LOCATION OF FAILURE PLANE BRICK (%)	TOP (%)	MORTAR (%)	BOTTOM (%)	BRICK (%)
1	94	0.24	0	49	17	44	0
2	87	0.30	0	54	36	11	0
3	88	0.28	0	11	17	73	0
4	69	0.32	0	43	46	10	0
5	72	0.28	24	22	41	10	6
6	49	0.30	71	24	5	0	0

Table 9.6. Suction Rate Programme Results based on Funton Stock Bricks and 1:1:6 Mortar.

defined in section 9.2, with the addition of tensile failures in either the top brick, or the bottom brick, according to the position in the table. In appendix 1, tables A1.26 and A1.27 these are designated by Br.

As a result of the difficulties in laying the higher suction rate bricks, the bond strength coefficients of variation are correspondingly higher. The values for the six bands are as follows:

Suction Rate Band	1	10.0%
" " "	2	17.2%
" " "	3	21.5%
" " "	4	21.4%
" " "	5	29.7%
" " "	6	36.0%

These values reflect the degree of incomplete contact shown by the higher suction rate brick couplets.

9.4. Curing Programme Results.

The four special curing conditions described in section 6.4 were chosen to give a wide variation of environments, which are analogous to site conditions that may occur in practice. The cabinet cured couplets were included as controls to reference back to the mortar programme.

Table 9.7 gives a summary of the results, which are shown in full in tables A1.28-A1.31 of appendix 1. The cabinet-cured couplets give bond strengths of 0.39N/mm^2 and 0.16N/mm^2 for the Holbrook and Southwater bricks respectively. These values may be compared with the corresponding strength values of 0.37N/mm^2 and 0.18N/mm^2 from the mortar programme.

Conditions in which the couplets were water

BRICK TYPE	CURING CONDITION	MIX	WATER CONTENT (%)	DROP. BALL PENETRATION (mm)	CUBE STRENGTH (N/mm2)	PRISM STRENGTH (N/mm2)	BOND STRENGTH (N/mm2)	LEVEL OF SIGNIFICANCE (%)	LOCATION OF FAILURE PLANE(%) TOP	MORTAR	BOTTOM
HOLBROOK FACING	CABINET	$1:\frac{1}{4}:3$	19	9.7	23.8	5.4	0.39		75	0	25
	WET/DRY			9.6	25.8	5.1	0.43	98	10	1	89
	FREEZE/THAW			9.2	16.4	3.4	0.34	98	30	1	69
	MIST ROOM			9.4	24.8	6.1	0.42	90	30	3	67
	CONSTANT TEMP/HUMID.			10.0	19.6	4.5	0.33	99	10	0	90
SOUTHWATER ENGINEERING	CABINET	1:1:6	20	9.6	8.5	3.0	0.16		100	0	0
	WET/DRY			9.8	8.0	2.4	0.20	95	70	1	29
	FREEZE/THAW			9.3	5.4	2.0	0.16	NOT SIGNIF.	98	3	0
	MIST ROOM			10.0	7.1	2.4	0.18	NOT SIGNIF.	58	11	30
	CONSTANT TEMP/HUMID.			9.6	6.5	2.2	0.09	99.9	100	0	0

Table 9.7. Curing Programme Results. Significance Levels are with Respect to Cabinet Cured Couplets.

saturated for some or all of the curing period give the highest bond strength after 28 days, although the higher strength obtained by mist-room curing of Southwater brick couplets is not significant. Significant levels for all the special curing conditions are given in table 9.7, from which it can be seen that the reduction in bond strength due to constant temperature/humidity curing is highly significant for both types of brick. As a check, the significance of the differences between the cabinet-cured couplets in the mortar and curing programmes was assessed. It was calculated that the differences were not at all significant.

For the particular combinations of brick and mortar used in this programme it may be concluded that:

(i) Wet curing conditions give higher bond strengths.

(ii) Dry curing conditions give lower bond strengths.

(iii) Freeze/thaw curing may lower the bond strength, although the bond is not destroyed.

Again the coefficients of variation are greater for the Southwater brick couplets than for the Holbrook brick couplets. The values are:

Holbrook	8.8%
Southwater	16.8%

From data on the location of the failure plane the following conclusions may be drawn:

(i) For Holbrook bricks, bottom-plane failures are more likely than top-plane failures.

(ii) For Southwater bricks, top-plane failures are much more likely than bottom-plane failures.

(iii) For Southwater bricks, the only bottom-plane failure occured as a result of wet curing conditions.

These conclusions follow the general pattern of the other programmes with respect to the difference in failure mode between the two brick types. A possible explanation is that the lower suction rate and smoother surface of the Southwater brick caused the mortar very close to the interface to have a high moisture content and consequent low strength. Again, this concept will be discussed fully in section 13.

10. DISCUSSION OF THE EXPERIMENTAL RESULTS IN RELATION TO EXISTING KNOWLEDGE.

In section 2 the important factors affecting bond strength were surveyed and a summary of the findings is given in section 2.13. Of the 21 points listed in that section, more than half are of direct relevence to the present experimental investigation and are discussed below. In the following statements the enumeration refers to items listed in section 2.13.

> (i) "Maximum bond strength is obtained when the suction rate of the brick is in the range 0.5-1.2kg/m^2 min."

Results from the suction rate programme given in table 9.6 are inconclusive due to the incomplete contact achieved, and because the couplets were manufactured using mortars of different water contents. It is clear, however, that using mortars of the same water content, high suction rate bricks would give a joint of lesser quality than moderate suction rate bricks.

> (iii) "The suction rate of the lower brick has a more significant effect than the suction rate of the upper brick."

Observations during the manufacture of couplets using the higher suction rate Funton bricks show that although mortar can be spread onto the lower brick, rapid dewatering of the mortar makes the laying of the top brick very difficult, regardless of its suction rate.

> (iv) "The brick type is important, but there is a lack of agreement as to which is best."

The results from the three programmes in which both facing and engineering bricks are used consistently show that the engineering bricks give a lower bond strength, despite both brick types having low suction rates. Differences between the two brick types are shape, weight, roughness and chemical composition, but it is not clear which has the greatest influence on bond strength.

> (v) "Generally smooth bricks give higher bond strength than rough bricks."

The trend of the experimental results is entirely contrary to this statement, the engineering bricks being more smooth than the facing, although because of the other differences stated above, it is not certain that smoothness is the cause of the lower bond strength.

> (ix) "Bond strength does not necessarily increase with cement content; high-lime mortars are often superior for use with stiff-mud shale bricks."

The engineering bricks are of this type and do show a higher bond strength with 1:1:6 mortar (figure 9.6). In contrast extruded facing bricks show a general increase in bond strength with cement content. The enhanced mechanical keying of the mortar to the rougher wire-cut facing brick would seem to offer the best explanation for this behaviour.

> (x) "High-lime mortars show improved workability and retentivity and less shrinkage."

Figure 9.1 shows that for mortars of identical water content, higher cement content gives higher consistence as measured by the dropping ball test. This, however, is not a measure of workability, which may be better judged by experience. Generally it was felt that high-lime mortars were less harsh and spread more easily onto the brick. It will be shown in section 11 that water retentivity is greatest for high-lime mortars.

> (xi) "Mortar consistence should be as high as practicable, particularly when high suction rate bricks are used."

The comments in section 9.3 on the laying of high suction rate bricks illustrate the above point. For bricks of this type, excess water is essential either in the mortar during mixing, or in the brick by pre-wetting, in order to counteract the stiffening of the mortar caused by high brick suction.

> (xii) "Higher consistence increases the ratio of bond strength to mortar tensile strength and induces failure to occur in the body of the mortar, rather than at the interface."

The mortar programme results given in tables 9.1 and 9.2 show that mortar consistence does not have any significant effect on either the mortar flexural strength or the couplet bond strength. Failure within the mortar tends to be related to consistence for Holbrook facing brick couplets with mortar grades (iii) and (iv), but not for Southwater engineering brick couplets. Table A1.9 shows the behaviour of Holbrook brick couplets more clearly.

> (xvi) "Pre-wetting low or medium suction rate bricks could reduce bond strength."

The overwhelming evidence from the mortar programme and the sand grading programme is in support of this statement. Bond strengths of facing and engineering bricks of low suction rate are reduced by up to 30%.

> (xviii) "Damp curing conditions improve bond strength."

It can be seen from table 9.7 that couplets subjected to wet curing conditions show significantly higher bond strength than those cured in relatively dry conditions.

> (xix) "Freezing can be detrimental to bond."

In the case of both facing and engineering brick couplets, freeze/thaw conditions gave lower bond strength than the standard cabinet curing conditions. In no cases, however, were the joints fractured due to freezing.

> (xx) "Delay between placing mortar and top brick will reduce bond strength, particularly for high suction rate bricks."

It was visibly apparent during the manufacture of couplets for the suction rate programme, that the upper surface of the mortar became progressively dewatered before the top brick could be placed. This effect was most pronounced when the highest suction rate bricks were used.

11. THE MOISTURE CHARACTERISTICS OF MORTAR.

As a general hypothesis of the bond strength of brickwork it may be stated that there will exist within the mortar a distribution of tensile strength, such that failure will be initiated from the point where the tensile stress first exceeds the tensile strength. From the literature reviewed in section 2 and the experimental results in section 9 it is clear that the movement of water from the mortar to the brick is an important factor contributing to the determination of the tensile strength (45).

This hypothesis will be discussed fully in section 13, but as a pilot study of the possibility of applying unsaturated flow theory to the problem of water movement, the work of this section was carried out.

In essence the theory regards a porous material as being homogeneous, and having behaviour characterised by three properties, which are functions of the moisture content, θ. These properties are the hydraulic conductivity, K; the diffusivity, D; and the capillary potential, Ψ (13). Each functional relationship can be determined experimentally and the three are related by the simple expression

$$D = K(d\Psi/d\theta).$$

Unsaturated flow theory seems to have certain advantages for the purpose of classifying building materials and predicting their behaviour. According to Hall (46), ".... the microstructures of technical building materials are complicated and cannot yet be adequately described mathematically. At present, flow processes in building materials are more amenable to macroscopic analysis." In addition, the theory relies on concepts which have a sound theoretical basis and, as such, is amenable to analytical and numerical development (eg. the infiltration solution of Brutsaert (47), which gives moisture content as a function of time and location within an initially dry porous medium).

In view of the possible future use of unsaturated flow theory for the prediction of moisture movement from mortar to brick a short series of experiments was carried out. This was designed to determine the relationship between **capillary potential** (soil suction) and moisture content for the four grades of mortar used in the mortar programme (section 6.1). Such a relationship is known as a moisture characteristic of the material.

The experimental set-up is based on the modified suction plate method of Croney, Coleman and Bridge (48). The apparatus, shown in figure 11.1, consists of a 50mm diameter sintered glass filter which sits inside a perspex tube. The filter porosity grade is the finest available (grade 4, mean pore size about 10μm) in order to minimize the possibility of air infiltration under suction. A 2m long, 2.5mm diameter capillary tube indicates movement of water from the sample. At the other end a movable-limb manometer controls the suction, which is increased in increments. Initially equilibrium is established by adjusting the manometer, with the water -saturated glass filter sealed onto its seating using

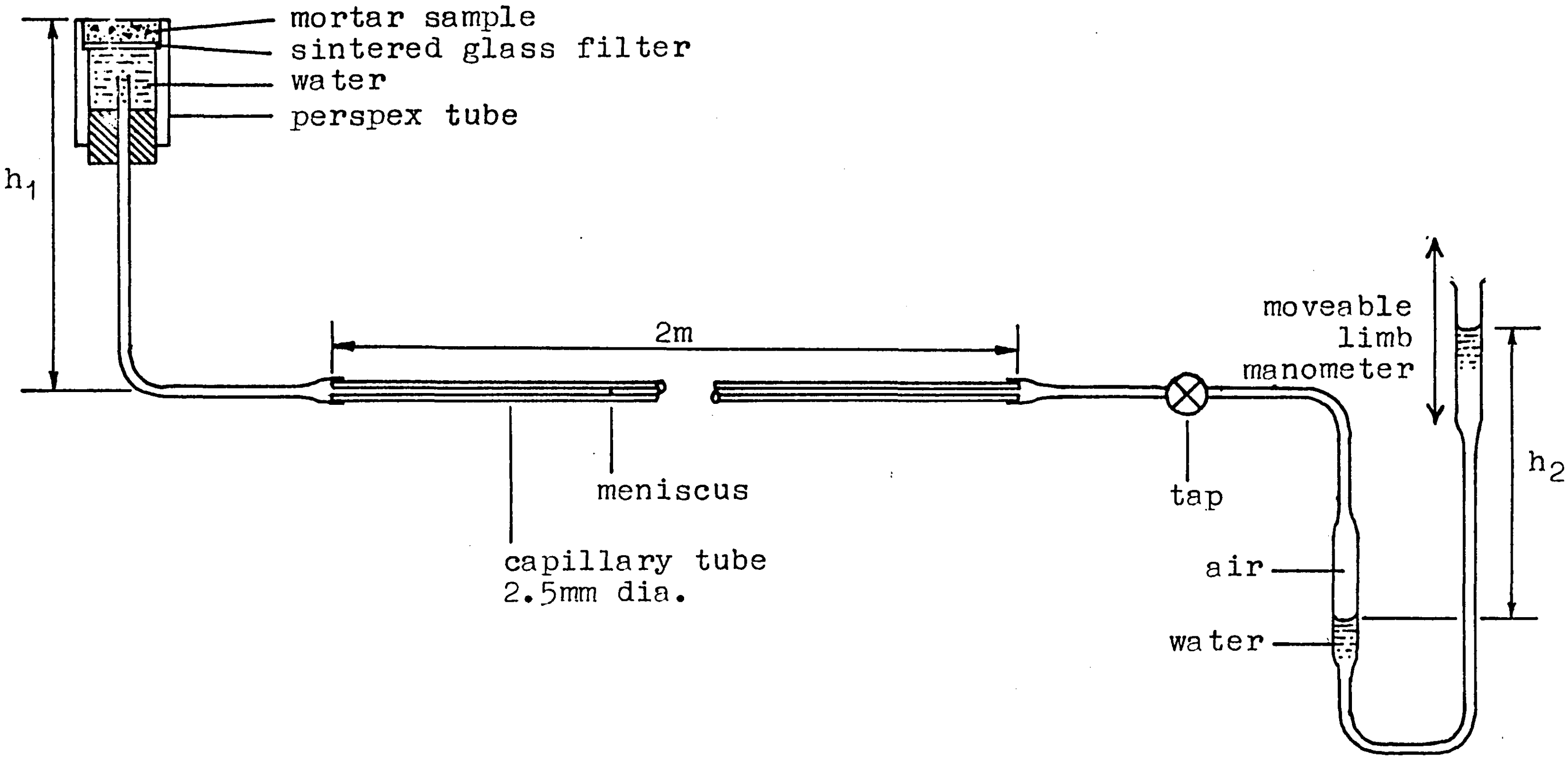


Figure 11.1. Modified suction-plate apparatus for determination of moisture characteristic.

vacuum grease. The mortar sample, of known water content, is packed onto the filter with the tap closed to avoid movement of the meniscus. The manometer limb is adjusted to allow for the additional pressure head due to the raising of the water surface from filter level to mortar level. Compensation must also be made for the capillary head at the meniscus, which for the 2.5mm tube amounts to about 12mm. At this point, h_1 and the capillary head combined should be exactly balanced by h_2, so that when the tap is opened the meniscus should remain stationary. The manometer limb is then successively lowered and readings are taken of the meniscus movement when equilibrium has been reached. In the early stages this may take several minutes to occur, but as the moisture content is reduced, equilibrium is reached more quickly. The test was stopped when the limit of travel of the manometer limb was reached or when the air began to leak past the sintered glass disc.

From the movement of the meniscus along the capillary, the moisture content of the mortar sample could be calculated, with the assumption that the moisture content was uniform throughout the thickness of the sample. The initial moisture contents of the four mortar mixes were determined according to appendix 3 and gave the following results:

Mortar grade	Initial Moisture Content (cm^3/cm^3)
1:¼:3	0.333
1:½:4½	0.331
1:1:6	0.329
1:2:9	0.329

The results of the suction tests are shown in figure

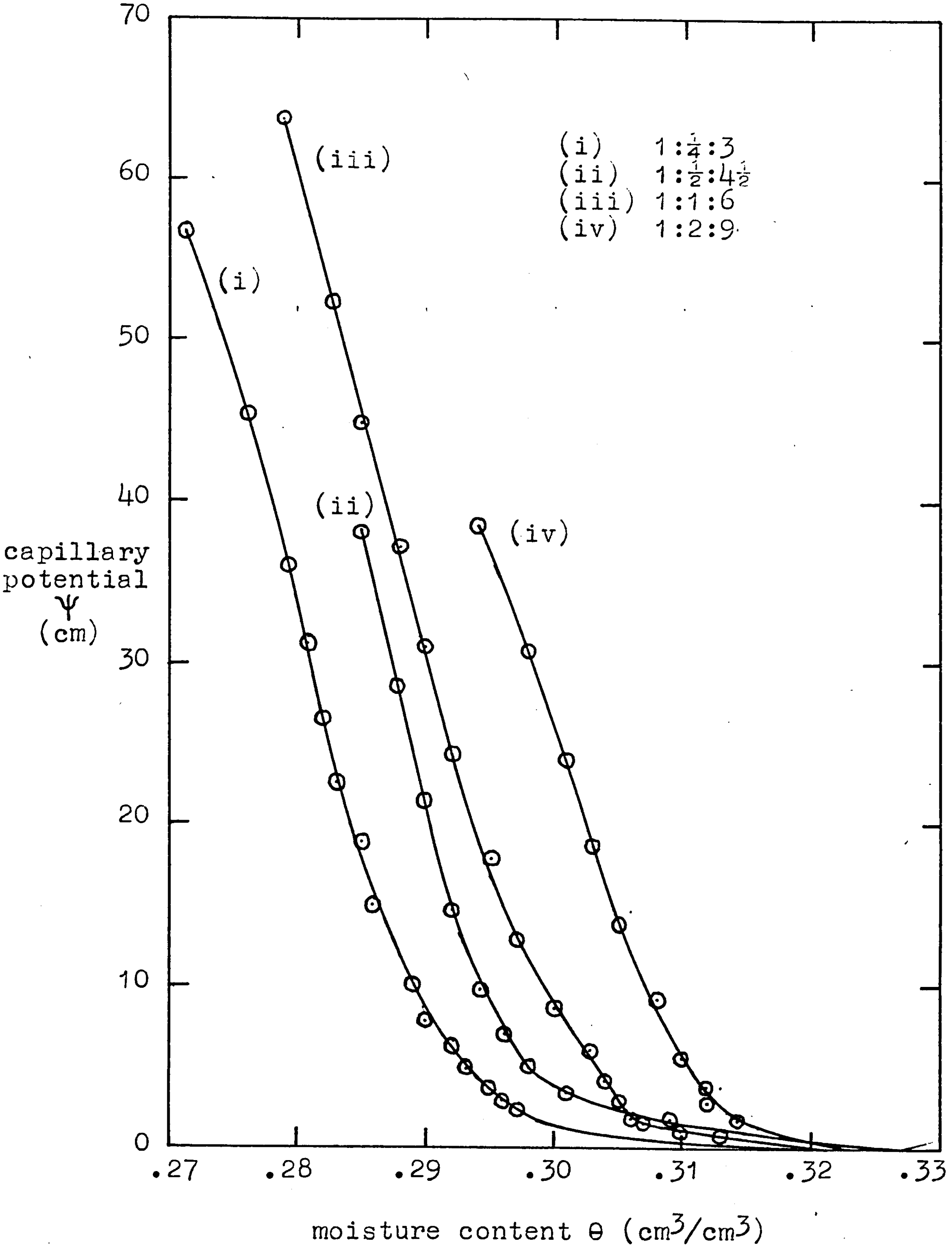


Figure 11.2. Moisture characteristics for mortars used in experimental programme.

