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FACTORS AFFECTING BOND STRENGTH AND RESISTANCE TO
MOISTURE PENETRATION OF BRICK MASONRY

BY

T. RITCHIE AND J. I. DAVISON

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ANALYZED

FACTORS AFFECTING BOND STRENGTH AND RESISTANCE TO MOISTURE PENETRATION OF BRICK MASONRY

BY T. RITCHIE¹ AND J. I. DAVISON¹

SYNOPSIS

Small panels of brick masonry have been used to study the resistance to moisture penetration and the strength of bond of brickwork in relation to several factors. Results of tests are presented to show the influence of properties of bricks and mortars on leakage and bond strength. Information is presented on the effects of several other factors that are governed by the technique used by the bricklayer in constructing masonry. These factors include the consistency of the mortar when used, the time interval between spreading a mortar bed and laying a brick in it, and the extent to which a brick is tapped into the mortar. The effects of tooling of mortar joints and varying the thickness of mortar joints are also considered.

Many studies of the weather-resisting and load-bearing properties of masonry walls have been reported in the technical literature in the last forty years. However, problems of rain penetration and of inadequate strength of brick masonry continue to arise. In recent years the Division of Building Research of the National Research Council of Canada has studied two main aspects of the problem of rain penetration: (1) the influence of properties of the materials—bricks and mortars, alone and in combination—on the permeability of brickwork, and (2) the influence of the method of assembly of the brickwork. In many of these studies, resistance to moisture penetration and strength of brickwork have been studied jointly, since both apparently depend in large measure on the nature of the bond between mortar and brick.

¹ Building Materials Section and Atlantic Regional Station, respectively, Division of Building Research, National Research Council, Ottawa, Canada.

Review of the work done in other laboratories, as well as results of early studies made in the Division on moisture penetration of relatively large test walls (1),² drew attention to the importance of the condition of the upper surface of a mortar bed at the moment a brick is laid in it. The condition of mortar after it is spread depends on such factors as the absorption of the bricks on which it is placed, its initial water content and inherent resistance to loss of moisture, the thickness of the mortar bed, and the time of contact between mortar and brick. The energy expended in forcing the brick into contact with the mortar bed also affects the nature of the bond.

Small panels of brick and mortar, consisting of 5 bricks in stack bond, have been used to investigate the influence of these factors on moisture penetration and strength of bond. The type of sample and the method of test have been

² The boldface numbers in parentheses refer to the list of references appended to this paper.

described (2), but test results from the use of the method have not been reported until now. Nearly 1000 panels have been constructed and tested in this series, and only representative test results have been selected to illustrate the influence of various factors on the properties of masonry. Conclusions are based on a larger number of tests than those to which direct reference is made.

The program was designed primarily for study of moisture penetration. Panels were cured after construction under controlled conditions (70 F, 50 per cent relative humidity) for two weeks before the leakage test was made. Bond strength tests were made two weeks after the leakage test. In the case of leaky panels, the water in the panel after the test may have affected the curing of the mortar and the strength of bond. Bond strength values given are comparative within a given series of tests and are not absolute values.

TEST METHODS FOR RAIN PENETRATION

Penetration of rain through walls usually occurs when rain is accompanied by high wind. The wind has a twofold effect: (1) it changes the vertical direction of fall of the rain drops so that they strike the wall surface, frequently forming a film of water that flows down the surface, and (2) it causes regions of differential air pressure to be set up in and around a building. The air pressure patterns depend on the wind speed, the shape of the structure, and its height. It is probable that a wall wetted by rain has an air pressure difference across it, with the outside pressure, when it is higher than that inside, having the effect of increasing the rate of passage of water through the wall.

In laboratory studies of rain penetration, various methods of simulating the combined effects of wetting and pressure have been used. One method was to

attach a reservoir of water to the surface of the masonry and to measure the movement of water into it (3); brickwork "chimneys" filled with water have also been used (4,5). Since the depth of water varied in such tests, the pressure did also. To obtain constant pressure, a test wall was placed horizontally with a pond of water maintained on the surface (6,7). In several studies water has been sprayed against the test wall, in some instances with no attempt to obtain an air pressure difference across the wall (8); in others the water spray has been accompanied by an air pressure difference across the test wall (9). Air pressure and wetting have been combined to obtain a useful representation of actual wall exposure conditions (10). The thickness of the test wall is also important, since it may influence the difference in pressure across the units of the outer part of the wall, thereby affecting the rate of penetration of moisture into the wall. The use of thin samples for rain penetration tests may, therefore, provide results difficult to apply in predicting the performance of thicker walls.

