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Erik Högberg:

MORTAR BOND

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By Fil. dr Erik Högberg

Puts- och Murbrukslaboratoriet, Malmö

The principal purpose of the present research was to investigate the effect of various factors on mortar bond, and to establish a basis for practical recommendations for obtaining good bond between mortar and masonry units.

Adhesion was studied on both fresh and hardened mortar. There was good agreement between the adhesion of fresh mortar and that of the hardened mortar.

Bond strength was measured with the help of Hinderson's apparatus and the contact between mortar and base was studied under the microscope.

The studies showed the following distinct tendencies:

1. To non-water absorbent materials bond declines with rising water/binder ratio in the mortar.
2. To water absorbent materials bond increases with rising water/binder ratio in the mortar.

The water/binder ratio depends mainly on the following parameters: type of binder, relation between binder and sand, sand-grading, admixtures and consistence of the mortar used. These parameters, therefore affect bond.

Binder-rich mortars usually have low water/binder ratio, and their bond to water absorbent bases is poor. Bond with these mortars improves if the capillary suction of the base is reduced. Capillary suction may be reduced by wetting the absorbent material, or by rendering it with a thin film of cement-rich binder paste or cement-rich fluid mortar. The studies have shown that these treatments of water absorbent bases improve bond considerably.

Admixtures affect the bond. Air-entraining agents usually impair bond to an absorbent base. Viscosity-improving additives, cellulose derivates, for example, on the other hand, often improve bond to water absorbent bases.

The studies have shown that there are mortars which may be used regardless of the capillary suction of the base. Mortars of a ratio of 1:6 or 1:5 by volume gave the best results. To ensure satisfactory bond strength the binder should contain 50—75 per cent by weight of Portland cement.

ACKNOWLEDGEMENT

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INTRODUCTION

Bond is perhaps the most important single physical property of mortar. Because many variables affect the bond, it is difficult to devise a single laboratory test which will consistently yield reproducible results and which will approximate construction results. These variables include water retentivity of mortar, suction of brick, texture of brick, elapsed time between spreading mortar and laying brick, pressure applied to masonry joints during forming, air content and others.

In all masonry work the purpose of mortar is to bond the blocks or bricks firmly together. The mortar serves primarily as a bonding agent but also as an equalizing medium. This is because variations in thickness of the masonry units can be compensated by modifying the thickness of the joints. If the masonry is subject to eccentric loads the adhesion between mortar and masonry units is of great importance. The adhesion of the mortar is also significant for the ability of brickwork to resist penetration by rain water. This is because rain water may easily penetrate voids which arise between the mortar and the bricks where the adhesion is poor (Fig. 1).

If ceilings and walls are to be rendered or plastered, it is very important that the coat adheres properly to the base material. Most of the cases of poor adhesion arise in this connection. Rendering coats are exposed to far more strains than masonry. Stresses arise at an early stage if the mortar or the base material shrinks. Slow deformations increase the stresses. External renderings are exposed to repeated wetting, to freezing and variations in temperature. Moisture migration, frost stresses and changes of volume can all contribute substantially to a deterioration of the adhesion between mortar and base material (Fig. 2).

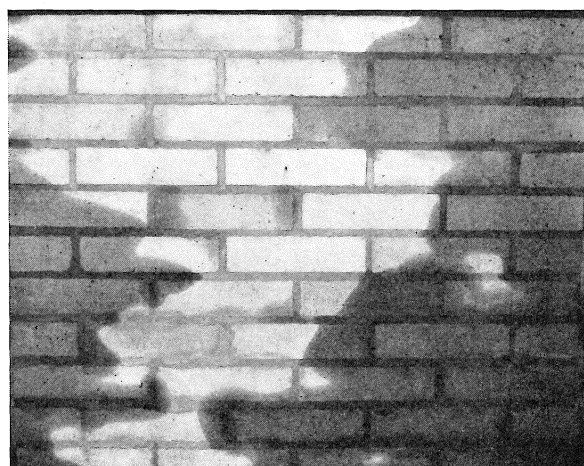As a rule mortar is used as a bonding and equalizing

Figure 1. Rain penetration in brickwork. PML test.
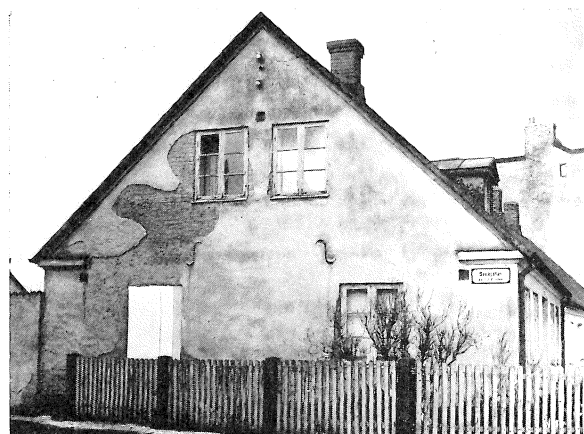
Figure 2. Failure of rendering.

agent when setting ceramic tiles. In this case the mortar is often required to adhere to two different types of material, i.e. the ceramic tile on one hand and the floor or wall material on the other. Floor tiles are frequently exposed to relatively heavy loads, which sometimes are applied eccentric. Great stresses can then be imposed on the adhesion of the mortar (Fig. 3).

Thinner and thinner masonry is being adopted thanks to the advances in design during recent years. Since the base material is becoming smoother and the tolerances of dimensional accuracy are becoming stricter, thinner mortar is being used. Smaller joints result. Rendering coats are also thinner. Very thin layers of mortar can be used for attaching ceramic tiles. This transition to thinner mortar layers as a rule intensifies the requirements for good adhesion of the mortar.

Many different factors affect the adhesion between mortar and masonry units.

The composition of the mortar varies according to whether it is intended to be used for masonry work, plastering and rendering or tile-setting. The bonding agents vary. Usually lime, lime-cement, masonry cement or cement are used. The proportion of bonding agent and sand varies from very rich to relatively lean mixes. The size grading and maximum particle size of the sand vary from one job to another. The different types of mortar are required to have good adhesion to a variety of materials such as bricks, sand-lime bricks, aerated concrete, concrete, ceramic tiles and glass. These materials differ in chemical composition and surface texture, and most of all in capillarity properties. Even in the same class of materials there occur wide variations. Thus, for example, clinker-
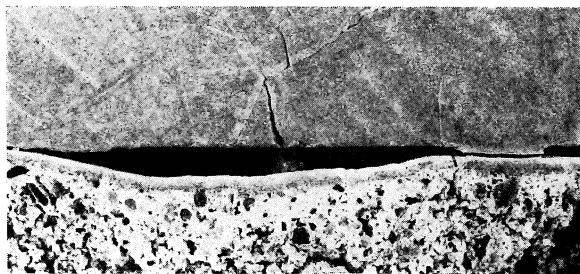
Figure 3. Rupture in bond in flooring tiles.

burned bricks have low capillary suction, while porous bricks have high capillarity. It appears that the capillarity of the material is an important factor with regard to adhesion.

The execution of the work also has great significance for the adhesion. Greatly-increased building activities have stepped up the tempo of the construction. Work goes on the year round nowadays, and it is not always that attention is paid to the climatic conditions.

The adhesion problem is highly complicated, and the result is correlated to the properties of the mortar and the base material, as well as to the execution of the work and other external conditions.

In this paper I wish to present the results of the investigations carried out under my supervision during the period 1955—1966. The work was done at the Plaster and Mortar Laboratory (PML), Malmö, Sweden, in order to elucidate the factors affecting the adhesion of mortar to various types of building material, and to endeavour to provide an explanation of the principal mechanism of adhesion.

EARLIER INVESTIGATIONS

A great number of research workers have studied the adhesion problem from various points of view. Previous investigations of the adhesion of mortar to masonry units mainly consist of trials carried out in an attempt to find the relationship between the capillarity of the masonry units and the adhesion of the mortar. No extensive or systematic tests have been carried out to solve the adhesion problem in this field. The investigations so far published are classified below into three groups—masonry work, rendering, and tile-setting.

Masonry work

At the Australian Building Research Congress in 1961, Youl and Coats (1961) had compiled a review of the literature available in English on the adhesion between brick and mortar. This review began by considering the effect of various factors on the adhesion.

The composition of the *cement* will affect the bond, due to variable magnitude of drying shrinkage.

The type, quality and quantity of *lime* in a mortar will affect the water-retention properties and the workability of the mortar.

In general the bond strength decreases with decreasing *water* content of the mortar.

The composition, particle shape and size grading of the *sand* are of prime importance because of their effect on workability and water requirements.

Little information is available on the effect of the *addition of finely-divided material* and *air-entraining agents* on brick-mortar bonds.

The rate at which a *brick* absorbs water affects the extent and strength of the bond. At present the degree to which variations in surface texture affect the bond is in doubt.

The review has indicated that certain known factors affect the bond. These are:

1. The absorption rate of the brick.
2. The water-retentive property of the mortar.

Recommended values of the absorption rate of the brick differ by different authors. For example, most workers indicate a desirable absorption rate of 5 g/dm², min, or less, for walls resistant to moisture, whilst maximum bond strength is obtained within the range 10 to 12 g/dm², min.

There is a great deal of evidence that high-absorbing bricks should be wetted in order to reduce their suction rate to a desirable value.

Most workers agree that mortar should be "water-retentive", "plastic" and "workable". There is no clear agreement as to the value of water retentivity which gives the best workability or the best bond with bricks of different absorption rates. High lime ratio in lime-cement mortars appears to be a requirement for good water retentivity, but the accurate meaning of the term "high lime" is vague.

There is some evidence that consistence or the quantity of water in a mortar is as important as the water retentivity in order to obtain good bond strength.

It seems that both water retentivity and the actual water content in the mortar, particularly after brick suction, are important if a good bond is to be achieved. The effects of both these factors require further investigation.

There is a divergence of opinion on the effect of mortar shrinkage on the bond.

Many of the mechanical variables which may affect bond strength do not appear to have been examined. Such variables could be joint thickness, methods of

applying jointing pressure, methods of spreading, tools used etc.

Whilst poor workmanship resulted in high permeabilities and good workmanship showed good resistance to water penetration, few tests have examined average workmanship. There is some evidence that the workmanship factor is not as critical in transverse loads on panels as it is in the moisture penetration tests.

Apart from one or two investigations, most of the research work on bond strength and extent has been carried out in the laboratory.

The bonding mechanism appears to depend upon movement of water from mortar to brick. However, the chemistry and physics of the interfacial layer and the mechanism of adhesion are not understood.

Youl and Coats give a list of references comprising some 50 investigations published in English during the period 1930—1956.

Those references applying to mortar bonds are also quoted in this paper.

Davison (1961) found that leakage and bond-strength tests on small brick panels indicate a weaker bond between the mortar bed and the brick above than between the mortar bed and the brick below. Loss of moisture from fresh mortars to bricks was studied to explain this difference. Reduction of the original moisture content of the mortar is accompanied by an impairing of the plasticity or bonding ability of the mortar. Loss of moisture from the mortar bed with the resulting reduction in "bonding ability" may explain inferior bonding at the interface between the mortar bed and the brick above it, as compared with the bond between the mortar bed and the brick below it.

Albrecht and Schneider (1964) have investigated in what way the suction of the bricks affects the strength of the masonry when loads are applied centric or eccentric to piers and panels. They also determined the adhesion between mortar and bricks. They found that the strength of the bond increased as the suction of the bricks decreased. When highly porous bricks were soaked for 15 minutes, their suction diminished resulting in better adhesion.

The investigations previously described have mainly applied to the adhesion between bricks and mortar. Copeland and Saxer (1964) have investigated the structural bond of masonry mortars to concrete blocks. The investigation dealt with the tensile and shearing strength of mortar joints in assemblies of concrete blocks. The investigations showed that the bond strength increased with increased cement content in the mortar. Air-entraining agents in masonry cement affected the adhesion adversely when the amount of air in the mortar exceeded 7 %.

The tensile strength of bond of lime-cement mortar was superior to that of masonry cement mortar in the same compressive strength range. The authors consider it to be reasonably certain that masonry mortar will ensure a bond with a tensile and shear strength exceeding 5 kp/cm^2. It appears that excessively rapid drying of the joints must be avoided and that mortar should have the following properties:

Proportion of Portland cement to total finely-ground cementitious and inert material, not less than 75 % by volume
Minimum compressive strength 175 kp/cm^2 at the flow used
Maximum air content 10 %
Minimum initial flow 130 %

If higher tensile bond strength is desired, masonry joints should be damp cured.

Rendering

Adhesion is one of the most important properties of mortars for rendering. As a rule very little bond strength is needed to prevent the coat from becoming detached from the base material by its own weight. In practice, however, much greater adhesion is necessary. The coat must not become detached when it is exposed to changes in volume occurring as the coat shrinks and the base material dries out. It is desirable that the strength of the bond does not decrease in spite of the coat being exposed to slow deformation and repeated shear stresses during alternate periods of rainfall and drying out.

In the literature there are very few papers which discuss the adhesion of rendering coats. Pilny and Struck (1959) have studied the adhesion of such coats to aerated concrete. They found both from practical and theoretical points of view that the stresses generated between the coat and the aerated concrete during periods of wetting and drying out are not powerful enough to break the bond obtained when the coat is properly applied to the aerated concrete.

Investigations have been carried out in cases where the rendering has fallen down from concrete ceilings. As a rule the ceilings were of smooth-cast concrete, and the coats were lime or plaster of Paris mixes which fell down after a few years. Hinderson (1958) and Albrecht and Steinbach (1962) found that satisfactory adhesion is obtained by using cement- and lime-cement mortars.

Piepenburg, Bühling and Behnke (1958) carried out an important investigation of the adhesion of rendering coats, in an attempt to discover the factors affecting their adhesion. They found that the water-absorption of the base material, the composition of the mortar and its water retentivity, as well as the technique of application are all of very great significance. The absorption by the base material must not be too great, nor must it be so small that the coat slides off.

I (Högberg 1961) determined the strength of the bond in the case of thin finishing coats using lime and lime-cement as a binder.

Weigler (1965) investigated the adhesion between the coat and aerated concrete, in an attempt to establish the factors affecting such adhesion. The preliminary tests showed that a spatterdash coat of a cement mortar applied to the aerated concrete ensured such good adhesion for the subsequent rendering that it was always the aerated concrete that ruptured during the tests of the bond strength. Straight lime mortars were unsuitable for rendering aerated concrete on account of their poor durability.

Tile-setting

In tile-setting, the problems of adhesion correspond fairly closely to those of masonry work, but are more complicated. The mortar is required to adhere to two materials which may have relatively different properties. The tiles may have been burnt in the same way as bricks, or they may be sintered. This gives rise to differences in capillarity which can affect the strength of the bond. In most cases the tiles are applied to an equalizing layer of mortar which may vary in composition and age. In some cases, however, the tiles are applied directly to smooth walls of concrete or aerated concrete. Relatively few investigations have been carried out to determine the factors affecting the adhesion of mortars used for tile-setting.

In order to study the adhesion of plaster, stucco and mortar coats, Johnston, Dear and Whittemore (1948) used tiles of differing absorption as backings. They found that as the flow of the bonding agent increased, the adhesion values increased to a maximum, and then decreased when the percentage of flow became too high. Higher values were obtained on shale tiles than on clay tiles, due to the low absorption rate of shale tiles.

Balinkin, McHugh and Scholz (1956) showed that the bond strength of ceramic mosaic tiles increases with the number of blows given to the tile. This results from better contact to the tile surface, and the mortar

becoming more compact, with resulting decrease of shrinkage and thus smaller residual internal stresses.

Waters (1959) has compared tile-setting using dry tiles and presoaked, glazed, whiteware wall tiles. He found that the dry tiles gave the best adhesion values, measured as shear strength. Waters explains that this is due to a decreasing of the water/cement ratio at the surface. Waters showed later (1960) that if the wet tiles were first primed with a layer of cement paste, the adhesion became as good as when dry tiles were used.

I (Högberg 1961) commenced my studies of adhesion by determining the bond strength of various mortars applied to glazed, whiteware wall tiles. I found that a 1:3 cement mortar showed poor adhesion to high absorbent tiles. However, the adhesion became good if the tiles had been saturated with water. This conflicts with the opinion of Waters.

Cement mortar 1:6 gave good adhesion without any wetting of the tiles. This also contradicts Waters' results, since he found better adhesion to dry tiles with a 1:3 cement mortar than with a 1:5 cement mortar.

The study also showed that a mortar containing air-entraining agents gave considerably poorer adhesion than a corresponding mortar without additives.

The principles for adhesion between mortars and ceramic tiles, based upon the above study, were presented by me (Högberg 1965), at the RILEM/CIB symposium 1965 in Helsinki on moisture problems in buildings. I consider that these principles can be extended to apply in general to the adhesion between mortars and masonry units.

This paper will discuss in detail my views on adhesion.

Methods of testing bonds

In several of the studies previously mentioned, the penetration of rain into masonry work has been determined. These results are affected by many factors, and can give only indirect values of the adhesion between mortars and masonry units. In connection with water penetration tests, Thornton (1953) measured the extent of bond between mortars and bricks. It was possible to measure this area more readily by adding dye to the water used in the penetration test. This stained the areas where the mortar was not attached to the masonry. Thornton found that the leaks and the dyed areas did not always coincide. In many cases where one mortar shows more leaks than another, the dyed areas can be almost the same. Often there are many potential leaks, although only a few leaks actually appear. The use of dye solutions
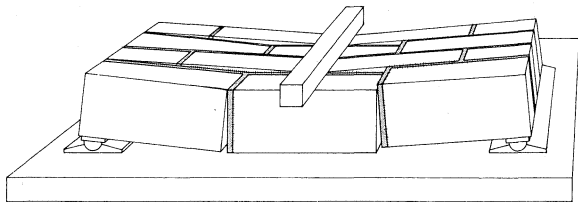
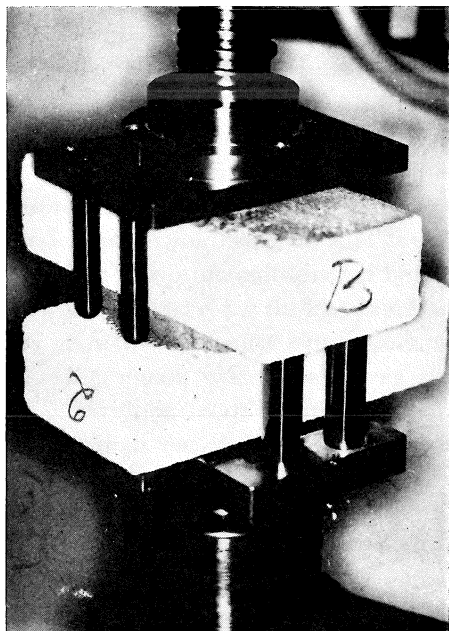Figure 4. Transverse loading test according to Ryder (1963).

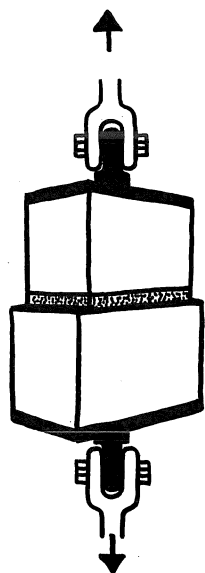Figure 5. Cross brick couplet according to ASTM.

Figure 6. Tensile bond strength test according to Kuenning (1966).

to study the contact layer between mortar and masonry units was done by Whittemore and Dear (1943), Thornton (1953), and others.

Granholm (1958) and Högberg (1962) studied the adhesion of fresh mortar to various materials.

The extent of bond gives a true value for the adhesion between mortar and base material. It must not be confused with the bond strength, which can show a high value even though the adhesive area is not large. In a similar way, a mortar with a large contact area can show a low bond strength, e.g. in the case where the strength of the mortar itself is low.

In most of the studies mentioned above, the bond strength was determined in one or two following ways. Two brick specimens were bond-tested by direct tension, or flexural bending tests were carried out on wall panels (Fig. 4).

Pearson (1943) studied the various methods in order to develop a method imitating job conditions and manipulation without involving too many uncontrolled variables. He found that the cross-brick couplet assembly (ASTM E 144-59C), seems to offer the most satisfactory means of investigating bond strength of mortar to bricks (Fig. 5).

Kuenning (1966) has newly devised and evaluated an improved method for fabricating and testing couplets of brick and mortar for the determination of tensile bond strength (Fig. 6). An apparatus has been designed for fabrication of couplets of standard mortar joint thickness. The couplets were tested in direct tension using steel plates resin-bonded to the top and bottom surfaces of the couplets. Comparison of data obtained in direct tension with similar data from tripod tests (such as those of ASTM Method E 144) shows that the cross-brick couplets yield values which vary from one-third to equal to those of half-brick couplets pulled in direct tension. The ratio of tripod to direct tension values decreases with increasing tensile bond strength. Kuenning claims that the tripod method may only be useful for determining relative tensile bond strengths when the values are about 0,5 kp/cm^2 or less.

In order to determine the adhesion of plastering and rendering coats, various methods were tried. Grooves were drilled in the coat, to which a metal plate was glued. The plate was in turn attached to the tensile strength test apparatus. The area of the section varied between 50 and 500 cm^2. Most of the measurements of bond strength done in Scandinavia were made with the Hinderson (1958) apparatus (Fig. 7). An aluminium disc with a diam. of 8 cm was glued to the surface of the coat. A hydraulic device was used to detach the section. Svendsen

Figure 7. Test set-up for determination of tensile bond strength according to Hinderson (1958). Left: Tension device. Right: Hand-operated hydraulic pump with pressure gauges.
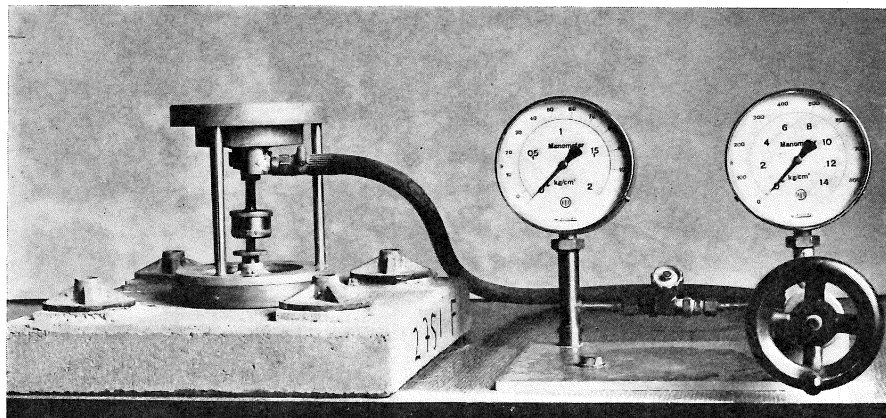
(1965) used Hinderson's apparatus to measure the adhesion of mortar. He did this by making a column six bricks high. A piece of gauze was laid on top of each brick, to prevent the mortar from sticking to the brick. After standing the necessary time, the bricks were taken apart, each one bearing mortar on its lower surface. A groove was routed in the mortar in order to isolate a section of it for the subsequent adhesion test. By this method the mortar was exposed to absorption by two bricks, just as in actual practice.

Ryder (1957) studied the bond between plaster and concrete both with a pull-off test according to the methods described above and by a compression test on plastered concrete slab (Fig. 8).

In order to determine adhesion in tile-setting, Waters (1959, 1960) used a shear strength test (Fig. 9). As with the flexural tests on wall panels, these measurements did not give the true bond strength, however.

I (Högberg 1961) determined the adhesion of tiles using Hinderson's apparatus. Tiles were cut down to a size of 7.5×7.5 cm in order to fit the apparatus.

I consider that Kuenning's method and the measurement made with Hinderson's apparatus should be the best determinations of the tensile bond strength.

Hypotheses for the bonding mechanism

Many research workers have studied the problems of adhesion, but most of them have discussed the gluing of different materials.

The most important problem is that the adhesive must wet the adherend. De Bruyne (1940) proposed the following rough and ready rule for adhesives: "Provided we use pure or simple substances as adhesives, then there is a good deal of evidence that
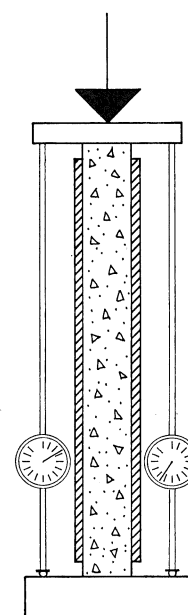

Figure 8. Compression test on plastered concrete slab according to Ryder (1957).
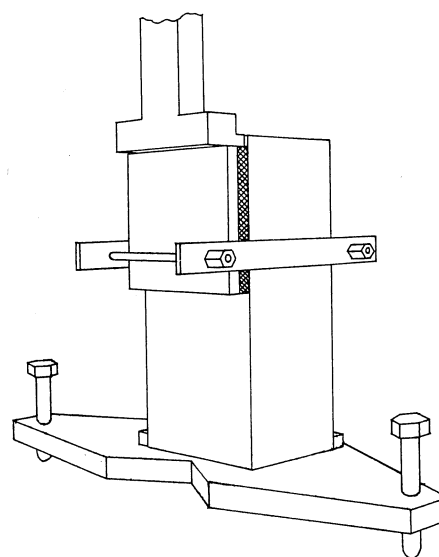

Figure 9. Shear strength test according to Waters (1959).