11.2. Capillary potential has been calculated as the net suction (h_1-h_2+approx.1.2cm) acting on the mortar and has been plotted against moisture content. It can be seen that above a suction of about 10cm each mortar grade shows a linear relationship of approximately the same slope and that the curves are ordered in the expected manner, implying that moisture is retained better by mortars containing more lime.

An interesting feature of the characteristics is the way that the moisture content is rapidly reduced from saturation under very low suctions in the early stages of the tests. This could be taken to imply that if mortar is subjected to very low suction forces (as, for example, from a dense engineering brick) the resulting moisture content of the mortar will be uncertain and the physical properties of the hardened mortar joint subject to correspondingly large variations. Perhaps this mechanism explains the higher coefficients of variation noted throughout section 9 for Southwater engineering brick couplets.

Following the successful tests on mortars, it was decided that bricks should be treated in the same way. However, practical difficulties meant that this could not be done. There were two main problems. Firstly, the sintered glass discs were not flat and good contact could not be achieved with the brick discs. Secondly, the porosity and suction forces of the bricks were such that the equipment was not sufficiently sensitive to give adequate results.

According to Philip (13), the processes of suction and absorption may be described by the following equation:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left(D\frac{\partial\theta}{\partial z}\right) - \frac{dk}{d\theta}\cdot\frac{\partial\theta}{\partial z}$$

where t=time, z=distance and the other symbols have been defined previously. The last term may be dropped if the effects of gravity are negligible, as suggested by Gummerson, Hall and Hoff (45). In view of the short periods of time involved and the small scale of the medium, this seems to be a reasonable assumption.

Solutions to this equation may be obtained for particular cases using the finite difference method, but analytical solutions of a general nature will require simplifying substitutions, such as Boltzmann's transformation to be made (13).

The theory has the potential to predict the movement of water from mortar to brick, but there are several difficulties:

(i) experimental data are required on the hydraulic properties of both mortar and brick,

(ii) Darcy's law may not hold due to the presence of solutes and mobile particles (46),

(iii) the hydration reactions cause continuous changes to occur in the properties of the liquid phase,

(iv) small changes (6-7%) in the bulk density of the mortar may cause large changes (up to 300%) in the hydraulic conductivity (49).

As an experimental verification of the theory, there are techniques which can be used for measuring the moisture content of the materials. Of these the most promising appears to be gamma ray absorption (50,51,52).

12. CHEMICAL ANALYSIS OF MORTAR BY X-RAY DIFFRACTION.

12.1. Introduction.

The purpose of this aspect of the work was to examine the possibility of using x-ray diffraction to determine the crystal structure of mortar from a brickwork joint, and to relate that structure to the various mechanisms involved. The structure of OPC hydrated under various water/cement ratios is examined and compared with mortar samples taken from brickwork joints.

X-ray diffraction is a method of chemical analysis whereby particular crystal structures, rather than the constituent elements, can be identified. Any compound which has a regular crystal structure will diffract x-rays in a way which depends on the arrangement of atoms within its crystal lattice. Substances which are amorphous in nature will not normally be detectable by this method. Any particular crystalline substance will show a diffraction pattern which is unique and can be identified by a matching-up process, using standard patterns.

Figure 12.1 shows a typical x-ray diffraction output with most of the peaks identified as either quartz (sand in the mortar) or the hydration products, which in this case are portlandite and calcite. Peak intensities are measured in counts per second (cps) or may be represented as a percentage of the highest peak.

Lattice spacings may be calculated using Bragg's Law, $2d \sin \theta = n\lambda$, where λ depends on the x-ray source.

Many of the hydration products of cement are crystalline in form and standard diffraction patterns

C - calcite
P - portlandite
Q - quartz

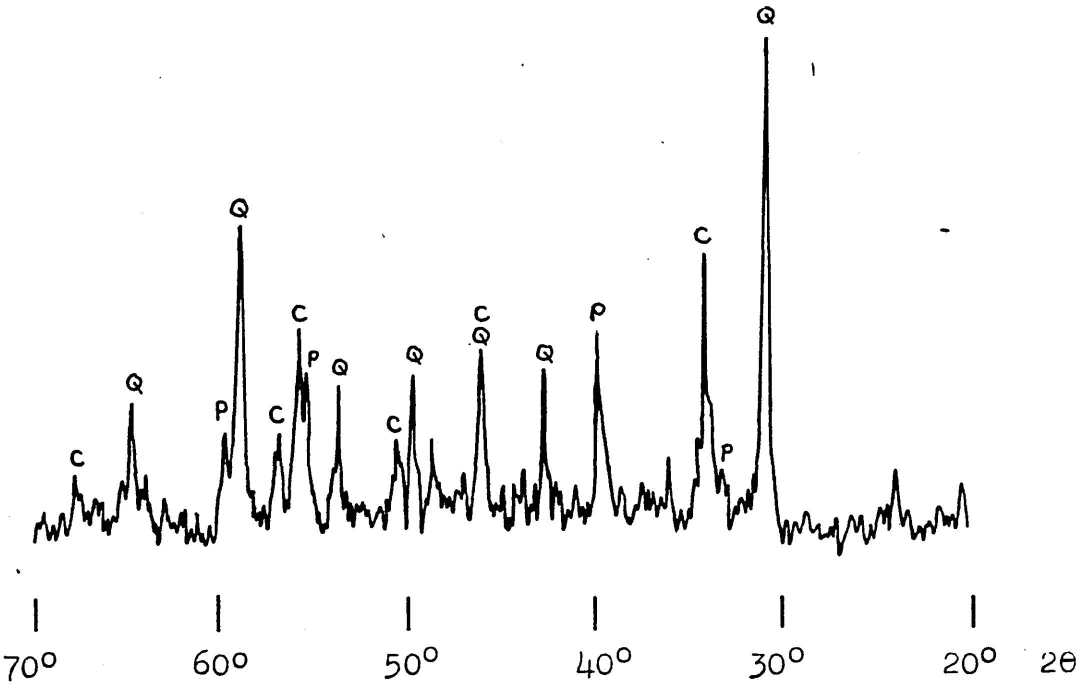


Figure 12.1. Typical x-ray diffraction output.

exist for them. A notable exception is the C-S-H gel, which is amorphous.

12.2. OPC Paste.

Samples of OPC paste were hydrated at water/cement ratios of 0.2,0.3,0.4 and 0.5 for 28 days before testing. Each mix was cast as a small slab (25x100x7mm) from which the test sample (10x10x7mm) was cut. The slabs were individually cured in sealed plastic bags during the hydration period. When removed from the bags, the slabs were still moist and water had condensed on the inside of the bags, showing that the curing environment must have had a high level of humidity.

The results of the four samples are shown in figure 12.2, from which it can be clearly seen that only two constituents are present in crystalline form, namely alite (calcium silicate) and portlandite (calcium hydroxide).

An approximate integration of the peak intensities shows that the ratios of alite to portlandite present are 16:1,24:1,13:1 and 4:1 for the four samples with water/cement ratios of 0.2,0.3,0.4 and 0.5 respectively.

The results show that the relative proportions of the hydration products in the cement paste are dependent upon the water/cement ratio.

12.3. Mortar from Couplets.

Specimens were prepared which consisted of each of the four grades of mortar in combination with both Southwater engineering and Holbrook facing bricks. Couplets were chosen that had been laid dry, using mortar of the

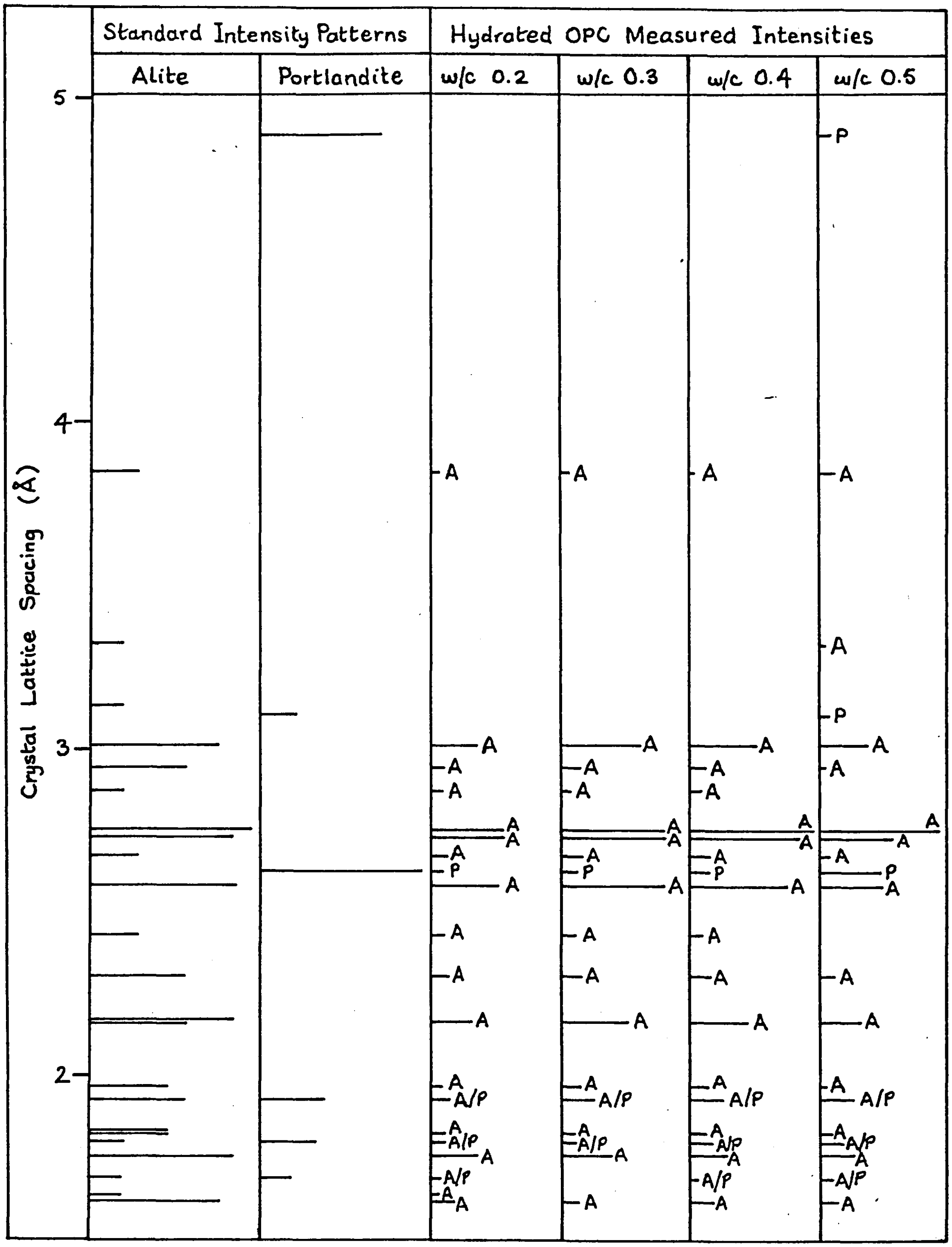


Figure 12.2. Comparison of hydrated OPC results with standard patterns.

same consistence. Specimens were prepared from the top failed interface for which the bond strength was about average for each batch.

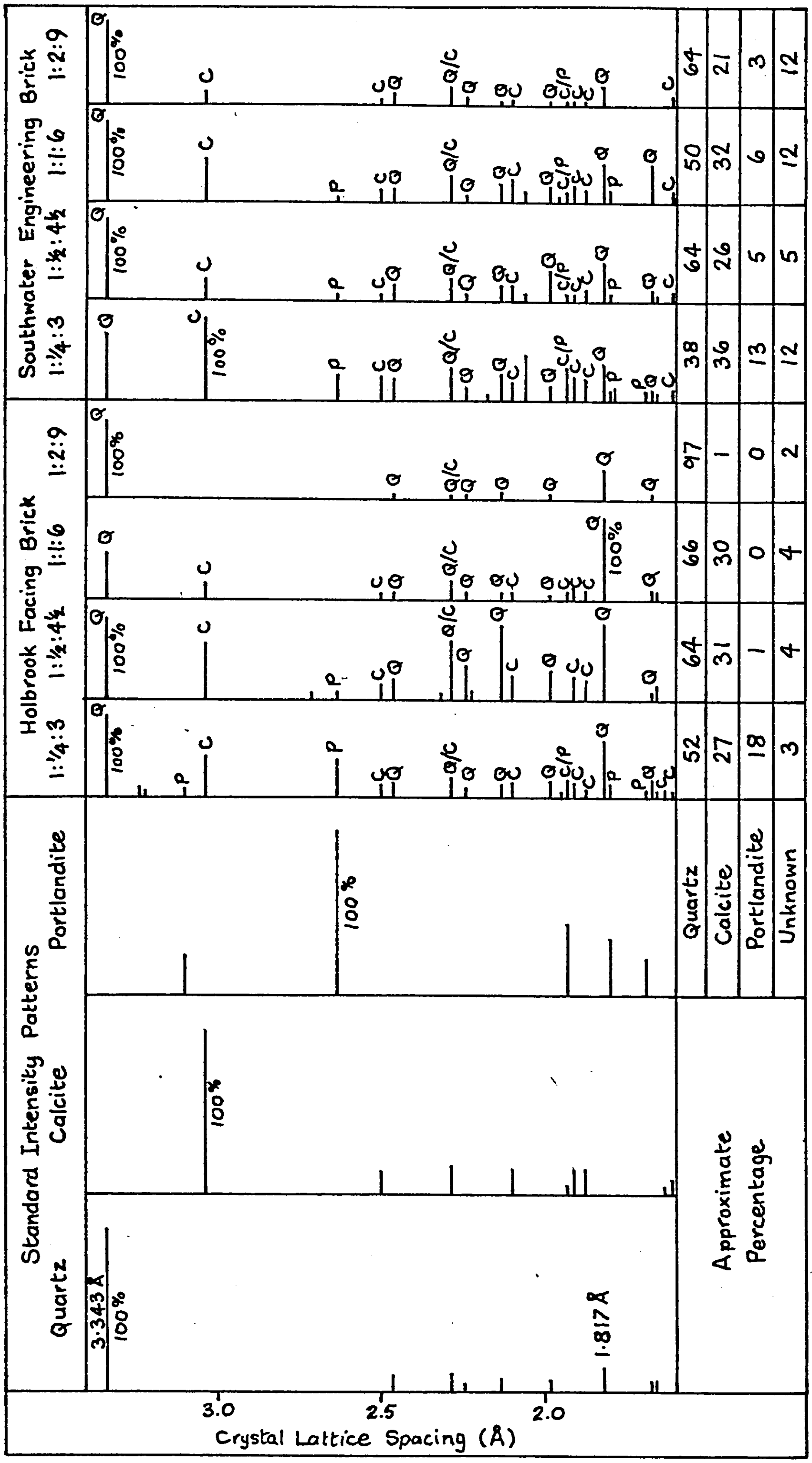
Figure 12.3 shows the results of these tests with the approximate constituent proportions tabulated for each of the eight samples. These values are obtained by the simplified method of summing the peak intensities (in cps) for all the peaks corresponding to that constituent.

Portlandite was found in greatest abundance in the 1:¼:3 mortars, but ettringite was not found at all. Some of the peaks remained unidentified, mainly for the mortars from the engineering brick couplets. The development of calcite is well advanced, probably because of the several months which elapsed between the manufacture of the couplets and the cutting of samples for x-ray diffraction.

Because of this delay, the proportions given in figure 12.3 can only give a general indication of the nature of the constituents, demonstrating the potential of this method of analysis.

The relative intensities of the peaks given in the standard patterns correspond to a random distribution and orientation of the microcrystals. If any test sample displays relative peak intensities which are different from the standard, it can be implied that there is a preferential orientation of the crystals, at least over the small area of the sample.

It can be seen in figure 12.3 that the mortar removed from the facing brick shows a marked difference in peak intensities from the standard for the major peaks of



Approximate Percentage	Holbrook Facing Brick 1:¼:3	Holbrook Facing Brick 1:½:4½	Holbrook Facing Brick 1:1:6	Holbrook Facing Brick 1:2:9	Southwater Engineering Brick 1:¼:3	Southwater Engineering Brick 1:½:4½	Southwater Engineering Brick 1:1:6	Southwater Engineering Brick 1:2:9
Quartz	52	64	66	97	38	64	50	64
Calcite	27	31	30	1	36	26	32	21
Portlandite	18	1	0	0	13	5	6	3
Unknown	3	4	4	2	12	5	12	12

Figure 12.3. Comparison of brick/mortar interface results with standard patterns.

quartz. This is particularly noticeable for mix 1:1:6 for which the 1.817Å quartz peak is greater than the 3.343Å peak, but the opposite is true for the intensities of the standard. These differences are much less marked for the engineering brick samples. A possible but tentative explanation of this behaviour is that the perforated facing bricks, which are the more porous of the two, allow a greater degree of consolidation of the mortar which could give rise to a preferential alignment of the sand grains. Of greater concern, however, would be any similar anomalies occuring in the peak intensities of the hydration products. An analysis for the peaks of portlandite from the couplet samples shows that the relative intensities seem to match those of the standard, indicating that the orientation of crystals is random, although the low intensities make quantitative analysis inaccurate. Calcite, on the other hand, with a higher intensity response, seems to be weaker than would be expected for the major peak at 3.035Å, for all specimens.