TEST METHODS FOR BOND STRENGTH

The most obvious forces that a brick wall must resist are those resulting from loads applied vertically, such as roof and floor loads. Detailed studies of the load-bearing capacity of brick masonry have been made by the British Building Research Station (11) and by the U. S. National Bureau of Standards (12,13). Considerable information has been obtained about the influence of brick and mortar properties, and of other factors, on the compressive strength of brick masonry. In addition to supporting vertically applied loads, a wall must resist lateral forces such as those caused by wind pressure. Tests of the transverse strength of brick walls were included in the studies mentioned (11,13).

In transverse tests of brick walls, failure usually results from a breakdown of the brick-mortar bond rather than from failure in tension of brick or mortar. The strength of adhesion between brick and mortar has been studied in many laboratories, particularly since a trend

recently been adopted as an ASTM standard method.³ Bond strength tests reported here were made by a method adapted from the crossed-brick couplet method, except that the entire bedding surfaces of the bricks were in contact with mortar (2).

FIG. 1.—Leakage of Bricks in Relation to Initial Rate of Absorption.

toward the use of thinner walls has stressed the importance of high resistance to lateral loading.

Various methods have been used to determine the strength of bond of brick to mortar. A detailed account of the development of such tests and the difficulties of obtaining consistent results from them was presented in 1943 (14). The "crossed-brick couplet" method has

INFLUENCE OF BRICK AND MORTAR PROPERTIES

Bricks:

Early moisture penetration tests indicated that the performance of brickwork could be varied by changing the

³ Method of Test for Bond Strength of Mortar to Masonry Units (E 149 - 59 T), 1961 Book of ASTM Standards, Part 5, p. 1071.

type of brick used. It is generally accepted that two properties of bricks may affect the resistance of a wall to moisture penetration: (1) the permeability of the brick to water, and (2) the ability of the brick to bond with mortar. In the first case water may pass through the brick in the wall and come out the other side. In the second case, certain properties of the brick may adversely affect the bonding between mortar and brick, so that channels form at the brick-mortar interface which enable water penetration. In addition to the influence of the initial rate of water absorption or suction of the brick on bonding between brick and mortar, interface channels may result from other flaws such as warpage, surface texture, deep scratches or cracks in the bedding surfaces, and dust on the bedding surfaces. The effect of cores and frogs in bricks must also be considered.

Permeability.—All bricks have a porous structure, the nature of which depends upon the raw material, the method of formation, and the firing temperature during the manufacturing process. Several investigators (3,11,14) have found that where materials are of good grade it is rare that bricks are permeable to such an extent that water will pass through them during a normal rain.

In the present study some of the moisture penetration tests indicated that leakage had occurred through the bricks as well as at the brick-mortar interface. To obtain information on their permeability bricks of various kinds were tested individually for moisture penetration in the same way as panels are tested, by spraying water on the face and simultaneously maintaining an air pressure differential of 2 in. of water across the brick. One series of tests used 17 bricks covering a wide range in the property of initial rate of absorption or suction, which is defined as the number of grams of water absorbed through 30

sq in. of brick bedding surface when the brick is placed in water to a depth of $\frac{1}{8}$ in. for 1 min. Since this property is to some extent a measure of the ease of movement of water into a brick, it was expected that it would be related in a general way to the permeability of the brick. The results of the tests are shown in Fig. 1, in which the amount of water passing through a brick in 24 hr has been plotted against initial rate of absorption.

Six extruded bricks were tested. For five of them there was no leakage, and three had no mark of dampness on the back surface. The amount of leakage of the sixth brick was very slight (0.5 ml in 24 hr). Ten dry-press bricks were tested; all leaked and in general the permeability increased with increasing initial rate of absorption, particularly for six bricks taken from the same lot that covered a wide range of initial rate of absorption. As shown in Fig. 1, the amount of water that passed through these bricks in 24 hr of test varied from 3 to 349 ml, with considerable increase in leakage when the initial rate of absorption exceeded about 55 g per min per 30 sq in.

As a result of these moisture penetration tests on individual bricks, together with the leakage test results from many panels, it is considered that the permeability of extruded (stiff-mud) bricks is not likely to be significant in the problem of moisture penetration of masonry, but the permeability of dry-press and soft-mud bricks may be important.