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strong joints can never be made by polar adherends with non-polar adhesives, or to non-polar adherends with polar adhesives."

Zisman (1962) found that a non-polar adhesive liquid would usually have a lower surface tension than the critical surface tension for wetting the polar adherend; hence good wetting and spreading should result.

In "The science of adhesive joints", Bikerman (1961) roughly sub-divided the problem into nine fields of study.

	Application	Setting	Final state
Two adherends			
Two boundary layers			
Adhesive film			

To some extent this method of classification may also be applied to mortar bonds.

Many research workers have studied the problem of adhesion between bricks and mortar, but few have attempted to explain what actually happens.

Voss (1933) proposed the following hypothesis:

"A leakless brick masonry wall may be produced by an assembly of brick and mortar where, first, the relation of the absorptive power of the brick to the amount of water in the mortar is such that the initial movement towards the brick plane sets in early and continues at an even rate for several hours; and where, second, the mortar is so constituted as to permit such loss of water and still provide a soluble product which in the process is concentrated at the brick plane and is available thereafter for a long period of time to form a compound with a minimum of differential shrinkage with the brick, the assembly being capable by its porous structure of permitting repetition of such action."

Thornton (1953) has also proposed a theory of what happens:

"Brick of high suction draws the water from the mortar into the brick and a poor bond results. A brick of low suction, but with more surface area, pulls the water from the mortar, and the pin-point contact leaves a path to the surface where the water spreads out on the face of the brick; as it dries, more moisture follows. The result is very little or no bond."

Habib and Leeds (1957) consider that the bond is affected by the flow of water carrying cementitious particles from the body of the mortar to the brick-mortar interface.

Waters (1960) believes that the apparent contact area between tile and mortar consists of a micro-mosaic of areas of contact and non-contact. When more effective contact is obtained, the proportion of contact to non-contact areas is increased, and it is this increase which is the main reason for the stronger bond. When a neat cement slurry is spread on the back of the tile, its lack of coarse particles should enable it to make a much more intimate contact with the back of the tile than a mortar does, and since the two have the same intrinsic strength this more intimate contact is probably the reason for the increased bond strength, i.e. the cement paste is brought into effective contact with a much greater area of the tile surface than would be the case if only mortar were used.

WORKING HYPOTHESIS

I have assumed that the bond between mortar and masonry units follows by and large the principles applying to the process of gluing.

The bond is accomplished by the slurry of binder and water. The practical limit for the adhesion that can be achieved is set by the cohesion of the mortar and the base. This cohesion is primarily dependent on the composition of the binder. In the case of mortar containing Portland cement, the intrinsic strength of the mortar is affected by the water content. This water content is in turn dependent on the amount of binder, the grading of the sand and the consistence of the mortar.

With masonry units of low initial rate of absorption, a mortar should give rise to an adhesion equal to its own cohesive strength, if the masonry material is assumed to be wetted by the slurry of binder and water.

In a corresponding way it is possible to achieve good adhesion to masonry units of high initial brick suction, if there is an adequate supply of available binding slurry. When a joint between bricks is made with mortar, the mortar generally does not have enough water to satisfy the capillary suction. Or else the water retentivity of the mortar is so high that the capillary suction is interrupted, and an air gap is created between the mortar and the brick.

In order to avoid this break in the contact between mortar and brick, it is important for the mortar to have a surplus of water which can easily be transmitted to the brick. As a rule lean mortars have a considerably higher water/binder ratio than rich mortars, which means that lean mortars can more easily release water.

The capillary suction of highly absorptive material can be reduced by soaking or wetting. Good adhesion may thus be obtained more easily, due to reduced suction of the base material.

I am of the opinion that a layer of binder slurry should be formed at the interface between the mortar and the base material if good adhesion is to be obtained. This layer is formed momentarily as soon as the mortar is applied, and is enhanced by the mechanical working of the mortar in connection with the processes of masonry work, plastering and rendering, and tile-setting. In this way the adhesion is directly affected by the working technique.

An initially satisfactory adhesion may deteriorate later due to stresses arising from shrinkage of the various materials, to creep and to external conditions.

It is not necessary for the binder paste to penetrate into the pores or capillary ducts in order to ensure good anchorage. It is possible for the mortar to adhere strongly to surfaces which are completely smooth and uniform. It may even be disadvantageous for the surface to be too rough, since air can be intrapped and prevent the whole surface from being utilized.

This working hypothesis is in good agreement with all the investigations hitherto carried out, with the exception of the conclusions drawn as to the effect of the water retentivity of the mortar. Above all, this property affects the execution of the work and the adhesion of the mortar to the brick above it. This problem will be discussed in greater detail in the experimental section, since good water retentivity of the mortar is in opposition to what I consider as desirable, viz. that the mortar should be able to release water in order to reduce the suction of highly absorbent masonry material.

In addition, the results of Waters' studies in 1959 do not agree with my working hypothesis viz. that a lean mortar provides better adhesion to highly absorbent glazed wall tiles than a rich mortar does. This difference in the results derived from the studies will also be discussed more fully later.

The method of carrying out the investigations emerges from table.

Since the binder is the most important component for the adhesion, attention was first devoted to the properties of the binder paste. The following were used as binders: Portland cement, hydrated lime, mixtures of these two, and in certain cases masonry cement. The properties of the binder paste and therefore of the mortar are strongly dependent on the water/binder ratio. The water/binder ratio in turn depends on the type of binder, on the binder/sand ratio, and on the grading of the sand. The suction of the base material has great significance for the adhesion. For these reasons the investigations have been divided into two groups: adhesion to non-water absorbent materials and to water absorbent materials.

The capillary suction of absorbent materials may be controlled by wetting. Such wetting affects the adhesion. A thin coating of cement mortar also affects the bond.

The adhesion to various materials is affected by admixtures in the form of air-entraining agents and agents which increase the viscosity of the binder slurry.

The strength of the bond may be reduced by aging, by freezing and thawing, and by slow deformations in the mortar and the base material.

	Influence of Bond			
	Between binder paste and		Between mortar and	
	Non-water absorbent material	Water absorbent material	Non-water absorbent material	Water absorbent material
Binder type	+	+	+	+
Water/binder ratio	+	+	+	+
Binder/sand ratio	—	—	+	+
Sand grading	—	—	+	+
Wetting	—	—	+	+
Thin cement-rich coating	—	—	+	+
Admixtures	+	+	+	+
Time (=Durability)	+	+	+	+

Portland cement from the factories of the Skånska Cementaktiebolaget at Köping, Limhamn and Slite conformed to the Swedish specifications, *Statliga cementbestämmelser, 1960.*

Hydrated lime for masonry purposes from the Skånska Cementaktiebolaget factories at Limhamn and Oaxen, most nearly corresponding to type S according to ASTM, C 207-49.

Masonry cement conformed to the Swedish specifications, *Murcementnormer, 1960.*

Sand from Fyledalen, satisfying demands on quality of standard sand to cement testing according to Cembureau-RILEM.

Tiles. Most of the adhesion tests were made on glazed whiteware wall tiles, 15×15 cm, from Uppsala-Ekeby, Ltd. Unglazed tiles of the same quality were also used. For the determination of adhesion, the tiles were, for test-technical reasons, divided into four parts, 7.5×7.5 cm each.

For some studies, vitreous ceramic tiles from Iföverken were used.

Aerated concrete of the Siporex and Ytong qualities, with bulk densities 0.4 and 0.5 kg/dm^3.

Concrete, paving slabs, $35 \times 35 \times 5$ cm from the Skånska Cementgjuteriet factory at Limhamn.

Sand-lime brick from factories at Baskarp, Bollebygd and Kvarntorp.

Clay brick from factories at Klippan and Borgeby.

DESIGNATIONS OF MORTAR

Binders are designated
C Portland cement
L Hydrated lime
M Masonry cement.

Mixtures of Portland cement and hydrated lime are designated LC. The composition of the mix is given by weight according to a proposal made by the Scandinavian Committee of Mortars and Renderings. (Dürkop, 1966.)

The total weight of the binder is always 100. This means that in mixtures of lime and cement the respective proportions of binders are given in percentage of the total weight of binder. This makes it easy to see what percentage of Portland cement a mixture of lime and cement contains. LC 35/65 means 35 parts by weight of hydrated lime and 65 parts by weight of Portland cement.

The weight of the sand is given in the last group of numerals in the mortar designation. E.g.:

C 100/400   = 100 parts of Portland cement
                    400 parts of dry sand
LC 35/65/800 = 35 parts of hydrated lime
                      65 parts of Portland cement
                    800 parts of dry sand

The composition of mortar is frequently given in parts by volume, e.g. 1:4 (binder: sand). The following volume weights may be used to convert volumes into weights.

Portland cement   1.30 kg/dm^3
Hydrated lime   0.65 kg/dm^3
Sand   1.35 kg/dm^3

A diagram has beeen constructed to simplify conversion from volume to weight and vice versa (Fig. 10).
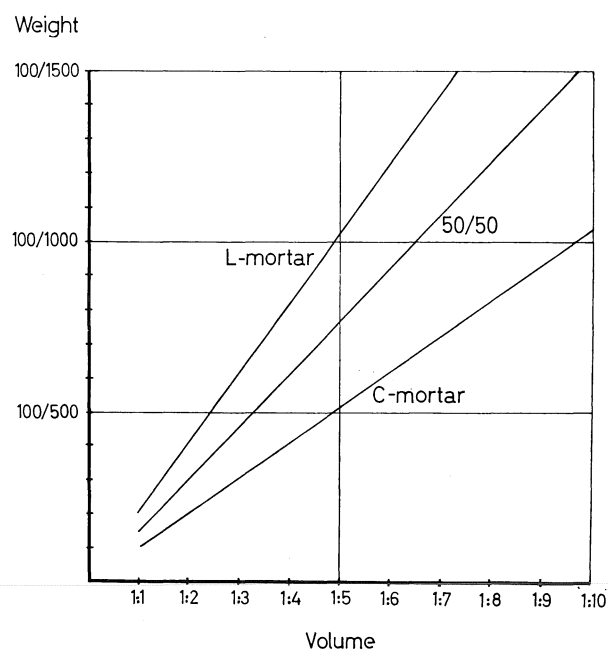
Figure 10. Diagram for conversion of mortar proportions from volume to weight and vice versa.

DEFINITIONS

Adhesion	here equivalent to *bond*
AEA	air-entraining agent
Bond	adhesion of mortar to different base materials
Bond strength	bond is here measured by tensile or shear testing
Cement	here equivalent to Portland cement
Initial brick suction	equivalent to *Initial rate of absorption* (IRA) but here expressed in g/dm^2, min
PML	Puts- och Murbrukslaboratoriet (Plaster and Mortar Laboratory)
Workability	that property of fresh mortar which determines the ease with which it can be mixed, placed and finished

TESTING METHODS

Fresh mortar

Workability. In testing, the consistence of stiffness of the mortars was measured with a Mo-meter (Fig. 11) in accordance with the Scandinavian Committee on Mortars and Renderings standards (Saretok and Strokirk, 1958). The Mo value for the mortars used varied between 18 and 22. The workability of the mortars was judged by a bricklayer in all the tests.

Extent of bond. The adhesion of the fresh mortar to different materials was determined with the help of a plexiglass mould, at the bottom of which was a tile or brick, covered with gauze (Fig. 12). Mortar was placed in the mould and the surplus mortar was wiped off. After a fixed period of time, the mortar was removed with help of the gauze. The extent of bond of the mortar was judged visually (Fig. 13). The water retentivity of the mortar was determined by the same set-up. The increase in the weight of the base material was determined by weighing it at definite intervals after the application of the mortar.

Hardened mortar

Compressive strength and flexural strength. The strength of the mortar was determined on test specimens $25 \times 25 \times 170$ mm, made according to the Scandinavian Mortar Committee's specifications (Fig. 14). The test specimens were stored at 95 per cent relative humidity, and the strengths were determined after 28 days.

Tensile strength. For this determination, the PML used a cylindrical test specimen, 80 mm in diameter and 10 mm high. The test specimens were made and stored in the same way as the prisms used in the compressive strength test. Before the tensile strength
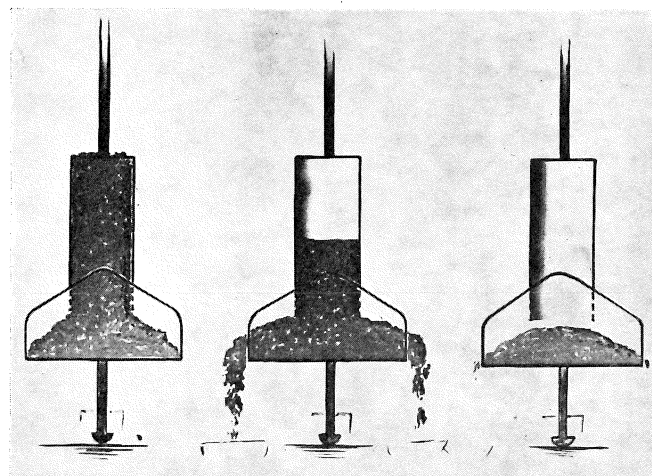
Figure 11. Mo-meter according to Nycander. Recommended by the Scandinavian Committee of Mortars and Renderings for the measurement of the consistence (stiffness) of fresh mortar.

was determined, the test specimens were attached to a concrete base with epoxy resin. On the upper side of the test piece was glued a metal plate with an attachment for the pull-off arrangement of Hinderson's apparatus.

Bond strength test. The adhesion of the mortar to different base materials was determined as the tensile bond strength with the help of Hinderson's apparatus. In a large number of tests the mortar was applied between two plates, like a sandwich, after which the test piece was glued to a firm base (Fig. 15). The pull-off arrangement of the adhesion apparatus was glued to the upper plate. When a bond rupture occurred, the plate which loosened was glued to the mortar with epoxy resin and a determination of the adhesion to the next plate could be made.

Figure 12. Plexiglass moulds used to determine the extent of the bond. Mortar is placed in the mould, at the bottom of which is a wall tile covered with gauze. After a predetermined interval of time, the mortar is removed with the help of gauze.
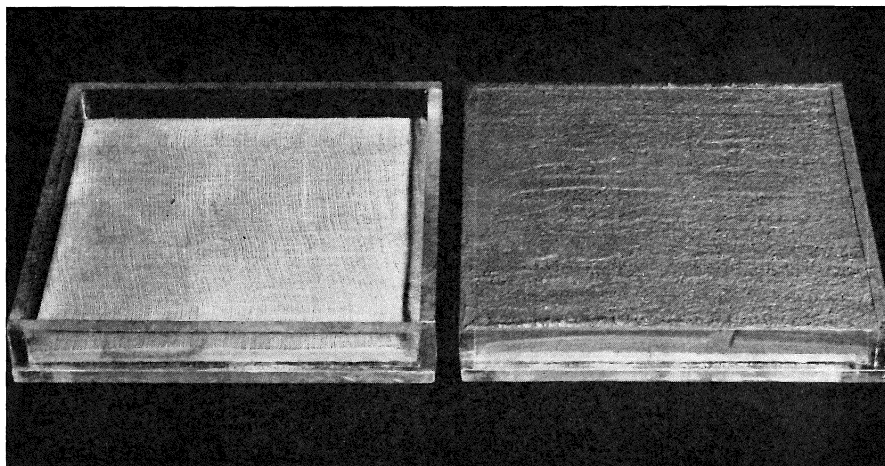
Figure 13. Rear side of wall tiles one minute after fixing. Gauze inserted between the mortar and the wall tile in order to facilitate the removal of the tile from the mortar.

Left: 1 :3 cement mortar. Cement grout adheres to the dry wall tile only at a few isolated points. Right: 1 :6 cement mortar. A large number of particles of cement grout are seen on the dry wall tile.
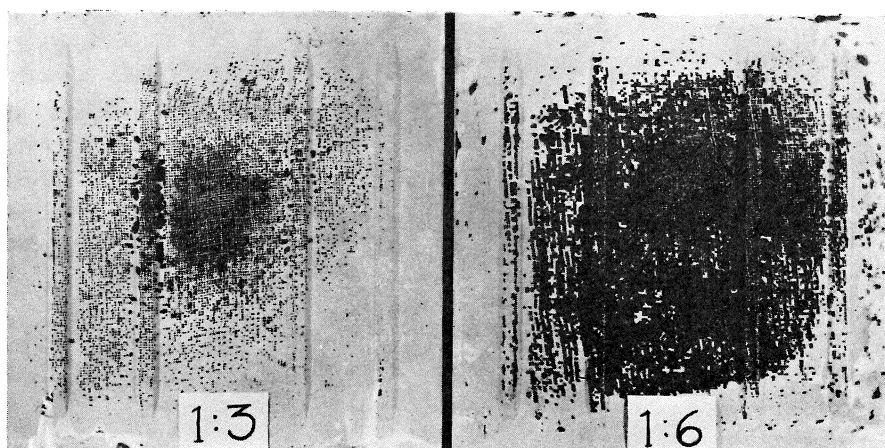
Figure 14. Preparation of test specimens for determination of mortar strength according to the Scandinavian Committee of Mortars and Renderings. Blotting-paper is used in order to extract water from the mortar in a natural way.

21
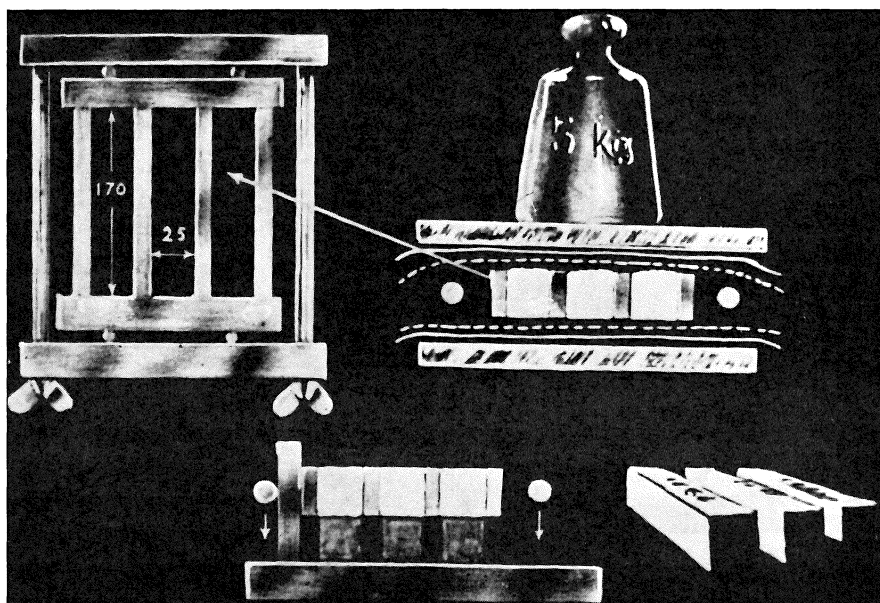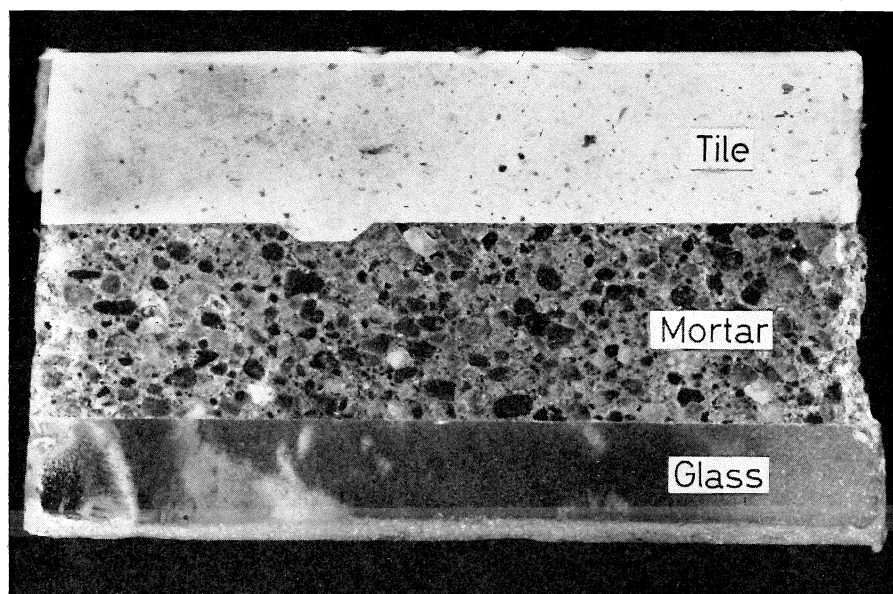
Figure 15. Specimen for bond tests to both non-water absorbent and water absorbent materials.
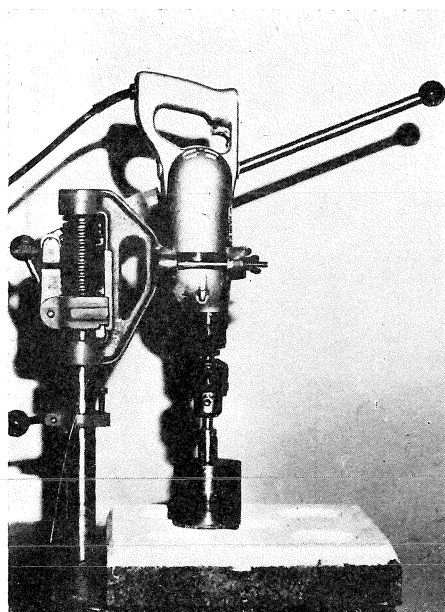
Figure 16. Diamond drill for cutting circular grooves in the surface of the mortar. ϕ 80 mm.
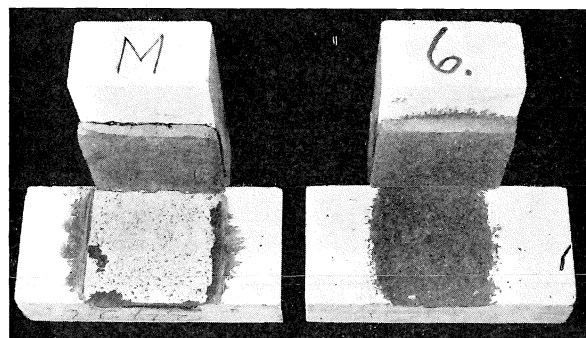
Figure 17. Bond test by the cross-brick method. Left: Bad bond. Right: Good bond.

At the second determination the mortar was applied to a base, after which, before the determination was made, grooves were drilled or sawn in the mortar in order to provide a suitable surface to which to attach the pulling unit (Fig. 16).

Even when a diamond drill is used, vibrations occur which may cause ruptures between the mortar and the base if the bond strength is less than 0.5 kp/cm².

Bond strength determinations were also made according to the cross-brick method (ASTM E 144-59 C) (Fig. 17). This method imitates a certain extent with what happens in practice, but the application of the mortar and the handling of the test pieces are more complicated than in the adhesion tests made with Hinderson's apparatus.

In my opinion, bond tests made with Hinderson's apparatus give the most reliable values, although the deviation due to variations in the material tested may be appreciable. The results given in the present study are from the PML tests of tensile strength made with Hinderson's apparatus. The values given are, as a rule, the means of four to six separate tests. Statistical information on the bond tests is given in Appendix.

Microscopy. Thin sections and polished specimens were made from sawn sections of the adhesion samples. These specimens were examined under a Leitz microscope, Ortholux-POL by reflected and direct illumination. Castings were made of the polished surface by a method developed by me (Högberg 1959), with the help of which it is easier to illustrate voids in the mortar and the boundary layers.

BINDER PASTE BOND

It is the binder in the mortar which supplies the adhesive properties. Portland cement, hydraulic lime and hydrated lime may, when mixed with water, be regarded as adhesives.

In *The Science of Adhesive Joints,* Bikerman (1961) writes as follows:

"Some of the oldest and newest adhesives belong to the third group, that which sets because of chemical reaction. The venerable plaster of Paris is a well-known example; calcium sulfate hemihydrate is mixed with water, reacts with it, and forms an agglomeration of calcium sulfate dihydrate crystals, strong enough for many purposes. The reactions causing the hardening of Portland cement are similar, but, in spite of its name, Portland cement probably would not qualify as adhesive."

In spite of Bikerman's negative attitude to Portland cement as an adhesive, Portland cement is undoubtedly the most used "adhesive" in the world today.