According to Grandet and Thenoz (53), there are carbonation reactions taking place in hydrated cement which convert portlandite, ettringite and amorphous C-S-H into calcium carbonate. They report that portlandite reacts very slowly to give calcite; ettringite reacts more quickly to give calcite and aragonite; and the C-S-H gel gives calcite and vaterite. Carbonation products other than calcite, however, have not been identified in the present analysis.

Taylor (54) and Grandet (55) are agreed on the early development of ettringite, but Taylor differs in that he gives the degeneration product of ettringite as monosulphate. Ettringite has been found by Grandet to form where the water content has been reduced.

12.4. Conclusions.

The present work and that of others, such as Grandet (53,55), show that the nature of the hydration products at the interface is dependent upon the mix proportions and on the moisture content at that position. The purpose of this aspect of the work can now be seen in relation to the unsaturated flow theory discussed in section 11. Results from a comprehensive series of x-ray diffraction tests might be used to predict the form of the hydration products at any point if the equilibrium moisture content is known at that point.

13. A FINAL REVIEW OF BOND AND A HYPOTHESIS.

In this section the hypothesis relating to the tensile strength of a brickwork joint will be given, together with detailed discussions of the three stages of strength development. The hypothesis is thought to be a step forward in the sense that concepts and techniques from several disciplines are drawn upon in an attempt to describe the tensile behaviour.

13.1. General Hypothesis.

The tensile strength of brickwork is very difficult to predict accurately because of the complex nature of the materials and physical processes involved and the ways in which they interact. The following hypothesis is an attempt to describe the events that take place when bricks and mortar are brought together.

When mortar is mixed, one of the first reactions to take place is that sulphate ions from the gypsum in the cement pass into solution. These ions attach themselves to grains of tricalcium aluminate and form around them a film of ettringite (56). If a bed of mortar is placed on a brick there will be an immediate movement of water from the mortar into the brick due to the suction of the brick. The water which is absorbed into the brick may take with it fine solid particles as well as dissolved ions.

As suction proceeds, unsaturated flow theory predicts that there will be a moisture gradient in both the mortar and the brick. If a brick is now placed on the mortar bed and either pressed or tapped down, the mortar will be subjected to a compressive stress. Consolidation of the mortar will take place causing an overall volume reduction and a change in moisture content.

Subsequently, when the application of stress has ceased, there will be a continuation of water movement due to suction, but now transfer will take place upwards as well as downwards. In the absence of any further disturbance, this process will continue at an ever decreasing rate as hydraulic equilibrium is reached and the hydraulic conductivity of the mortar reduces due to hydration. Early reactions which will reduce the conductivity are the formation of an ettringite network, particularly where the water/cement ratio is low (57,58), and the growth of a hydrated layer around the C_3S grains, although Taylor (58) expresses doubts that such a layer forms.

Thus the processes of absorption and consolidation will control the distribution of the various constituents within the mortar, with the result that at any point within the joint there will exist a set of constituents giving a particular tensile strength at that point. Not only will there be a distribution of constituents, but also a distribution of tensile strength with failure occuring at the weakest point. Experience shows that this weakest point is usually very close to the brick/mortar interface.

13.2. Moisture Movement.

There are two measured parameters of the materials which are in present use to describe this behaviour, namely the suction rate of the brick and the retentivity of the mortar. However, these properties are an over-simplification of the situation and their limitations should be noted.

The suction rate is defined as the mass of water absorbed vertically through unit area of the bed face of a brick in one minute. However, even if the suction rate is a valid parameter, there are difficulties with its measurement. It has been found to vary at different points on the bed face, possibly increasing towards the edge of the brick (33,41,59), although in some cases this can be attributed to the high capillary action caused by a rough textured stretcher face (21,60). West (41) has calculated the effect of the meniscus on the suction rate for solid and perforated bricks and concluded that the error in the calculation of the contact area is increased substantially for a 23 perforation brick if the net area is used instead of the gross area. In fact the use of the net area will underestimate the contact area by about 45%, which is almost five times the error in using the gross area.

Clearly then, there are practical problems with the suction rate test, but they can be allowed for without too much difficulty. Unfortunately there are more fundamental problems which are not so easily dealt with.

It is known that calcium silicate bricks have a moderate suction rate, but will continue to absorb water for a longer period than clay bricks, which may have a higher suction rate. Different types of brick have different patterns of behaviour and it is the relationship between water absorbed and time that is important, rather than the one minute suction rate, which is just a single value from this relationship (45). Furthermore, there are difficulties in applying a value of suction rate determined from free water absorption, to a situation in which water is being drawn from a complex porous medium such as mortar (19,61). It is possible that the mortar is initially saturated and there will be free water available, but after a time the capillary potential of the mortar begins to resist dewatering and the behaviour will be quite different from free water absorption. Grandet and Thenoz (61) suggest that the specific surface of the dry mortar constituents is a useful parameter at this stage.

In order to explain the water absorption behaviour, theories of capillary absorption are usually developed which rely on the concept of pore-size distribution. These theories are almost always based on a simple cylindrical pore model, whereas the true situation is very much more complicated. Pandey and Singhal (62) recognised the difficulties caused by large discontinuous pores having a small entry diameter. The behaviour of these pores is known as the "ink-bottle" effect and forms one of the main arguments against the cylindrical pore model. Pandey and Singhal concluded that there is no direct way of knowing the real pore-size distribution and that the capillary pressure is influenced by the size and shape of individual pores and by the interconnectivity of the overall pore system. The problem had been tackled earlier by Astbury

(63) who developed a non-uniform pore hypothesis based on the following assumptions:

(i) pores are straight and aligned in the direction of flow,

(ii) pores are circular in cross-section,

(iii) pore radius varies randomly along its length,

(iv) this randomness is the same all along a pore and for all pores,

(v) the inner surface should be wetted at all times,

(vi) Poiseuille flow is maintained.

His theory gives correction factors for the simple cylindrical pore theory which seem to offer a definite improvement (64,65).

More recently, van Brakel (66) has examined many different theories of water absorption and many forms of capillary. He challenged the terms "pore" and "pore-size distribution" on the grounds that in a real material they do not exist. He defined a porous medium as "a solid phase dispersed with a non-solid phase between." This non-solid phase is the continuous pore-space, which does not consist of interconnected pores because a pore has, by definition, a certain length and recognisable walls.

For water movement through mortar, the problem is even more acute. Here the concept of seperate pores, or even an average pore size, appears erroneous. In fact there is only one meniscus, the radius of which changes from point to point (66).

Jansson (67), a decade previously, pointed out that a real material consists of either a basic mass of solid material with connected or closed air cells, or solid particles in the form of grains which are more or less in contact with each other. He assumed that during water absorption the moisture content behind the wetting front was uniform and constant, an assumption which he seemed to confirm experimentally.

Figure 13.1 shows a typical brick surface magnified 970 times, which illustrates the extent to which a real **brick** differs from a theoretical cylindrical-pore model.

A recent approach (46,68) has been the use of unsaturated flow theory developed in soil physics. This is essentially a macroscale analysis, which describes water flow in relation to potentials which can be defined and measured without reference to microstructure. The purposes of unsaturated flow theory are to relate the water absorption behaviour to the well-defined hydraulic properties of the material and to determine the moisture content as a function of position and time as described in section 11.

Using unsaturated flow theory it can be shown (68) that for horizontal infiltration the total amount of water absorbed is proportional to the square root of the time. The constant of proportionality is known as the sorptivity and has units of $kg/m^2s^{\frac{1}{2}}$. For vertical infiltration the effect of gravity complicates the analysis but Gummerson, Hall and Hoff have shown (45,68) that gravity does not seem to have a significant effect on the experimental water absorption by a clay brick.

Test results which confirm the sorptivity relation-

Figure 13.1. Fletton brick surface using SEM (970x).

ship are given by Palmer and Parsons (1) on six different materials. They assumed, however, that the absorption relationship was $i=st^{\frac{1}{3}}$ instead of the theoretical $i=st^{\frac{1}{2}}$, but analysis of the data presented by these workers on page 629 of their paper shows that the actual behaviour falls between these two assumptions with a mean of approximately 0.4 for the exponent of t.

Section 11 describes a technique for the determination of the moisture characteristics of fresh mortar, which has been used successfully to show the qualitative difference in behaviour between mortar grades. This method allows the property of water retentivity to be related to the concepts of unsaturated flow theory.

Recent techniques have introduced the possibility of the direct measurement of the moisture content. Nuclear magnetic resonance has been employed in other fields, particularly medicine (69), for some time, but its use in the moisture measurement of building materials is recent (70). Other methods in existence which might prove useful for this problem are x-ray absorption analysis (50) and gamma ray attenuation (51). These techniques would be used to measure the moisture content gradient that unsaturated flow theory predicts will occur within the material. Although Jansson has stated otherwise (67), there is good evidence that such a gradient exists (33,59).

According to Hall (46) the assumption of Darcian behaviour, on which unsaturated flow theory is based, may not always be valid because of the presence of solutes and small, mobile particles. These objections would seem to be particularly relevent to the situation in which water is being absorbed from mortar, although the magnitude of their effect is not known.

An approximate assessment of the likelihood of particle transport can be obtained by the method given by Cedergren (71). He gives two conditions which determine whether migration of fine particles takes place through a matrix of larger size material. Applied to mortar these conditions are

$$\frac{D_{15}(\text{sand})}{D_{85}(\text{cementitious})} > 5 \text{ and } \frac{D_{50}(\text{sand})}{D_{50}(\text{cementitious})} > 25$$

where, for example, D_{15} is the diameter below which 15% of the material falls.

The following particle diameters have been interpolated from the grading curves of cement and lime (obtained from the manufacturers) and of the regraded Auckley sand used in the experimental programme.

Material	D_{15} (mm)	D_{50} (mm)	D_{85} (mm)
Sand F	0.102	0.183	
N	0.113	0.223	
1C	0.135	0.238	
2C	0.165	0.248	
3C	0.190	0.272	
4C	0.159	0.280	
5C	0.220	0.420	
Cement		0.015	0.035
Lime		0.016	0.039

Table 13.1. Particle size data for Cedergren's method (71).

From the data of table 13.1 the conditions for migration can be evaluated.

Sand	$D_{15}(s)/D_{85}(c)$		$D_{50}(s)/D_{50}(c)$	
	Cement	Lime	Cement	Lime
F	2.9	2.6	12.2	11.4
N	3.2	2.9	14.9	13.9
1C	3.9	3.5	15.9	14.9
2C	4.7	4.2	16.5	15.5
3C	5.4*	4.9	18.1	17.0
4C	4.5	4.1	18.7	17.5
5C	6.3*	5.6*	28.0*	26.2*

Table 13.2. Conditions for migration using Cedergren's method (* satisfied).

From table 13.2 it can be concluded that this method of evaluation predicts that there will be migration of cement and lime towards the brick in the case of sand 5C (the result for sand 3C is inconclusive).

13.3. Hydration and Carbonation Reactions.

Having established in the previous section that the mechanical forces of absorption and consolidation will give rise to distributions of the constituents within the mortar joint, the various hydration and carbonation reactions will now be discussed.

The earliest reactions will be the formation of an ettringite network and the growth of a hydrated layer around the C_3S grains. Crystallisation of calcium hydroxide as portlandite begins after about an hour and seems to occur in places where there is a high concentration of calcium ions and a high residual water content (55).

There is physical evidence that the hydration products are not distributed uniformly throughout the mortar (55,56). Ettringite has been found to occur at the brick-mortar interface in cases where suction has taken place, but if mortar is bonded to glass plates, the distribution of portlandite and ettringite will be uniform throughout the mortar. As long ago as 1940, Staley (72) stated that lime particles are carried in suspension and solution to the brick, increasing the strength and extent of bond after carbonation has taken place. His findings were based on examinations of the brick-mortar interface of many existing walls.

Carbonation reactions take place slowly over many years and result in a gradual solidification and strengthening of the mortar matrix. Most of the hydration products of cement appear to be subject to carbonation. The reactions, given in section 12.3, were reported by Grandet and Thenoz (53). A by-product of most of the carbonation reactions is water, which will give rise to secondary hydration. Gypsum and aluminium hydroxide, formed during the carbonation of ettringite, may also combine with portlandite to form more ettringite (53).

The experimental techniques described in section 12 show that it is possible to determine the hydration products present on any surface cut from a mortar joint. Such a technique may provide the link between the analysis of moisture movement and the prediction of tensile strength.

13.4. Nature of Tensile Bond.

As part of the working hypothesis it is necessary to examine the nature of the tensile failure of a brickwork joint. The tensile strength is usually referred to as the bond strength, but for some mortars, particularly those with a high lime content, failure occurs in the body of the mortar rather than at the interface. It is doubtful whether the term "bond strength" is strictly applicable to this situation. Indeed, careful examination of the surface of a brick taken from any failed tensile couplet will reveal a thin layer of mortar coating the brick. This suggests that failure occurs always in the body of the mortar, albeit very close to the brick, rather than at the interface. This concept is supported by Bikerman (73), who suggests that failure exactly along such an interface is virtually impossible.

Because of the nature of the failure mode it seems natural to assume that across a mortar joint there will be a variation in tensile strength, with failure occuring at the weakest point. (More specifically, failure will be initiated at the point where the tensile stress first exceeds the tensile strength, which will be the weakest point in an idealised situation with uniform stress.) Waters (23) also suggests the existence of a strength distribution and experimental confirmation comes from Lea (57) who reports that the microhardness testing across a cement-aggregate interface reveals a hard layer of thickness 20-30μm adjacent to the aggregate, followed by a weaker layer, before passing into the still harder regions within the main body of the cement. If this is also the case at the brick-mortar interface, then such a layer would probably be regarded as a surface stain and the fracture categorised as an interfacial bond failure.

Bearing these remarks in mind, the hypothesis is largely concerned with the determination of the relationship between the properties of the materials used and the tensile strength variation within the mortar body. However, the actual bond between the brick and the mortar must exist, although its nature is in some doubt. The three possibilities are mechanical, physical and chemical bond, and it is likely that the true situation is a combination of all three types.

For mechanical bond to take place there should be intimate contact between the mortar and the brick, which may be facilitated by the use of high-lime mortars (72). The actual bonding requires the crystalline products of hydration to form within the voids of the brick (4,5,74, 75,76). According to Grandet et al (75), close to the brick, the main constituent of the hydrated cement, is ettringite. This occurs as needle shaped crystals approximately 0.05μm in diameter, but usually occurs in clusters of 0.2-0.3μm diameter. Thus the diameter of the voids in the brick should be at least 0.05μm and preferably about five times this size. Having achieved its interlocking, the crystal structure must be strong enough to transfer the stress from within the voids to the body of the mortar outside (3).

The interface samples examined by x-ray diffraction and discussed in section 12 showed no evidence of ettringite but calcite was present. However, it should be remembered that due to carbonation, ettringite evolves into calcite.

When two particles are close together there are physical forces which attract them. It is likely that the major physical force is Van der Waal's (76), which may be as high as 20N/mm^2 (57). For this force to be important, contact should be over as large an area as possible and as close as possible. According to Javelas et al (76), the distance between calcite aggregate and the hydration products is about 20Å (about ten times the effective diametr of an atom). Contact must be very close as Van der Waal's forces vary as R^{-6}, where R is the separation (77).

Concerning chemical bonding, there is some disagreement. Many workers are of the opinion that such bonds cannot occur between brick and mortar, but Hogberg (4), for example, holds the opposite view. Others, such as Javelas (76), agree that chemical bonds do exist under certain conditions, such as bonding with calcite aggregate. Calcite is attacked chemically by the cement gel, forming an intermediate solid made up of C-S-H from the gel, combining with Ca^{++} and CO_3^{--} ions from the calcite. In the body of the mortar, Lea (57) attributes compressive strength to chemical valency bonds, which are about one hundred times as strong as the Van der Waal forces, the latter governing tensile behaviour. It seems likely, however, that most brick material will be chemically inert in relation to cement and that chemical bonds play virtually no part in brick-mortar bond.

14. GENERAL CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK.

In this final section the present work will be reviewed in general terms and in relation to the state of the art, the relevance of the various aspects of the work to the bond hypothesis will be discussed and recommendations for futuree work will be made.

14.1. The Tensile Test System.

The apparatus described in section 4 has proved to be very successful for the determination of tensile bond strengths in the range encountered. It is simple both to manufacture and to operate and, being fully adjustable, can compensate for differences in joint thickness within a couplet, or for badly shaped bricks. Including initial trials, over 1000 couplets have been tested having bond strengths in the range 0.05-0.51N/mm^2. Because a variable range tensometer was used, the accuracy of the results was largely independent of the failure load.

14.2. Tensile Test Results.

From table 14.1 it can be seen that direct comparison of results is difficult, because of the difference in brick types, etc. The BS5628 strengths apply to bricks of less than 7% water absorption, into which category both the Holbrook and the Southwater bricks fall. However, the Southwater brick couplets give much lower strengths than the Holbrook. Other workers results which are directly comparable are also shown as being in general agreement.

	Mortar Designation			
	(i)	(ii)	(iii)	(iv)
Holbrook facing brick couplets	0.38	0.33	0.27	0.22
Southwater engineering brick couplets	0.14	0.17	0.19	0.14
BS5628 characteristic tensile strengths	0.35	0.25	0.25	0.20
Kampf(3)			0.19	
Habib,Leeds(12)	0.38			
Palmer,Hall(20)	0.22		0.16	

Table 14.1. Comparison of tensile bond strength (N/mm^2) results with other sources.

14.3. Importance of Water Absorption.

From the literature review in section 2 and from the experimental results of the present work it is clear that the most important process affecting the tensile bond strength is the absorption of moisture from the mortar, by the brick. In turn, this will be affected by the absorptive properties and initial moisture content of the brick, by the retentive properties of the mortar and by the method of laying.