Absorption of Water.—The absorption properties of a brick determine the amount of water that may be extracted in a given time from mortar placed on the brick. The loss of water influences the state of plasticity of the mortar when another brick is laid in it and thus affects the nature of the bond established between the two (15).

FIG. 2.—Influence of Brick Suction on Bond Strength and Permeability.

TABLE I.—EFFECT OF WETTING BRICKS ON PROPERTIES OF BRICK MASONRY.

Condition of Brick when Laid	Time for Leakage to Start, min	Total Leakage in 24 hr, ml	Tensile Bond Strength, psi ^a
Dry.....	2	5441	11.3
Dry.....	2	4948	14.6
Wet.....	47	436	20.7
Wet.....	44	514	36.4

^a Average of all joints of the panel.

Some 200 panels were tested in this series to study the effect of the suction of the brick on the permeability and

strength of bond of masonry. Results are illustrated by a series of tests of 22 panels involving bricks of various suction values made into panels with a masonry cement mortar. The mortar, mixed to a flow of 120 per cent, was placed on the brick. After 1 min the brick was bedded in the mortar by the tap of a 4-lb hammer dropped 1½ in. Each panel was tested for moisture penetration, after which the tensile strength of bond between brick and mortar was measured. The permeability of the panels is compared in Fig. 2 on the basis of the amount of water that passed through

a panel in 24 hr of test. Highly permeable panels resulted from the use of high suction bricks. For some, the leakage may have consisted, in part, of water passing through bricks, but it is considered that most of the leakage was at the brick-mortar interface where the effective bond between the two was influenced by the suction of the brick. Variation in bond strength with change of brick suction is also evident in Fig. 2. The relationship follows the same pattern described in earlier studies (16).

Table I indicates the improvements obtained in the greater strength of bond and greater resistance to moisture penetration resulting from wetting the bricks. Those used in these tests were high in suction, varying from 38 to 75 g per min per 30 sq in. Two test panels were made of this brick laid dry, and two others were made of it after soaking in water for 10 min. The mortar was prepared from masonry cement and sand in proportions 1:3 by volume, and its flow was 115 per cent. The mortar was

TABLE II.—COMPARISON OF PANELS MADE OF CORED BRICKS AND SOLID BRICKS.

Mortar Composition, by volume ^a	Type of Brick	First Appearance of Dampness, min	Total Leakage in 24 hr, ml	Bond Strength, psi ^b
1:3 MC:S.....	cored	after 7 hr	nil	11.9
1:3 MC:S.....	cored	after 7 hr	nil	19.1
1:3 MC:S.....	solid	30	702	34.8
1:3 MC:S.....	solid	1 hr	nil	24.3
1:3 MC:S.....	solid	1½ hr	nil ^c	40.5
1:1:6 C:L:S.....	cored	1 hr	9	2.4
1:1:6 C:L:S.....	cored	30	nil ^c	12.7
1:1:6 C:L:S.....	solid	3	8	24.3
1:1:6 C:L:S.....	solid	3	nil ^c	40.4
1:2:9 C:L:S.....	cored	30	nil ^c	6.6
1:2:9 C:L:S.....	cored	55	nil	4.4
1:2:9 C:L:S.....	solid	20	nil	10.9
1:2:9 C:L:S.....	solid	20	nil	17.1

^a MC = masonry cement, S = sand, C = portland cement, L = lime.

^b Average of all joints of the panel.

^c Free water appeared on the back of the panel but none ran off.

Bond strength increased to a maximum value at brick suction between 10 and 20 g and decreased sharply when the suction exceeded 30 g, thus substantiating the generally accepted principle that optimum bonding occurs when brick suction is less than 20 g.

Wetting of Bricks.—Wetting high-suction bricks before they are laid in mortar improves the properties of the brickwork, probably because the brick suction is reduced to a lower value conducive to better bonding with mortar. Wetting of bricks is popular with bricklayers because it makes it easier to set the bricks in place in the mortar.

placed on a brick, and after ½ min a second brick was placed on the mortar and bedded into it by tapping with a 4-lb hammer falling 1½ in. Table I shows that much less water passed through the panels in which soaked bricks had been used and that the strength of bond of the mortar joints of these panels was considerably greater than that of the panels in which the bricks had been laid dry. Some leakage occurred through the bricks and was common to all four panels.