Most students of cement consider that the reaction between Portland cement and water is, to a certain extent, a dissolving and sedimentation reaction. Different kinds of cement hydrate, mainly calcium silicate hydrates and calcium hydroxide, are formed. The calcium silicate hydrates, which are the active ingredients in the hardening of the cement paste, are sedimented in the form of an amorphous hydrogel, becoming denser with time, of very small, badly crystallized or colloidal particles of various shapes.

The cohesion of this hydrogel is caused by the development of contact interfaces between particles in contiguous aggregates. Most of the bonds are probably hydrogen bonds either developed between hydroxyl groups in adjacent surfaces of hydrated particles or transmitted via complete interlamellar layers of water molecules.

A certain volume of water is required for the binding of the cement. For standard Portland cement a water/cement ratio of about 0.35 is considered necessary to form a good gel. A surplus of water in the mixture gives the same gel, but with a larger volume of capillary pores partly filled with the water remaining after the reaction. In the course of drying and hardening, the surplus water disappears and voids and stresses arise in the paste, due to contraction of the cement gel. These phenomena usually have a detrimental effect on the adhesion of the cement.

Since time immemorial, lime has been used as a binder in mortar. The reactions for lime are simpler than those for Portland cement. The binder paste consists of a suspension of calcium hydroxide particles in water, and corresponding ions dissolved in the water.

During the binding reactions, calcium hydroxide crystals are formed, and these, with the help of the carbon dioxide in the atmosphere, are successively transformed into different kinds of calcium carbonate, with calcite as the final product. This reaction takes a long time, and is therefore difficult to follow in the laboratory. The results of the adhesion experiments to be reported in the following were based mainly on Portland cement and mixtures of Portland cement and hydrated lime.

Water/binder ratio

In order to get a binder paste with the same viscosity, hydrated lime requires much more water than Portland cement. Thus the amount of water needed for different binders varies, which may be due to the fineness of the binder or other specific features.

The PML has, with the help of a rotation viscosimeter, determined the water/binder ratio for pastes

Table 1. Water/binder ratio of pastes with same viscosity (1500 cP)

Paste	Water/binder ratio
Portland cement paste	0.45
Masonry cement paste	0.65
Lime-cement paste, LC 50/50	0.85
Hydrated lime paste	1.30

Table 2. Volume binder paste per binder weight

Composition	Lime paste	Cement paste
Binder, g	1000	1000
Water, g	1300	450
Total volume, ml	1730	770

Table 3. Water content of different mortars

Mortar	Water content* in percent
Portland cement mortar	12—15
Masonry cement mortar	12—14
Lime-cement mortar	13—18

* Calculated on dry mortar weight.

Figure 18. A given weight of lime gives almost twice the volume of binder paste as the same weight of Portland cement. Lime requires much more water to give a mortar with the same consistence as cement paste.

of Portland cement, masonry cement, lime and cement mixes and hydrated lime with the same viscosity (Table 1).

At this viscosity, the pastes are relatively viscous. When the water/binder ratio for cement mortar is increased to 0.60, the viscous paste becomes more fluid, and particles of cement sink to the bottom rather quickly.

If the water content in a paste of hydrated lime is increased in the same way, the sedimentation is not so marked as in the cement paste, for lime particles are much finer and stay in suspension longer than the coarser particles of cement. This phenomenon can also be observed in a paste of lime and cement.

The content of water also affects the volume of the binder paste obtained per weight unit of binder. Using the water/binder ratios given in Table 2, more than twice the volume of binder paste is obtained with hydrated lime than with Portland cement (Fig. 18).

The more binder paste obtained, the more sand may be used per unit by weight of binder, without changing the consistence of the mortar.

Thus, the type of binder has much influence on the water/binder ratio. The amount of sand in a mortar also affects the water/binder ratio. If the amount of sand per binder unit is increased, the water/binder ratio increases, too (Fig. 19). This is because the larger amount of sand has a greater volume of voids to be filled. If the proportion of binder remains constant, the proportion of water must be increased. In this case, the consistence of the binder paste becomes more fluid as more water is added.

In mortars usually containing Portland cement, lime-cement and masonry cement as binders, the variations in the content of water, calculated on the dry weight of the mortar, are not very great, as is shown in Table 3.

On the other hand, the variations in the water/binder ratio are much greater.

Thus, the binder paste used for one and the same binder varies in consistence. It changes from viscous
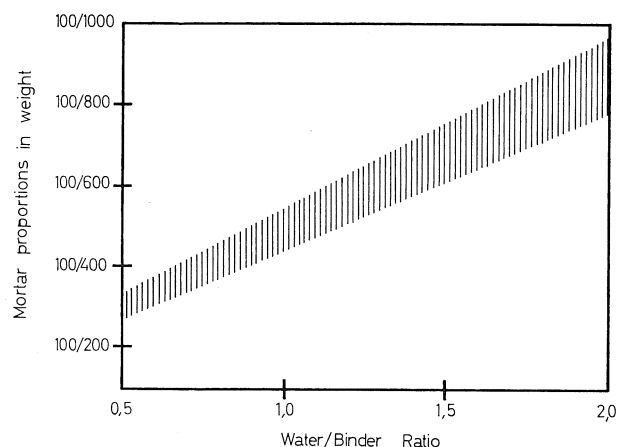
Figure 19. Relation between binder/sand ratio and water/binder ratio. The relation is almost independent of type of binder.

Figure 20. Portland cement paste between two sheets of glass. After drying for a day, a network of small cracks has formed in the paste. The test specimen was used as a negative in the enlarger. 2 ×.

to fluid. The water content of the binder paste will affect the character of the mortar. Concrete technology has shown that strength declines with rising water/cement ratio.

In the subsequent adhesion tests, the water/binder ratio was within the limits shown in Table 4. In several tests the bond strength of a binder paste with a low water/binder ratio was compared with that of a high one.

Bond between binder paste and non-water absorbent materials

A binder paste of Portland cement and water was used as an adhesive to stick two sheets of glass together. In these tests the binder paste was applied to one of the pieces of glass, after which the paste was pressed with the other piece of glass to a thickness of 0.3 mm or less. The test pieces were then stored in a moist room. About seven days, the sheets of glass were pulled apart with the help of Hinderson's apparatus.

Table 5 shows that the bond strength between cement paste and glass is very good at the lowest water/cement ratio, but decreases with successively increased content of water in the cement paste.

If Portland cement needs a water/cement ratio of only 0.35 to form a good gel, it is quite natural that the surplus water evaporates and leaves voids in the paste. This makes the adhesion surface smaller and the stresses that arise during the drying process may contribute to impaired adhesion. To illustrate this, the test pieces, comprising binder paste between two plates of glass, were used as negatives in an enlarger (Fig. 20).

Table 4. Water/binder ratio of different mortars

Mortar	Water/binder ratio
Portland cement mortar	0.40—1.00
Masonry cement mortar	0.50—1.25
Lime-cement mortar	0.60—1.75

Table 5. Bond strength between Portland cement paste and glass

Water/cement ratio	Tensile bond strength kp/cm²	
	7 days	28 days
0.50	6	9
0.75	2	3
1.00	1	2

Table 6. Bond strength between lime-cement paste and glass

Water/binder ratio (Binder LC 50/50)	Tensile bond strength 28 days, kp/cm²
1.00	3
1.25	2
1.50	1

Table 7. Bond strength between masonry cement paste and glass

Water/binder ratio	Tensile bond strength 28 days, kp/cm²
0.75	3
1.00	1

25

Corresponding adhesion tests were also made with pastes of lime-cement and water and masonry cement and water (Table 6 and 7).

Pastes of hydrated lime and water were also tested, but their adhesion to glass was very poor.

The results show that binders containing cement give relatively good adhesion values between cement and glass, but a higher content of water in binder paste reduces the tensile bond strength.

Water retentivity of binder paste

When a mortar comes into contact with a material exerting capillary suction, the water retentivity of the mortar may have some effect on the bond strength. The ability of a mortar to retain water depends to a very large extent on the composition of the binder paste. The type of binder and the content of water are of decisive importance for the water retentivity of the binder paste.

The water retaining properties of binder paste have been determined in several ways by the PML. At one test the binder paste was placed in an ASTM apparatus to determine the water retentivity of a mortar (ASTM C 91—64), and the amount of water drawn off in a minute was obtained by weighing the binder paste before and after the test.

In another test, the binder paste was placed in a folded filter and the amount of water that had run off after five minutes was determined. These tests give a good picture of the difference in retentivity between pastes of Portland cement and hydrated lime (Fig. 21).

In a third test, the binder paste was placed on tiles with high capillary suction and the flow of the binder paste was studied (Fig. 22).

The results of the tests show, as expected, that pastes made of hydrated lime retain water better than corresponding pastes of Portland cement. By corresponding is meant pastes of the same viscosity. If pastes of the same water/binder ratio are compared, the difference between lime pastes and cement pastes is still greater.

Bond between binder paste and water absorbent materials

In the later tests, one of the sheets of glass in the test pieces was exchanged for a ceramic tile with high capillary suction. This meant that the binder paste lost water immediately.

Not yet glazed whiteware wall tiles from Uppsala-

Ekeby were used at this stage. The binder paste was applied to the sheet of glass, and the smooth upper surface of the ceramic tile was pressed to the binder paste. Tests were made with both dry tiles and tiles saturated with water (Table 8).

The results show that with dry tiles the bond strength increases with rising water/cement ratio, while the bond strength declines with rising water/cement ratio with saturated tiles. The same tendency was observed with pastes of lime-cement.

This suggests that wetted tiles give the same results as non-water absorbent material. The fact that dry tiles give better adhesion with rising water/cement ratio may be because the binder paste with a higher water/cement ratio can give off surplus water and reduce further suction.

References to the literature

I have not found any literature dealing with the adhesion of binder pastes to different building materials. On the other hand, studies on the adhesion of cement paste to different aggregates exist. Nepper-Christensen (1965) studied the contact between cement paste and particles of gravel and found information in the literature that cement paste reacts chemically with siliceous rocks. Waters (1956) studied attacks on wall tiles by Portland cement and found by laboratory tests that under suitable conditions there is a slow reaction between glass wall tile and high-alkali Portland cement to produce sodium silicate, which may cause serious cracking and disruption of the glass.

The forces uniting binder paste and the glass thus arise through chemical reaction, but may also be of a physical character. Even the smooth surface of glass is really rough. According to Bikerman (1961), a smooth glass surface consists of microscopic hills and valleys, which can give the adhesive mechanical anchorage.

Conclusions

A binder paste containing Portland cement has good adhesion to glass and ceramic material, due to chemical and physical binding. No deep penetration of binder paste into pores and the like seems necessary, for good adhesion is obtained on smooth surfaces. A rising content of water in the binder paste reduces the bond to non-water absorbent material, but may increase it to water absorbent material.

These conclusions are probably valid for adhesion between binder paste and most aggregates.
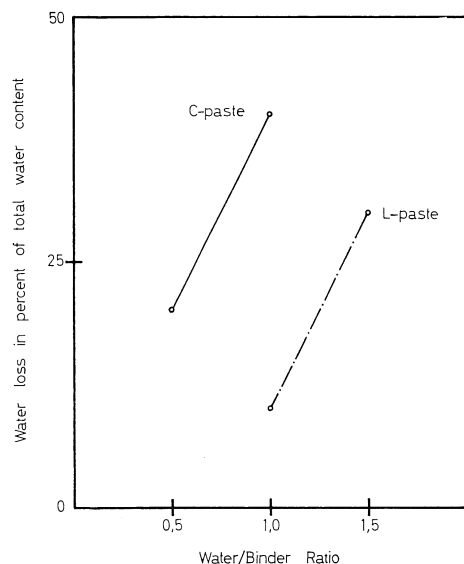
Figure 21. Water retaining properties of the binder paste. The pastes are placed in folded filters and the amount of water that runs off after five minutes is determined.

Table 8. Bond strength between cement paste and dry or wetted tiles

Water/cement ratio	Tensile bond strength 7 days, kp/cm²	
	Dry tile	Wetted tile
0.50	2	3
1.00	3	1

Binder paste

water/cement ratio			water/lime ratio
0,4			1,0
0,6			1,5
0,8			2,0
1,0			3,0
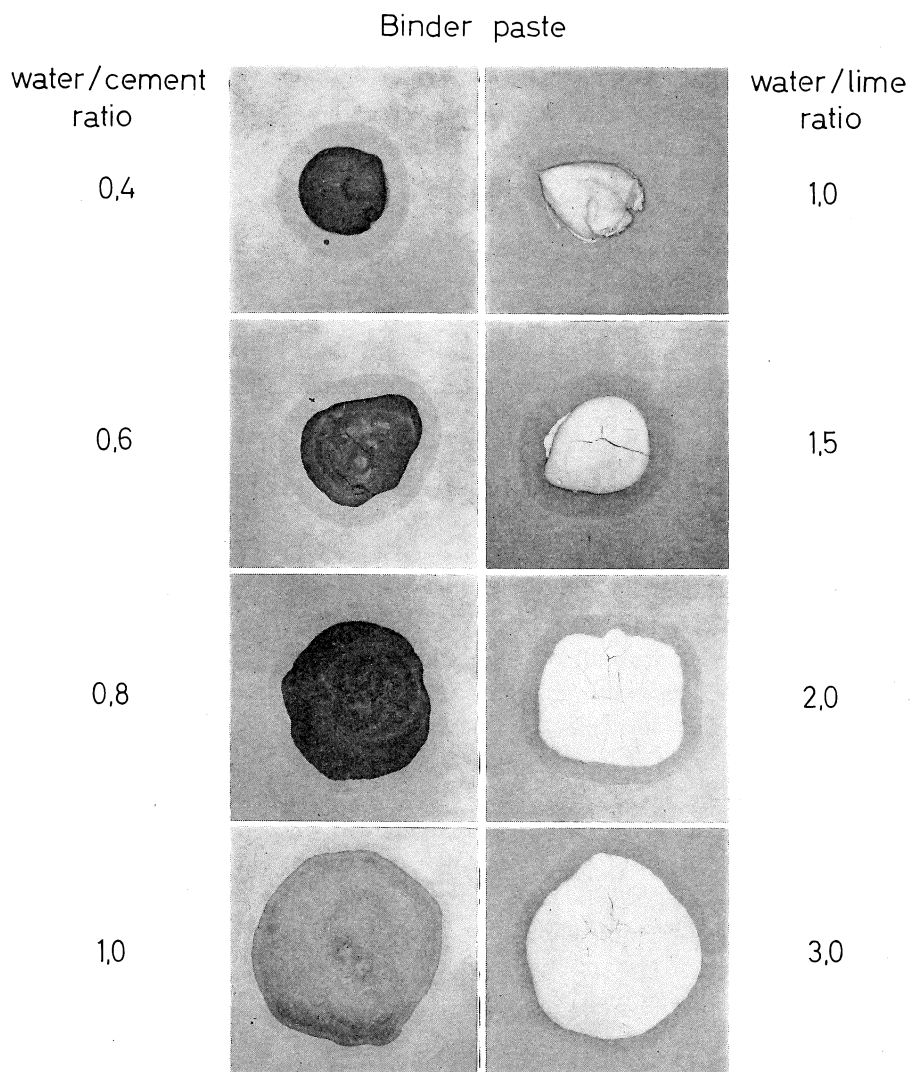
Figure 22. Binder paste of Portland cement and hydrated lime on water absorbent tiles. To obtain the same consistence, hydrated lime requires more water than Portland cement. Lime pastes with a high content of water crack greatly on drying.

MORTAR BOND

In the previous section, the influence of the binder paste on bond was demonstrated. The results have shown that very good bond values can be obtained with binder paste only.

In addition to binder paste, mortar contains sand. The purpose of the sand is chiefly to obtain a consistence which makes it easy to work with the mortar. Binding paste alone can be used in only very thin layers. As such, binder paste has been used in lime and cement paint. The mortar must be able to diminish variations in the size of bricks and level off roughness.

In mortar, sand occupies, by and large, the same volume as the whole mortar. It is the voids between the grains of sand that must be filled with binder paste, at the same time as each grain of sand must be enveloped in paste. In fresh mortar, the binder paste must act as a lubricant around the grains of sand. In hardened mortar, the sand must serve as a skeleton in the mortar and reduce the effect of the shrinkage of the binder paste during drying.

The type of binder—lime, lime-cement, masonry cement, Portland cement—influences the workability and strength of the mortar. The adhesion of the mortar may be good with all types of binder, but the bond strength increases with rising amount of cement in the binder. The strength and the bond of the mortar are also affected by the amount and grading of the sand.

It can be seen clearly from previous investigation that the water retentivity of the mortar, in combination with the capillary suction of the base material, influences bond. The water retaining properties of mortars are affected by type and amount of binder, the grading of the sand and, above all, by various organic admixtures. These problems will be dealt with in the following sections.

Mortar strength

Bond strength is influenced by the strength of the mortar itself. The cohesion of the mortar fixes a practical limit for the bond strength that can be obtained with a mortar.

The type of binder affects the strength of the mortar. As a rule, the content of Portland cement in a binder decides its strength (Fig. 23). The strength of the mortar is also affected by the ratio between binder and sand. Strength diminishes with rising amount of sand.

The more Portland cement there is in the binder, the greater will be the difference between the compressive strength and the flexural strength of the mortar. The cement content in the mortar increases the strength but reduces the elasticity.

The tensile strength provides a measure of the bond strength which may be obtained in favourable conditions with different mortars (Fig. 24).

Conclusions

The maximum bond strength of a mortar is greatly dependent on the strength of the mortar itself. High bond strength can be obtained with mortar with a high content of Portland cement. The extent of bond, however, is not dependent on the strength of the mortar. A low value of bond strength need not necessarily mean that adhesion is poor in itself.

Influence of binder/sand ratio

In most countries, proportioning rules for mortar are based more on experience than on actual scientific research.

The most common qualities of mortar are one part binder to three parts sand by volume. The most likely

Compressive strength, kp/cm²

400

300

C-mortar

200

LC 35/65

100

LC 50/50

100/400   100/600   100/800   100/1000

Binder/Sand

Flexural strength, kp/cm²

75

50

C-mortar

LC 35/65

25

LC 50/50

100/400   100/600   100/800   100/1000

Binder/Sand

Compressive strength, kp/cm²

300

200

100

25 x 25 mm

170 mm

Flexural strength

Compressive strength

Flexural strength, kp/cm²

75

50

25

L 100   80   60   40   20   0 %
C 0   20   40   60   80   100 %

Proportion of lime (L) : cement (C) in mortar (L+C) : sand = 1:4 by volume
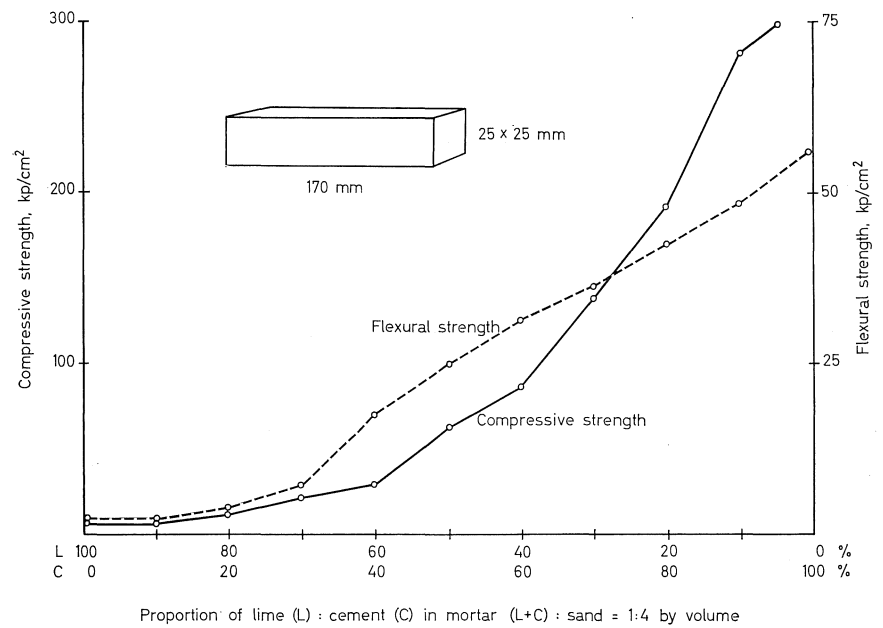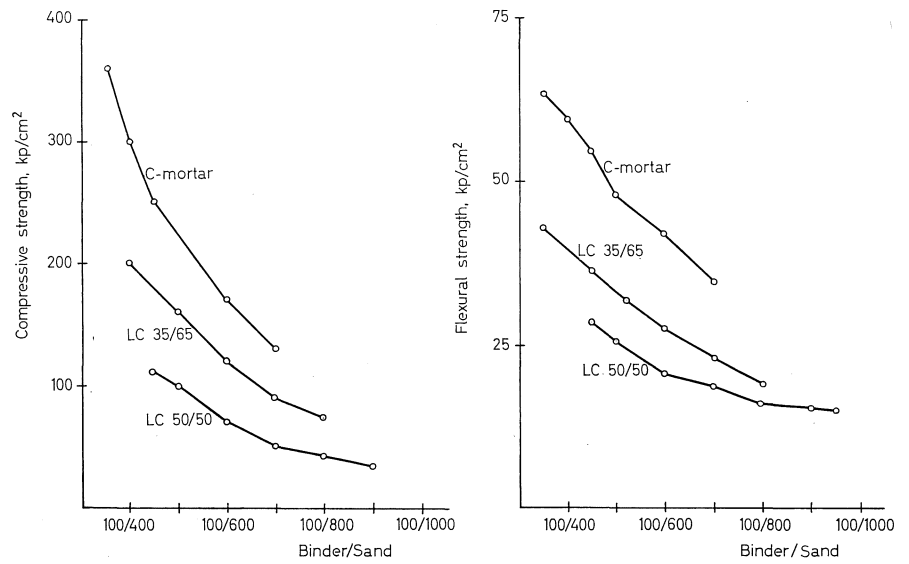
Figure 23. Strength of mortars of different compositions. Test specimens stored at 95 % relative humidity and 20° C.

Tensile strength, 28 days. kp/cm²

30

20

10

0

5   10   15   20   25
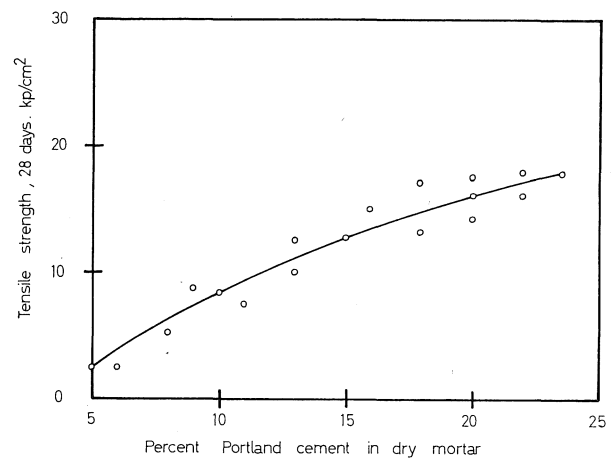
Percent   Portland   cement   in   dry   mortar

Figure 24. Tensile strength, measured on cylindric test specimens ⌀ 80 mm and 10 mm thick, stored at 95 % relative humidity and 20° C.

reason for this is the demand made by bricklayers on plastic mortar, and plastic mortar was formerly easiest to achieve by a high content of binder.

In Scandinavia a change has gradually taken place from 1:3 to 1:4 by volume, and quite often 1:5 or even leaner mixtures are used. In England a mix of one part binder to six parts sand in cement mortar with air-entraining agents is used.

Masonry cement often contains a relatively high content of inert filler. In Swedish qualities of masonry cement the filler content is ca. 50 per cent of the weight of the binder. Thus the binder content is actually only half of the weight of the masonry cement, and the actual volume ratio between active binder and sand is 1:8 or even leaner.

I have shown (Högberg, 1961) that the relation between binder and sand may affect the bond strength. On a very porous base, cement mortar 1:6 gave much better bond strength than cement mortar 1:3.

The water/binder ratio in a mortar depends greatly on the proportions of binder and sand. If we start from the same amount of sand, it contains voids that must be filled with binder and water. As the content of binder is reduced, the amount of water must be increased in order to fill these voids. This is observed most clearly in changes in the water/binder ratio. Changes in the water content of the mortar are not noticed so clearly (Table 9).

The water/cement ratio of cement mortar 1:6 is twice as high as that of cement mortar 1:3, while the water content of the two mortars is roughly the same.

The water/cement ratio of cement mortar 1:6 changes rapidly when a dry, glazed whiteware wall tile absorbs water from the mortar, while the water/cement ratio of cement mortar 1:3 changes only slightly (Fig. 25).