14.4. Hypothesis of Tensile Bond Strength.

The general hypothesis developed throughout this work is that the physical and chemical processes of absorption and hydration create within the mortar joint a distribution of constituents and tensile strength which govern the tensile behaviour. The term "tensile strength" is, in this context, more appropriate than the usual "bond strength", as it refers to a failure in tension at some point within the joint, rather than exclusively at the interface.

14.5. Moisture Characteristics.

Any predictive method which follows the tensile strength hypothesis will require both the mortar and the bricks to be quantified according to the properties used in soil physics. The work described in section 11 shows that the relationship between capillary potential and moisture content can be readily determined for mortars, although a more sensitive method is required for bricks of low suction rate.

14.6. X-Ray Diffraction.

This is a method of chemical analysis which will identify crystalline compounds on the surface of a small ($1 cm^2$) sample of mortar or brick. The results of section 12 have shown that under different initial conditions, there will be a variety of hydration products. Such a method might be used to correlate equilibrium moisture content distributions obtained from unsaturated flow theory with the predicted hydration products from cement chemistry.

14.7. Future Work.

The following are recommendations which would further the knowledge of tensile bond strength and support the hypothesis developed in the present work.

(i) Further experimental strength tests on couplets using bricks without perforation or frogs, for a range of suction rates and initial moisture contents and for a range of mortars.

(ii) Developments of unsaturated flow theory to encompass the case of brick/mortar/brick.

(iii) Measurement of hydraulic properties of brick and mortar, and correlation with established properties such as suction rate, sand grading, etc.

(iv) Adoption of techniques such as gamma ray attenuation for the measurement of moisture content as a function of position and time.

(v) Development of x-ray diffraction, or similar chemical analysis method, to identify hydration products as a function of position within the mortar.

(vi) Relate nature of hydration products to equilibrium moisture content and to microstrength within the mortar.

(vii) Unification of all these techniques to achieve the ultimate objective of predicting the tensile strength and mode of failure based on the properties of the materials and the method of laying and curing.

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APPENDIX 1. FULL RESULTS FROM BOND STRENGTH TESTS.

The results from independent couplet tests are given in tables A1.1 to A1.31. Explanatory notes are given below.

Tables A1.1 - A1.16

Brick : F = Holbrook facing; E = Southwater engineering.

Mortar : (i) = 1:$\frac{1}{4}$:3; (ii) = 1:$\frac{1}{2}$:4$\frac{1}{2}$; (iii) = 1:1:6; (iv) = 1:2:9.

Water : Figure given is percentage by weight of dry constituents.

Laying : D = laid dry; W = laid after suction rate adjustment.

Number : Number of individual couplets within group.

Joint Thickness : Measured at each corner of mortar joint prior to testing.

Failure Load : Ultimate direct tensile failure load in kN.

Length, width : Dimensions of failed surface of couplet.

Failure Stress : Failure load/Area of failed surface.

Mode : T = top plane failure; B = bottom plane failure; M = failure within mortar; BT etc. = combination of these.

Tables A1.17 - A1.25

Sand : F = fine; N = normal; 1C etc. = coarse.

T,M,B : Values are percentages of failure plane area occuring at the respective locations. For couplets whose failure areas total more than 100%, some of the mortar became detached at failure.

Tables A1.26 - A1.27

Br,T,M,B,Br : Location of failed surface as a percentage, in the top brick, top plane, mortar, bottom plane and bottom brick respectively. Totals of more than 100% as before.

Tables A1.28 - A1.31

Curing : a = sealed in curing cabinets for 28 days;
b = wet/dry - submerged for 24 hours on days 2,9,16,23;
c = freeze/thaw - 24 hour cycle (-4°C to 10°C);
d = mist room - 100%r.h.,18°C;
e = constant temperature/humidity - 60%r.h.,20°C.

Brick	Mortar	Water (%)	Laying	Number	Joint Thickness (mm)				Failure Load(kN)	Length(mm)	Width(mm)	Failure Stress(N/mm2)	Mode
F	(i)	17½	D	1	11	12	12	11	4.80	147	100	0.33	B
F	(i)	17½	D	2	12	12	10	10	5.80	152	97	0.39	T
F	(i)	17½	D	3	11	11	10	10	4.30	150	100	0.29	B
F	(i)	17½	D	4	10	10	11	10	5.15	150	100	0.34	B
F	(i)	17½	D	5	10	10	10	10	4.60	147	100	0.31	B
F	(i)	18	D	1	10	12	11	10	5.70	151	99	0.38	B
F	(i)	18	D	2	12	12	11	11	5.50	149	99	0.37	B
F	(i)	18	D	3	10	11	10	10	5.35	147	98	0.37	T
F	(i)	18	D	4	10	10	10	10	6.65	151	100	0.44	B
F	(i)	18	D	5	10	11	10	10	5.60	150	100	0.37	B
F	(i)	18½	D	1	10	10	11	10	4.95	152	98	0.33	T
F	(i)	18½	D	2	10	10	11	10	4.35	149	100	0.29	B
F	(i)	18½	D	3	10	11	12	12	6.60	153	100	0.43	B
F	(i)	18½	D	4	10	10	10	10	5.10	152	100	0.34	B
F	(i)	18½	D	5	10	10	10	11	7.55	149	100	0.51	B
F	(i)	19	D	1	10	10	10	11	6.50	154	94	0.45	T
F	(i)	19	D	2	10	11	11	11	5.20	151	99	0.35	B
F	(i)	19	D	3	10	10	10	10	5.40	151	96	0.37	BT
F	(i)	19	D	4	10	10	10	10	5.25	153	96	0.36	T
F	(i)	19	D	5	10	10	10	11	4.95	148	99	0.34	B
F	(i)	19½	D	1	10	10	10	10	6.35	149	99	0.43	B
F	(i)	19½	D	2	10	10	11	12	4.70	147	100	0.32	B
F	(i)	19½	D	3	10	10	10	10	5.40	152	94	0.33	T
F	(i)	19½	D	4	10	10	11	11	6.15	153	94	0.43	T
F	(i)	19½	D	5	10	11	11	10	5.85	154	94	0.40	T
F	(i)	20	D	1	12	10	11	9	6.80	148	101	0.46	B
F	(i)	20	D	2	10	11	10	9	7.10	152	99	0.47	B
F	(i)	20	D	3	10	10	10	10	5.45	151	99	0.36	T
F	(i)	20	D	4	10	9	9	9	4.65	148	98	0.32	T
F	(i)	20	D	5	10	10	11	9	5.70	150	98	0.39	T

Table A1.1. Mortar Programme Results, Holbrook Facing Brick, Mortar Grade (i), Laid Dry.

Brick	Mortar	Water (%)	Laying	Number	Joint Thickness (mm)				Failure Load(kN)	Length(mm)	Width(mm)	Failure Stress(N/mm^2)	Mode
F	(i)	17½	W	1	11	12	10	10	3.90	152	100	0.26	B
F	(i)	17½	W	2	10	11	11	11	5.80	151	100	0.38	B
F	(i)	17½	W	3	10	10	10	9	5.45	152	98	0.37	T
F	(i)	17½	W	4	10	10	10	10	6.20	151	97	0.42	T
F	(i)	17½	W	5	11	10	10	10	5.25	154	100	0.34	B
F	(i)	18	W	1	11	10	11	11	5.40	152	97	0.37	BT
F	(i)	18	W	2	11	10	11	11	6.10	155	98	0.40	TB
F	(i)	18	W	3	10	10	10	10	5.60	155	96	0.38	T
F	(i)	18	W	4	11	11	11	11	5.10	154	100	0.33	B
F	(i)	18	W	5	11	12	10	10	4.90	151	100	0.32	B
F	(i)	18½	W	1	10	10	10	10	6.05	147	100	0.41	B
F	(i)	18½	W	2	10	11	10	10	6.10	152	100	0.40	B
F	(i)	18½	W	3	11	11	11	11	5.45	154	96	0.37	T
F	(i)	18½	W	4	10	10	11	11	5.00	150	97	0.34	T
F	(i)	18½	W	5	10	10	11	11	5.10	154	97	0.34	T
F	(i)	19	W	1	10	11	11	11	4.85	154	97	0.32	T
F	(i)	19	W	2	10	10	11	11	4.75	154	97	0.32	T
F	(i)	19	W	3	11	11	10	11	5.20	156	95	0.35	T
F	(i)	19	W	4	10	10	11	11	4.50	152	99	0.30	B
F	(i)	19	W	5	10	10	11	11	4.70	155	100	0.30	B
F	(i)	19½	W	1	10	10	10	10	4.94	151	96	0.34	T
F	(i)	19½	W	2	10	10	10	10	4.77	152	97	0.32	T
F	(i)	19½	W	3	10	10	11	11	5.60	154	99	0.37	B
F	(i)	19½	W	4	10	10	11	11	5.50	155	95	0.37	T
F	(i)	19½	W	5	10	10	10	10	5.05	154	97	0.34	T
F	(i)	20	W	1	10	10	10	10	6.30	152	100	0.41	B
F	(i)	20	W	2	10	10	11	9	4.60	151	97	0.31	T
F	(i)	20	W	3	11	10	10	9	6.10	151	96	0.42	T
F	(i)	20	W	4	10	10	10	10	5.30	153	97	0.36	T
F	(i)	20	W	5	10	10	10	10	4.60	152	98	0.31	T

Table A1.2. Mortar Programme Results, Holbrook Facing Brick, Mortar Grade (i), Laid Wet.

Brick	Mortar	Water (%)	Laying	Number	Joint Thickness (mm)				Failure Load (kN)	Length (mm)	Width (mm)	Failure Stress (N/mm^2)	Mode
E	(i)	17½	D	1	10	10	10	12	1.36	155	98	0.09	T
E	(i)	17½	D	2	11	11	11	10	1.39	155	99	0.09	T
E	(i)	17½	D	3	10	10	11	11	1.25	155	99	0.08	T
E	(i)	17½	D	4	10	10	13	11	2.06	157	99	0.13	T
E	(i)	17½	D	5	11	10	10	10	2.41	157	99	0.16	T
E	(i)	18	D	1	10	12	10	10	1.88	157	99	0.12	T
E	(i)	18	D	2	10	11	10	10	2.50	156	98	0.16	T
E	(i)	18	D	3	10	9	10	10	1.86	157	98	0.12	T
E	(i)	18	D	4	10	11	11	12	1.90	154	98	0.13	T
E	(i)	18	D	5	11	11	12	12	1.86	156	99	0.12	TB
E	(i)	18½	D	1	10	12	10	10	2.10	162	97	0.13	TB
E	(i)	18½	D	2	10	10	11	11	0.38	163	100	0.02	TB*
E	(i)	18½	D	3	10	10	10	11	2.40	165	101	0.14	B
E	(i)	18½	D	4	11	11	10	12	0.81	161	99	0.05	T*
E	(i)	18½	D	5	11	10	11	10	2.53	163	100	0.16	B
E	(i)	19	D	1	9	12	10	8	2.12	155	99	0.14	T
E	(i)	19	D	2	9	8	9	11	2.13	154	99	0.14	T
E	(i)	19	D	3	10	9	10	10	1.62	152	98	0.11	T
E	(i)	19	D	4	10	10	10	10	2.26	155	100	0.15	T
E	(i)	19	D	5	9	11	10	10	1.80	158	99	0.12	T
E	(i)	19½	D	1	9	10	10	9	2.14	156	98	0.14	T
E	(i)	19½	D	2	11	10	10	10	2.11	156	99	0.14	T
E	(i)	19½	D	3	10	9	10	10	2.88	157	98	0.19	T
E	(i)	19½	D	4	11	10	10	10	1.89	158	99	0.12	T
E	(i)	19½	D	5	10	10	11	10	2.44	159	98	0.16	T
E	(i)	20	D	1	9	10	10	9	1.90	157	100	0.12	T
E	(i)	20	D	2	8	10	9	10	3.95	160	102	0.24	T
E	(i)	20	D	3	9	9	10	9	3.21	158	100	0.20	T
E	(i)	20	D	4	8	9	9	7	1.93	160	101	0.12	T
E	(i)	20	D	5	8	8	9	8	3.49	163	100	0.21	T

* Brick surface contaminated by resin from wood packing

Table A1.3. Mortar Programme Results, Southwater Engineering Brick, Mortar Grade (i), Laid Dry.

Brick	Mortar	Water (%)	Laying	Number	Joint Thickness (mm)				Failure Load(kN)	Length(mm)	Width(mm)	Failure Stress(N/mm2)	Mode
E	(i)	17½	W	1	11	11	11	10	1.20	155	99	0.08	T
E	(i)	17½	W	2	11	11	11	11	1.92	156	98	0.13	T
E	(i)	17½	W	3	12	10	11	9	2.50	157	100	0.16	B
E	(i)	17½	W	4	11	11	11	9	1.11	158	97	0.07	T
E	(i)	17½	W	5	10	11	10	11	1.31	160	100	0.08	T
E	(i)	18	W	1	10	11	11	10	1.54	154	98	0.10	T
E	(i)	18	W	2	10	10	10	10	1.57	157	100	0.10	T
E	(i)	18	W	3	12	10	10	10	1.87	158	99	0.12	T
E	(i)	18	W	4	11	10	11	10	1.91	160	100	0.12	T
E	(i)	18	W	5	10	10	10	12	1.96	158	98	0.13	T
E	(i)	18½	W	1	10	12	10	11	0.80	154	99	0.05	T
E	(i)	18½	W	2	10	10	10	10	1.24	158	99	0.08	T
E	(i)	18½	W	3	10	10	10	9	1.98	158	99	0.13	T
E	(i)	18½	W	4	10	9	10	11	1.37	157	98	0.09	T
E	(i)	18½	W	5	10	9	9	10	1.68	157	100	0.11	T
E	(i)	19	W	1	10	10	11	11	2.26	157	98	0.15	T
E	(i)	19	W	2	10	11	10	10	1.34	156	97	0.09	T
E	(i)	19	W	3	10	10	10	10	0.89	160	98	0.06	T
E	(i)	19	W	4	10	11	10	9	2.30	158	97	0.15	TB
E	(i)	19	W	5	9	9	9	10	1.60	156	97	0.11	T
E	(i)	19½	W	1	9	11	9	9	2.09	161	99	0.13	T
E	(i)	19½	W	2	9	10	9	10	1.19	158	98	0.08	T
E	(i)	19½	W	3	10	10	10	11	0.99	156	99	0.06	T
E	(i)	19½	W	4	10	10	10	11	1.68	157	99	0.11	T
E	(i)	19½	W	5	9	11	10	9	1.50	162	98	0.09	T
E	(i)	20	W	1	8	9	10	10	-	165	101	-	TB
E	(i)	20	W	2	8	9	9	8	1.93	162	100	0.12	TB
E	(i)	20	W	3	8	9	9	12	2.05	158	99	0.13	T
E	(i)	20	W	4	11	11	9	10	1.99	156	99	0.13	T
E	(i)	20	W	5	10	10	10	10	2.07	157	100	0.13	T

Table A1.4. Mortar Programme Results, Southwater Engineering Brick, Mortar Grade (i), Laid Wet.

Brick	Mortar	Water (%)	Laying	Number	Joint Thickness (mm)				Failure Load (kN)	Length (mm)	Width (mm)	Failure Stress (N/mm^2)	Mode
F	(ii)	18½	D	1	10	10	10	10	4.40	152	100	0.29	B
F	(ii)	18½	D	2	10	10	10	10	4.45	152	100	0.29	B
F	(ii)	18½	D	3	10	10	11	11	4.90	152	100	0.32	B
F	(ii)	18½	D	4	10	10	11	11	3.80	146	100	0.26	B
F	(ii)	18½	D	5	11	10	11	11	5.55	154	101	0.36	B
F	(ii)	19	D	1	12	12	10	10	4.85	152	97	0.33	T
F	(ii)	19	D	2	12	13	10	10	4.80	152	98	0.32	T
F	(ii)	19	D	3	10	11	10	10	4.55	149	100	0.30	B
F	(ii)	19	D	4	12	11	11	10	4.70	153	100	0.31	B
F	(ii)	19	D	5	10	10	12	12	5.80	151	99	0.39	B
F	(ii)	19½	D	1	10	10	10	10	5.10	152	97	0.35	T
F	(ii)	19½	D	2	10	10	14	14	3.60	153	97	0.24	T
F	(ii)	19½	D	3	10	10	11	10	4.00	148	99	0.27	T
F	(ii)	19½	D	4	10	10	10	11	4.00	149	99	0.27	T
F	(ii)	19½	D	5	10	10	11	11	4.65	151	99	0.31	B
F	(ii)	20	D	1	10	10	12	12	4.80	152	98	0.32	T
F	(ii)	20	D	2	10	10	12	12	5.20	149	100	0.35	B
F	(ii)	20	D	3	10	10	12	12	5.40	152	97	0.37	T
F	(ii)	20	D	4	10	10	10	10	5.20	152	100	0.34	BM
F	(ii)	20	D	5	10	10	10	10	4.90	151	99	0.33	B
F	(ii)	20½	D	1	9	11	10	10	5.30	148	99	0.36	T
F	(ii)	20½	D	2	10	10	10	10	5.45	150	97	0.38	TB
F	(ii)	20½	D	3	9	10	10	10	5.40	152	95	0.37	T
F	(ii)	20½	D	4	10	10	10	10	4.60	150	98	0.31	T
F	(ii)	20½	D	5	11	10	12	12	5.50	153	99	0.36	TB
F	(ii)	21	D	1	10	10	10	10	4.35	150	97	0.30	T
F	(ii)	21	D	2	10	10	12	12	5.05	150	98	0.34	TB
F	(ii)	21	D	3	10	10	12	12	5.70	150	96	0.40	BT
F	(ii)	21	D	4	11	10	11	11	4.80	152	97	0.33	TB
F	(ii)	21	D	5	11	11	11	10	4.90	153	97	0.33	T

Table A1.5. Mortar Programme Results, Holbrook Facing Brick, Mortar Grade (ii), Laid Dry.