Results indicate that wetting of high-suction bricks can be an effective method of reducing moisture penetration by lowering the suction of bricks to a level

at which better bonding with mortar will occur.

Core Holes and Texture of Bricks.—In addition to the properties of water absorption and permeability of bricks, other properties such as the presence of core holes and the type of surface texture have been studied in relation to the performance of brick masonry. Core holes conceivably can provide channels for the movement of water within the wall, although only minor differences have been observed in the permeability and bond strength of masonry made of cored and solid bricks otherwise having the same properties (17,18).

In this study, only a limited number of panels were constructed. Cored and solid bricks of the same materials manufactured at the same plant were used, with the only apparent difference being the presence of core holes in some of the bricks. A comparison of properties of panels of the two types of brick is given in Table II. The bricks ranged in suction from 2 to 7 g per min per 30 sq in. They were used with three mortars: (1) 1:3 masonry cement:sand, (2) 1:1:6 cement:lime:sand, and (3) 1:2:9 cement:lime:sand. Each mortar had a flow value of 120 per cent. In making these panels the mortar remained in contact with the brick for 30 sec before the next brick was placed on it and bedded by the tap of a 4-lb hammer dropping $1\frac{1}{2}$ in.

Although there was no significant difference in the total amount of water that leaked from panels of cored and solid bricks in 24 hr of test, there was a difference in the rapidity with which dampness appeared on the back of the panels after the start of the test. In all cases dampness was delayed in penetrating the panels of cored brick. This was particularly noticeable for panels of cored brick and masonry cement mortar; these showed no dampness for over 7

hr, while the panels of solid bricks showed dampness in less than $1\frac{1}{2}$ hr. For panels of all three mortars the strength of bond of those of cored bricks was less than the strength of the panels of solid bricks. The decrease in strength was more than could be accounted for by the decreased area available for contact between brick and mortar.

Although no specific studies were made of the effect of surface texture of bricks on properties of masonry, it was observed in several tests that leakage had occurred at the brick-mortar interface where a deep scratch or depression across the brick had not been filled by mortar, thus producing a channel along which moisture penetration occurred.

Mortar:

Studies (3,6,9,16) show the importance of properties of mortar on the performance of brick masonry. Two properties have received particular attention: (1) the consistency of fluidity of a particular mortar when it is being used in laying bricks, and (2) its water retention value. The former property is frequently expressed as the flow of the mortar, which is the increase in diameter of a cone of mortar when it is bumped 25 times on a dropping table, thereby indicating the ease with which the mortar spreads or flows. Water retention value is defined as the ratio of two flow values of a mortar, that of the mortar after it has had water extracted from it by a certain suction applied for 1 min (to correspond to the loss of water from mortar in contact with an absorptive brick), and that of the freshly mixed mortar. Water retention value, therefore, provides a measure of the ability of a mortar to retain its flow when in contact with a brick.

Flow of Mortar.—Studies (17,19,20) indicate that bonding between bricks and a particular mortar is improved when

that mortar is used at high flow values. The upper limit occurs when segregation of water from mortar takes place or the mortar is so fluid that it runs from the joints.

The effects of variation in flow of mortar on the permeability and bond strength of masonry are illustrated by

hours for dampness to appear on the backs of the two panels of high-flow mortar, and for the latter panels no water leaked off the back surface during the test. The strength of bond decreased from about 60 psi for the high-flow mortar to about 10 psi for the low-flow mortar.

FIG. 3.—Influence of Flow of Mortar on Resistance to Moisture Penetration and Strength of Bond.

the results in Fig. 3 obtained from tests of six panels. The panels were made from bricks of suction in the range 19 to 22 g per min per 30 sq in., with mortar composed of 1:1:6 portland cement:lime:sand. The flow of the mortar was varied from 104 to 136 per cent. Moisture penetration of the two panels of low-flow mortar occurred immediately after the start of the test, but it took several

Water Retention Value.—The water retention value of a particular mortar is dependent on its composition. To change this value requires a change in composition, which may also change other properties of the mortar. The effects on the properties of masonry of variation in water retention value are, therefore, difficult to establish.