The mortar strength is much greater for cement mortar 1:3 than for cement mortar 1:6. The bond strength to a slightly absorbent material such as concrete is somewhat better with cement mortar 1:3 than with cement mortar 1:6.

With absorbent material such as wall tiles, the bond strength of cement mortar 1:3 was greatly impaired, while that of cement mortar 1:6 was not so much impaired.

Previous tests have shown that the bond strength of binder paste to non-absorbent materials—glass tiles—was impaired as the water/cement ratio increased. Corresponding tests have been made with mortar with one sheet of glass exchanged for a dry, glazed wall tile (Table 10).
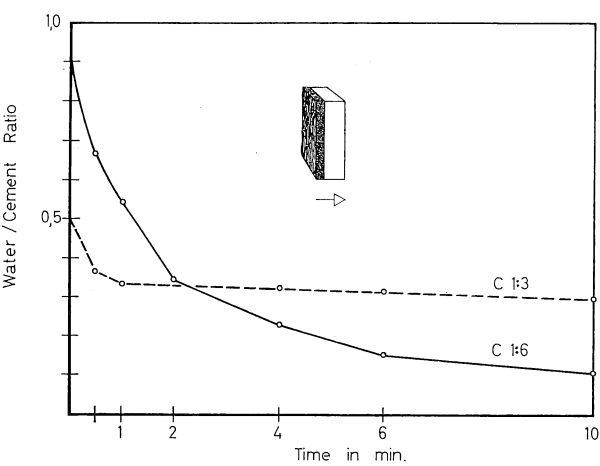
Figure 25. Variation in the water/cement ratio of the 1:3 cement mortar and 1:6 mortar due to absorption of water by a dry wall tile.

Table 9. Comparison between cement mortar 1:3 and 1:6 by volume

Mortar properties	Cement mortar	
	C 100/300	C 100/600
	1:3 by volume	1:6 by volume
Fresh mortar		
Water/cement ratio	0.48	0.93
Water content %	12.0	13.3
Hardened mortar Compressive strength		
28 d., kp/cm²	400	200
Mortar bond 28 d., kp/cm²		
to concrete	16	12
to dry wall tile	0	7

Table 10. Bond strength between cement mortar and glass or tile

Water/cement ratio	Mortar	Tensile bond strength 7 days, kp/cm²	
		Glass Mortar Glass	Glass Mortar Tile
0.50	C 100/275	3.5	0
0.75	C 100/350	1.5	1.5
1.00	C 100/475	0.5	5.5

The results suggest that bond strength of cement mortar to an absorbent base increases when the water/cement ratio rises. As Fig. 25 shows, the tile rapidly absorbs water from the lean mortar and reduces the water/cement ratio. The poor adhesion with a fat mortar is more difficult to explain. Relatively good adhesion was achieved with cement paste on the same absorbent material, even with a high water/cement ratio (Table 8). This good value may be due to the fact that the layer of cement paste was relatively thick.

Adhesion tests with lime-cement mortar have shown the same tendency as cement mortar as far as adhesion to non-water absorbent materials and water absorbent materials are concerned (Table 11).

Adhesion tests were also made with a further increase in the content of hydrated lime in the binder (Table 12).

The results show that the compressive strength declines with increased amount of sand and simultaneously increased water/binder ratio, while adhesion to an absorbent surface rises in corresponding conditions. With a non-water absorbent material both tensile bond and compressive strength decline with a higher content of sand in the mortar. At a ratio of 1:5 by volume between binder and sand, equally good bond strength was obtained with both non-absorbent and absorbent materials (Fig. 26).

Adhesion tests with lime-cement mortar were also made on sand-lime bricks. In these tests the mortar was applied in layers ca. 10 mm thick. After 28 days' storage, grooves were drilled in the mortar for the bond strength test (Fig. 27).

Although the sand-lime brick quality is slightly absorbent, the same tendency was observed as with highly absorbent dry ceramic tiles (Table 13).

In another investigation, the PML compared lime-cement mortar in the ratios 1:3 and 1:6 by volume in respect of bond strength with different bases.

Figure 26. The bond to non-water absorbent materials declines with rising content of sand in the mortar, but increases to water absorbent materials.
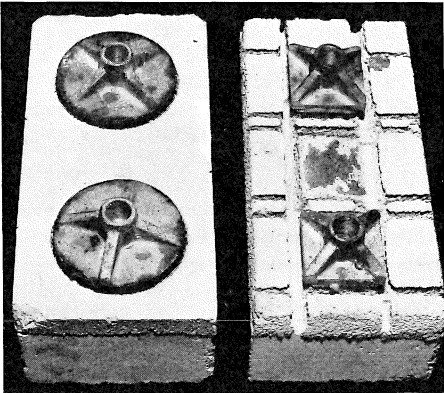
Figure 27. Drilled and sawn grooves in the mortar on sand-lime bricks for determination of bond.

Table 11. Bond strength between lime-cement mortar and glass or tile

Water/binder ratio	Mortar	Tensile bond strength 28 days, kp/cm^2	
		Glass Mortar Glass	Glass Mortar Tile
0.70	LC 35/65/400 1:3 by volume	6	0
1.40	LC 35/65/800 1:6 by volume	4	6

Table 12. Bond strength between lime-cement mortar and glazed whiteware wall tile

Water/binder ratio	Mortar	Compressive strength 28 days, kp/cm^2	Tensile bond strength 28 days, kp/cm^2
0.95	LC 50/50/500 1:3 by volume	60	0.5
1.25	LC 50/50/650 1:4 by volume	50	1.0
2.00	LC 50/50/1000 1:6 by volume	25	2.5

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Figure 28. Glazed whiteware wall tiles fixed to dry and wetted clay bricks and aerated concrete slabs.

Table 13. Bond strength between lime-cement mortar and sand-lime bricks

Water/binder ratio	Mortar	Tensile bond strength 28 days, kp/cm^2
0.80	LC 35/65/400 1 :3 by volume	0.5
1.60	LC 35/65/800 1 :6 by volume	5.0

Initial brick suction — 15 g/dm^2, min.

Table 14. Bond strength between lime-cement mortar and different materials (see Fig. 28)

Combination of dry wall tile and different backings	Tensile bond strength 28 days, kp/cm^2	
	LC 50/50/475 1 :3 by volume	LC 50/50/925 1 :6 by volume
Dry wall tile	2.0	9.0
Concrete	5.0	0.5
Dry wall tile	1.5	6.0
Aerated concrete (Siporex)	0.5	4.0
Dry wall tile	1.0	6.0
Dry brick	0.5	6.0

Table 15. Bond strength between cement mortar and tile (Waters, 1959)

Glazed whiteware wall tile Dry	Shear strength 7 days, kp/cm^2	
	Cement mortar 1 :3	Cement mortar 1 :5
Experiment no. 1	6.3—7.6	3.6—7.0
Experiment no. 2	6.1—15.8	6.6—9.4

The mortar was applied to dry, glazed whiteware wall tiles, which were then pressed to bases of concrete, aerated concrete and brick (Fig. 28). At the tests, the adhesion of the mortar to the tiles and the different base materials could be determined as long as the mortar had not broken. After the bond rupture, the mortar was glued to the base from which it had loosened with epoxy resin. The bond strength tests could then be continued (Table 14).

If the results of the adhesion tests on lime-cement mortar are compared, it will be found that bond strength is consistently better with the absorbent base materials with mortar of the ratio 1 :6 than with the ratio 1 :3.

References to the literature

In the investigations, the results of which have been published, mortars with one part binder to three parts sand were generally used. On account of this, there is only little information in the literature on how the ratio between binder and sand affects bond strength.

Piepenburg *et al.* (1958), in their investigations of the adhesion of rendering, tested mortars with different proportions of binder and sand. They found that the compressive strength rises with rising content of binder in the mortar, but in respect of bond strength, they preferred not to draw any conclusions from the results obtained. In some cases, mortar of the ratio 1 :5 gave bond strength as good as or better than a 1 :3 mortar.

Waters (1959) reported that cement mortar 1 :3 gave better bond than cement mortar 1 :5 with dry absorbent tiles. Thus Waters' result differs greatly from mine (Table 15).

Figure 29. Test pieces made by Waters in Malmö, 1965. Fresh mortar 1:6 adheres to water absorbent tiles better than 1:3 cement mortar does.
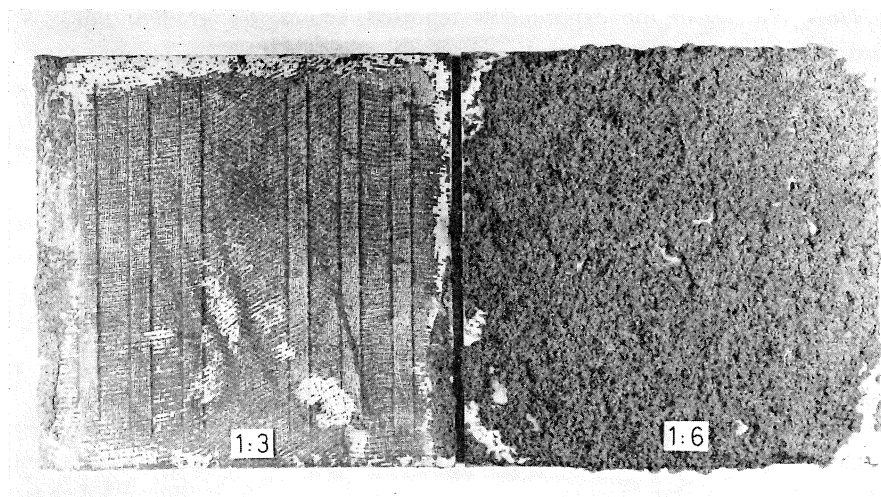
During a visit to Malmö in the summer of 1965, Waters was able to observe that adhesion between cement mortar 1:6 and a dry wall tile was much better than with cement mortar 1:3 when the extent of bond was examined immediately after the application of the mortar (Fig. 29). On this occasion, the procedure was exactly the same as that used in Waters' earlier experiment. During a discussion of the cause of the differences between the results, it was found that in the experiments in Australia only the shear strength, not the tensile bond strength of the mortar had been determined. (See Fig. 7.) In these tests, the rupture had occurred in the mortar, and the actual bond strength had therefore never been determined. In Waters' tests, the tile was beaten into the mortar, while in the PML tests mortar was applied to the rear side of the tile, after which the tile was pressed to a concrete surface. Mechanical treatment of the contact surface improves adhesion. Balinkin, McHugh and Scholz (1956) obtained an increased bond strength when the tiles were beaten into the mortar.

In my opinion, the good adhesion of cement mortar 1:6 to an absorbent base material is due largely to the fact that the ratio between water and cement is relatively high. This is on the whole in agreement with Waters' experiment no. 3 (1959), referring to the interaction of the water/cement ratio in cement mortar 1:5.

The results given in Table 16 show that Waters, with highly absorbent dry tiles, obtained better shear strength with rising water/cement ratio. With tiles of low absorption, the case was the opposite.

Table 16. Interaction of water/cement ratio on 1:5 mortar (Waters, 1959)

Glazed wall tile	Shear strength, 7 days kp/cm² Water/cement ratio		
	0.8	1.0	1.2
Dry tiles, high absorption			
Type B: Glazed whiteware tile (absorption 11.6 %)	4	5	8
Type F: Glazed light-mottled earthenware body wall tile (absorption 12.9 %)	4	6	5
Dry tiles, low absorption			
Type E: Fine-grained red earthenware floor tile (absorption 2.4 %)	7	6	3

During the discussion of Youl's and Coats' paper at the Australian Building Research Congress in 1961, Waters reported some tests made by the Division of Building Research in the bonding of concrete to hardened concrete. The experiments had revealed that the bond strength, with increasing or decreasing water content of the mortar applied, depends on the suction of the underlying material. A saturated material gave a lower bond strength with an increase in the water content of the applied layer, while a dry underlying material gave a higher bond strength with an increase in the water content of the mortar.

Thus Waters, in the experiments reported, found that a higher water/cement ratio improves adhesion to an absorbent base material. This is in agreement with my findings.

Conclusions

The experiments made at the PML showed clearly that the ratio between binder and sand affects the bond strength.

With a non-absorbent base material, the bond strength is impaired when the amount of sand in the mortar is increased and the water/binder ratio rises in consequence. With an absorbent base material, the bond strength is usually improved when the amount of sand in the mortar increases.

The binder/sand ratio and the water/binder ratio are intimately interrelated.

Influence of sand grading

In most countries, researchers have tried to obtain a grading of sand for mortar to get a relatively dense mortar. The grains of sand are to form a skeleton in the mortar, while the binder and water are to fill the voids between the grains of sand and give the mortar the plasticity required for the work. In order to avoid excessive shrinkage in the mortar, the voids between the large grains must be filled with smaller grains. The smaller the volume of voids between the grains of sand, the smaller the amount of binder needed in the mortar.

Many investigations have been made to find the grading of the grains to give the densest packing. Spherical grains of the same size give, regardless of size, the largest volume of voids. It has been demonstrated experimentally that a mass of equally large balls has, in the most favourable circumstances, voids equal to 39 per cent of the external volume of the mass. The theoretical value is 26 per cent. With balls of different sizes, it is possible theoretically to attain a volume of voids less than 1 per cent of the total volume. Experimentally it is very difficult to obtain values below 20 per cent voids.

I have studied how densely sand is packed in fresh mortar. For sand of one grain size only, the voids occupied about 50 per cent of the total volume, while the voids with well-graded sand were seldom below 35 per cent. By studying thin sections under the microscope, I found that the grains of sand are surrounded by binder, and because of this, the interstices between the grains of sand in mortar are always larger than the voids between the grains of sand themselves. The densest packing of grains of well-graded sand is achieved at a binder/sand ratio of 1:4 or leaner by volume. If the mortar contains more binder, the binder paste presses the grains of sand apart, with a consequent looser packing of the grains of sand (Fig. 30).

In volume proportioning of sand, single-grain sand contains a larger volume of voids to be filled with binder and water than a well-graded sand. With the same quantity of binder, more water is required with single-grain sand than with well-graded sand to obtain a workable mix. The water/binder ratio will be higher with single-grain sand than with well-graded sand. When the water/binder ratio rises, the strength of the mortar usually declines.

The PML has made mortar with different gradings of sand and measured the bond strength and the volumes of the voids (Table 17).

The results suggest that there is relationship between the volume of voids in the sand and the water/binder ratio (Fig. 32).

In order to investigate the influence of the grading of sand on bond strength, the PML used standard sand and the individual fractions forming standard sand in Sweden. Sand no. 3 consists of the coarsest grains, 1—2 mm, and must be regarded as single-grained. Sand no. 1 is fine-grained and is somewhat better graded than sand no. 3 (Figs. 33, 34 and Table 18).

Table 17. Influence of sand grading on water/binder ratio

Sand (Fig. 31)	Voids %	Water/binder ratio (LC 50/50/600)
C	50	2.11
A	49	2.22
B	46	1.86
E	43	1.72
D	39	1.27
F	38	1.32

Table 18. Influence of sand grading on compressive strength and bond strength

Mortar LC 50/50/600	Standard sand	Sand no. 1	Sand no. 3
Water/binder ratio	1.20	1.75	2.00
Compressive strength, 28 d.	45	20	15
Bond strength, 28 d.			
to non-absorbent material	2.5	1.0	0.5
to absorbent material	2.5	5.0	3.0
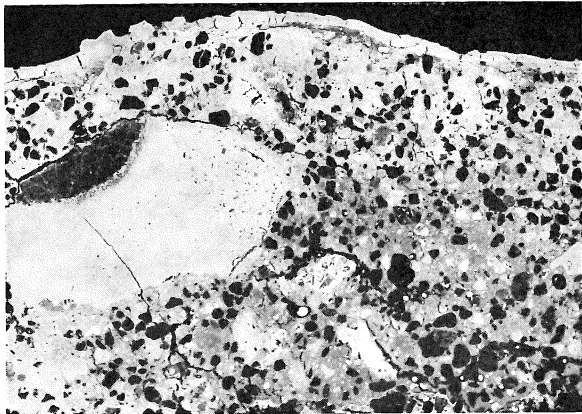
Figure 30. The grains of sand in a test piece rich in binder do not form a skeleton in the mortar. Lime mortar dating from the 12th century.
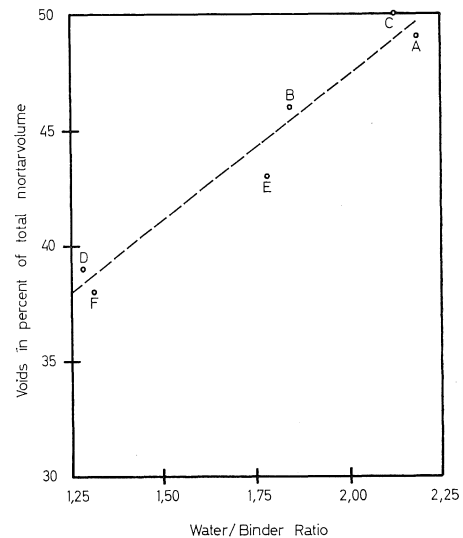
Figure 32. Relation between the volume of voids in the sand and the water/binder ratio.

Figure 31. The influence of sand grading on the strength of mortars. The diagram shows the strength of mortar, LC 50/50/650, in kp/cm², prepared with different kinds of sand. The test pieces were stored 28 days at 95 percent relative humidity and 20° C.
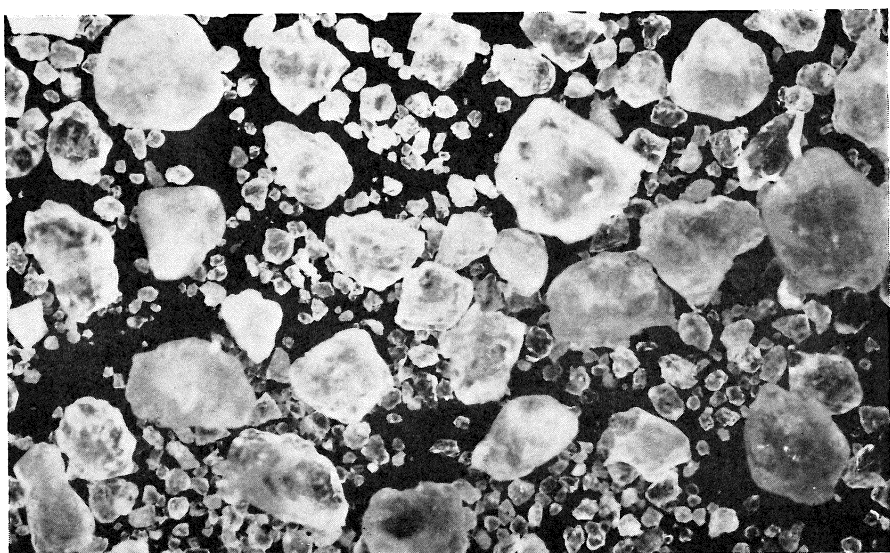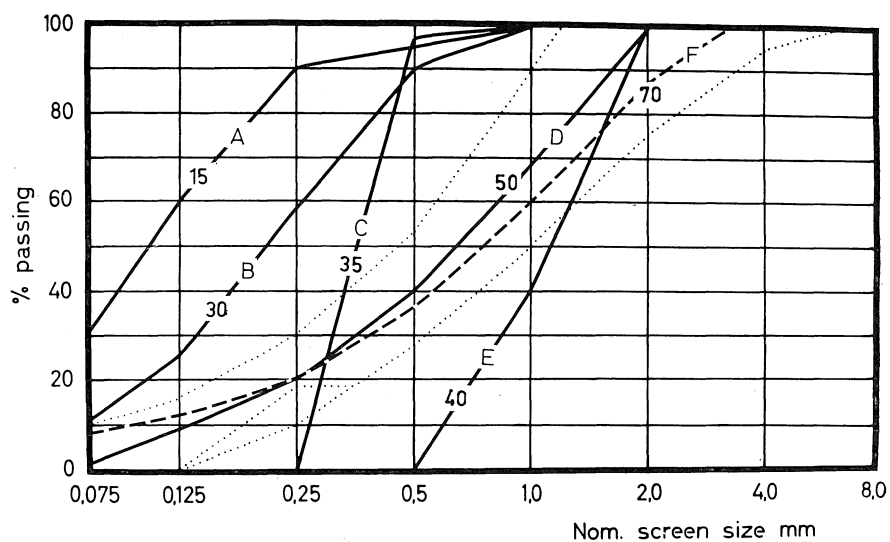
Figure 33. Standard sand from Fyledalen, Sweden. 10×.
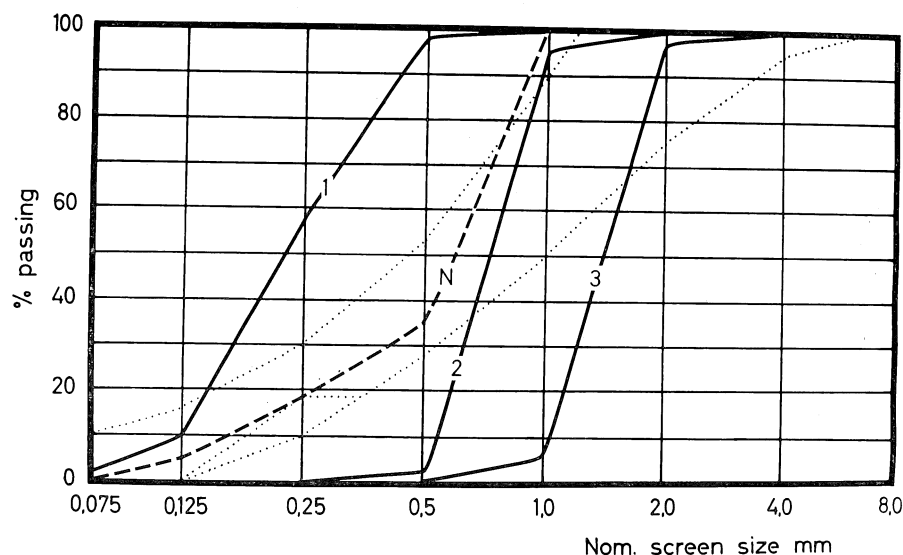
Figure 34. Standard sand consists of three fractions 1, 2 and 3, which are mixed in equal parts by weight=N.

The results show that compressive strength decreases with rising water/binder ratio. In the same way, bond strength to a non-absorbent material declines with rising water/binder ratio. On the other hand, bond strength to an absorbent material does not seem to be impaired with rising water/binder ratio.

Sand no. 3, which is single-grained, gave the lowest compressive strength with the lime-cement mortars tested; bond strength to absorbent material was good. The mortar had very bad workability, however. Mortar with sand no. 1 had the best bond strength to absorbent materials.

References to the literature

The influence of sand grading on the adhesion of mortar has not yet been fully investigated. Piepenburg *et al.* (1958), in a study of the adhesion of rendering, compared a relatively well-graded sand "A" with a fine-grained sand "C". In a mortar with one part binder to three parts sand by volume, the finer sand "C" had much better adhesion than sand "A". The situation was the contrary with a 1:5 mortar. These results are impossible to interprete, for nearly all the ruptures occurred in the mortar. They do suggest, however, that the adhesion of a 1:3 mortar to all the absorbent base materials was improved with sand "C", which has a larger volume of voids than sand "A". Thus the water/binder ratio is higher in a mortar with sand "C" than with sand "A", and this, according to investigations made by the PML, should improve adhesion to absorbent base materials. In a 1:5 mortar, the water/binder ratio is always

higher than in a 1:3 mortar and a further increase of the water/binder ratio by using sand "C" may lead to impairment of the bond strength.

Conclusions

Sand grading affects the water/binder ratio of the mortar. A single-grain sand gives a higher water/binder ratio than a well-graded sand. The bond strength to absorbent base materials rises with rising water/binder ratio. If the water/binder ratio rises to an extremely high value, adhesion might be impaired. The bond strength to non-absorbent materials falls with rising water/binder ratio.

A single-grain sand, which might be unsatisfactory from other aspects for use in mortar, may give a mortar with satisfactory adhesion to absorbent materials.

Fresh mortar bond

I have observed earlier (Högberg, 1965) that the final bond of a mortar is determined at the moment the mortar is applied.