Brick	Mortar	Water (%)	Laying	Number	Joint Thickness (mm)				Failure Load (kN)	Length (mm)	Width (mm)	Failure Stress (N/mm^2)	Mode
F	(ii)	18½	W	1	10	10	12	11	4.80	153	98	0.32	T
F	(ii)	18½	W	2	10	10	12	12	4.10	153	99	0.27	T
F	(ii)	18½	W	3	11	10	11	10	3.40	152	97	0.23	T
F	(ii)	18½	W	4	10	10	11	11	4.25	151	99	0.28	T
F	(ii)	18½	W	5	10	10	10	11	4.20	154	98	0.28	T
F	(ii)	19	W	1	10	10	10	9	4.30	152	100	0.28	B
F	(ii)	19	W	2	9	10	10	10	4.50	153	98	0.30	T
F	(ii)	19	W	3	10	9	10	11	3.90	151	99	0.26	T
F	(ii)	19	W	4	10	10	10	10	4.15	153	98	0.28	T
F	(ii)	19	W	5	10	9	11	12	4.90	152	100	0.32	B
F	(ii)	19½	W	1	10	10	12	12	4.20	155	98	0.28	TB*
F	(ii)	19½	W	2	10	10	13	13	3.75	154	98	0.25	T
F	(ii)	19½	W	3	10	10	12	13	3.80	152	100	0.25	B
F	(ii)	19½	W	4	10	10	11	11	4.40	152	96	0.30	T
F	(ii)	19½	W	5	10	10	12	12	4.30	151	98	0.29	T
F	(ii)	20	W	1	10	10	10	11	4.30	155	96	0.29	T
F	(ii)	20	W	2	10	10	11	10	3.93	154	95	0.27	T
F	(ii)	20	W	3	10	10	10	10	4.37	153	96	0.30	T
F	(ii)	20	W	4	10	10	10	10	3.95	152	97	0.27	T
F	(ii)	20	W	5	10	10	11	10	4.60	154	100	0.30	B
F	(ii)	20½	W	1	10	10	10	10	4.65	154	98	0.31	T
F	(ii)	20½	W	2	10	10	11	11	3.75	154	98	0.25	T
F	(ii)	20½	W	3	11	10	12	12	4.05	155	96	0.27	T
F	(ii)	20½	W	4	10	10	12	11	4.00	154	99	0.26	T
F	(ii)	20½	W	5	10	10	9	10	4.40	155	98	0.29	T
F	(ii)	21	W	1	10	9	11	10	3.05	148	98	0.21	T
F	(ii)	21	W	2	10	10	11	10	3.30	150	97	0.23	T
F	(ii)	21	W	3	9	10	10	10	3.90	155	98	0.26	T
F	(ii)	21	W	4	11	10	11	11	3.70	154	96	0.25	T
F	(ii)	21	W	5	9	10	11	11	3.40	148	96	0.24	T

* Bottom brick broke into two pieces

Table A1.6. Mortar Programme Results, Holbrook Facing Brick, Mortar Grade (ii), Laid Wet.

Brick	Mortar	Water (%)	Laying	Number	Joint Thickness (mm)				Failure Load(kN)	Length(mm)	Width(mm)	Failure Stress(N/mm2)	Mode
E	(ii)	18½	D	1	11	10	11	11	2.39	165	100	0.14	BT
E	(ii)	18½	D	2	10	10	11	11	1.97	160	100	0.12	B
E	(ii)	18½	D	3	10	11	11	11	1.73	155	98	0.11	T
E	(ii)	18½	D	4	10	10	11	12	1.89	160	100	0.12	T
E	(ii)	18½	D	5	10	10	11	11	1.77	155	100	0.11	T
E	(ii)	19	D	1	10	9	11	11	2.76	153	99	0.18	T
E	(ii)	19	D	2	10	10	10	10	2.35	154	99	0.15	T
E	(ii)	19	D	3	11	11	10	10	2.38	156	99	0.15	T
E	(ii)	19	D	4	10	10	11	10	2.40	155	100	0.16	T
E	(ii)	19	D	5	11	10	12	11	2.29	154	99	0.15	T
E	(ii)	19½	D	1	9	11	10	9	2.43	155	100	0.16	T
E	(ii)	19½	D	2	11	10	10	10	2.25	156	100	0.14	T
E	(ii)	19½	D	3	10	10	10	10	2.77	155	100	0.18	T
E	(ii)	19½	D	4	10	10	12	10	2.81	159	100	0.18	T
E	(ii)	19½	D	5	10	10	10	11	2.53	156	99	0.16	T
E	(ii)	20	D	1	11	10	10	9	2.52	160	99	0.16	TB
E	(ii)	20	D	2	10	9	10	10	2.56	158	97	0.17	T
E	(ii)	20	D	3	10	10	11	10	3.07	155	99	0.20	TB
E	(ii)	20	D	4	10	9	11	10	3.05	157	101	0.19	T
E	(ii)	20	D	5	10	10	9	11	2.80	158	100	0.18	T
E	(ii)	20½	D	1	10	9	10	9	3.90	162	101	0.24	B
E	(ii)	20½	D	2	10	10	9	12	2.81	165	100	0.17	B
E	(ii)	20½	D	3	10	10	9	11	3.15	157	99	0.20	T
E	(ii)	20½	D	4	10	9	10	10	3.54	158	99	0.23	T
E	(ii)	20½	D	5	10	10	10	10	3.00	156	100	0.19	T
E	(ii)	21	D	1	11	9	9	10	3.19	161	99	0.20	T
E	(ii)	21	D	2	9	9	10	11	2.06	163	101	0.12	B
E	(ii)	21	D	3	10	8	9	10	*				
E	(ii)	21	D	4	9	8	9	10	3.04	157	98	0.20	T
E	(ii)	21	D	5	10	9	9	12	2.55	157	99	0.16	T

* Gap too narrow to test

Table A1.7. Mortar Programme Results, Southwater Engineering Brick, Mortar Grade (ii), Laid Dry.

Brick	Mortar	Water (%)	Laying	Number	Joint Thickness (mm)				Failure Load(kN)	Length(mm)	Width(mm)	Failure Stress(N/mm^2)	Mode
E	(ii)	18½	W	1	11	11	11	11	2.71	157	99	0.17	T
E	(ii)	18½	W	2	9	10	11	11	2.40	158	101	0.15	T
E	(ii)	18½	W	3	9	9	11	11	1.67	157	99	0.11	T
E	(ii)	18½	W	4	10	11	11	10	1.86	158	99	0.12	T
E	(ii)	18½	W	5	11	11	11	10	1.36	158	99	0.09	T
E	(ii)	19	W	1	11	11	12	10	2.17	154	99	0.14	T
E	(ii)	19	W	2	10	10	10	11	1.22	157	98	0.08	T
E	(ii)	19	W	3	10	10	11	10	1.26	157	99	0.08	T
E	(ii)	19	W	4	10	10	11	10	3.04	153	98	0.20	T
E	(ii)	19	W	5	10	10	11	11	2.75	165	100	0.17	B
E	(ii)	19½	W	1	10	11	10	9	1.69	157	99	0.11	T
E	(ii)	19½	W	2	11	11	9	8	1.99	152	99	0.13	T
E	(ii)	19½	W	3	9	10	10	9	1.88	153	99	0.12	T
E	(ii)	19½	W	4	10	11	11	12	2.40	158	99	0.15	T
E	(ii)	19½	W	5	10	9	10	9	2.42	158	102	0.15	T
E	(ii)	20	W	1	11	9	10	11	2.46	165	100	0.15	B
E	(ii)	20	W	2	11	10	11	9	1.60	158	99	0.10	T
E	(ii)	20	W	3	10	9	9	11	1.55	157	96	0.10	T
E	(ii)	20	W	4	10	10	10	9	1.76	158	99	0.11	T
E	(ii)	20	W	5	10	9	10	11	1.96	158	101	0.12	T
E	(ii)	20½	W	1	9	9	7	10	2.01	162	100	0.12	T
E	(ii)	20½	W	2	9	8	9	10	2.14	163	101	0.13	T
E	(ii)	20½	W	3	9	9	8	11	2.23	165	100	0.14	T
E	(ii)	20½	W	4	9	8	8	9	1.78	158	102	0.11	T
E	(ii)	20½	W	5	9	10	9	10	3.47	165	100	0.21	T
E	(ii)	21	W	1	9	8	9	9	2.38	162	97	0.15	T
E	(ii)	21	W	2	10	9	9	9	1.80	160	100	0.11	T
E	(ii)	21	W	3	10	10	9	12	2.21	163	100	0.14	B
E	(ii)	21	W	4	10	8	8	10	1.81	162	99	0.11	T
E	(ii)	21	W	5	10	10	9	10	2.07	160	98	0.13	T

Table A1.8. Mortar Programme Results, Southwater Engineering Brick, Mortar Grade (ii), Laid Wet.

Brick	Mortar	Water (%)	Laying	Number	Joint Thickness (mm)				Failure Load(kN)	Length(mm)	Width(mm)	Failure Stress(N/mm^2)	Mode
F	(iii)	19½	D	1	11	11	10	10	4.00	150	99	0.27	T
F	(iii)	19½	D	2	12	14	12	10	3.41	149	96	0.24	T
F	(iii)	19½	D	3	11	11	10	10	4.08	146	99	0.28	B
F	(iii)	19½	D	4	12	11	10	10	3.50	150	98	0.24	T
F	(iii)	19½	D	5	11	10	11	9	4.62	150	96	0.32	T
F	(iii)	20	D	1	11	11	10	9	4.13	148	100	0.28	B
F	(iii)	20	D	2	12	12	10	10	3.93	147	99	0.27	T
F	(iii)	20	D	3	11	14	12	10	3.99	147	100	0.27	B
F	(iii)	20	D	4	12	12	10	10	4.06	146	100	0.28	B
F	(iii)	20	D	5	10	10	12	11	4.51	151	100	0.30	B
F	(iii)	20½	D	1	10	9	10	11	3.56	148	99	0.24	T
F	(iii)	20½	D	2	10	10	10	10	4.41	150	99	0.30	BM
F	(iii)	20½	D	3	11	10	10	10	3.69	148	99	0.25	T
F	(iii)	20½	D	4	10	10	10	10	4.06	147	100	0.28	B
F	(iii)	20½	D	5	11	10	11	10	4.00	150	99	0.27	T
F	(iii)	21	D	1	11	11	11	11	3.35	151	98	0.23	T
F	(iii)	21	D	2	10	10	11	10	3.85	153	100	0.25	BM
F	(iii)	21	D	3	10	10	10	10	3.68	152	97	0.25	T
F	(iii)	21	D	4	10	10	10	12	4.28	154	99	0.28	TBM
F	(iii)	21	D	5	10	12	12	10	3.87	150	100	0.26	B
F	(iii)	21½	D	1	11	12	10	9	4.80	153	100	0.31	BM
F	(iii)	21½	D	2	11	11	11	9	4.50	152	98	0.30	TM
F	(iii)	21½	D	3	10	10	10	11	4.32	149	99	0.29	T
F	(iii)	21½	D	4	10	11	10	10	4.62	150	99	0.31	BTM
F	(iii)	21½	D	5	10	11	11	10	4.30	153	98	0.29	T
F	(iii)	22	D	1	10	10	11	11	4.42	151	97	0.30	T
F	(iii)	22	D	2	9	9	9	9	4.25	152	101	0.28	BM
F	(iii)	22	D	3	10	9	10	11	4.35	151	99	0.29	BTM
F	(iii)	22	D	4	10	10	11	11	4.30	151	97	0.29	T
F	(iii)	22	D	5	10	10	12	12	4.60	150	97	0.32	TBM

Table A1.9. Mortar Programme Results, Holbrook Facing Brick, Mortar Grade (iii), Laid Dry.

Brick	Mortar	Water (%)	Laying	Number	Joint Thickness (mm)				Failure Load (kN)	Length (mm)	Width (mm)	Failure Stress (N/mm^2)	Mode
F	(iii)	19½	W	1	12	15	10	10	3.32	151	98	0.22	T
F	(iii)	19½	W	2	13	12	11	10	3.89	153	99	0.26	TB
F	(iii)	19½	W	3	12	13	10	10	3.27	150	98	0.22	T
F	(iii)	19½	W	4	11	13	10	10	2.85	147	97	0.20	T
F	(iii)	19½	W	5	12	13	11	10	3.68	152	98	0.25	T
F	(iii)	20	W	1	10	10	10	9	3.71	150	97	0.26	T
F	(iii)	20	W	2	12	11	10	9	2.88	151	97	0.20	T
F	(iii)	20	W	3	10	10	11	11	4.82	152	98	0.32	TB
F	(iii)	20	W	4	9	10	11	10	4.65	152	96	0.32	T
F	(iii)	20	W	5	10	12	11	9	4.17	154	97	0.28	T
F	(iii)	20½	W	1	11	10	10	10	2.57	146	98	0.18	T
F	(iii)	20½	W	2	10	10	12	12	3.45	147	99	0.24	T
F	(iii)	20½	W	3	9	10	10	10	2.90	148	99	0.20	T
F	(iii)	20½	W	4	10	10	12	11	2.56	148	99	0.18	T
F	(iii)	20½	W	5	11	10	9	10	2.81	148	99	0.19	T
F	(iii)	21	W	1	10	10	11	11	3.12	155	99	0.20	T
F	(iii)	21	W	2	11	12	10	9	4.14	155	99	0.27	T
F	(iii)	21	W	3	11	10	10	11	3.95	153	99	0.26	T
F	(iii)	21	W	4	9	10	10	9	3.62	149	99	0.24	T
F	(iii)	21	W	5	10	11	10	10	2.88	151	99	0.19	T
F	(iii)	21½	W	1	11	12	11	10	2.97	152	97	0.20	T
F	(iii)	21½	W	2	10	11	10	9	3.79	149	96	0.26	T
F	(iii)	21½	W	3	10	11	11	11	3.41	152	95	0.24	T
F	(iii)	21½	W	4	10	10	10	10	2.71	154	96	0.18	T
F	(iii)	21½	W	5	10	10	10	10	2.89	152	99	0.19	T
F	(iii)	22	W	1	11	11	11	10	4.06	155	98	0.27	TBM
F	(iii)	22	W	2	10	9	8	9	4.48	151	98	0.30	T
F	(iii)	22	W	3	8	7	9	9	4.53	158	101	0.28	TBM
F	(iii)	22	W	4	10	9	9	10	2.98	154	99	0.20	T
F	(iii)	22	W	5	10	10	9	10	4.06	153	98	0.27	T

Table A1.10. Mortar Programme Results, Holbrook Facing Brick, Mortar Grade (iii), Laid Wet.

Brick	Mortar	Water (%)	Laying	Number	Joint Thickness (mm)				Failure Load(kN)	Length(mm)	Width(mm)	Failure Stress(N/mm^2)	Mode
E	(iii)	19	D	1	10	10	11	12	3.27	155	102	0.21	TM
E	(iii)	19	D	2	11	10	11	13	3.16	160	100	0.20	B
E	(iii)	19	D	3	9	9	11	8	2.29	157	100	0.15	T
E	(iii)	19	D	4	11	9	10	9	2.60	156	100	0.17	T
E	(iii)	19	D	5	10	11	11	10	2.90	157	102	0.18	T
E	(iii)	19½	D	1	10	11	11	10	3.34	155	99	0.22	T
E	(iii)	19½	D	2	11	10	12	11	3.80	160	100	0.24	B
E	(iii)	19½	D	3	10	10	11	10	3.59	155	99	0.23	TB
E	(iii)	19½	D	4	10	11	10	10	3.19	152	100	0.21	T
E	(iii)	19½	D	5	11	11	11	9	2.51	157	100	0.16	T
E	(iii)	20	D	1	9	9	10	10	3.00	156	99	0.19	T
E	(iii)	20	D	2	11	11	10	10	3.10	157	99	0.20	T
E	(iii)	20	D	3	9	9	10	9	2.35	160	100	0.15	T
E	(iii)	20	D	4	9	9	10	9	2.69	158	100	0.17	T
E	(iii)	20	D	5	10	11	10	10	3.02	154	100	0.20	T
E	(iii)	20½	D	1	10	9	9	10	2.07	153	102	0.13	T
E	(iii)	20½	D	2	9	9	8	10	2.56	155	101	0.16	T
E	(iii)	20½	D	3	10	9	10	11	2.48	155	99	0.16	T
E	(iii)	20½	D	4	10	11	10	9	1.70	151	100	0.11	T
E	(iii)	20½	D	5	10	9	9	10	2.62	153	101	0.17	T
E	(iii)	21	D	1	9	9	10	10	4.68	155	102	0.30	TM
E	(iii)	21	D	3	10	8	10	10	3.19	155	102	0.20	T
E	(iii)	21	D	4	9	8	10	9	2.51	160	101	0.16	T
E	(iii)	21½	D	1	8	11	10	8	2.32	165	99	0.14	B
E	(iii)	21½	D	2	9	10	10	10	3.41	158	100	0.22	T
E	(iii)	21½	D	3	9	11	10	8	2.33	165	100	0.14	T
E	(iii)	21½	D	4	9	10	10	10	3.26	158	100	0.21	T
E	(iii)	21½	D	5	10	10	10	10	3.03	157	101	0.19	T

Table A1.11. Mortar Programme Results, Southwater Engineering Brick, Mortar Grade (iii), Laid Dry.