Few tests were made in the present

program on the effect on the properties of masonry of changing the water retention value of mortar. In one test series, six panels were constructed of bricks in the suction range 42 to 44 g per min per 30 sq in. Two panels were made of a masonry cement mortar with a water retention value of about 70. In the other panels, part of the masonry cement was replaced by lime, which increased the water retention value to about 74 and 78 depending on the amount of lime. For all panels the flow of the mortar was between 116 and 119 per cent. Resistance

TABLE III.—EFFECT OF CHANGE IN WATER RETENTION VALUE OF MORTAR ON PROPERTIES OF MASONRY.

Panel	Water Retention Value of Mortar	Amount of Water Passing through Panel in 24 hr, ml	Bond Strength, psi ^a
No. 1.....	70.5	1030	9.5
No. 2.....	70.5	1225	9.6
No. 3.....	74.3	510	12.8
No. 4.....	74.3	165	12.6
No. 5.....	78.0	25	16.9
No. 6.....	78.0	68	10.2

^a Average of all joints of the panel.

to moisture penetration and strength of bond are compared in Table III. As the water retention value of the mortar increased, resistance to moisture penetration and the strength of bond also tended to increase. Two factors may have influenced the strength of bond. The improved extent of bond resulting from the increased water retention value of the mortar (as reflected in greater tightness of panels) would tend to increase the bond strength because of greater contact area between brick and mortar. Replacement of masonry cement by lime, however, would result in lower strength of the mortar, thus tending to reduce the tensile bond strength.

OTHER FACTORS

In addition to the influence of the properties of bricks and mortars on the performance of masonry, there are other factors connected with the method of bringing bricks and mortar together which have important effects on the resistance to moisture penetration and the strength of masonry. Careless work, in which mortar joints are not completely filled with mortar or where bricks are moved after the mortar around them has stiffened, affects the strength and tightness of brick masonry (4,8,18).

Even when bricklaying is done with great care, certain factors connected with the technique of laying the bricks may have a considerable influence on the quality of the brickwork. For example, the length of time that elapses between laying a bed of mortar on a course of bricks and placing bricks in it may vary over a wide range, depending on (1) the distance the bricklayer strings out the mortar bed in advance of this work and (2) how rapidly he places the bricks. A brick may be set in the mortar by a shove of the hand, or more usually, by one or more taps of a trowel. The energy expended in bedding the brick, therefore, may vary and undoubtedly results in variations in the properties of the masonry. Changes in the properties of mortar caused by moisture loss as it stands on the board before being used, and the inevitable retempering to more suitable flow, may also affect the properties of the brickwork.

VARIATION IN TIME INTERVAL

There are few references in the literature to the length of time that elapses between spreading out a mortar bed and placing bricks in it. In a recent study (21) the time interval varied from a minimum of 20 sec to a maximum of 2 min and 25 sec.

The influence of this time interval factor on resistance to moisture penetration and strength of bond was studied in the present program. Its importance is shown by the results obtained from the tests of the group of six panels made of

time interval of 60 sec; and two others with a time interval of 90 sec. The moisture penetration and bond strength properties are shown in Fig. 4. In the test for moisture penetration, there was no leakage for the first two panels (30-sec

FIG. 4.—Effect of Time Variation on Properties of Masonry.

bricks ranging in suction from 11 to 17 g per min per 30 sq in. and mortar composed of cement, lime, and sand in the proportions 1:1:6 by volume (having a flow of 110 per cent). Two panels were made with a time interval of 30 sec between placing the mortar and laying the next brick; two panels were made with a

time interval) during the 24-hr test. The second two (60-sec time interval) leaked slightly. The two panels assembled with a 90-sec time interval were considerably more permeable. The strength of bond decreased sharply as the time interval increased. The properties of one of the panels of 60-sec time interval were

affected by the flow value of the mortar, which was considerably lower for this panel than for the other five. Additional tests indicate that the importance of the time factor depends to some extent on the particular combination of brick and mortar being used. In conjunction with the time factor, the brick-mortar combination influences the plastic condition of the mortar at the time a brick is placed in it, thus affecting the nature of the bond established.

VARIATION IN TAPPING IMPACT

After a bricklayer places a brick on a bed of mortar he may tap it with his

the bricks properly in mortar, it was suggested that one heavy tap rather than several light ones be given to save time in the bricklaying operation. The need for adjustment in the technique of bricklaying in relation to the properties of brick and mortar is an interesting point raised in this early study, suggesting the dependence, to some extent, of the bricklayer's technique or workmanship on the properties of the materials being used.