In the investigation made by the PML of the water retentivity of mortars, it was possible to study, at the same time, the adhesion of fresh mortar to different materials. In the tests, a piece of gauze was placed between the mortar and the base, and after a predetermined interval of time the mortar was removed from the base with the help of the gauze (Fig. 35). This operation revealed that sometimes the whole surface of the base was covered with a thin layer of binder, and sometimes only isolated patches

Figure 35. Plexiglass moulds for standard bricks. The moulds are 10 mm higher than the brick so that the mortar can be applied at a constant thickness. The gauze is used to remove the fresh mortar and to determine the extent of bond and the suction of the brick. Even after the mortar has hardened, it is easy, thanks to the gauze, to remove the mortar from the brick.
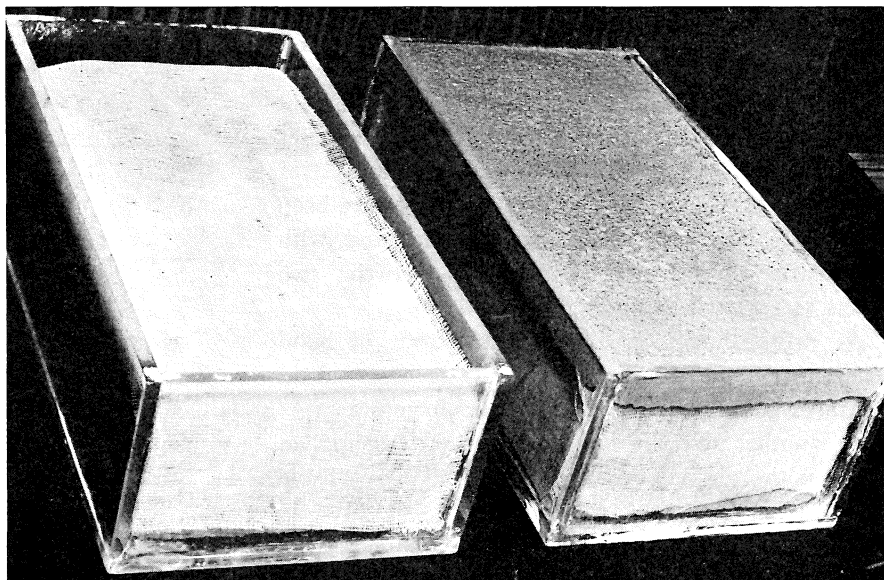
Figure 36. Comparison of fresh and hardened mortar. The large, lower tiles were removed from the mortar immediately after it was applied. The small, upper tiles are bond tests on equivalent mortar 28 days later. Left: Both fresh and hardened mortar have good adhesion. Right: Both fresh and hardened mortar have bad adhesion.
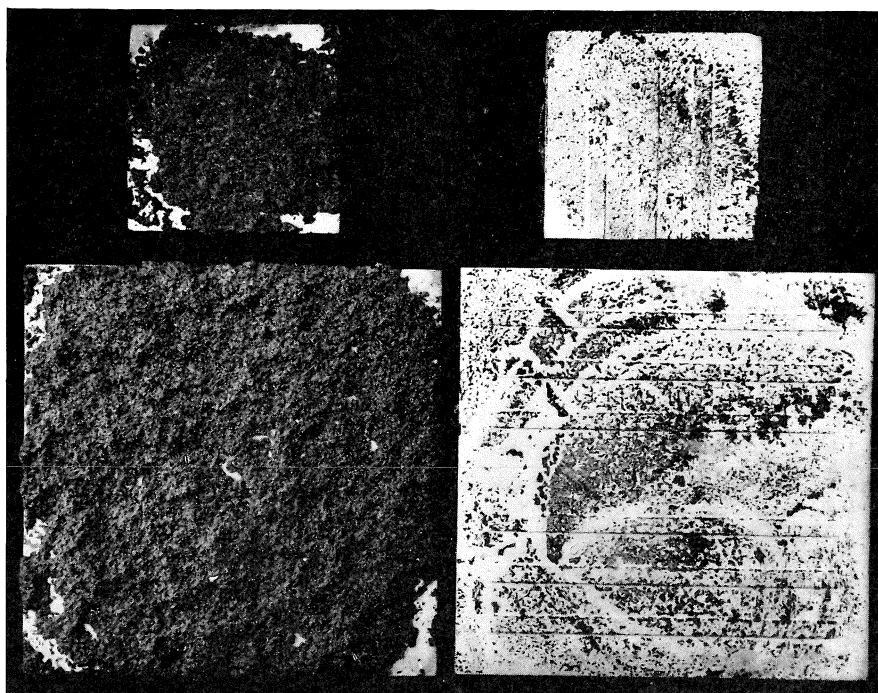
of binder could be seen on the surface. At the determination of adhesion seven or twenty-eight days after the application of the mortar, it was found that there was a distinct relationship between the bond surface of the fresh mortar and the hardened mortar (Fig. 36).

The relationship between the adhesion of fresh and hardened mortar could be observed clearly on absorbent base materials.

This method makes it easy to get a quick answer to the question whether the final bond strength will be satisfactory. If, according to this method, the fresh mortar has good bond, it is not known with certainty whether the adhesion will be permanent, for later stresses may arise in the process of drying and shrinking in the mortar and the base material.

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Bond between mortar and non-water absorbent materials

The bond between binder paste and non-absorbent material is, as shown earlier, good, but the more water the binder paste contains, the poorer the bond.

Corresponding tests as with binder pastes have been made with Portland cement and standard sand, with a layer of mortar ca. 10 mm thick between two sheets of glass (Table 19).

As with binder paste, an impairment of bond strength to non-absorbent materials is observed in mortar when the water/cement ratio increases.

In another test, lime-cement mortar was applied between the glazed surfaces of two wall tiles (Table 20).

Bond strength declines here, too, with decreasing content of binder and rising water/binder ratio.

The bond tests were made with glass and glazed surfaces as non-water absorbent materials. Glass in combination with mortar is used only to a small extent in the building trade. Generally speaking, only glass blocks or glass wall tiles are bonded with mortar.

Other materials with low capillary suction which come nearest tests with glass are compact concrete and vitreous ceramic tiles. Adhesion to these materials should not differ much from the results obtained with glass. It is quite possible, however, that the specific features of the surfaces of these materials show great difference which may influence adhesion.

The PML studied the bond strength between different mortars and concrete (Table 21).

The results suggest that the bond strength between mortar and concrete is very good, and somewhat better than between mortar and glass. The tensile bond strength of the mortars is almost as high as their tensile strength.

Conclusions

Mortar, like binder paste, usually has good bond strength to non-absorbent materials. The bond strength declines with rising water/binder ratio. Thus penetration into the base is not necessary to obtain satisfactory adhesion.

Bond between mortar and water absorbent materials

Most building materials used in combination with mortar have capillary suction. The variations in this capillary suction are very great. Compact concrete and hard-burned ceramic material have low capillary suction, while soft-burned ceramic materials have relatively strong capillary suction.

Table 19. Bond strength between cement mortar and glass

Water/cement ratio	Mortar	Tensile bond strength	
		7 d., kp/cm²	28 d., kp/cm²
0.50	C 100/275	3.5	6.0
0.75	C 100/350	1.5	3.5
1.00	C 100/475	0.5	1.5

Table 20. Bond strength between lime-cement mortar and glazed tile surface

Water/binder ratio	Mortar	Tensile bond strength 28 days, kp/cm²
LC 50/50/450	1.25	2.5
LC 50/50/650	1.50	2.0
LC 50/50/950	1.75	1.0

Table 21. Bond strength between mortar and concrete

Type of mortar	Tensile bond strength 28 days, kp/cm²
Cement mortar	
1 :3 by volume	15
1 :6 by volume	14
Lime-cement mortar	
Binder LC 35/65	
1 :3 by volume	12
1 :6 by volume	10
Masonry cement mortar	
1 :3 by volume	8
1 :6 by volume	4
Lime mortar	
1 :3 by volume	1
1 :6 by volume	1

A number of investigations reported in the literature show that bond strength is affected by the capillary suction of the material and the water retentivity of the mortars.

References to the literature

When studying the water absorption of a material it is customary first to determine the total water absorption by immersing a test specimen in water. It is often desirable to know the rate of absorption.

In most countries the initial rate of absorption (IRA) of brick is measured by laying brick on its flat side for one minute in water a few millimetres deep. In respect of adhesion the problem is to as-

certain how quickly and with what force water is drawn from the mortar into the material.

Jansson (1965) found that the amount of water absorbed by porous materials plotted against the square root of time gives a reasonably straight line. In the laboratory, Jansson measured the water absorption of different qualities of brick and aerated concrete (Fig. 37). The results are in good agreement with his theoretical calculations. Jansson holds the view that the standard test of water absorption by bricks (the one-minute test) provides little information about the properties of bricks.

Weigler (1965) determined the capillary suction of aerated concrete by a method making possible continuous determinations of the water absorption after only two seconds. The test piece is placed on a filter paper which is in contact with a water surface. When water is absorbed by the test pieces, changes in level occur in narrow glass tubes full of water in communication with the free water surface. In diagrams, Weigler gave the upper and lower limits for various qualities of aerated concrete with high capillary suction (Fig. 38).

Sneck (1965) determined the water absorption of three types of clay bricks and two sand-lime bricks in the same way as Jansson (Fig. 39). He also showed what happens when two sand-lime bricks are placed in contact with a lime-cement mortar. The sand-lime brick with a high initial rate of absorption from a free water surface drew less water from the mortar than the other sand-lime brick, which had a low initial rate of absorption (Fig. 40). Sneck therefore queried the value of the initial rate of absorption from a free water surface as a criterion of the influence on the properties of the bond.

Davison (1961) studied how the water content of mortar changes when bricks with different capillary suction are allowed to affect the mortar during definite periods of time. He found that the water-content determinations on mortars during a five-minute period of contact with bricks in six initial rate of absorption ranges revealed a substantial drop in water-content (Fig. 41). Water-content losses for each mortar increased until relatively high initial rates of absorption were reached.

Davison also showed that different bricks with similar rates of absorption gave the same result in water-content determinations on mortars.

It is frequently stated in the literature that material with a high initial rate of absorption gives poor mortar bond.

Haller (1959) found that the strength of brickwork diminishes with rising initial rate of absorption
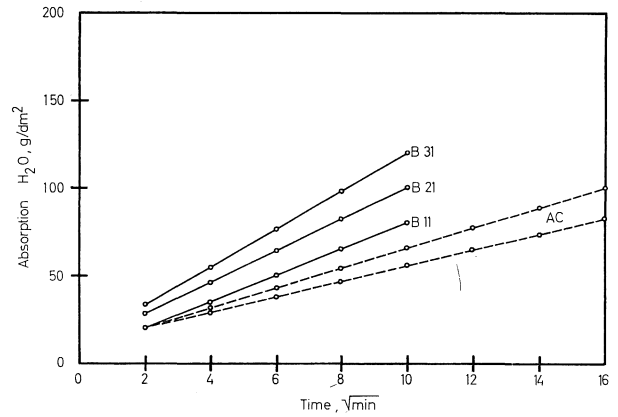

Figure 37. Suction of clay bricks (B 11—31) and aerated concrete blocks (AC), according to Jansson (1965).
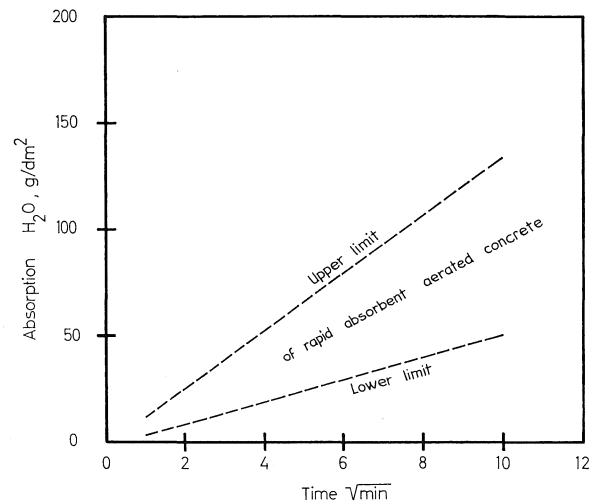

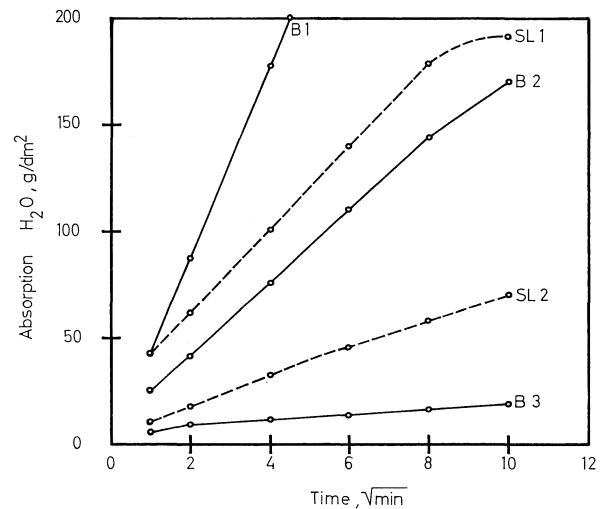Figure 38. Suction of rapid absorbent aerated concrete blocks, according to Weigler (1965).

Figure 39. Suction of clay bricks (B 1—3) and sand-lime bricks (SL 1—2) according to Sneck (1965).
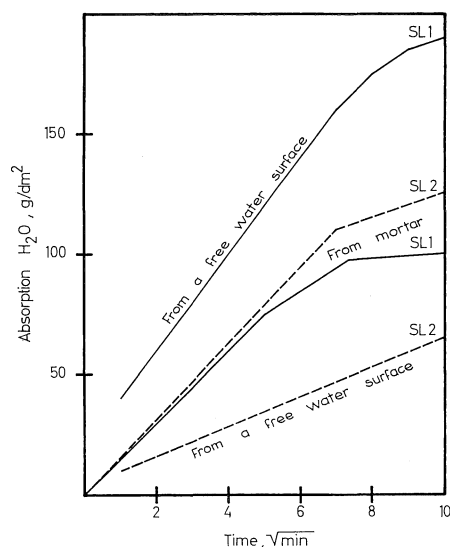
Figure 40. Comparison of suction from a free water surface and from mortar (LC 35/65/450). The sand-lime brick no. 2 with the lower initial rate of absorption has removed more water from the mortar than brick no. 1 with higher rate of absorption. According to Sneck (1965).
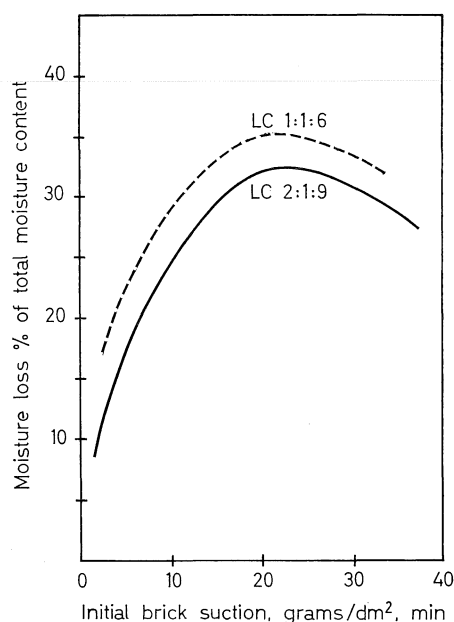

Figure 41. Moisture loss from lime-cement mortar by suction of bricks with different initial rates of absorption. Contact time, 4 minutes. According to Davison (1961).

of the bricks used. He considers that high-quality bricks should not have one-minute suction greater than 15—20 g/dm^2, min.

Palmer and Parson (1934) found that the bond strength increased with initial suction, to reach a maximum when the initial rate of absorption was about 10 g/dm^2, min. (Fig. 42).

Collin (1935) drew the following conclusions from his investigations:

1. Low absorption bricks develop a medium bond strength with both cement and lime-cement mortars, when set either dry or wet.
2. Medium absorption bricks develop a high bond strength with both cement and lime-cement mortars, when set either dry or wet.
3. High absorption bricks develop only a low bond with cement and lime-cement mortars when set dry, and this bond strength is materially increased when these bricks are set wet.

In Technical notes (1961) on brick and tile construction from the Structural Clay Products Institute in Washington it is claimed that in practically all cases, mortar bonds best to brick whose suction is 3—10 g/dm^2, min. at the time of laying. If brick suction exceeds 30 g/dm^2, min. when laid, bond may be extremely poor.

The relation between the initial rate of absorption of a material and the water retentivity of mortar has been discussed by many research workers. The water retentivity of mortar is often determined by subjecting the fresh mortar to suction, in a vacuum, for one minute (ASTM C 91). The water extracted is not usually measured; instead, water retentivity is expressed as a relation between the flow of the mortar before and after suction.

Voss (1933) found that highly absorbent bricks require lime-cement mortars with a high content of lime.

Many investigations by Palmer and Parson (1932) and others have shown that lime mortar has better water retentivity than cement mortar. When water is drawn from mortars, they stiffen. Increasing the lime content in a lime-cement mortar tends to decrease the rate of stiffening.

Tytherleigh and Youl (1961) also observed that the retentivity of the mortar, i.e. its ability to retain water against suction, increases with increasing lime content.

I have found (Högberg, 1965) that a mortar with poor water retentivity gives better adhesion to a very absorbent base material than a mortar with good water retentivity.

My results do not agree with the conclusions Palmer and Parsons (1934) drew from their studies of the permeability of brick wallettes. They found that the wallettes constructed of porous bricks set dry were more water-tight with mortars of high than with mortars of low water-retaining capacity. Also the extent of bond increased as the water-retaining capacity of the mortars increased. In "Discussion" of Palmer and Parson's work, Gonnerman maintained that these authors' conclusions regarding the relation between the water-retentivity of the mortar and the suction of the bricks used are very doubtful.

In most of the investigations mentioned here, bond strength was determined by the cross-brick or some similar method. Both leakage and strength tests point to a weaker bond between the mortar and the brick above than between the mortar and the brick below.

Davison (1961) also studied the moisture gradient in the mortar bed. He applied the mortar to a brick, and after a certain time he divided the mortar into an upper and a lower part, and measured the water contents of the two halves (Fig. 43). The results clearly established the presence of a moisture gradient in the mortar bed, for in all cases the moisture content of the top half was substantially higher than that of the bottom half. Davison considered that the loss of moisture from the mortar bed, with the resulting reduction in "bonding ability" might explain inferior bonding at the interface between the mortar bed and the brick above it, as compared with the bond between the mortar bed and the brick beneath it.

Anderegg (1942) also determined the moisture gradient in mortar in contact with a given brick for definite periods of time. He removed the mortar carefully and measured the water content of the layer left clinging to the brick and of six successive 1 mm layers taken from the detached mortar. He found the lowest water content in the mortar nearest the brick, and the highest in the top layer (Fig. 44). More remarkable is that Anderegg, like Sneck (1965) later, found that most moisture was drawn out by some bricks with the lowest initial absorption rate of water. In this experiment, Anderegg showed that the higher initial absorption rate, the greater was the apparent tendency to form a highly congealed layer of mortar on the brick surface. The rest of the mortar could be readily peeled from the congealed layer.

According to Anderegg, moisture is apparently removed so rapidly from the surface of the mortar by bricks of high initial suction capacity that a condensed layer is formed with a permeability varying inversely with initial suction.
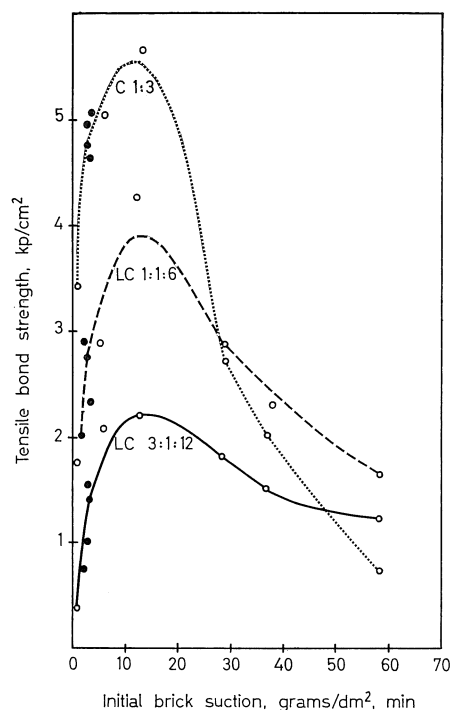

Figure 42. Relation between brick suction and tensile bond strength. According to Palmer and Parsons (1934).
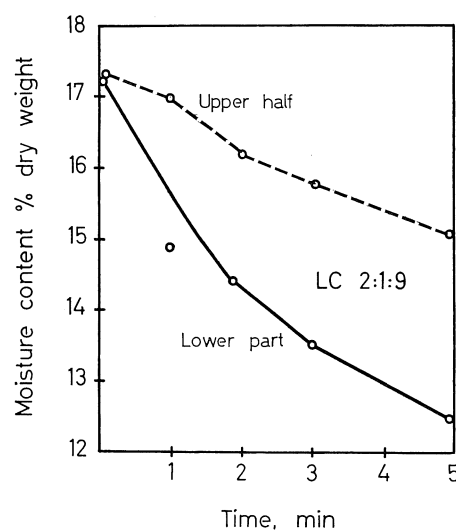

Figure 43. Moisture content of upper and lower halves of mortar bed in contact with a brick (initial brick suction= 40 g/dm², min.). According to Davison (1961).
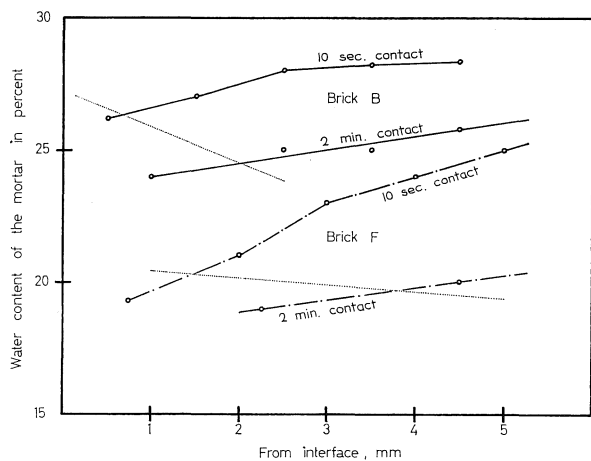
Figure 44. Moisture gradient in mortar (LC 2:1:9) in contact with different bricks. The layer of mortar nearest the contact zone has lost more water than parts of the mortar farther away from the interface. The area left from the dotted line indicates the approximate thickness of the congealed layer. According to Anderegg (1942).
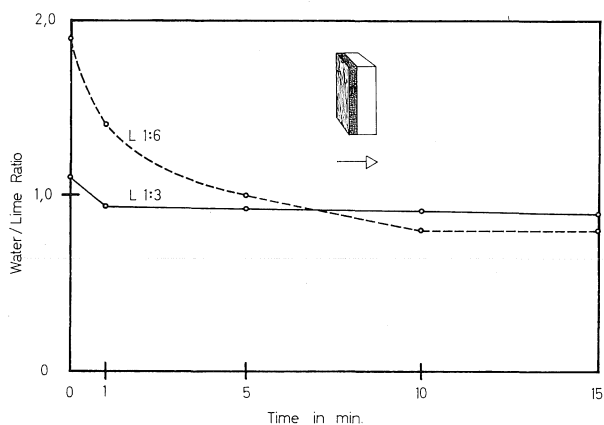

Figure 45. Changes in water/binder ratio in lime mortars due to absorption of water in a dry water absorbent wall tile.
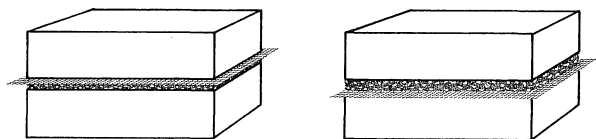

Figure 46. Set-up to test water absorption and bond in a unit of bricks and mortar. Thanks to the gauze, the upper or lower brick can be easily removed.

The investigations reported here show that many factors influence the bond. In the following sections I shall attempt, by a series of investigations, to explain how different factors affect the bond between mortar and an absorbent material.

Investigations at the Plaster and Mortar Laboratory

In a previous section, "Influence of binder/sand ratio", the results of investigations showed that mortar 1:6 by volume gives better adhesion to absorbent bases than mortar 1:3, as shown in Table 22.

If mortars 1:3 by volume are compared, it will be observed that more lime in the mortar improves the bond strength somewhat. Thus there is a tendency for lime in mortar to improve the bond. If, on the other hand, mortars with a ratio of 1:6 by volume are compared, it will be found that bond strength declines with rising content of lime. This is because all the mortars with a ratio of 1:6 by volume have good bond to very absorbent materials, and that adhesion falls in proportion to the strength of the mortar.

I have demonstrated (Högberg, 1965) that cement mortar 1:6 loses more water during the first few minutes of suction than cement mortar 1:3 to an absorbent base, which means that the mortar with the best adhesion has the worst retentivity.

Corresponding tests were made on lime-cement mortar and lime mortar (Fig. 45). In these tests, gauze was placed between the mortar and the base. With the help of this gauze the fresh mortar can easily be removed from the base at a convenient moment. The increase in weight of the base was determined in this way. The results suggest that a mortar 1:6 has lower water retentivity than mortar 1:3. At the same time, the bond result showed better values with mortar 1:6 than with mortar 1:3 on very absorbent bases. In these tests, the mortar was exposed to suction in one direction only.