Brick	Mortar	Water (%)	Laying	Number	Joint Thickness (mm)				Failure Load(kN)	Length(mm)	Width(mm)	Failure Stress(N/mm^2)	Mode
E	(iii)	19	W	1	11	10	11	10	3.15	165	100	0.19	B
E	(iii)	19	W	2	11	11	10	10	2.40	158	100	0.15	T
E	(iii)	19	W	3	11	12	11	10	1.92	155	100	0.12	T
E	(iii)	19	W	4	9	10	10	9	2.89	155	101	0.18	T
E	(iii)	19	W	5	10	11	12	10	2.38	156	100	0.15	T
E	(iii)	19½	W	1	10	9	11	10	2.26	155	100	0.15	T
E	(iii)	19½	W	2	11	11	10	10	1.71	156	97	0.11	T
E	(iii)	19½	W	3	10	10	10	10	2.16	155	100	0.14	T
E	(iii)	19½	W	4	10	10	10	10	2.03	155	99	0.13	T
E	(iii)	19½	W	5	10	11	10	9	1.61	152	100	0.11	T
E	(iii)	20	W	1	9	9	10	11	1.84	161	100	0.11	T
E	(iii)	20	W	2	9	12	9	9	2.12	156	100	0.14	T
E	(iii)	20	W	3	10	11	11	10	1.50	155	99	0.10	T
E	(iii)	20	W	4	10	10	11	10	2.66	155	98	0.18	T
E	(iii)	20	W	5	11	11	10	10	2.57	155	99	0.17	T
E	(iii)	20½	W	1	8	9	9	8	1.50	160	102	0.09	T
E	(iii)	20½	W	2	9	10	10	9	2.24	160	102	0.14	T
E	(iii)	20½	W	3	8	10	10	8	1.95	162	105	0.12	T
E	(iii)	20½	W	4	9	9	9	9	2.42	158	101	0.15	T
E	(iii)	21	W	1	9	9	9	9	1.94	160	102	0.12	T
E	(iii)	21	W	2	9	9	9	10	1.72	165	101	0.10	B
E	(iii)	21	W	3	10	10	10	9	1.69	157	100	0.11	T
E	(iii)	21	W	4	9	10	10	9	2.30	165	100	0.14	B
E	(iii)	21½	W	1	9	10	12	10	3.40	157	101	0.21	T
E	(iii)	21½	W	2	9	8	10	9	3.14	160	103	0.19	T
E	(iii)	21½	W	3	8	9	9	9	2.54	162	100	0.16	TM
E	(iii)	21½	W	4	8	10	9	8	1.91	165	99	0.12	T
E	(iii)	21½	W	5	9	10	10	8	1.79	164	100	0.11	T

Table A1.12. Mortar Programme Results, Southwater Engineering Brick, Mortar Grade (iii), Laid Wet.

Brick	Mortar	Water (%)	Laying Number	Joint Thickness (mm)				Failure Load(kN)	Length(mm)	Width(mm)	Failure Stress(N/mm^2)	Mode
F	(iv)	20	D 1	10	10	10	10	3.32	151	100	0.22	BM
F	(iv)	20	D 2	10	10	10	10	2.46	148	98	0.17	BM
F	(iv)	20	D 3	10	10	11	10	3.68	153	99	0.24	TM
F	(iv)	20	D 4	10	12	11	10	3.45	153	95	0.24	TMB
F	(iv)	20	D 5	10	11	12	11	3.20	155	99	0.21	BM
F	(iv)	20½	D 1	10	10	10	10	3.03	150	100	0.20	BM
F	(iv)	20½	D 2	10	10	10	10	3.06	152	100	0.20	BM
F	(iv)	20½	D 3	10	10	10	10	2.84	147	97	0.20	TM
F	(iv)	20½	D 4	11	12	10	10	2.70	152	96	0.18	TM
F	(iv)	20½	D 5	10	11	11	11	3.71	150	100	0.25	BTM
F	(iv)	21	D 1	11	10	10	10	3.32	151	100	0.22	BM
F	(iv)	21	D 2	11	10	11	10	3.04	152	99	0.20	BM
F	(iv)	21	D 3	10	10	10	11	3.47	150	99	0.23	MB
F	(iv)	21	D 4	10	11	10	10	3.84	151	99	0.26	MB
F	(iv)	21	D 5	10	10	10	10	3.31	149	98	0.23	MBT
F	(iv)	21½	D 1	10	10	10	10	3.25	155	99	0.21	MB
F	(iv)	21½	D 2	10	11	10	11	3.87	150	96	0.27	MB
F	(iv)	21½	D 3	10	11	11	10	3.23	150	99	0.22	MB
F	(iv)	21½	D 4	11	10	10	11	3.20	154	99	0.21	MB
F	(iv)	21½	D 5	11	11	11	10	3.27	150	100	0.22	MB
F	(iv)	22	D 1	10	10	11	11	2.93	152	95	0.20	MT
F	(iv)	22	D 2	10	10	10	10	3.18	147	99	0.22	MB
F	(iv)	22	D 3	10	10	11	11	3.16	147	95	0.23	MT
F	(iv)	22	D 4	10	10	11	11	2.61	151	96	0.18	TM
F	(iv)	22	D 5	10	10	11	10	3.70	147	97	0.26	MBT
F	(iv)	22½	D 1	10	9	11	10	3.71	152	97	0.25	MB
F	(iv)	22½	D 2	10	10	10	10	3.51	152	97	0.24	MTB
F	(iv)	22½	D 3	10	10	11	11	3.78	151	96	0.26	M
F	(iv)	22½	D 4	10	10	11	11	2.27	151	97	0.16	T
F	(iv)	22½	D 5	10	10	10	11	3.35	148	97	0.23	MTB

Table A1.13. Mortar Programme Results, Holbrook Facing Brick, Mortar Grade (iv), Laid Dry.

Brick	Mortar	Water (%)	Laying Number	Joint Thickness (mm)				Failure Load (kN)	Length (mm)	Width (mm)	Failure Stress (N/mm²)	Mode
F	(iv)	20	W 1	10	10	11	11	3.69	152	99	0.24	TM
F	(iv)	20	W 2	10	10	12	12	3.20	151	99	0.21	TMB
F	(iv)	20	W 3	10	10	11	11	2.73	152	96	0.19	TM
F	(iv)	20	W 4	12	11	11	11	1.98	154	97	0.13	T
F	(iv)	20	W 5	11	11	11	11	2.91	153	95	0.20	T
F	(iv)	20½	W 1	10	10	10	10	2.00	152	99	0.13	TM
F	(iv)	20½	W 2	11	11	11	11	2.62	151	97	0.18	T
F	(iv)	20½	W 3	10	10	10	11	2.29	153	97	0.15	T
F	(iv)	20½	W 4	10	10	10	10	3.61	152	98	0.24	MB
F	(iv)	20½	W 5	10	10	11	10	3.59	150	98	0.24	MTB
F	(iv)	21	W 1	10	10	10	11	2.85	152	95	0.20	MT
F	(iv)	21	W 2	10	10	11	11	3.20	152	96	0.22	MT
F	(iv)	21	W 3	10	10	10	10	3.08	150	100	0.20	MTB
F	(iv)	21	W 4	10	10	12	11	2.88	152	95	0.20	MT
F	(iv)	21	W 5	10	10	11	11	3.50	152	96	0.24	MT
F	(iv)	21½	W 1	10	10	10	10	2.40	154	95	0.16	T
F	(iv)	21½	W 2	10	10	12	12	2.10	155	95	0.14	T
F	(iv)	21½	W 3	10	11	12	11	2.65	152	94	0.18	TM
F	(iv)	21½	W 4	10	10	10	11	2.41	152	94	0.17	T
F	(iv)	21½	W 5	10	11	12	11	2.02	155	96	0.14	T
F	(iv)	22	W 1	10	10	10	10	2.11	148	97	0.15	T
F	(iv)	22	W 2	10	10	11	10	2.80	150	95	0.20	TM
F	(iv)	22	W 3	10	10	11	10	3.13	150	97	0.22	T
F	(iv)	22	W 4	10	11	10	11	2.10	150	94	0.15	T
F	(iv)	22	W 5	10	10	11	11	2.50	153	97	0.17	T
F	(iv)	22½	W 1	10	10	11	11	3.52	149	96	0.25	M
F	(iv)	22½	W 2	10	10	12	11	3.35	150	95	0.24	MT
F	(iv)	22½	W 3	10	9	12	11	3.18	151	95	0.22	MT
F	(iv)	22½	W 4	9	9	11	10	2.41	151	97	0.16	TBM
F	(iv)	22½	W 5	10	10	12	11	2.16	150	95	0.15	TM

Table A1.14. Mortar Programme Results, Holbrook Facing Brick, Mortar Grade (iv), Laid Wet.

Brick	Mortar	Water (%)	Laying	Number	Joint Thickness (mm)				Failure Load(kN)	Length(mm)	Width(mm)	Failure Stress(N/mm²)	Mode
E	(iv)	20	D	1	10	10	11	11	1.86	154	101	0.13	T
E	(iv)	20	D	2	11	10	11	11	1.64	160	101	0.10	BM
E	(iv)	20	D	3	11	11	10	10	1.84	155	96	0.12	T
E	(iv)	20	D	4	10	10	10	10	2.23	156	100	0.14	BM
E	(iv)	20	D	5	9	10	10	12	1.91	156	99	0.12	T
E	(iv)	20½	D	1	11	10	10	12	1.88	160	101	0.12	BM
E	(iv)	20½	D	2	10	9	10	10	2.65	158	99	0.17	T
E	(iv)	20½	D	3	11	10	10	10	2.40	153	99	0.16	T
E	(iv)	20½	D	4	11	11	10	10	1.87	156	98	0.12	T
E	(iv)	20½	D	5	10	10	10	11	2.61	153	100	0.17	TM
E	(iv)	21	D	1	10	9	9	11	2.71	157	100	0.17	T
E	(iv)	21	D	2	11	10	11	10	2.49	155	100	0.16	T
E	(iv)	21	D	3	12	10	10	10	2.88	157	100	0.18	MB
E	(iv)	21	D	4	9	8	8	9	2.59	158	100	0.16	TM
E	(iv)	21	D	5	10	9	10	11	2.22	157	99	0.14	T
E	(iv)	21½	D	1	10	9	11	10	2.03	158	95	0.14	T
E	(iv)	21½	D	2	11	11	11	10	1.46	155	96	0.10	T
E	(iv)	21½	D	3	10	11	12	11	1.02	156	97	0.07	T
E	(iv)	21½	D	4	10	11	11	10	2.08	155	97	0.14	T
E	(iv)	21½	D	5	10	9	9	11	2.44	156	98	0.16	TM
E	(iv)	22	D	1	10	11	10	10	1.70	151	98	0.12	T
E	(iv)	22	D	2	10	10	11	10	2.30	156	98	0.15	TM
E	(iv)	22	D	3	10	9	11	10	1.90	155	97	0.13	TM
E	(iv)	22	D	4	10	9	8	10	2.03	157	98	0.13	T
E	(iv)	22	D	5	9	10	10	9	1.78	157	98	0.12	T
E	(iv)	22½	D	1	10	9	9	10	2.50	158	95	0.17	T
E	(iv)	22½	D	2	11	10	9	11	2.90	158	99	0.18	T
E	(iv)	22½	D	3	9	10	10	9	1.74	160	98	0.11	T
E	(iv)	22½	D	4	10	8	9	11	2.30	158	99	0.15	T
E	(iv)	22½	D	5	10	10	10	9	1.81	157	97	0.13	T

Table A1.15. Mortar Programme Results, Southwater Engineering Brick, Mortar Grade (iv), Laid Dry.

Brick	Mortar	Water (%)	Laying	Number	Joint Thickness (mm)				Failure Load (kN)	Length (mm)	Width (mm)	Failure Stress (N/mm^2)	Mode
E	(iv)	20	W	1	10	9	10	11	2.61	157	99	0.17	T
E	(iv)	20	W	2	9	9	9	10	2.00	156	100	0.13	T
E	(iv)	20	W	3	10	8	10	10	1.52	157	100	0.10	T
E	(iv)	20	W	4	10	10	11	11	2.95	155	99	0.19	BM
E	(iv)	20	W	5	10	10	10	10	2.12	157	101	0.13	T
E	(iv)	20½	W	1	10	8	10	11	1.77	157	101	0.11	BM
E	(iv)	20½	W	2	10	10	9	11	1.89	158	100	0.12	T
E	(iv)	20½	W	3	10	10	11	10	2.37	155	99	0.15	T
E	(iv)	20½	W	4	10	8	11	9	2.21	159	101	0.14	T
E	(iv)	21	W	1	11	9	7	9	1.21	162	100	0.08	T
E	(iv)	21	W	2	11	9	10	13	1.60	158	99	0.10	T
E	(iv)	21	W	3	10	8	9	10	2.06	160	100	0.13	T
E	(iv)	21	W	4	10	10	8	14	1.24	157	100	0.08	T
E	(iv)	21	W	5	10	9	9	11	1.36	157	98	0.09	T
E	(iv)	21½	W	1	10	10	10	9	1.39	155	98	0.09	T
E	(iv)	21½	W	2	10	11	11	10	1.38	148	98	0.10	T
E	(iv)	21½	W	3	10	9	9	9	1.55	156	98	0.10	T
E	(iv)	21½	W	4	11	10	10	10	1.52	153	97	0.10	T
E	(iv)	21½	W	5	10	10	10	9	1.87	158	99	0.12	T
E	(iv)	22	W	1	11	10	10	10	1.55	156	98	0.10	T
E	(iv)	22	W	2	9	7	8	10	1.51	161	100	0.09	T
E	(iv)	22	W	3	11	9	8	11	1.59	155	98	0.10	T
E	(iv)	22	W	4	9	9	9	9	1.83	160	98	0.12	T
E	(iv)	22	W	5	9	10	10	9	1.74	154	98	0.12	T
E	(iv)	22½	W	1	10	9	9	10	1.58	158	99	0.10	T
E	(iv)	22½	W	2	10	10	9	9	2.22	157	97	0.15	T
E	(iv)	22½	W	3	10	11	10	9	1.88	158	98	0.12	T
E	(iv)	22½	W	4	9	8	9	10	2.16	156	98	0.14	T
E	(iv)	22½	W	5	12	9	8	10	2.05	158	98	0.13	T

Table A1.16. Mortar Programme Results, Southwater Engineering Brick, Mortar Grade (iv), Laid Wet.

Brick	Sand	Laying	Number	Joint Thickness (mm)				Failure Load(kN)	Length(mm)	Width(mm)	Failure Stress(N/mm^2)	Failure Plane Location		
												T	M	B
F	F	D	1	10	9	10	10	3.60	148	96	0.25	100		
F	F	D	2	10	10	10	10	4.00	151	97	0.27	100		
F	F	D	3	10	11	11	11	4.10	148	96	0.29	100		
F	F	D	4	10	11	10	10	4.50	148	100	0.30			100
F	F	D	5	10	10	10	10	4.15	149	96	0.29	100		
F	F	D	6	10	10	10	11	4.15	148	97	0.29	100		
F	F	D	7	11	10	10	11	4.25	151	96	0.29	100		
F	F	D	8	9	10	10	10	4.60	148	99	0.31			100
F	F	D	9	10	10	11	11	4.85	149	100	0.33			100
F	F	D	10	10	11	11	10	3.95	148	100	0.27			100
F	N	D	1	10	10	11	11	5.35	152	97	0.36	100		
F	N	D	2	10	10	10	10	5.75	150	100	0.38			100
F	N	D	3	10	11	11	11	5.90	149	100	0.40		10	90
F	N	D	4	10	10	10	10	4.80	151	96	0.33	100		
F	N	D	5	10	10	10	10	4.40	151	98	0.30	100		
F	N	D	6	10	10	10	10	5.10	146	100	0.35			100
F	N	D	7	11	10	10	10	4.55	149	99	0.31			100
F	N	D	8	10	10	10	10	4.20	150	97	0.29	100		
F	N	D	9	10	9	11	11	4.85	152	96	0.33	100		
F	N	D	10	10	10	11	10	4.70	150	97	0.32	100		
F	1C	D	1	10	11	10	11	4.85	149	100	0.33			100
F	1C	D	2	12	12	11	11	4.65	155	98	0.31	100		
F	1C	D	3	10	10	10	10	4.60	152	97	0.31	100		
F	1C	D	4	10	10	10	11	4.80	149	97	0.33	100		65
F	1C	D	5	10	10	11	11	4.65	152	100	0.31			100
F	1C	D	6	10	10	10	11	4.70	146	100	0.32			100
F	1C	D	7	10	10	10	10	4.50	148	97	0.31	100		
F	1C	D	8	10	10	10	11	5.50	151	98	0.37	100		
F	1C	D	9	10	10	10	10	5.00	150	96	0.35	100		
F	1C	D	10	10	10	10	10	5.30	149	99	0.36	10	15	80

Table A1.17. Sand Grading Programme Results, Holbrook Facing Brick, Laid Dry.

Brick	Sand	Laying	Number	Joint Thickness (mm)				Failure Load(kN)	Length(mm)	Width(mm)	Failure Stress(N/mm^2)	Failure Plane Location		
												T	M	B
F	F	W	1	11	11	11	11	4.06	149	98	0.28	100		
F	F	W	2	10	10	10	11	4.51	151	98	0.30	100		
F	F	W	3	10	10	10	10	4.11	153	97	0.28	100		
F	F	W	4	10	10	10	10	4.95	148	98	0.34	100		
F	F	W	5	10	11	10	10	4.52	150	97	0.31	100		
F	F	W	6	10	10	10	9	4.50	149	98	0.31	100		
F	F	W	7	10	10	10	10	3.90	146	98	0.27	100		
F	F	W	8	10	10	11	10	3.79	147	98	0.26	100		
F	F	W	9	10	10	10	10	3.87	147	98	0.27	100		
F	F	W	10	9	10	10	11	4.00	150	98	0.27	100		
F	N	W	1	10	10	10	10	3.65	150	97	0.25	100		
F	N	W	2	10	10	10	10	3.70	151	99	0.25	100		
F	N	W	3	9	10	10	11	5.00	150	96	0.35	100		
F	N	W	4	10	9	10	10	4.10	153	97	0.28	100		
F	N	W	5	10	10	10	11	4.75	154	99	0.31	60		40 *
F	N	W	6	11	11	11	11	4.15	151	96	0.28	100		
F	N	W	7	11	10	10	11	4.30	149	100	0.29			100
F	N	W	8	10	9	10	10	4.50	147	100	0.31			100
F	N	W	9	11	10	10	10	5.00	149	100	0.34			100
F	N	W	10	11	10	10	10	4.45	152	97	0.30	100		

* Bottom brick broke into two pieces

F	1C	W	1	10	10	10	10	4.30	152	100	0.28			100
F	1C	W	2	11	10	10	11	5.00	151	97	0.34	100		30
F	1C	W	3	10	10	10	10	2.85	149	97	0.20	100		
F	1C	W	4	10	10	10	10	4.00	153	96	0.27	100		
F	1C	W	5	11	10	11	11	3.65	153	96	0.25	100		
F	1C	W	6	11	10	10	11	4.25	150	97	0.29	100		
F	1C	W	7	10	10	12	11	3.85	152	95	0.27	100		
F	1C	W	8	10	10	10	11	3.60	149	97	0.25	100		
F	1C	W	9	10	11	10	9	3.60	146	99	0.25			100
F	1C	W	10	10	10	10	10	3.35	150	96	0.23	100		

Table A1.18. Sand Grading Programme Results, Holbrook Facing Brick, Laid Wet.