The effect of variation in the tapping impact given to bricks when they are bedded in mortar was studied in the present program. In making certain

TABLE IV.—EFFECT OF VARIATION IN METHOD OF BRICKLAYING ON BOND STRENGTH.

Type of Brick	Mortar Composition by Volume ^a	Conditions of Construction	Bond Strength psi ^b
Extruded.....	1:3 MC:S	2-lb hammer ^c	22.5
Extruded.....	1:3 MC:S	4-lb hammer ^c	26.8
Extruded.....	1:3 MC:S	bricklayer	46.5
Extruded.....	1:1:6 C:L:S	2-lb hammer	19.6
Extruded.....	1:1:6 C:L:S	4-lb hammer	27.4
Extruded.....	1:1:6 C:L:S	bricklayer	36.9
Dry-press.....	1:1:6 C:L:S	2-lb hammer	7.5
Dry-press.....	1:1:6 C:L:S	4-lb hammer	14.2
Dry-press.....	1:1:6 C:L:S	bricklayer	19.2

^a MC = masonry cement, S = sand, C = portland cement, L = lime.

^b Average of all joints of three panels.

^c Dropped 1½ in.

trowel to bring it to line, or, depending on the circumstances, he may shove the brick into place without tapping it. In the former case the tapping may vary in both heaviness and number of taps, and there may also be variation in the rapidity with which they are made. An early study of the bricklaying operation made by a pioneer in the field of time and motion study (22) found that tapping bricks is not necessary if (1) the mortar has the correct temper, (2) the bricks have been wetted sufficiently, and (3) the size of the joints is suitable. If for some reason tapping is necessary to bed

panels, the brick was placed on the mortar bed and tapped by a 2-lb hammer, which fell from a height of 1½ in. In other panels, a 4-lb hammer was dropped from the same height. Comparison of the test results indicated a general increase in the resistance to moisture penetration and in the strength of bond when the tapping impact was increased by the use of the heavier hammer. The heavier tap tends to force the brick into more complete contact with the mortar. The extent of improvement of properties of masonry resulting from a greater tapping impact appeared to depend to

some extent on the properties of the materials being used.

The influence of the method of brick-laying on properties of masonry is indicated by Table IV. Panels for this series of tests were constructed in three ways: 2-lb and 4-lb hammers were used as described previously, and the third set of panels were built by a bricklayer. His panels differed from the others in the method of placing the brick in the mortar. The bricklayer used his normal method of work, spreading a bed of mortar on the brick (to a depth greater than used in the other panels), pressing the brick into the mortar and tapping it into place with a rapid series of taps of a trowel.

Three combinations of brick and mortar were studied. An extruded brick of suction in the range 31 to 55 g per min per 30 sq in. was used with a masonry cement mortar (1:3 by volume) and with a cement-lime mortar (1:1:6). A dry-press brick of suction in the range 46 to 87 g per min per 30 sq in. was used with the 1:1:6 mortar. Three panels were built by each method. The test of these panels for resistance to moisture penetration revealed only slight differences, which could be attributed to the method of construction. Strength of bond, however, was clearly affected by the method of bedding the brick in the mortar, as is shown by the test results listed in Table IV. The bond strength given in the table for each combination of brick and mortar is the average of all the mortar joints of three panels. In this series of tests the bricklayer-constructed panels were considerably higher in strength of bond than were the others, while those made by the tap of the 4-lb hammer were of greater bond strength than those made with the lighter hammer.

The results of these tests also demonstrate the influence of properties of

bricks on bond strength. Bond strength between the extruded brick and 1:1:6 mortar was considerably higher for all three methods of construction than the bond strength between the dry-press brick and the same mortar.

RETEMPERING MORTAR

Another variable in the bricklaying operation is introduced by the practice of retempering mortar. After it is mixed, there is an interval of time before mortar is placed in the wall. If this waiting period is sufficiently long (and this

TABLE V.—EFFECT OF TIME INTERVAL BEFORE RETEMPERING OF MORTAR ON PROPERTIES OF MASONRY.

Panel	Mortar Retempered After Time, hr	Total Leakage in 24 hr, ml	Bond Strength, psi ^a
No. 1.....	0	nil	46.7
No. 2.....	0	nil	44.7
No. 3.....	2	nil	43.3
No. 4.....	2	2353 ^b	42.0
No. 5.....	3	nil	39.0
No. 6.....	3	4068 ^b	22.5
No. 7.....	4	438	16.8
No. 8.....	4	600	22.0

^a Average of all joints of panel.