Even if mortar is exposed to suction in two directions, as occurs in the joints of a wall, it does not necessarily follow that adhesion to the upper and lower brick is the same.

The PML has studied this according to the following method. A brick was placed in a plexiglass mould (Fig. 46). On this brick, which was covered with a piece of gauze, was placed a 10 mm thick layer of mortar. After a predetermined period of time, one or two minutes after the mortar had been applied to the brick, another brick was pressed into the mortar. The test unit, now consisting of two bricks with mortar between, was then removed from the mould (Fig. 47). The test piece was then stored in a
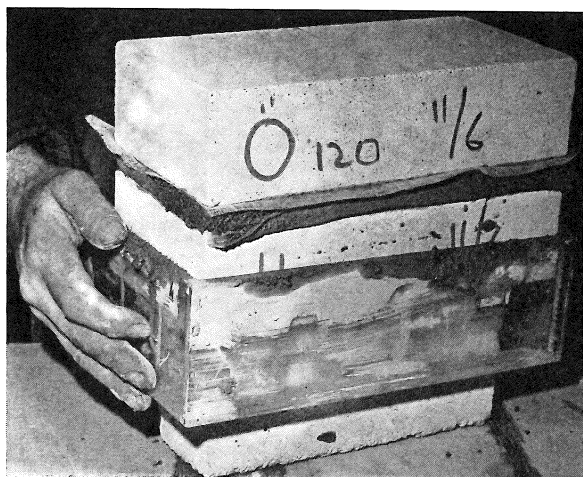
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Figure 47. The couplet of bricks and mortar is removed from the plexiglass mould.

moist room. A day or so before the determination of the bond strength was to be made, the brick with the gauze was removed. This was rather easy, thanks to the gauze. After that grooves were made in the mortar with a diamond drill or a saw in order to attach the pulling device of the adhesion apparatus (see Fig. 27). It was possible in this way to measure the adhesion to the upper brick. Adhesion tests were made on the lower brick in the same way, except that the upper brick was then covered with gauze.

The water absorption of the bricks could be measured with the same set-up. In these tests both the upper and the lower brick were covered with gauze. After definite intervals of time, the unit was divided and the increase in weight of each brick was determined. Clay and sand-lime bricks of standard size were used in these tests. Aerated concrete was sawn into suitable sizes.

At the first tests, clay bricks with a relatively high initial rate of absorption (25 g/dm², min.) were tested. Cement mortars, 1:3 and 1:6 by volume were used. The absorption was determined one minute after the upper brick had been placed on the mortar. The lower brick had then been in contact with the mortar for two minutes (Table 23). The same tests were made with lime-cement mortar (Table 24).

The results of the two tests show that water absorption into the upper brick was quite insignificant, while the lower brick had very high water absorption. The water loss from lime-cement mortar was smaller than from cement mortar. Mortar 1:3 by volume lost less water than mortar 1:6. Corresponding tests were also made with bricks of medium initial rate of absorption, 15 g/dm², min. (Table 25).

Table 22. Bond strength between highly absorbent material and mortar 1:3 and 1:6 by volume

Binder	Tensile bond strength 28 days, kp/cm²	
	Mortar 1:3 by volume	Mortar 1:6 by volume
Portland cement	0	10
Lime cement		
LC 35/65	0	6
LC 50/50	1	4
Lime	1	2

Table 23. Water loss from the cement mortar to upper and lower brick

Brick with high initial rate of absorption	Water loss in % from cement mortar	
	C 100/300 1:3 by volume	C 100/600 1:6 by volume
Upper brick	1	2
Lower brick	35	55

Note. The water absorption was calculated as loss of water during one minute in per cent of the original water content of the mortar.

Table 24. Water loss from lime-cement mortar to upper and lower brick

Brick with high initial rate of absorption	Water loss in % from lime-cement mortar	
	LC 35/65/400 1:3 by volume	LC 35/65/800 1:6 by volume
Upper brick	2	1
Lower brick	20	30

Table 25. Water loss from lime-cement mortar to upper and lower brick

Brick with medium initial rate of absorption	Water loss in % from lime-cement mortar	
	LC 35/65/400 1:3 by volume	LC 35/65/800 1:6 by volume
Upper brick	8	5
Lower brick	12	30

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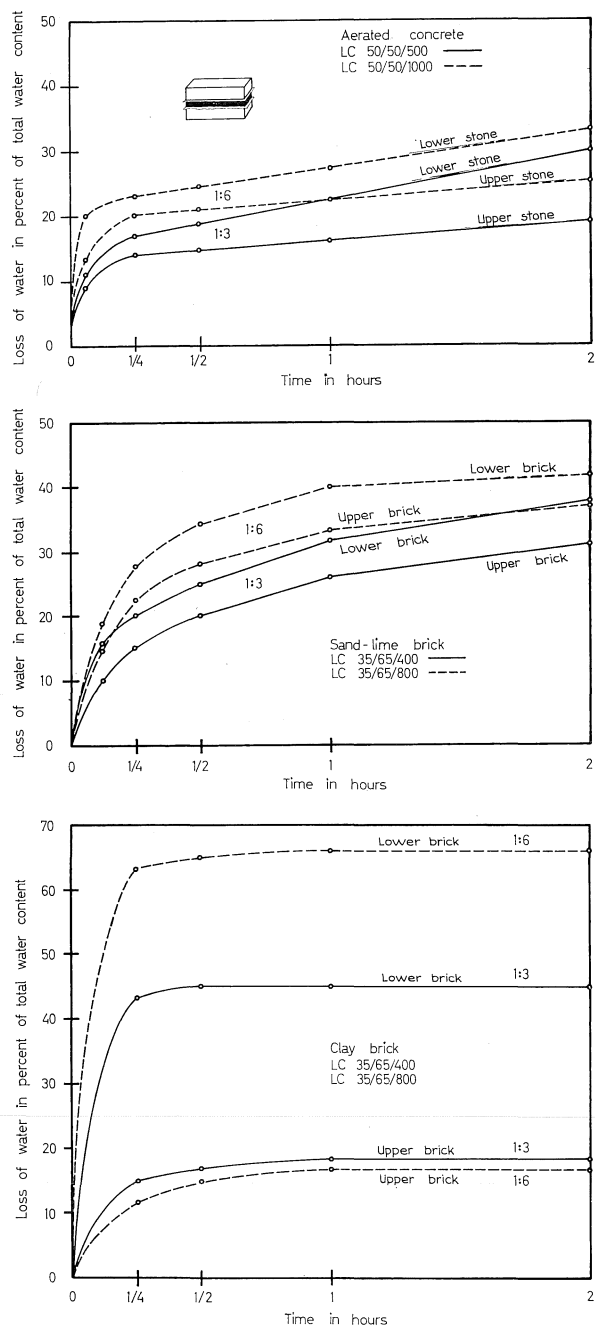
Figure 48 A. Loss of water from the mortar to the upper and lower brick.

Figure 48 B. Mortar between bricks changes the water/binder ratio at the loss of water to the two bricks.
The water/binder ratio of mortar 1:6 decreases rapidly.

When the initial rate of absorption drops, the differences between water absorption in the upper and lower brick are neutralized. The water loss from mortar 1:3 with a brick of medium initial rate of absorption was almost the same for the upper and lower brick. If the initial rate of absorption falls even further, the difference for mortar 1:6 is also eliminated (Table 26).

Water absorption by the upper and lower brick was measured successively during two hours (Fig. 48). The tests showed that from the very beginning there is a difference between water absorption by the upper and the lower brick, and that this difference is not eliminated as time goes by. The lower brick, with a 1:3 mortar, has about the same water absorption as the upper one with a 1:6 mortar.

Table 26. Water loss from lime-cement mortar to upper and lower brick

Materials with low initial rate of absorption	Water loss from lime-cement mortar 1 :6	
	LC 35/65/800 to sand-lime brick	LC 50/50/900 to aerated concrete "Siporex"
Upper brick	11	7
Lower brick	14	10

Figure 50. Set-up to test water absorption and bond. With the help of plastic bag, the joint can be loaded with a non-water absorbent brick.

As soon as mortar comes into contact with an absorbent material, water is drawn from the mortar. The PML determined initial absorption in the following way. A 10 mm thick layer of mortar was placed in a plexiglass mould. The porous surface of a glazed whiteware wall tile, covered with gauze, was pressed into the mortar. After 15 seconds the tile was removed from the mortar and weighed. Water absorption after 30, 45 and 60 seconds was measured in the same way, with fresh mortar and a new tile each time. The tests showed that after only 15 seconds the difference between loss of water from mortar 1 :3 and mortar 1 :6 was great (Fig. 49). Water retentivity was greatest in mortar with a ratio of one to three by volume.

The water retentivity of mortar may be of influence in two ways in respect of adhesion between two absorbent materials.

a. A mortar with *poor* water retentivity easily loses water to an absorbent material with which it comes into contact. It is feasible that adhesion to such material is improved by this circumstance. When mortar loses water it becomes stiffer, and adhesion to a material coming into contact with the mortar later may be impaired.

b. A mortar with *good* water retentivity loses only a small amount of water to the absorbent material with which it comes into contact. Since the mortar loses only little water, its consistence should not chan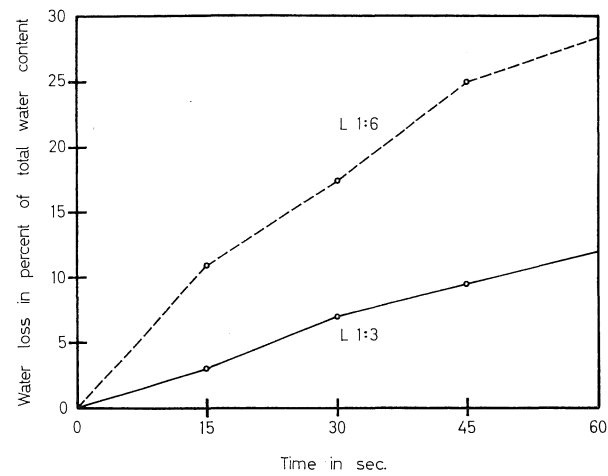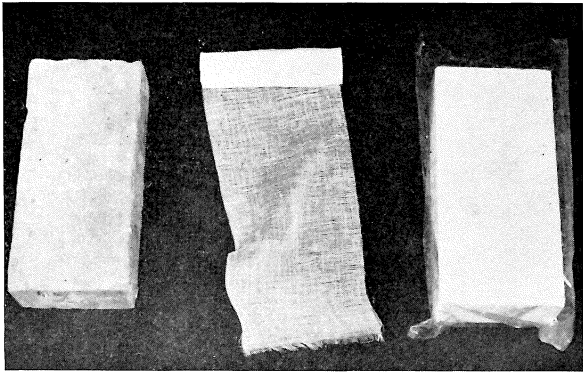ge much. Adhesion to the first or a subsequent material with which the mortar comes into contact should be about the same.

The water absorbent materials expose the mortars, regardless of the water retentivity of them, to equally powerful suction. It is not impossible that when a mortar with very great water retaining properties is subjected to powerful suction, a rupture occurs in the capillary water transport which may lead to an impairment of the bond strength.

The PML first investigated whether adhesion of mortar to an underlying absorbent material is impaired when the mortar is also exposed to suction by an upper brick. In this test, the bond to an underlying brick was studied when the layer of mortar was loaded with a non-absorbent brick or with an absorbent brick (Fig. 50). The results obtained with a series of different materials suggest that bond strength to the underlying material is not impaired by exposing the mortar to suction by an upper brick, too.

The adhesion of fresh mortar to an upper and lower brick was also determined at the tests (Fig.

Figure 49. Changes in the water/binder ratio of the mortar during the first minute's suction by a dry, water absorbent wall tile. Mortar 1 :6 loses more water than mortar 1 :3.

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Figure 51. Bricks, which have been in contact with lime-cement mortar 1:6 have clear traces of binder paste along the whole of the contact surface. Bricks, which have been in contact with mortar 1:3 have only slight traces of binder paste.

51). After one minute's suction, it was clearly observed that on bricks with a relatively high rate of initial absorption there were distinct deposits of binder on both the upper and lower bricks. With a mortar 1:3 these deposits were insignificant.

Similar results of the tests of the adhesion of fresh mortar were also obtained with aerated concrete (Fig. 52).

The results are based on the adhesion of lime-cement mortar to clay bricks, sand-lime bricks and aerated concrete.

The purpose of Table 27 is to show how materials with different rate of absorption tend to influence bond strength with mortar 1:3 and mortar 1:6.

The bond strength of mortar of a ratio of 1:6 by volume was consistently better than with mortar of a ratio of 1:3 by volume. Especially marked is the difference between materials with high rates of absorption. When the initial rate of absorption falls, the bond strength of mortar 1:3 improves.

The bond strength of three different mortar/brick combinations is given in Tables 28, 29 and 30.

In the tests reported, the upper brick was placed on the mortar one minute after the mortar had been applied to the lower brick. Simultaneously with these tests, the bond strength was studied when the upper brick was not placed on the mortar until two minutes had elapsed. The results suggest that there is a tendency for mortar 1:6 to have a somewhat lower bond strength on a highly absorbent base if placing the upper brick in position is delayed.

The tests made to ascertain the bond to both the upper and the lower bricks were technically very difficult to perform. When determining the water ab-

Table 27. Bond strength in % to upper and lower brick

Initial rate of absorption	Tensile bond strength in %* Lime-cement mortar	
	1:3 by volume	1:6 by volume
High		
Upper brick	10	75
Lower brick	25	100
Medium		
Upper brick	50	100
Lower brick	50	100
Low		
Upper brick	75	75
Lower brick	75	100

* Tensile bond strength between mortar 1:6 and lower brick = 100

sorption, both bricks in the same bond could be used, but this was impossible in the tests of bond strength. In these tests, the upper brick had to be taken from one bond and the lower from another. In bricks with high initial rate of absorption, the deviation between the single brick is great. Sand-lime bricks and aerated concrete from the same suppliers had a more uniform absorption value than clay bricks. When grooves are drilled in the surface of the mortar in order to attach the pulling device for the adhesion apparatus, stresses occur between the mortar and the base, and these may give rise to ruptures if adhesion is poor (Fig. 53).
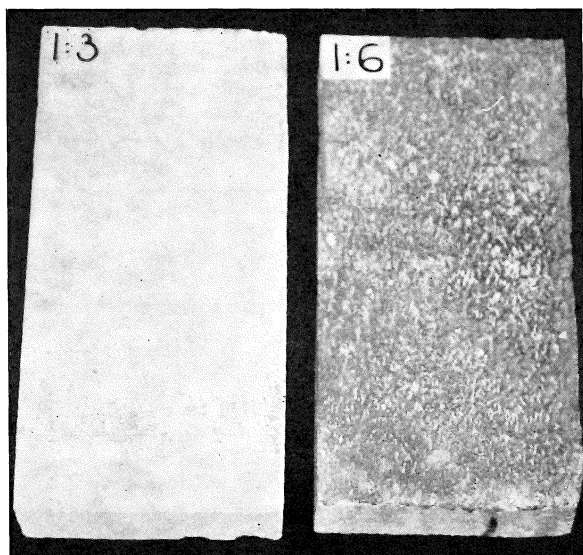
Figure 52. Aerated concrete slabs that have been in contact with lime-cement mortar 1 :3 and 1 :6. As in the tests with clay bricks (see Fig. 51) mortar 1 :6 has left much more binder paste on the contact surface than mortar 1 :3.
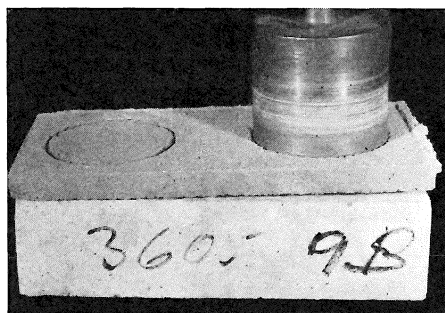
Figure 53. When grooves are drilled in the mortar, the whole layer of mortar may loosen if adhesion is bad.

Table 28. Bond strength between lime-cement mortar and upper and lower clay brick

Clay brick*	Tensile bond strength 28 days, kp/cm^2	
	LC 35/65/400 1 :3 by volume	LC 35/65/800 1 :6 by volume
Upper brick	0.5	3.0
Lower brick	1.5	3.0

* Initial rate of absorption = 25 g/dm^2, min.

Table 29. Bond strength between lime-cement mortar and upper and lower sand-lime brick

Sand-lime brick*	Tensile bond strength 28 days, kp/cm^2	
	LC 35/65/400 1 :3 by volume	LC 35/65/800 1 :6 by volume
Upper brick	1.5	3.0
Lower brick	1.0	2.5

* Initial rate of absorption = 15 g/dm^2, min.

Table 30. Bond strength between lime-cement mortar and upper and lower aerated concrete

Aerated concrete* (Siporex)	Tensile bond strength 28 days, kp/cm^2	
	LC 50/50/475 1 :3 by volume	LC 50/50/925 1 :6 by volume
Upper stone	1.0	1.5
Lower stone	1.5	3.0

* Initial rate of absorption = 15 g/dm^2, min.

Conclusions

Bond between mortar and absorbent materials is dependent on many factors. Adhesion to *highly* absorbent material will as a rule be better with mortar 1 :6 by volume than with mortar 1 :3.

Bond strength for mortar uniting *two* absorbent materials depends on the capillary suction of the material the mortar first comes into contact with. Gen-erally speaking, adhesion is better here, too, with mortar 1 :6 to both the upper and lower brick than with mortar 1 :3.

The water retaining properties of mortar vary with methods of determination. Mortar with a ratio of 1 :6 by volume usually has lower water retentivity than mortar 1 :3. Thus, mortar with low water retentivity should give better adhesion to absorbent materials than mortar with better water retaining properties.

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Influence of wetting absorbent materials

An earlier section, "Bond between mortar and water-absorbent materials" showed clearly that bond strength between mortar 1:3 and a highly absorbent base material is usually unsatisfactory.

If a highly absorbent material is wetted in order to reduce capillary suction, the bond strength increases.

Rapid immersion or spraying an absorbent material is not always sufficient to reduce capillary suction. Complete saturation is unnecessary, too. The surface of the base material must not be wet when the mortar is applied. A film of water between the mortar and the base material always reduces the bond strength. In some cases, wetting highly absorbent material may have a detrimental effect on adhesion.

I have shown (Högberg, 1965) that wetting highly absorbent material may improve bond strength (Table 31). The improvement in adhesion can be observed in the adhesion of fresh mortar to wetted tiles (Fig. 54). Corresponding observations have been made concerning the adhesion of lime-cement mortar to dry and wetted tiles (Fig. 55).

On several occasions, the PML has investigated whether wetting aerated concrete improves adhesion. The tests were made on aerated concrete with a moisture ratio usual for building sites. Wetting increased the usual moisture ratio from ca. 15 to 20 %.

The results suggest that there is a tendency for adhesion to improve with lime-cement mortar 1:4 when aerated concrete is wetted (Table 32).

A similar test was made with sand-lime bricks. Improved bond strength was observed with lime-cement mortar 1:3 by volume when the sand-lime bricks were wetted, but with a lime-cement mortar 1:6 no improvement was observed. Wetting compact concrete surfaces clearly gave poorer bond strength with all the mixes of mortar tested.

The PML has also studied the effect of wetting on the strength of brickwork piers with centric and eccentric load. The piers were constructed of brick with lime-cement mortar, were one meter high, and had a base area of 1 × 1 brick. Before the loading test, they were stored for 28 days in plastic bags (Fig. 56 and Table 33). Wetting bricks led to an improvement with both centric and eccentric loading (Fig. 57).

A comparison was also made between cement mortars 1:3 and 1:6 with clay bricks and sand-lime bricks.

The results suggest that wetting gives rise to consistent improvement of pier strength with mortar 1:3 with both centric and eccentric loading. Mortar 1:6 by volume gave consistently lower pier strength when the bricks were wetted (Table 34).

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Table 31. Influence of wetting absorbent material

Tiles	Tensile bond strength 28 days, kp/cm^2	
	Cement mortar 1:3	Cement mortar 1:6
Dry glazed whiteware tiles	0	5—10
Wetted tiles	>10	>10

Table 32. Influence of wetting aerated concrete

Mortar LC 50/50/600 1:4 by volume	Bulk density	Tensile bond strength 28 days, kp/cm^2	
		Aerated concrete	Wetted aerated concrete
Aerated concrete Siporex	0.4	1,5	1.6
	0.5	1.2	1.8
Ytong	0.4	1.0	1.8
	0.5	1.4	2.0

Table 33. Influence of wetting brick at centric and eccentric load

Mortar LC 50/50/600 by volume	Brick	Load	Pier strength 28 days, kp/cm^2	
			Dry brick	Wetted brick
1:4	"Klippan"	Centric	80	110
		Eccentric	50	60
1:4	"Borgeby"	Centric	85	95
		Eccentric	40	55

	"Klippan"	"Borgeby"
Initial brick suction, g/dm^2 min.	15	25
Brick compressive strength, kp/cm^2	450	245

Tests showed that a deterioration of pier strength occurs by wetting the bricks when the ratio by volume between binder and sand is somewhere between 1:4 and 1:6.

When the piers were constructed it was found that laying the bricks was made more difficult when the sand-lime bricks were saturated with water. The piers built with wetted bricks had, compared with those built of dry bricks, much efflorescence.

Figure 54. Rear side of glazed whiteware wall tiles shown one minute after setting with 1 :3 cement mortar.
Left: Dry wall tile with a few isolated blobs of cement grout.
Right: Water-saturated wall tile. Cement grout particles over almost the whole surface of the tile.

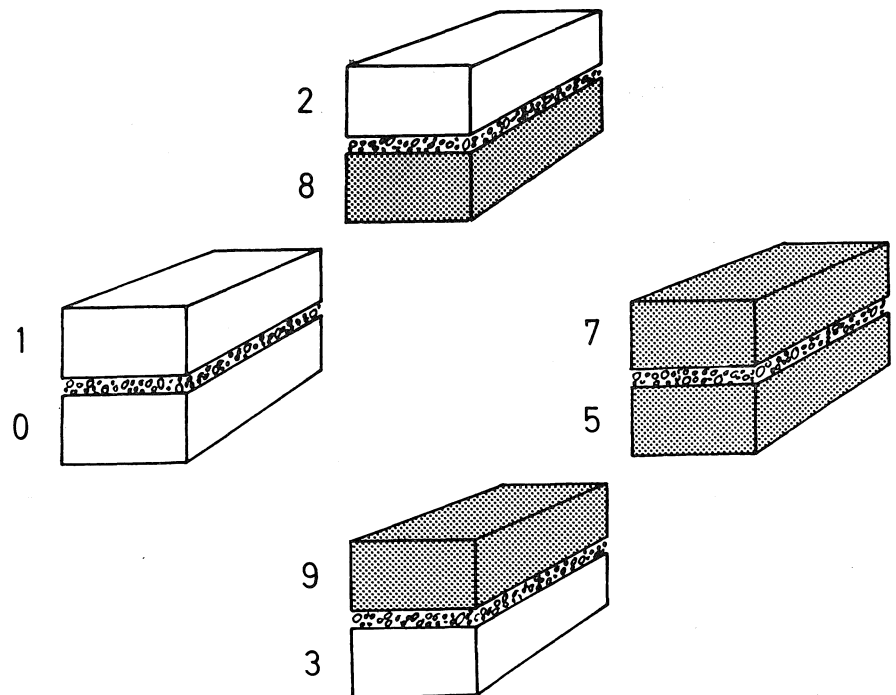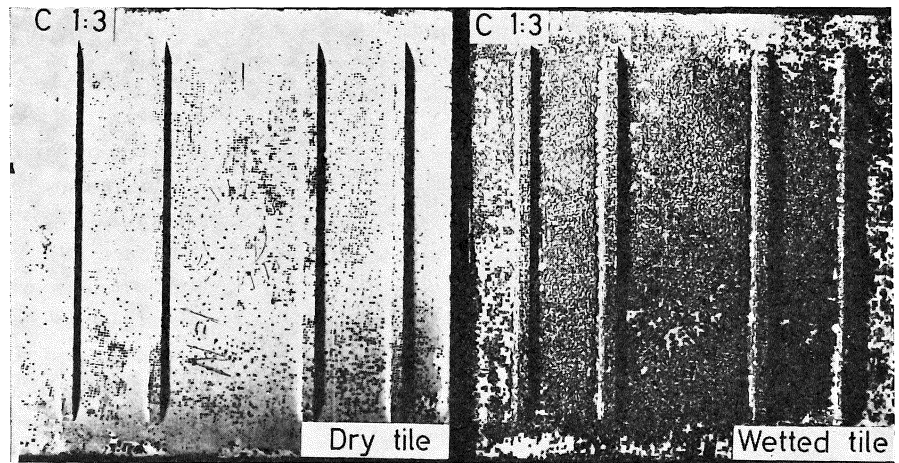Figure 55. Bond strength in kp/cm², between dry or water-saturated solid bricks and lime-cement mortar (LC 2 :1 :9) after 28 days. The dots refer to water-saturated bricks. These results demonstrate clearly the important effect of wetting on bond strength.