Brick	Sand	Laying	Number	Joint Thickness (mm)				Failure Load(kN)	Length(mm)	Width(mm)	Failure Stress(N/mm^2)	Failure Plane Location		
												T	M	B
F	2C	D	1	12	11	11	11	5.80	150	100	0.39	10	25	65
F	2C	D	2	11	10	10	10	5.35	149	100	0.36		30	70
F	2C	D	3	10	11	10	11	5.30	146	99	0.37	5	20	75
F	2C	D	4	10	10	10	11	6.00	151	97	0.41	100		
F	2C	D	5	10	10	11	10	5.25	148	99	0.36			100
F	2C	D	6	12	10	10	10	4.60	147	95	0.33	100		
F	2C	D	7	10	10	11	12	5.65	151	97	0.39	100		
F	2C	D	8	10	11	11	10	4.95	147	100	0.34			100
F	2C	D	9	10	10	11	10	4.60	150	97	0.32	100		
F	2C	D	10	10	10	10	11	5.70	146	100	0.39		5	95
F	3C	D	1	10	10	11	10	4.85	146	95	0.35	100		
F	3C	D	2	10	11	11	11	4.25	146	97	0.30	100		
F	3C	D	3	10	11	11	10	5.30	149	98	0.36		5	95
F	3C	D	4	10	10	10	11	5.15	151	95	0.36	100		50
F	3C	D	5	10	10	11	11	5.20	150	95	0.36	100		
F	3C	D	6	10	10	11	10	4.85	150	96	0.34	100		
F	3C	D	7	10	11	11	11	5.25	150	95	0.37	100		
F	3C	D	8	10	11	10	11	5.25	152	97	0.36	100		
F	3C	D	9	10	10	10	11	4.45	147	100	0.30			100
F	3C	D	10	10	10	11	11	5.25	151	94	0.37	100		
F	4C	D	1	10	10	11	11	4.15	150	96	0.29	100		
F	4C	D	2	10	11	10	11	4.75	148	96	0.33	100		
F	4C	D	3	10	10	10	10	5.75	150	96	0.40	100		
F	4C	D	4	10	10	10	10	6.30	151	99	0.42		5	95
F	4C	D	5	10	10	10	10	6.55	152	97	0.44	60		60
F	4C	D	6	10	10	10	11	5.65	153	95	0.39	100		55
F	4C	D	7	10	11	11	10	5.00	151	96	0.34	100		
F	4C	D	8	10	10	11	11	6.00	151	94	0.42	100		
F	4C	D	9	10	10	10	11	6.20	154	96	0.42	100		
F	4C	D	10	10	11	11	12	5.35	151	97	0.36	100		

Table A1.19. Sand Grading Programme Results, Holbrook Facing Brick, Laid Dry.

Brick	Sand	Laying	Number	Joint Thickness (mm)				Failure Load(kN)	Length(mm)	Width(mm)	Failure Stress(N/mm^2)	Failure Plane Location T	M	B
F	20C	W	1	10	11	10	10	3.50	155	97	0.23	100		
F	20C	W	2	10	11	10	11	4.65	149	98	0.32	100		
F	20C	W	3	10	10	10	10	3.35	150	98	0.23	100		
F	20C	W	4	10	11	10	10	3.40	148	96	0.24	100		
F	20C	W	5	10	11	11	11	3.70	152	97	0.25	100		
F	20C	W	6	10	10	10	10	4.10	150	97	0.28	100		
F	20C	W	7	10	10	10	10	3.40	150	99	0.23	100		
F	20C	W	8	11	10	11	10	4.70	152	96	0.32	100		
F	20C	W	9	10	11	11	10	4.05	150	96	0.28	100		
F	20C	W	10	9	11	10	10	4.00	149	97	0.28	100		
F	30C	W	1	10	11	11	10	4.20	153	98	0.28	100		
F	30C	W	2	11	11	11	10	4.65	153	96	0.32	100		
F	30C	W	3	10	11	11	11	4.75	151	98	0.32	10	10	80
F	30C	W	4	10	10	10	10	3.70	152	97	0.25	100		
F	30C	W	5	10	11	11	10	4.30	147	100	0.29			100
F	30C	W	6	10	11	10	11	5.95	153	96	0.40	100		
F	30C	W	7	10	11	11	11	4.05	154	96	0.27	100		
F	30C	W	8	11	10	11	10	4.45	152	96	0.30	100		
F	30C	W	9	11	10	11	11	3.70	151	96	0.26	100		
F	30C	W	10	10	10	10	10	3.90	150	97	0.27	100		
F	40C	W	1	10	10	11	10	4.35	152	95	0.30	100		
F	40C	W	2	10	10	10	10	4.00	150	95	0.28	100		
F	40C	W	3	11	11	11	11	3.90	150	96	0.27	100		
F	40C	W	4	10	11	10	10	3.75	151	96	0.26	100		
F	40C	W	5	11	10	11	11	4.15	149	97	0.29	100		
F	40C	W	6	10	10	11	10	5.10	152	97	0.35	100		
F	40C	W	7	11	12	11	10	4.00	150	97	0.28	100		
F	40C	W	8	10	10	11	11	4.10	149	97	0.28	100		
F	40C	W	9	11	11	10	10	5.05	148	97	0.35	75		55
F	40C	W	10	10	10	10	10	4.60	146	100	0.32		5	95

Table A1.20. Sand Grading Programme Results, Holbrook Facing Brick, Laid Wet.

Brick	Sand	Laying	Number	Joint Thickness (mm)				Failure Load(kN)	Length(mm)	Width(mm)	Failure Stress(N/mm^2)	Failure Plane Location		
												T	M	B
F	5C	D	1	10	10	10	10	5.70	142	101	0.40		5	95
F	5C	D	2	10	10	11	10	5.00	147	97	0.35	95	5	
F	5C	D	3	10	10	10	10	4.40	145	97	0.31	95	5	
F	5C	D	4	10	10	10	10	6.40	146	98	0.45	95	5	
F	5C	D	5	10	9	10	11	5.70	145	100	0.39		5	95
F	5C	D	6	10	10	11	10	4.70	148	95	0.33	100		
F	5C	D	7	10	10	10	11	5.40	148	101	0.36		15	85
F	5C	D	8	10	10	10	11	6.15	151	96	0.42	95	5	30
F	5C	D	9	10	10	11	11	5.50	148	98	0.38	95	5	
F	5C	D	10	10	10	11	11	6.75	154	96	0.46	90	10	35
E	F	D	1	10	9	10	11	3.34	155	99	0.22	100		
E	F	D	2	11	10	10	10	3.12	161	101	0.19			100
E	F	D	3	11	9	11	10	4.05	160	101	0.25		10	90
E	F	D	4	9	11	10	12	3.54	158	100	0.22	100		
E	F	D	5	11	9	10	9	2.33	156	101	0.15	100		
E	F	D	6	9	12	10	11	3.35	157	98	0.22	95	5	
E	F	D	7	10	12	10	12	3.87	158	99	0.25	100		
E	F	D	8	10	10	11	12	3.21	155	99	0.21	100		
E	F	D	9	9	10	9	8	3.91	157	100	0.25		10	100
E	F	D	10	11	11	10	10	3.09	155	98	0.20	100		
E	N	D	1	10	10	10	10	3.50	160	100	0.22		30	70
E	N	D	2	10	9	11	8	2.10	158	97	0.14	95	5	
E	N	D	3	9	11	10	9	2.68	151	98	0.18	100		
E	N	D	4	10	11	10	10	3.28	157	100	0.21			100
E	N	D	5	10	11	10	10	2.41	155	99	0.16	100		
E	N	D	6	11	10	10	10	3.20	155	98	0.21	100		
E	N	D	7	10	11	9	10	3.80	160	100	0.24		10	90
E	N	D	8	9	9	11	9	3.14	156	99	0.20	100		
E	N	D	9	9	10	12	10	3.65	156	98	0.24	100		
E	N	D	10	9	9	10	9	1.65	158	97	0.11	100		

Table A1.21. Sand Grading Programme Results, Bricks Laid Dry.

Brick	Sand	Laying	Number	Joint Thickness (mm)				Failure Load(kN)	Length(mm)	Width(mm)	Failure Stress(N/mm^2)	Failure Plane Location		
												T	M	B
F	50	W	1	10	9	11	10	5.10	151	97	0.35	100		
F	50	W	2	10	10	10	11	5.00	152	95	0.35	100		
F	50	W	3	11	10	11	10	5.60	151	95	0.39	100		
F	50	W	4	10	9	12	11	4.10	152	95	0.28	100		
F	50	W	5	11	10	11	11	5.25	150	96	0.36	100		
F	50	W	6	9	8	11	12	4.55	151	96	0.31	100		
F	50	W	7	10	11	11	11	4.80	152	95	0.33	55		55
F	50	W	8	11	10	11	10	5.90	149	95	0.42	70	5	70
F	50	W	9	11	10	10	11	3.35	152	97	0.23	100		
F	50	W	10	10	10	10	10	3.70	151	96	0.26	100		
E	F	W	1	11	11	9	10	1.80	155	100	0.12	100		
E	F	W	2	10	11	9	10	2.07	155	100	0.13	100		
E	F	W	3	10	10	10	9	1.79	149	99	0.12	100		
E	F	W	4	10	10	9	10	1.56	151	101	0.10	100		
E	F	W	5	10	11	10	10	2.57	152	99	0.17	100		
E	F	W	6	9	8	10	10	1.93	154	100	0.12	100		
E	F	W	7	10	10	9	9	1.88	156	101	0.12	100		
E	F	W	8	10	10	9	9	1.83	151	101	0.12	100		
E	F	W	9	10	10	9	9	1.60	151	99	0.11	100		
E	F	W	10	10	11	9	8	2.09	156	99	0.14	100		
E	N	W	1	10	11	11	10	3.19	158	98	0.21		10	90
E	N	W	2	9	10	10	9	3.11	158	100	0.20	100		
E	N	W	3	8	9	10	9	2.24	163	98	0.14	100		
E	N	W	4	10	10	10	10	3.12	154	99	0.20	95	5	
E	N	W	5	10	10	10	10	3.39	155	100	0.22	100		
E	N	W	6	9	9	10	10	2.90	156	96	0.19	100		
E	N	W	7	9	9	9	9	3.28	161	99	0.21			100
E	N	W	8	10	10	10	9	3.02	157	96	0.20	95	5	
E	N	W	9	9	11	10	9	3.21	156	96	0.21	100		
E	N	W	10	9	11	10	9	1.87	161	99	0.12			100

Table A1.22. Sand Grading Programme Results, Bricks Laid Wet.

Brick	Sand	Laying	Number	Joint Thickness (mm)				Failure Load(kN)	Length(mm)	Width(mm)	Failure Stress(N/mm2)	Failure Plane Location		
												T	M	B
E	1C	D	1	10	10	10	9	4.09	154	99	0.27	100		
E	1C	D	2	9	11	9	9	4.61	158	99	0.30		25	75
E	1C	D	3	10	10	10	9	3.60	154	100	0.23	100		
E	1C	D	4	9	11	10	10	3.95	159	100	0.25		30	70
E	1C	D	5	10	11	11	10	3.66	155	100	0.24	100		
E	1C	D	6	9	11	10	9	2.62	155	98	0.17	100		
E	1C	D	7	11	10	13	10	2.35	154	97	0.16	100		
E	1C	D	8	11	10	10	11	3.74	153	100	0.24	100		
E	1C	D	9	10	11	10	9	4.20	152	98	0.28	100		
E	1C	D	10	10	10	10	9	4.55	153	98	0.30	100		
E	2C	D	1	10	10	11	11	4.21	158	101	0.26		20	80
E	2C	D	2	9	10	9	10	3.84	160	101	0.24		5	95
E	2C	D	3	9	9	10	10	4.50	160	99	0.28		10	90
E	2C	D	4	9	10	10	10	3.30	157	100	0.21	95	5	
E	2C	D	5	7	11	9	10	2.96	158	99	0.19	100		
E	2C	D	6	9	9	9	10	4.39	157	98	0.28	100		
E	2C	D	7	9	9	10	11	3.35	162	100	0.21		30	70
E	2C	D	8	10	10	9	10	4.00	157	100	0.26		40	60
E	2C	D	9	9	11	12	11	3.74	157	101	0.24		30	70
E	2C	D	10	8	12	11	11	3.33	162	100	0.21		15	85
E	3C	D	1	8	10	9	9	3.28	156	100	0.21	95	5	
E	3C	D	2	10	10	11	10	4.36	156	99	0.28	100		
E	3C	D	3	9	9	10	9	3.27	157	99	0.21	55	45	
E	3C	D	4	9	10	10	10	3.97	158	100	0.25	10	45	45
E	3C	D	5	9	10	10	10	2.60	159	98	0.17	95	5	
E	3C	D	6	8	10	9	9	3.12	157	98	0.20	95	5	
E	3C	D	7	10	10	10	10	3.42	154	99	0.22	95	5	
E	3C	D	8	9	10	10	9	2.70	158	98	0.17	100		
E	3C	D	9	8	10	10	9	3.47	162	100	0.21	100		55
E	3C	D	10	8	10	10	9	4.08	160	100	0.26	100		

Table A1.23. Sand Grading Programme Results, Southwater Engineering Brick, Laid Dry.

Brick	Sand	Laying	Number	Joint Thickness (mm)				Failure Load(kN)	Length(mm)	Width(mm)	Failure Stress(N/mm^2)	Failure Plane Location		
												T	M	B
E	1C	W	1	10	10	10	10	2.25	157	98	0.15	100		
E	1C	W	2	10	11	10	10	2.30	156	98	0.15	100	15	
E	1C	W	3	10	10	10	10	3.60	155	97	0.24	100		
E	1C	W	4	10	12	9	11	2.48	158	99	0.16	100		
E	1C	W	5	9	11	11	10	2.14	157	100	0.14	100		
E	1C	W	6	10	10	10	9	2.80	158	98	0.18	100		
E	1C	W	7	10	10	10	11	2.91	165	100	0.18		5	95
E	1C	W	8	11	10	10	10	2.76	157	97	0.18	100		
E	1C	W	9	9	10	9	9	2.79	155	99	0.18	100		
E	1C	W	10	9	10	10	9	2.59	158	100	0.16	100		
E	2C	W	1	8	10	11	10	2.71	157	99	0.17	100		
E	2C	W	2	9	11	10	10	3.13	156	98	0.20	100		
E	2C	W	3	10	10	10	10	1.61	153	99	0.11	100		
E	2C	W	4	9	10	10	10	3.39	154	100	0.22	90	10	45
E	2C	W	5	8	10	11	8	3.10	157	98	0.20	100		
E	2C	W	6	9	10	10	9	3.02	157	99	0.19	100		
E	2C	W	7	10	9	9	10	2.92	158	98	0.19	100		
E	2C	W	8	11	11	10	9	3.90	154	97	0.26	100		
E	2C	W	9	9	10	10	10	3.31	154	97	0.22	100		
E	2C	W	10	8	10	11	10	3.40	155	98	0.22	100		
E	3C	W	1	9	10	10	9	2.41	160	99	0.15	100		
E	3C	W	2	9	9	10	9	2.20	159	99	0.14	100		
E	3C	W	3	8	8	9	9	1.86	161	100	0.12	100		
E	3C	W	4	8	9	10	9	2.97	158	99	0.19	100		
E	3C	W	5	10	9	10	10	4.13	159	100	0.26		20	80
E	3C	W	6	8	9	10	9	2.95	160	98	0.19	100		
E	3C	W	7	8	11	11	9	2.20	158	98	0.14	100		
E	3C	W	8	9	10	11	9	2.27	156	98	0.15	100		
E	3C	W	9	9	10	10	10	2.40	154	97	0.16	100		
E	3C	W	10	9	10	11	8	2.98	158	100	0.19			100

Table A1.24. Sand Grading Programme Results, Southwater Engineering Brick, Laid Wet.

Brick	Sand	Laying	Number	Joint Thickness (mm)				Failure Load(kN)	Length(mm)	Width(mm)	Failure Stress(N/mm^2)	Failure Plane Location		
												T	M	B
E	4C	D	1	9	10	10	9	3.12	162	100	0.19	100		
E	4C	D	2	10	10	9	9	3.15	157	100	0.20	95	5	
E	4C	D	3	8	10	10	9	2.96	160	101	0.18	95	5	
E	4C	D	4	9	10	10	9	3.00	160	101	0.19	95	5	
E	4C	D	5	9	10	10	10	2.97	160	101	0.18	100		
E	4C	D	6	9	8	8	9	2.92	161	100	0.18	100		
E	4C	D	7	8	10	10	10	3.12	157	100	0.20	95	5	
E	4C	D	8	10	9	10	9	2.53	159	101	0.16	100		
E	4C	D	9	8	9	10	8	3.00	158	100	0.19	95	5	
E	4C	D	10	8	9	9	9	3.67	159	100	0.23	80	20	
E	4C	W	1	7	9	10	8	1.94	160	101	0.12	100		
E	4C	W	2	9	9	9	9	2.78	160	99	0.18	100		75
E	4C	W	3	10	10	10	11	2.21	155	97	0.15	100		
E	4C	W	4	9	9	10	10	1.60	160	100	0.10	100		
E	4C	W	5	8	10	10	8	2.47	160	100	0.15	100		
E	4C	W	6	9	11	12	10	2.40	155	97	0.16	100		
E	4C	W	7	8	9	11	10	2.62	159	99	0.17	100		
E	4C	W	8	8	8	8	7	2.41	161	100	0.15	100		
E	4C	W	9	7	8	9	8	2.13	161	100	0.13	100		
E	4C	W	10	8	10	10	9	2.24	158	99	0.14	100		

Table A1.25. Sand Grading Programme Results, Southwater Engineering Brick, Sand 4C.