^b Leakage believed due to greater warpage of some of the bricks of these panels.

probably depends on the particular mortar mix and the conditions of storage), the plasticity of the mortar may change so much that the bricklayer may have to rework the stiffened mortar with water to restore it to a suitable consistency.

To determine the effect of retempering mortar on properties of masonry, several series of tests were made. In one of them, bricks of suction 13 to 17 g per min per 30 sq in. were used with 1:1:6 cement-lime mortar. Two panels were made of this mortar immediately after it had been mixed to a flow of 120 per cent. Other panels were made of the same mortar after it had stood after mixing

for periods of 2, 3, and 4 hr. After these periods of time the mortar was remixed, with sufficient water to restore the flow to 120 per cent. The results of leakage and bond strength tests for the series are presented in Table V. For each panel the total amount of water (in milliliters) which passed through in 24 hr of test is listed, along with the average tensile bond strength of the joints of the panel. The panels made with mortar used immediately after mixing were free of leakage, but leakage occurred in those panels made of the mortar which had stood for 4 hr. The results of the leakage tests for panels built of mortar retempered after 2 and 3 hr were inconsistent, and the permeability of these panels was believed to have been affected by excessive warpage of a few of the bricks. Change in bond strength with increasing time interval before retempering ranged from a value well over 40 psi for mortar used immediately after mixing to a value of about 20 psi for mortar retempered 4 hr after mixing.

THICKNESS OF MORTAR BED

The thickness of the mortar spread by the bricklayer before laying bricks in it is usually not controlled carefully and varies along the length of the mortar bed. The average thickness may be influenced to some extent by variation in properties of brick and mortar and also by the finished thickness required for the joints. The thickness of the freshly laid mortar may be expected to have some effect on the bond with the brick laid in it, since in a given length of time after the mortar is placed the plasticity of its upper surface will probably be greater for the thicker mortar bed.

In several tests in this program, the thickness of the mortar bed was varied from $\frac{5}{8}$ to $\frac{1}{4}$ in. in steps of $\frac{1}{8}$ in. The result of decreasing the thickness of the mortar joint was, in general, a decrease in

strength of bond and an increase in permeability of the panel, but the effect of changing the thickness of the bed depended also on the particular mortar being used. In one series of tests in which mortar joints $\frac{5}{8}$ in. and $\frac{1}{2}$ in. thick were used, panels were free of moisture penetration, whereas in panels made with $\frac{3}{8}$ -in. and $\frac{1}{4}$ -in. joints, moisture penetration occurred. At the same time, the strength of bond decreased as the thickness of the mortar joint decreased.

CONCLUSION

The resistance of brick masonry to moisture penetration and the strength of bond between brick and mortar primarily depend on the properties of the materials used and the manner in which brick and mortar are brought together to form masonry. Leakage may take place through the brick, depending on its permeability, but more usually it occurs through channels at the brick-mortar interface. In this connection the extent of bond between brick and mortar is critical and depends largely on the condition of the upper surface of the mortar bed when a brick is laid in it.

Factors affecting the condition of the mortar at the time of bricklaying include the rate of water absorption of the bricks on which the mortar is spread, the inherent resistance of the fresh mortar to loss of moisture (water retention value) and the amount of water in the fresh mortar, the thickness of the mortar bed, the length of time that elapses before a brick is placed in the mortar, and the energy used to bed a brick.

The strength of bond between brick and mortar also depends on the nature of the bond between the two. A particular brick and mortar combination may, however, have a complete extent of bond at interface and have relatively low strength of bond, whereas another combination may have a "patchy" or in-

complete extent of bond with greater strength. The extent of contact between brick and mortar and the tensile strength of the mortar appear to influence the bond strength.

A selection of typical test results involving almost 1000 panels illustrates the effects of various factors on the properties of masonry. The extent of these effects is frequently difficult to assess because the factors are interdependent. A certain factor may be important under one set of conditions and have little significance when these conditions are varied by using materials having different properties or by altering bricklaying techniques.

In practice, deficiencies in the properties of materials may be recognized

and partially compensated for by the bricklayer. For example, he may call for a very fluid mortar to offset high suction of the brick being used, or he may shorten the "string-out" of a mortar bed to compensate for its low water retention properties. Inconsistent results in some tests, however, indicate that there are unrecognized factors, or combinations of factors, affecting properties of masonry.

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