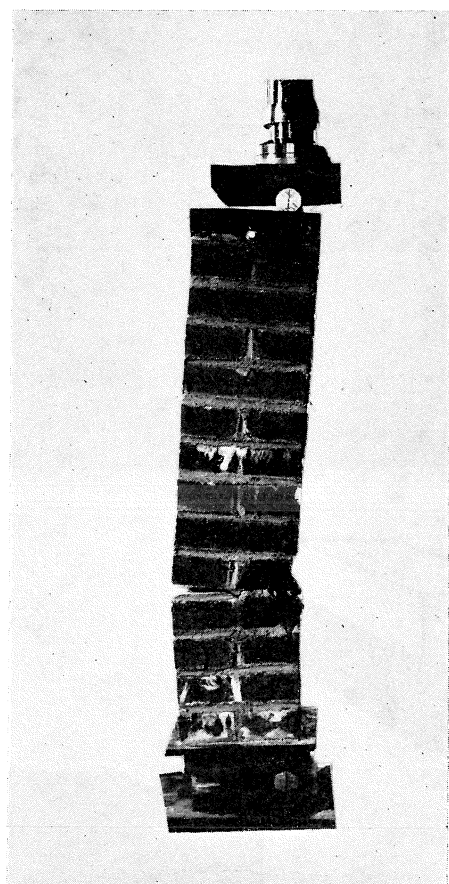Figure 56. Storing brick piers in plastic bags.

Figure 57. Eccentric loading of brick pier at the PML tests.

Table 34. Influence of wetting brick at centric and eccentric load

Binder LC 35/65 Mortar by volume	Brick	Load	Pier strength 28 days, kp/cm²	
			Dry brick	Wetted brick
1:3	"Klippan"	Centric	170	200
1:6	"Klippan"	Centric	150	100
1:3	Sand-lime	Centric	115	100
1:6	Sand-lime	Centric	110	75
1:3	"Klippan"	Eccentric	60	70
1:6	"Klippan"	Eccentric	65	45
1:3	Sand-lime	Eccentric	40	55
1:6	Sand-lime	Eccentric	40	35

	"Klippan"	Sand-lime brick
Initial brick suction, g/dm², min.	15	10
Brick compressive strength, kp/cm²	465	165

References to the literature

It has long been known that wetting porous bricks improves the resistance of brickwork to rain, as well as the bond strength between mortar and bricks.

The purpose of wetting is to reduce the capillary suction in a water absorbent material.

Palmer and Hall (1931) found that the highest bond strength with highly absorbent bricks were obtained when the bricks were about 80 per cent saturated, and the lowest when the bricks were laid dry. Wetting bricks of low rates of absorption did not lead to any great improvement; indeed, in some cases, the bond strength even decreased (Fig. 58).

Collin (1935) showed that high absorption bricks develop a low bond strength with cement and lime-cement mortar when laid dry, and that the bond strength was materially increased when such bricks were wetted before being laid.

Anderegg (1942) studied adhesion between a lime-cement mortar (LC 2:1:9) and absorbent bricks wetted in several stages to reduce suction. As water was added to the bricks, the bond strength increased to a maximum, after which it declined (Fig. 59).

Forkner et al. (1948) found that an adjustment of relatively high suction rates (23—28 g/dm², min.) to lower suction rates (15—20 g/dm², min.) increases the tensile bond strength.

Albrecht and Schneider (1963) successively reduced the capillary suction of bricks by immersing them in water for 3 seconds, 1 minute and 15 minutes. After 15 minutes' immersion, the initial rate of absorption was 0 for the two qualities of bricks tested; their original rates of suction were 24 and 62 g/dm² min. Adhesion increased in a lime-cement mortar throughout the test (Fig. 60).

Thus there is much evidence that bricks of high absorption should be wetted in order to reduce their suction rate to a desirable value.

When setting highly absorbent tiles, Waters (1959) found that wetting impaired adhesion. In these tests it was found that brief soaking, 20 seconds, did not weaken the bond; it was not until the tiles had been immersed for two minutes that deterioration occurred.

Thus, Waters' results differ from those I (Högberg, 1961) obtained on similar material. This can be explained partly by the fact that Waters determined the shear strength, and the PML the tensile bond strength. In several studies of loosened tiles, the PML found that the mortar used was very rich in binder and that the tiles had not been pre-wetted. This experience from buildings is in good agreement with results obtained by the PML in laboratory tests.
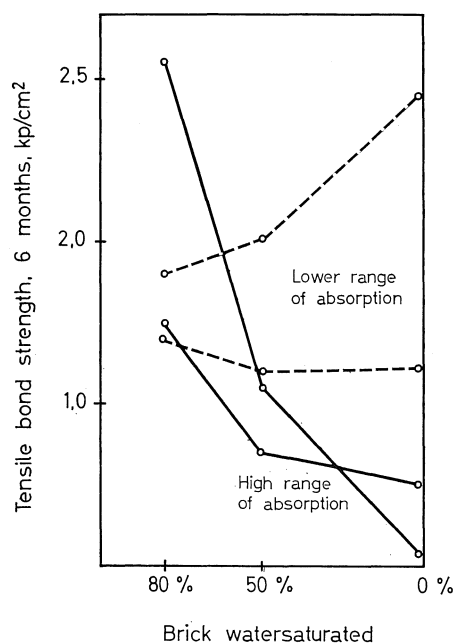
Figure 58. Effect of degree of wetting brick on the bond strength. According to Palmer and Hall (1931).

Figure 60. Effect of wetting brick on the bond strength. According to Albrecht and Schneider (1963).

Figure 59. Effect of wetting brick on the strength of the bond. According to Anderegg (1942).

Table 35. Influence of wetting brick at centric and eccentric load according to Albrecht and Schneider (1963)

Mortar LC 44/56/358 1 :2.7 by volume	Load	Pier strength 30 days, kp/cm²	
		Dry brick	Wetted brick (1 min.)
Brick L	Centric	56	63
	Eccentric	39	38
Brick S	Centric	43	55
	Eccentric	34	34

	Brick L	Brick S
Initial brick suction, g/dm², min.	24	62
Brick strength, kp/cm²	432	248

Regarding brickwork tests, Albrecht and Schneider (1963) also made tests on piers with centric and eccentric loading, and compared dry and saturated bricks (Table 35).

With centric loading, an improvement was obtained by wetting the bricks. With eccentric loading the same strengths were obtained with dry and wetted

bricks. In my opinion, greater strength should also have been present in eccentric loading with wetted bricks and the mortar used. One reason for the absence of improvement in strength may be that perforated bricks were used in the German tests, while the PML used solid bricks. In brickwork of perforated bricks, the mortar is pressed up into the

holes, which gives mechanical bond between mortar and brick, and strength is not so dependent on the actual adhesion between mortar and brick.

Bond strength tests were also made in the German investigation. They showed clearly that the bond of the mortar was improved by wetting the bricks. (See Fig. 60.)

Conclusions

There is strong evidence that the bond between mortar with a ratio of 1:3 by volume, and bricks of high absorption is good when the bricks are wetted to reduce their suction rate to an acceptable value.

Wetting absorbent material may have disadvantages, however. If too much water is added, the bricks will slide on the bed of mortar and it will be difficult to build the wall plumb.

It is never possible to get as good strength with a brick adjusted by wetting as with a brick that had relatively low suction from the beginning.

If bricks are soaked too long, so that a film of water covers the surface, bond strength will be impaired.

Wetting may cause great efflorescence.

Influence of a thin, cement-rich coat

When aerated concrete is to be rendered, a fluid cement-rich mix of cement and sand is recommended as a spatterdash coat. The purpose of this coat is primarily to improve adhesion between the aerated concrete and the following thicker coat of mortar. In several investigations when the rendering has fallen from the wall, it has been found that the aerated concrete had not been grounded (Fig. 61).

Together with the Siporex Factory, the PML studied how spatterdash coat affects adhesion to and water permeability of aerated concrete. Slabs of Siporex ($50 \times 50 \times 7$ cm), rendered about 12 mm thick with a lime-cement mortar 1:4 (LC 50/50/600), were used in the investigation. Half of the slabs were coated with a fluid cement-rich lime-cement mortar (LC 10/90/350). The spatterdash coat was ca. 1.5 mm thick. Bond was determined on test specimens drilled out after 28 days (Table 36).

When concrete surfaces are to be rendered, they are often coated with a thin, cement-rich mortar. The principal reason for this is to give the next coat better adhesion than can be obtained on a smooth concrete surface.

A study was made by the PML to find out whether this coat is of importance for adhesion.

Concrete slabs were rendered with a lime-cement mortar and cement mortar. Half of the slabs were coated with a thin cement-rich mortar (LC 10/90/

Table 36. Influence on bond of a spatterdash coat on aerated concrete

Aerated concrete "Siporex" Bulk density kg/dm3	Tensile bond strength 28 days, kp/cm2	
	Without spatterdash coat	With spatterdash coat
0.4	1.5	3.0
0.5	1.2	2.8

Table 37. Influence on bond of a spatterdash coat on concrete

Mortar 1:4 by volume	Tensile bond strength 28 days, kp/cm2	
	Without spatterdash coat	With spatterdash coat
Cement mortar (C 100/400)	10	6
Lime-cement mortar (LC 50/50/600)	4	6

Table 38. Influence on bond of a thin cement paste layer on dry, glazed whiteware tiles

Dry tiles	Tensile bond strength 7 days, kp/cm2	
	Mortar C 1:3	Mortar C 1:6
Untreated	0.5t	7.0g
With a fresh layer of cement paste	1.5t	0.5g
With a dry, 24 h old layer of cement paste	3.5tg	9.0gm

Failure between mortar and tile = t
Failure between mortar and glass = g
Failure in mortar = m

Table 39. Water suction from tiles with and without a layer of cement paste

Dry tiles	Loss of water in percent of the total water content in mortar (suction 1 minute)	
	Mortar C 1:3	Mortar C 1:6
Without a layer of cement paste	35	55
With a layer of cement paste	30	50

Figure 61. Failure of rendering on aerated concrete. The first, important treatment of the aerated concrete surfaces with a thin spatterdash coat of liquid, cement-rich mortar was "forgotten".
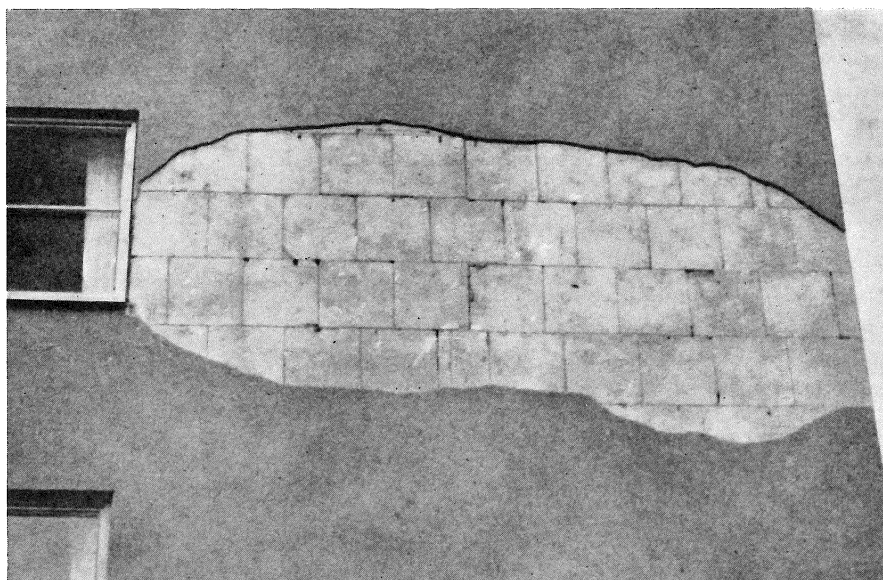
350). Coating was done the day before rendering (Table 37).

The results suggest that a better bond is obtained on cement with lime-cement mortar if the surface is coated first, but thin coating may have a detrimental effect on bond strength if cement mortar is used. This is because the spatterdash mix is a thin cement mortar with a relatively high water/binder ratio, which gives a rather good bond strength. Cement mortar 1:4 has a lower water/cement ratio and has, for this reason, better bond strength on a concrete surface than the spatterdash coat. Lime-cement mortar has lower bond strength than cement mortar to concrete and for this reason a spatterdash coat improves the bond strength of the lime-cement mortar.

When wall tiles are to be set it sometimes happens that, immediately before the mortar is applied, absorbent tiles are coated with cement grout taken from the fluid part of the mortar. This is somewhat similar to the rendering of aerated concrete.

In order to establish whether a thin cement paste applied as a thin layer improves adhesion, the following tests were made. Dry, glazed whiteware tiles were coated with a thin layer of cement paste with a water/cement ratio of 1. The tiles coated with cement paste were allowed to dry until the following day, when they were used for the adhesion test. Cement mortars 1:3 and 1:6 were applied in layers 10 mm thick to sheets of glass, after which the cement-coated surfaces of the tiles were pressed to the mortar like a sandwich. Corresponding tests were made with tiles with a fresh coat of cement paste (Table 38).

The investigation showed that the best results are obtained when the cement paste has been allowed to dry for a day. A reduction in the bond strength occurs with cement mortar 1:6 when the dry tile is coated with cement paste immediately before setting. This is only natural, since coating with cement paste gives a non-absorbent base. Thus, as already shown, adhesion to glass is relatively poor with cement mortar 1:6.

With cement mortar 1:3, failure occurred between the tile and the cement paste applied at the same time as the mortar. This coating of cement paste had a higher water/cement ratio than the cement mortar, and consequently adhesion to the absorbent tile should be better in this case.

When fresh cement paste is applied to an absorbent material, the water is drawn from the fluid paste into the capillaries, thereby reducing the suction.

The PML investigated whether capillary suction changed when the cement paste was allowed to dry for a day (Table 39).

The results suggest that the dry layer of cement paste has no marked effect on the capillary suction of the tile.

A similar test was made on aerated concrete test pieces with and without a spatterdash coat. In this test the water absorption of the slabs was measured after they had been sprayed with water for two hours. It was found that the spatterdash coat did not improve the rain-resisting properties of the rendering, i.e. all the slabs absorbed as much water during the test.

Weigler (1965) found that a cement-rich spatterdash coat on aerated concrete improved considerably the adhesion of the ordinary rendering coat. Bond strength was usually so great with a spatterdash coat that the rupture occurred in the aerated concrete itself. If the failure was in the bond, it was usually between the spatterdash coat and the mortar. Since the main purpose of Weigler's investigation was to study the adhesion between mortar and aerated concrete, the spatterdash coat gave such good values in the tests that it could not be included in the principal tests.

Weigler also found that the spatterdash coat did not so much alter the absorption of the aerated concrete as the surface of the concrete. The fluid consistence of the spatterdash coat gives a good mechanical bond to aerated concrete, and the rougher and more uneven the surface obtained after drying, the better the key for the next layer of rendering.

Albrecht and Steinbach (1962) studied the adhesion of rendering to a concrete roof. Their investigations showed that very good adhesion is obtained by using cement mortar 1:3 as a spatterdash coat. Even on the very smooth concrete surfaces given by the use of steel shuttering, good adhesion is obtained with such a spatterdash coat. After it is dry, the thinly coated concrete surface is a good base for the next layer of mortar.

Bring (1966) studied the adhesion of a concrete screed poured on a floor slab of cured concrete. In order to ensure good adhesion between the lower and the added screed layer, the lower concrete surface should be coated with thin cement mortar with a ratio of 1:1 or 1:2 by volume. This mortar must be worked into the surface of the base by energetic brushing. Before the application of this mortar, the surface must be moist, but dry on the surface. Bring considered that the screed layer should be applied while the thin coat is still wet. No adhesion tests however were made after the coat had dried.

Waters (1960) studied the effect of neat cement on the strength of the tile/mortar bond. He treated soaked tiles with a thin layer of cement paste and immediately after pretreatment the tiles were set on clay bricks. The shear strength was determined after curing for seven days (Table 40).

Compared with soaked tile without cement paste, the treatment with cement paste gave distinctly improved shear strength. Waters claimed that a neat cement slurry makes a much more intimate contact surface with the back of the tile than a mortar does.

In the discussion following on Anderegg's paper

Table 40. Shear strength of tiles with and without neat cement paste. According to Waters (1960)

Cement mortar	Cement paste Water/cement ratio	Shear strength 7 days, kp/cm^2	
		Soaked tile	Soaked tile + cement paste
1:3	0.6	3.9	12.7

(1942) on the effect of brick absorption characteristics, Connor mentioned that the Bell Telephone Laboratories had found a considerable improvement in the extent of bond when the surfaces of the brick were wiped with a thin coat of mortar before brick laying.

Conclusions

Treatment of an absorbent or non-absorbent surface with a thin layer of cement-rich binder paste or a spatterdash coat may mostly have a favourable effect on the adhesion of the next coat of rendering.

A spatterdash coat on aerated concrete is recommended in most instructions in order to improve the adhesion of the rendering.

A spatterdash coat on concrete does not always improve the bond strength but gives a better key for the next coat. The best results are obtained if the spatterdash is allowed to dry before the next layer of rendering is applied.

Coating absorbent tiles with cement paste immediately before setting may improve adhesion.

Influence of different admixtures on bond

Owing to increasing speed of building, and all-the-year-round building the traditional lime mortar has been replaced by lime-cement and masonry cement mortar. The greater content of cement made the mortar difficult to work with at first, but this drawback was eliminated by the addition of plasticizers. The agents most commonly used to improve the workability of mortar belong to the group known as air-entraining agents. Such admixtures are used all over the world. In Sweden, for example, practically all binders used in mortar contain air-entraining agents. In England, pure cement mortar, with added air-entraining agents, is frequently used in bricklaying.

Air-entraining agents are surface-active agents, either nonionic or anionic active, which, when mixed with binder, sand and water, form a froth of small, relatively stable bubbles. This mixture of air makes the

mortar lighter, and bricklayers consider that the workability of the mortar is greatly improved.

For some special mortars, such as Dry Set Mortar, additives are used to increase the viscosity of the mortar. These agents, which are frequently cellulose derivatives, are used primarily to prevent the relatively thin layers of mortar from drying too quickly. These additives also have an air-entraining effect and improve the workability of the mortar. The additives which increase the viscosity are usually more expensive and more of them is required than of air-entraining agents, and they are therefore not used in ordinary mortar.

Both air-entraining agents and viscosity modifiers enhance the workability and many other properties of mortar. How they affect adhesion will be shown in subsequent sections.

AIR-ENTRAINING AGENTS

I have shown in an earlier work (Högberg, 1961) that the formation of air pores in cement mortar impairs adhesion to dry, glazed whiteware tiles (Table 41).

The results indicated that air-entraining agents in cement mortar reduce bond strength with both dry and wetted tiles. The reason for the investigation was a complaint concerning five tall blocks of flats, where the wall tiles in nearly all the bathrooms had loosened. It was found that some of the cement mortar had been changed on the site for masonry cement in order to improve workability. The masonry cement contained air-entraining agents. Laboratory studies showed, that a small addition of masonry cement to a cement mortar diminished the bond strength.

At the first International Lime Conference held in Berlin in 1965, I gave a lecture entitled "Experience with plasticized binders in Sweden", (Högberg, 1966), dealing with the effects of air-entraining agents on the properties of mortar.

Typical of all air-entraining agents is that they reduce the amount of water needed in mortars. The water/binder ratio for lime mortar drops to half by the addition of an air-entraining agent. For cement mortar the drop is not so marked (Fig. 62). The water retentivity of the mortar is increased by the addition of air-entraining agents. Bleeding is usually completely eliminated.

Air-entraining agents reduce the surface tension of the mixing water and give rise to froth. The bubbles formed, which have a diameter of about 0.1 mm, make the mortar lighter and improve its plasticity (Fig. 63). The volume of the fresh mortar is in-
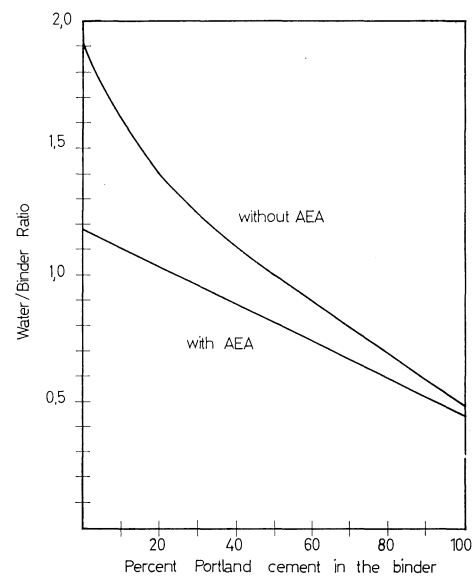
Figure 62. The addition of air-entraining agents reduces the water/binder ratio of mortars.
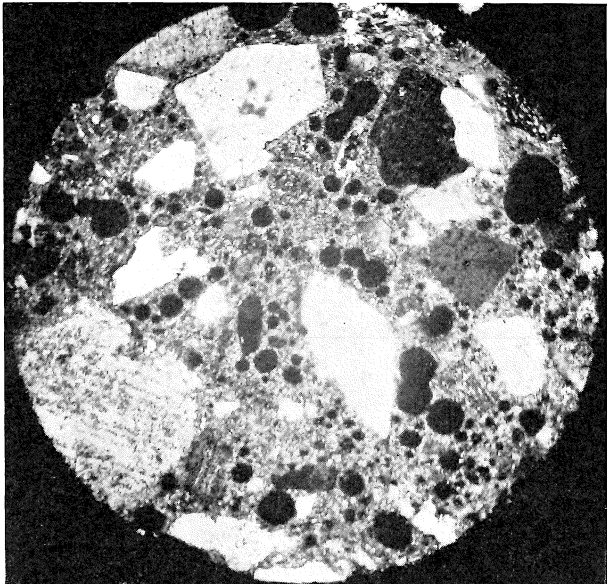

Figure 63. Air-bubbles in mortar caused by the air-entraining agent. Mean diameter of the bubbles is about 0,1 mm.

Table 41. Influence of air-entraining agents on bond

Glazed whiteware tiles	Tensile bond strength 28 days, kp/cm²	
	Cement mortar 1:6	
	With AEA	Without AEA
Dry tiles	1	10
Wetted tiles	4	13

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creased somewhat by the intake of air, but the increase is not so great as the volume of air added, owing to the need for less water.

If workability is to be improved markedly, the content of air must be at least 10 per cent of the volume of the mortar.

Air-entraining agents affect the bond strength of the hardened mortar. The compressive strength for cement mortar and cement-rich lime-cement mortar declines, while the flexural strength remains almost unchanged.

The original purpose of air-entraining agents was to improve the poor workability of cement-rich mortars, but at the same time a considerable improvement in the frost resistance of hardened mortar was obtained. The most serious disadvantage of air-entraining agents is that they reduce the adhesion of the mortar, especially to absorbent base materials.

Further studies at the PML confirmed the observations made earlier.

At the tests reported in Table 42, cement pastes with the given water/cement ratio were made, after which standard sand was added until the mortars had about the consistence for masoning. Tests were made with lime-cement mortar, too (Table 43).

Straight lime mortars, with and without air-entraining agents, were also tested in the same way. The test pieces in this case were stored at 70 per cent relative humidity to obtain the best carbonization atmosphere for the lime (Table 44).

Here, too, the results suggest that the addition of air-entraining agents to a lime mortar reduces bond strength in the same way as for cement mortar and lime-cement mortar.

A corresponding reduction of bond strength to brick and aerated concrete was observed when air-entraining agents were added to lime-cement mortars.

The results shown in Table 45 imply that the addition of air-entraining agents to lime-cement mortars has a detrimental effect on the bond strength to both bricks and aerated concrete.

What is it then that causes air-entraining agents to have a detrimental effect bond:

a. changes in the surface tension of the water,
b. reduction of contact surface by bubbles,
c. reduction of the water/binder ratio,
d. improvement in the water retentivity of the mortars?