Suc.Rate	Number	Water (%)	Joint Thickness (mm)				Failure Load(kN)	Length(mm)	Width(mm)	Failure Stress(N/mm²)	Failure Plane Location				
											Br	T	M	B	Br
1	1	20	10	12	13	14	3.70	147	96	0.26			25	75	
1	2	20	14	16	14	14	3.35	152	96	0.23		60	5	50	
1	3	20	15	15	10	11	3.55	152	90	0.26		95	5		
1	4	20	16	11	11	11	3.45	150	90	0.26		90	10		
1	5	20	10	13	12	11	3.85	152	94	0.27		30	30	60	
1	6	20	12	15	11	12	3.30	150	92	0.24		50	15	75	
1	7	20	11	13	12	12	3.90	152	91	0.28		40	35	35	
1	8	20	14	13	15	13	3.55	152	93	0.25		30	30	60	
1	9	20	12	12	13	10	2.85	151	95	0.20		95	5		
1	10	20	11	13	13	10	3.00	150	97	0.21			10	90	
2	1	20	11	12	11	10	3.35	145	93	0.25		95	5		
2	2	20	13	12	12	14	4.75	151	95	0.33		85	15		
2	3	20	11	12	11	10	3.80	146	91	0.29		80	20		
2	4	20	13	11	12	12	3.90	145	94	0.29		65	15	30	
2	5	20	12	12	10	11	3.80	146	91	0.29		60	40		
2	6	20	13	13	14	13	3.40	144	90	0.26		20	80		
2	7	20	12	11	10	12	5.30	137	90	0.43		15	60	25	
2	8	20	11	15	12	12	4.25	151	93	0.30		50	50		
2	9	20	11	10	12	10	2.30	141	65	0.25		50	50		
2	10	20	10	12	11	13	3.60	146	93	0.26		15	30	55	
3	1	20½	13	11	13	12	2.00	140	90	0.16			80	20	
3	2	20½	12	10	12	12	3.90	145	95	0.28				100	
3	3	20½	12	11	15	12	4.0 *	137	95	0.31			35	65	
3	4	20½	13	10	11	10	4.0 *	137	96	0.30				100	
3	5	20½	10	12	10	15	4.0 *	139	97	0.30			15	85	
3	6	20½	10	13	14	14	3.68	146	97	0.26			5	95	
3	7	20½	11	13	12	11	5.20	No bond failure					[illegible]	[illegible]	
3	8	20½	10	11	12	13	4.55	140	93	0.35			5	95	
3	9	20½	10	10	12	11	4.00	138	91	0.32			5	95	
3	10	20½	11	10	9	12	4.00	147	90	0.30		95	5		

* Stylus arm restricted giving low readings

Table A1.26. Suction Rate Programme Results.

Suc.Rate	Number	Water (%)	Joint Thickness (mm)				Failure Load(kN)	Length(mm)	Width(mm)	Failure Stress(N/mm^2)	Br	Failure Plane Location T	M	B	Br
4	1	21	12	10	13	13	2.40	142	65*	0.26		70	30		
4	2	21	12	10	12	13	3.15	143	65*	0.34			100		
4	3	21	11	11	10	10	1.85	142	50*	0.26		100			
4	4	21	10	12	11	10	4.15	110	80*	0.47		80	20		
4	5	21	14	11	11	13	2.60	110	95*	0.25		70	30		
4	6	21	11	11	13	11	3.90	145	80*	0.34			95	5	
4	7	21	11	13	14	10	5.25	No bond		failure					
4	8	21	10	11	14	12	5.00	135	97	0.38			25	75	
4	9	21	10	11	10	12	3.80	130	94*	0.31		25	75		
4	10	21	12	14	9	12	4.50	As no.7		above					
5	1	21½	11	11	11	10	0.50	V.small		-		100			
5	2	21½	11	11	13	10	3.04	138	98	0.22				70	30
5	3	21½	11	12	11	10	2.33	140	35*	0.48		70	30		
5	4	21½	13	13	11	11	1.40	140	55*	0.18			100		
5	5	21½	11	11	11	10	4.66	145	98	0.33	10	20	60	10	
5	6	21½	11	10	12	11	3.51	125	95*	0.30		5	95	10	15
5	7	21½	12	13	10	12	2.83	135	70*	0.30	90	5	5		
5	8	21½	15	13	11	15	2.88	140	90	0.28	10	5	80		5
5	9	21½	13	12	13	12	3.32	140	85*	0.28	80	10	10		
5	10	21½	10	11	11	11	2.91	140	80*	0.26	50	10	30	10	10
6	1	22	12	13	12	10	3.07	140	70*	0.31	100				
6	2	22	12	12	12	10	2.91	140	50*	0.42	90	5	5		
6	3	22	10	13	12	13	2.00	120	50*	0.33	100				
6	4	22	13	14	11	11	1.78	150	50*	0.24	80	10	10		
6	5	22	11	11	11	10	2.50	140	40*	0.45	80	20			
6	6	22	14	11	11	13	0.91	140	45*	0.14	70	30			
6	7	22	13	11	12	13	3.26	90	90*	0.40	85	15			
6	8	22	12	11	11	11	0.67	50	90*	0.15		80	20		
6	9	22	11	11	12	11	2.45	140	50*	0.35	30	60	10		
6	10	22	Broke during handling												

* Estimates based on incomplete contact

Table A1.27. Suction Rate Programme Results.

Brick	Curing	Number	Joint Thickness (mm)				Failure Load(kN)	Length(mm)	Width(mm)	Failure Stress(N/mm^2)	Failure Plane Location T	M	B
F	a	1	10	11	10	10	7.40	150	100	0.49			100
F	a	2	10	11	11	10	6.10	151	100	0.40			100
F	a	3	11	10	11	11	5.95	151	97	0.41	100		
F	a	4	12	11	11	12	5.65	151	99	0.38	50		75
F	a	5	10	10	11	12	5.05	150	95	0.35	100		
F	a	6	10	10	10	10	5.20	150	97	0.36	100		
F	a	7	10	10	10	10	5.70	153	96	0.39	100		
F	a	8	11	10	10	10	5.65	150	96	0.39	100		
F	a	9	10	10	10	10	5.35	151	96	0.37	100		
F	a	10	11	10	11	11	5.70	151	98	0.38	100		
F	b	1	10	10	11	10	6.15	145	100	0.42			100
F	b	2	11	11	11	10	6.00	149	100	0.40			100
F	b	3	11	10	11	10	7.05	146	100	0.48		6	94
F	b	4	10	11	11	10	6.10	149	100	0.41			100
F	b	5	11	11	10	10	5.90	147	100	0.40			100
F	b	6	10	11	10	11	6.50	151	101	0.43			100
F	b	7	11	10	10	11	6.50	150	100	0.43			100
F	b	8	10	10	10	10	6.30	147	100	0.43			100
F	b	9	11	11	10	10	7.10	152	97	0.48	100		
F	b	10	11	11	10	10	6.45	149	100	0.43		3	97
F	c	1	10	10	10	10	4.80	152	97	0.33	100		
F	c	2	11	10	10	10	6.30	149	100	0.42		5	95
F	c	3	10	10	10	10	5.10	152	100	0.34			100
F	c	4	10	11	10	10	5.75	146	100	0.39		5	95
F	c	5	11	11	11	10	4.50	150	100	0.30			100
F	c	6	11	11	11	10	5.55	154	98	0.37	100		
F	c	7	11	11	10	10	4.65	147	99	0.32			100
F	c	8	11	10	10	10	5.10	153	95	0.35	100		
F	c	9	10	10	10	10	4.75	148	100	0.32			100
F	c	10	10	10	10	11	4.55	152	100	0.30			100

Table A1.28. Curing Programme Results, Holbrook Facing Brick.

Brick	Curing	Number	Joint Thickness (mm)				Failure Load(kN)	Length(mm)	Width(mm)	Failure Stress(N/mm^2)	Failure Plane Location		
											T	M	B
F	d	1	10	10	10	11	6.30	148	100	0.43			100
F	d	2	11	11	11	10	5.95	148	100	0.40			100
F	d	3	10	11	11	10	6.50	154	100	0.42		13	87
F	d	4	11	11	11	10	6.10	155	100	0.39		8	92
F	d	5	11	11	11	10	6.10	149	97	0.42	100		
F	d	6	10	11	11	10	6.35	150	98	0.43	100		
F	d	7	11	10	10	10	7.05	155	97	0.47	100		
F	d	8	11	11	10	10	6.55	150	100	0.44		5	95
F	d	9	11	11	11	11	5.70	150	100	0.38			100
F	d	10	11	11	10	11	5.60	149	100	0.38		2	98
F	e	1	11	10	11	11	5.30	153	98	0.35	100		
F	e	2	11	10	10	11	5.50	151	100	0.36			100
F	e	3	10	10	11	11	5.30	148	100	0.36			100
F	e	4	10	10	11	12	4.60	151	100	0.30			100
F	e	5	11	10	11	12	4.45	150	99	0.30			100
F	e	6	11	10	10	11	5.75	153	100	0.38			100
F	e	7	10	10	10	12	5.10	150	100	0.34			100
F	e	8	10	10	10	10	4.50	149	100	0.30			100
F	e	9	11	10	11	11	5.00	148	99	0.34			100
F	e	10	10	11	12	11	4.35	150	100	0.29			100

Table A1.29. Curing Programme Results, Holbrook Facing Brick.

Brick	Curing	Number	Joint Thickness (mm)				Failute Load(kN)	Length(mm)	Width(mm)	Failure Stress(N/mm^2)	Failure Plane Location		
											T	M	B
E	a	1	11	10	9	11	1.64	160	100	0.10	100		
E	a	2	11	10	9	7	2.77	158	100	0.18	100		
E	a	3	11	12	10	10	2.80	155	99	0.18	100		
E	a	4	11	10	12	10	1.87	158	98	0.12	100		
E	a	5	10	9	10	12	2.38	155	100	0.15	100		
E	a	6	10	9	9	10	1.77	160	100	0.11	100		
E	a	7	10	10	9	11	2.30	156	100	0.15	100		
E	a	8	10	9	10	10	3.49	156	101	0.22	100		
E	a	9	10	11	11	10	3.54	155	100	0.23	100		
E	a	10	10	12	11	9	2.00	148	99	0.14	100		
E	b	1	11	11	10	10	2.69	156	95	0.18	100		
E	b	2	11	10	10	11	3.42	152	101	0.22			100
E	b	3	12	11	11	10	3.28	155	99	0.21	100		
E	b	4	11	13	9	9	3.39	153	99	0.22	100		
E	b	5	11	10	12	9	2.64	157	101	0.17	100		
E	b	6	9	11	11	10	3.26	155	99	0.21	100		
E	b	7	10	10	11	10	2.58	156	100	0.16	100		
E	b	8	10	11	10	9	3.20	160	101	0.20			100
E	b	9	11	11	10	10	3.84	160	101	0.24		10	90
E	b	10	9	10	10	9	2.61	156	100	0.17	100		
E	c	1	10	10	10	10	2.07	157	100	0.13	100		
E	c	2	12	10	9	11	2.82	157	101	0.18	85	15	
E	c	3	9	10	10	10	2.31	157	101	0.15	100		
E	c	4	10	9	10	10	2.62	154	101	0.17	100	15	
E	c	5	11	9	9	11	2.73	155	100	0.18	100		
E	c	6	10	10	10	11	2.65	155	101	0.17	100		
E	c	7	10	10	9	9	2.14	156	99	0.14	100		
E	c	8	9	10	10	9	2.22	157	101	0.14	100		
E	c	9	8	11	11	8	2.94	157	99	0.19	100		
E	c	10	10	10	10	10	2.92	152	101	0.19	100		

Table A1.30. Curing Programme Results, Southwater Engineering Brick.

Brick	Curing	Number	Joint Thickness (mm)				Failure Load(kN)	Length(mm)	Width(mm)	Failure Stress(N/mm^2)	Failure Plane Location		
											T	M	B
E	d	1	11	10	12	9	2.40	160	104	0.14		2	98
E	d	2	9	10	11	9	3.07	158	101	0.19	100		
E	d	3	10	11	11	9	2.60	156	99	0.17	95	5	
E	d	4	10	13	10	9	3.42	155	100	0.22	92	8	
E	d	5	11	10	10	11	3.11	159	102	0.19		30	70
E	d	6	11	10	11	10	2.98	158	98	0.19	100		
E	d	7	10	10	10	10	3.40	156	101	0.22		45	55
E	d	8	9	11	9	9	1.58	163	102	0.10		20	80
E	d	9	10	9	9	9	2.72	159	102	0.17	97	3	
E	d	10	10	11	10	10	2.68	155	101	0.17	100		
E	e	1	9	10	10	11	1.27	156	99	0.08	100		
E	e	2	10	9	11	10	1.50	157	98	0.10	100		
E	e	3	11	10	11	12	1.73	155	98	0.11	100		
E	e	4	9	8	12	9	1.31	161	98	0.08	100		
E	e	5	11	10	10	11	1.59	156	99	0.10	100		
E	e	6	10	9	11	11	1.50	157	99	0.10	100		
E	e	7	9	9	10	10	1.39	156	100	0.09	100		
E	e	8	10	10	10	10	1.52	157	101	0.10	100		
E	e	9	9	10	10	11	1.17	158	98	0.08	100		
E	e	10	10	10	10	12	1.65	157	98	0.11	100		

Table A1.31. Curing Programme Results, Southwater Engineering Brick.

APPENDIX 2. CORRELATION OF BOND STRENGTH WITH WATER CONTENT.

The results of the mortar programme are summarised in section 9.1. In this programme there were a total of 480 couplets, divided into 16 groups. Each group is a different combination of the two brick types, the two suction rate conditions and the four mortar grades. Within each group are five couplets at each of six mortar water contents. A least squares analysis has been carried out on each of the 16 groups to determine the correlation of bond strength with the water content of the mortar. The following relationship is postulated.

$$f = aw + b$$

where f is the couplet bond strength in N/mm^2, w is the water content of the mortar as a percentage, by mass, of the dry constituents, and a and b are the coefficients to be determined.

The coefficient of correlation, r, is given by the following expression

$$r = \frac{\frac{1}{N}\Sigma fw - \bar{f}\bar{w}}{\sigma_f \sigma_w}$$

where $\sigma_f^2 = \frac{1}{N}(\Sigma f^2) - (\bar{f})^2$

$\sigma_w^2 = \frac{1}{N}(\Sigma w^2) - (\bar{w})^2$

and N is the number of couplets in the group.

From r, Student's t may easily be calculated.

$$t = \frac{r\sqrt{(N-2)}}{\sqrt{(1-r^2)}}$$

As an example to illustrate the method, the results for the facing brick couplets, laid dry, using mortar grade (i) are given in table A2.1. The coefficients a and b may now be calculated.

$$N = 30 \qquad \bar{w} = 18.75 \qquad \bar{f} = 0.3758$$

$$a = \frac{\Sigma wf - N\bar{w}\bar{f}}{\Sigma w^2 - N\bar{w}^2} = 0.01792$$

$$b = \frac{\Sigma w \Sigma wf - \Sigma f \Sigma w^2}{(\Sigma w)^2 - N\Sigma w^2} = 0.0398$$

The significance of these values may be determined by calculating r and t.

$$\sigma_w = 0.8539 \qquad \sigma_f = 0.0545$$

$$r = 0.281 \qquad t = 1.55$$

From statistical tables,

t=1.17 at the 25% probability level for 28 degrees of freedom
t=1.70 " " 10% " " " " " " "

therefore it can be concluded that the positive correlation is not particularly significant.

Other sets of results yield values of r from -0.448 (significant negative correlation) to 0.674 (highly significant positive correlation) but there is no pattern to the behaviour.

	w	f	w^2	f^2	wf
	17.5	0.327	306.25	0.1069	5.7225
	17.5	0.393	306.25	0.1544	6.8775
	17.5	0.287	306.25	0.0824	5.0225
	17.5	0.343	306.25	0.1176	6.0025
	17.5	0.313	306.25	0.0980	5.4775
	18.0	0.381	324.00	0.1452	6.8580
	18.0	0.373	324.00	0.1391	6.7140
	18.0	0.371	324.00	0.1376	6.6780
	18.0	0.440	324.00	0.1936	7.9200
	18.0	0.373	324.00	0.1391	6.7140
	18.5	0.332	342.25	0.1102	6.1420
	18.5	0.292	342.25	0.0853	5.4020
	18.5	0.431	342.25	0.1858	7.9735
	18.5	0.336	342.25	0.1129	6.2160
	18.5	0.507	342.25	0.2570	9.3795
	19.0	0.449	361.00	0.2016	8.5310
	19.0	0.348	361.00	0.1211	6.6120
	19.0	0.373	361.00	0.1391	7.0870
	19.0	0.357	361.00	0.1274	6.7830
	19.0	0.338	361.00	0.1142	6.4220
	19.5	0.430	380.25	0.1849	8.3850
	19.5	0.320	380.25	0.1024	6.2400
	19.5	0.328	380.25	0.1076	6.3960
	19.5	0.428	380.25	0.1832	8.3460
	19.5	0.404	380.25	0.1632	7.8780
	20.0	0.455	400.00	0.2070	9.1000
	20.0	0.471	400.00	0.2218	9.4200
	20.0	0.365	400.00	0.1332	7.3000
	20.0	0.321	400.00	0.1030	6.4200
	20.0	0.388	400.00	0.1505	7.7600
Σ	562.5	11.274	10568.75	4.3257	211.7795

Table A2.1. Data for Correlation of strength with water content of mortar.

APPENDIX 3. MOISTURE CONTENT OF MORTAR SAMPLE.

Moisture content, θ, is defined as the volume of water per unit volume of mortar. The following quantities will be required:

M_d = mass of dry constituents before mixing.

M_w = mass of water added to above.

M_s = mass of small sample of mixed mortar.

V_w = volume of water added to dry constituents.

V_s = volume of small sample of mixed mortar.

The mortar is prepared with a known water content, α, so that

$$M_w = \alpha M_d.$$

The small sample of mortar will be some proportion, β, of the total mass, so that

$$\begin{aligned} M_s &= \beta(M_w+M_d) \\ &= \beta(1+\alpha)M_d. \end{aligned}$$

The sample moisture content may now be defined in terms of the above quantities,

$$\begin{aligned} \theta_s &= \beta \frac{V_w}{V_s} \\ &= \frac{M_s}{(1+\alpha)M_d} \cdot \frac{V_w}{V_s} \\ &= \frac{M_s}{(1+\alpha)M_d} \cdot \frac{M_w}{V_s} \\ &= \frac{M_s}{(1+\alpha)M_d} \cdot \alpha \frac{M_d}{V_s} \end{aligned}$$

$$\theta_s = \frac{\alpha}{(1+\alpha)} \gamma_s$$

where γ_s is the measured density of the mixed mortar. In section 10 the mortars were mixed using a water content of 20%, so that in this case, $\theta_s = \frac{\gamma_s}{6}$.