In order to ascertain why air-entraining agents impair the bond strength, the PML made a series of investigations. First a study was made to find out

Table 42. Influence of air-entraining agents on bond between cement mortar and dry glazed, whiteware tile

Water/cement ratio	Tensile bond strength 28 days, kp/cm^2	
	Cement mortar	
	With AEA	Without AEA
0.50	0	0
0.75	1.0	3.5
1.00	1.5	6.0

Table 43. Influence of air-entraining agent on bond between lime-cement mortar and dry glazed whiteware tiles

Binder LC 50/50	Tensile bond strength 28 days, kp/cm^2	
	Lime-cement mortar	
	With AEA	Without AEA
Mortar by volume		
1 :3	0.2	1.5
1 :6	1.5	6.0

Table 44. Influence of air-entraining agent on bond between lime mortar and dry glazed whiteware tiles

Lime mortar	Tensile bond strength 28 days, kp/cm^2	
	Lime mortar	
	With AEA	Without AEA
1 :3 by volume	0.5	0.5
1 :6 by volume	0.5	2.0

whether the reduction in the surface tension of the mixing water due to air-entraining agents affects the bond strength. Changes in the surface tension of the mixing water should be easiest to observe in the bond to non-absorbent materials. Binder, air-entraining agent and water were mixed carefully to avoid frothing to pastes of varying viscosity. The pastes were placed on a sheet of glass and pressed immediately with another sheet of glass. After the sandwich-like test pieces had been stored for 28 days in a damp room, the bond to glass was determined in comparison with a corresponding binder paste without an air-entraining agent (Table 46).

The results suggest that air-entraining agents in a cement paste, mixed without frothing, do not reduce bond strength to glass.

Table 45. Influence of air-entraining agent on bond between lime-cement mortar and brick and aerated concrete

Backing/Mortar	Tensile bond strength 28 days, kp/cm^2	
	Lime-cement mortar	
	With AEA	Without AEA
Brick, dry		
LC 50/50/475 (1:3)	0.5	3.0
LC 50/50/925 (1:6)	1.5	6.5
Aerated concrete (Siporex) dry		
LC 50/50/475 (1:3)	0.3	1.0
LC 50/50/925 (1:6)	0.2	2.5

Table 46. Influence of air-entraining agent on bond between cement paste and glass

Water/cement ratio	Tensile bond strength 28 days, kp/cm^2	
	Cement paste	
	With AEA	Without AEA
0.50	6.0	5.5
0.75	2.5	2.0
1.00	0.2	0.8

Note. AEA was added in such amounts that mortars with an air content between 15 and 20 per cent were obtained.

Table 47. Influence of air-entraining agent on bond between cement paste and glass

Cement paste Water/cement ratio 0.5	Tensile bond strength 7 days, kp/cm^2
With AEA	7.0
Without AEA	6.5

Figure 64. Cement paste between two sheets of glass. After drying for a day, shrinkage cracks were formed in the paste. 10 ×.
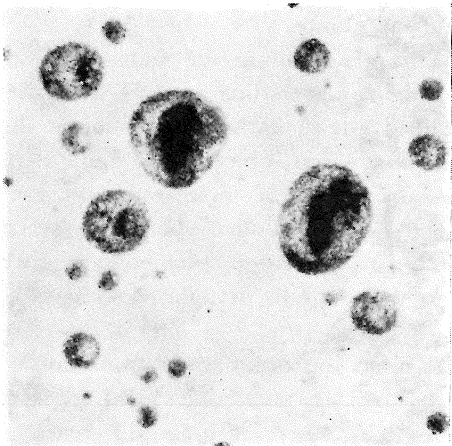
Figure 65. Cement paste containing air-entraining agent. No shrinkage cracks appeared in the paste during drying. 10 ×.

It is feasible that air pores in the mortar reduce the contact surface between mortar and base. In order to find out if this is so, the PML studied the adhesion surfaces of binder pastes with and without air-entraining agents. At the tests the binder pastes with the air-entraining agents had a rather large content of bubbles. The binder pastes were spread on a sheet of glass to a thin layer covering the whole surface. It can be seen then that the bubbles in the pastes with air-entraining agents are pressed out so that their diameter has clearly become greater. The following day, when the binder pastes were dry, the

bubbles could be seen clearly when the sheets of glass were held up to the light. The sheets of glass were placed in an enlarger and used as negatives to make enlargements. Figs. 64 and 65 are reproductions of enlargements made in this way. If binder pastes with and without air-entraining agents are compared, it will be found that the pastes without air-entraining contain numerous shrinkage cracks which occurred during drying. No such shrinkage cracks appear in binder pastes containing air-entraining agents. Bond strength was determined for the pastes between the sheets of glass (Table 47).

The results show that cement paste with air-entraining agents has the same bond strength as cement paste without admixtures, in spite of the fact that the contact surface seems smaller on account of the bubbles. A scrutiny of these bubbles under the microscope revealed that the bubbles have a thin skin of cement paste (Fig. 66). Shrinkage cracks in cement paste without air-entraining agents may have a detrimental effect on the bond strength.

A previous section dealt with the influence of the water/binder ratio on bond strength. Bond strength to absorbent bases improves with rising water/binder ratio. Air-entraining agents usually reduce the water/binder ratio, and for this reason the bond strength of mortars containing air-entraining agents should be impaired somewhat on an absorbent material. This factor is probably not of any great significance, for with pure cement mortar the greatest differences in bond strength were between mortar with and mortar without air-entraining agents, at the same time as changes in the water/binder ratio were of the least importance.

When determining the water retaining properties of a mortar according to ASTM, higher values are obtained almost without exception if the content of air in the mortar is increased to more than 10 per cent by the addition of air-entraining agents (Fig. 67). The PML also studied whether air-entraining agents affect the water retentivity of mortar when it is exposed to suction by dry, glazed whiteware tiles (Table 48).

Attempts to extract water from mortar by the help of the capillary suction of highly absorbent material showed that there is great difference in the water retentivity between mortars with and mortars without air-entraining agents. In these tests, as in those made according to ASTM, the suction time was one minute. The PML also determined the loss of water from mortars after 15, 30 and 45 seconds (Fig. 68). Here, too, the difference in water retentivity between mortar with and mortar without admixtures was significant.

In connection with these tests to determine the loss of water from mortars to absorbent materials, the adhesion of fresh mortar to the respective materials was also studied. It was found that bond strength was much lower with air-entraining agents in the mortar than without (Fig. 69). Traces of mortar containing air-entraining agents on the absorbent tiles were insignificant compared with mortar without admixtures. This is in good agreement with the results obtained at determinations of bond on the hardened mortar.

Thus the tests made showed that the reduced bond strength with air-entraining agents was not due to a change in the surface tension of the mixing water or to a reduction of the contact surface of the mortar. Changes in the water/binder ratio may have some effect, but probably not a very important one. At the determination of the water retaining properties of mortars according to ASTM, water retentivity is usually better when the mortar contains air-entraining agents. When the mortar was exposed to capillary suction by an absorbent material, the difference in water retentivity between mortar with and mortar without admixtures was here too significant. Immediately after the application of the fresh mortar, it was observed that the adhesion of the mortar to an absorbent material is not so good for a mortar containing air-entraining agents as for an equivalent mortar without admixtures. One very likely reason for this lower bond strength for mortars with air-entraining agents than for equivalent mortars without additives is that no binder layer is formed in the contact zone between mortar and base.

References to the literature

There are only few notices in the literature concerning the influence of air-entraining agents on bond strength.

In Technical Notes from Structural Clay Products Institute (1961), the following is said about the effect of air content: "Although few data have been published, available information indicates that a definite relationship exists between air content and tensile bond strength of mortar. In general, an increase in air content is accompanied by a decrease in bond. Data on masonry grouts also indicate that poor bond is associated with high air content, confirming the experience with mortars."

In England, Ryder (1963), at the Building Research Station, studied brick/mortar bonds by a simple transverse test. In these investigations lime-cement mortar (LC 1:1:6) was compared with aerated cement mortar (C 1:6).

The results of bond tests on panels built of bricks of varying suction showed that the aerated cement mortar gave the strength "nil" on panels built of dry bricks with an initial rate of absorption of ca. 25 g/dm², min. Not until the bricks were soaked for 24 hours and drained for 24 hours did the aerated cement mortar give the same strength as the comparative mortar, LC 1:1:6.

Copeland and Saxer (1964), in tests of structural bond of masonry mortars to concrete blocks, found that, in general, substituting masonry cement for all

Figure 66. Enlargement of a bubble in the cement paste shown in Fig. 65. The skin of the bubble contains particles of binder. 50 ×.
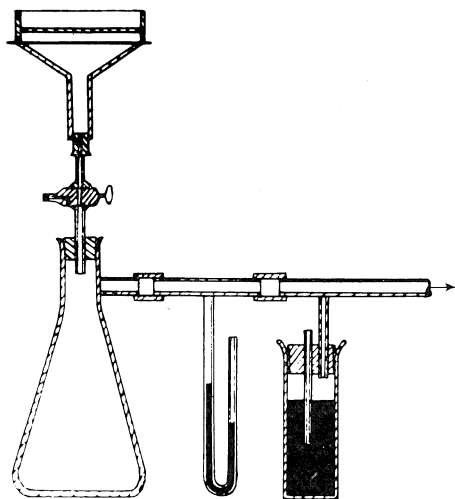
Figure 67. Apparatus for the measurement of the water retaining properties of a mortar, according to the ASTM.

Table 48. Influence of air-entraining on water suction of mortars

Absorbent material/mortar	Water loss in percent of total water content during 1 minute's suction	
	With AEA	Without AEA
Dry tile		
C 1 :3	5	22
C 1 :6	15	33
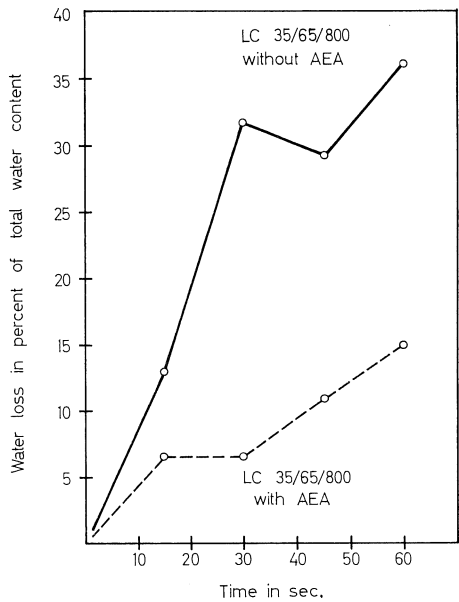
Figure 68. Changes in the water/binder ratio of mortars during the first minute's suction by a dry, water absorbent tile. Mortar without air-entraining agent gives off water easier than mortar with additives.

Figure 69. Rear side of glazed whiteware wall tiles one minute after setting. The addition of air-entraining agent to the mortar impairs the adhesion of the fresh mortar.

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or part of the Portland cement resulted in an increase in air content, a lower compressive strength, and a large reduction in adhesion (Fig. 70). In their conclusions regarding the effect of more important factors, they demonstrated that the tensile bond decreased as the air content of mortar was increased beyond about 7 or 8 per cent, and to be reasonably certain of obtaining tensile and shear bond exceeding 5 kp/cm^2 the air content must not exceed 10 per cent.

Conclusions

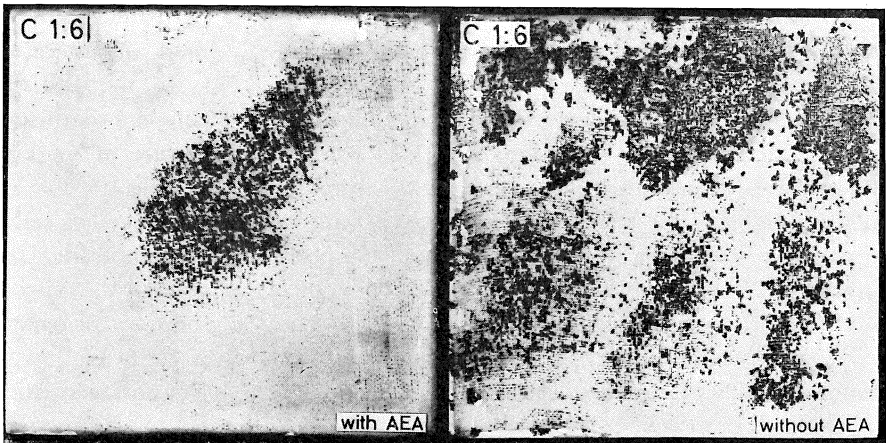The addition of air-entraining agents reduces the adhesion of the mortar to both non-absorbent and absorbent materials, but this reduction is especially noticeable on highly absorbent materials.

This reduction in adhesion can be observed as soon as the fresh mortar is applied to an absorbent base material.

VISCOSITY MODIFIERS

The principal admixtures used to modify the viscosity of mortar are cellulose derivatives such as methyl cellulose, carboxy-methyl cellulose and ethyl-hydroxyl-ethyl cellulose. Such admixtures are used in some special mortars, e.g. mortars for joining and setting ceramic tiles. These special mortars have Portland cement as binder, and the addition of cellulose derivatives was made chiefly to improve the water retaining properties of the mortars. At the same time, the plasticity of the mortar was improved.

The most important advantage of the addition of cellulose derivatives is that the special mortars can be used in very thin layers without risking too rapid drying on highly absorbent materials. In contrast with pure cement mortar, ceramic tiles may be moved and even twisted round when setting without any loss of adhesion. The addition of cellulose derivatives delays the drying of the mortar, which provides a longer "open time", i.e. the time during which work can be continued with the mortar without noticeable changes in its consistence.

In the patent deeds concerning the adding of cellulose derivatives to cement mortars, the amount added varies between 0.5 and 10 per cent, calculated on the weight of the cement. As additive, a mixture of cellulose derivative and polyvinylacetate or polyvinylalcohol is often given. Mixtures of cellulose ether and sodium pentachlorophenate are also used. The additions of cellulose derivatives are much greater than those of air-entraining agents.

Cellulose derivatives, like air-entraining agents,
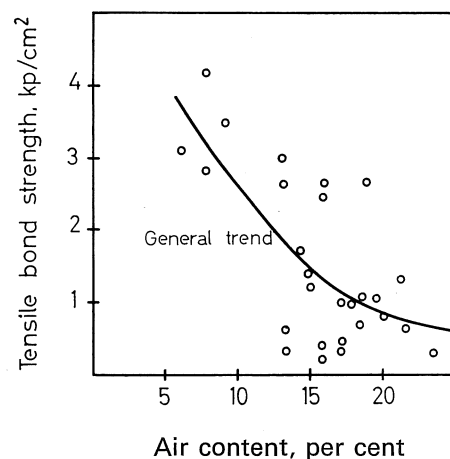
Figure 70. An increase of the air content of a mortar seems to reduce the tensile bond strength. According to Copeland and Saxer (1964).

Table 49. Bond between a mortar with cellulose derivative as only binder and dry, ceramic tiles

Mortar Standard sand and cellulose derivative	Tensile bond strength 28 days, kp/cm^2
1 % solution	0.3
2 % solution	0.7
3 % solution	1.0

cause a considerable increase in the air content of the mortars. The consistence of the mortars is reminiscent of whipped cream. The air pores are different in appearance from those caused by the addition of air-entraining agents (Fig. 71).

The investigations made at the PML showed that cellulose derivatives, in spite of the increase in air content they cause, have no detrimental effect of bond strength. This may be because the cellulose derivatives can also act as binders and are sometimes used as glue for paper-hanging, for example.

At the PML investigations, the properties of a cellulose derivative used in Sweden in the manufacture of mortar were studied. The product tested belongs to the group nonionic water-soluble ethyl-hydroxyethyl cellulose.

The addition of cellulose derivatives to water increases the viscosity of the solution. A 2 per cent solution of the tested cellulose derivative has a viscosity of 4000—5000 cP according to Brookfield. The surface tension of the water drops from 70 dynes/cm to 40 dynes/cm.

Figure 71. Air pores in a binder paste containing cellulose derivative. 10×.

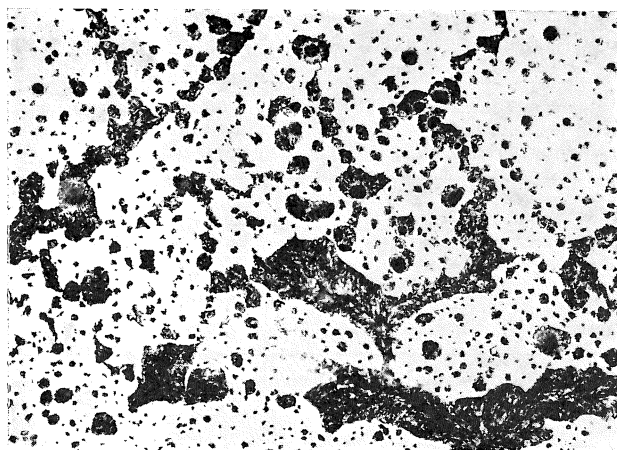The bond properties of cellulose derivatives were determined as follows:

Solutions of cellulose derivatives in water were mixed with standard sand, and the mortars made in this way were used to unite two dry, smooth and porous ceramic tiles (Table 49).

The bond strengths rise with rising addition of the nonionic cellulose ether.

Compared with cement mortar, the bond strength that can be achieved by only cellulose derivative as binder is very small. Tests were made with successively increased additions of cellulose derivative to a cement mortar 1:3, the consistence being kept constant.

Vitreous ceramic tiles were attached to concrete with the different mortars. After 7 days the bond strength was determined (Table 50).

The results imply that bond strength is impaired somewhat by the addition of cellulose derivatives.

The most important advantage of the addition of cellulose derivatives is in adhesion to highly absorbent materials (Table 51).

Bond strength to highly absorbent tiles is improved considerably by the addition of cellulose derivatives.

Fat mortars 1:3 usually give poor adhesion to highly absorbent materials, according to the PML. In order to find out how large the dose of cellulose derivative should be to ensure adhesion of lime-cement mortar LC 50/50/475 (LC 2:1:9) to dry, glazed whiteware tiles, the following test was made (Table 52).

The results show that the amount of cellulose derivative added must be at least 0.3 per cent of the dry weight of the mortar, which is equivalent to about 15 g cellulose derivative per kilogramme mixing water.

Table 50. Influence on bond by additives of cellulose derivative

Cement mortar 1:3 with additives of cellulose derivative	Water/cement ratio	Tensile bond strength 7 days, kp/cm^2
0 %*	0.75	9
0.2	0.73	5
0.3	0.73	7
0.4	0.73	5
0.5	0.73	6

* Calculated on dry mortar weight.

Table 51. Influence of cellulose derivative on bond between cement mortar and ceramic tiles with different suction

Ceramic tiles	Tensile bond strength 28 days, kp/cm^2 Cement mortar 1:3	
	With cellulose derivative	Without cellulose derivative
Vitreous ceramic tiles	10	12
Dry glazed, whiteware tiles	5	0

Table 52. Influence on bond of cellulose derivative on bond between lime-cement mortar and dry glazed whiteware tiles.

Lime-cement mortar LC 2:1:9 with additives of cellulose derivative	Tensile bond strength 28 days, kp/cm^2
0 %*	0
0.05	0
0.1	0
0.2	1.5
0.3	2.5

* Calculated on dry mortar weight.

It is well known that cellulose derivatives improve the water retentivity of mortar. In the tests reported in Table 52, the water retaining properties of mortar were also measured, with reference to the various amounts of cellulose derivative added, by a method developed by the Cement Marketing Co., Ltd., London. The procedure was as follows: 100 g mortar was placed in a brass ring ca. 1 cm high, in the bottom of which were six layers of blotting-paper.

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After ten minutes' suction, the mortar was removed and the increase in the weight of the blotting-paper was measured (Table 53).

As in the determinations of bond strength, it is not until the admixture reaches 0.2 per cent of the dry weight of the mortar that a change can be observed, which becomes even more marked at 0.3 per cent. The water retentivity of the mortar is improved considerably by the addition of 0.3 per cent cellulose derivative to the mortar.

If cement mortars 1:3 with and without the addition of air-entraining agent or cellulose derivative are compared, marked differences are found when they come into contact with highly absorbent ceramic tiles. During the first few minutes, mortar containing cellulose derivative does not lose any water, while cement mortar without admixtures loses very much. Mortar containing air-entraining agent occupies an intermediate position. After a long period of suction, one hour, equilibrium is reached. The improved water retentivity of a mortar due to cellulose derivative, varies somewhat according to the composition of the mortar and the cellulose derivative used. (Fig. 72.)

If the adhesion of fresh mortar to an absorbent material is studied with gauze and dry, glazed ceramic tiles in the way described earlier, no patches of mortar remain on the backs of the tiles if the mortar contains cellulose derivative. This may be because the gauze prevents contact between the mortar and the tiles. When mortar has very high water retentivity, the gauze allows only an insignificant amount of water to reach the tile, and the patches of binder paste will therefore be very small.

If, instead, the mortar is laid direct on the tile, without gauze, and shaken off after one minute, the result is different. Mortar containing cellulose derivative adheres to the tile (Fig. 73). Compared with mortar without additives, good adhesion is obtained with fresh mortar containing cellulose derivative.

References to the literature

In Sweden, Nycander (1962), many years ago recommended an addition of one gram cellulose derivative (Modocoll) per litre mixing water to improve the workability of mortar. Investigations by the PML have shown that this dose of cellulose derivative does not affect the bond strength of the mortars to any appreciable degree.

Weigler (1965), in Germany, studied whether applying a coat of cellulose derivative to aerated concrete surfaces would reduce suction and thereby improve the adhesion of mortar to the surface. Weigler found that highly absorbent aerated con-

Table 53. Influence of cellulose derivative on the water retentivity of the mortar

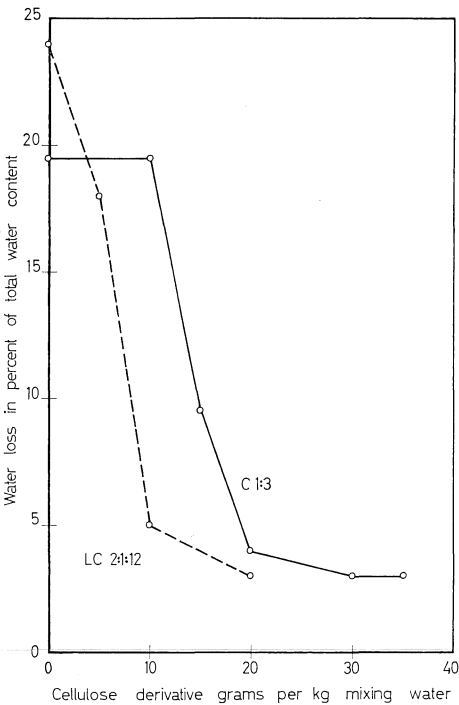| Lime-cement mortar LC 2 : 1 : 9 with additives of cellulose derivative	Loss of water during 10 min. in % of the total water content
0 %*	30
0.05	30
0.1	30
0.2	15
0.3	5

* Calculated on dry mortar weight.

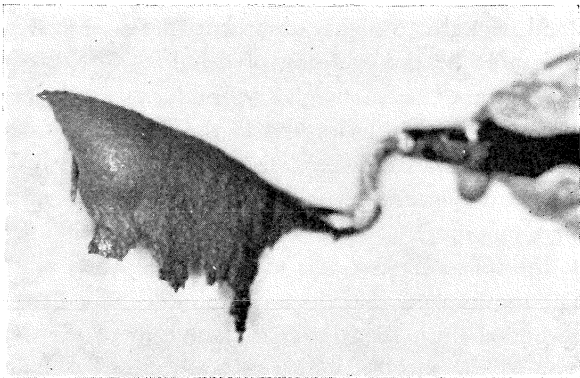Figure 72. Addition of cellulose derivative improves the water retaining properties of mortars.

Figure 73. Mortar with cellulose derivative shows a characteristic stickiness.

crete surfaces can be coated with 10—12 g/dm² of a 1 per cent cellulose derivative solution (Tylose) to obtain a suitably low suction. If a stronger solution is used, there arises a risk that a water-soluble film of the cellulose derivative is formed in the contact surface between mortar and base.

Weigler also tested mortar to which cellulose derivative had been added. He found that the water retentivity of mortar is improved by dosing it with ca. 4 g per litre mixing water. Bond strength, however, did not seem to be improved during the tests by the addition of cellulose derivative. All the values for the mortars tested with and without the addition of cellulose derivatives were below 0.55 kp/cm². In the principal tests, other combinations of mortar with higher bond strength were tested. In these tests, there was a clear tendency towards improvement in adhesion by the addition of cellulose derivative.

Using the same types of mortar, Weigler also tested a dose of 3 per cent polyvinylacetate. The additive does not seem to have improved the bond strength.

In the patent deeds can be found further information on what improvements are to be obtained by dosing mortar with cellulose derivatives.

Wagner (1962) considered that the most important property of cellulose derivatives is to prevent the loss of water from hydraulic cement compositions to a dry backing base, or to the absorptive back of dry wall tiles pressed into contact with the mortar. This water retentivity is obtained by making the viscosity of the liquid phase so high that no egress of water to tile or base will occur, or to ensure that the rate of such water loss is greatly diminished. In order to give the water phase the necessary viscosity, and to allow at the same time of effective use with Portland cement, certain types of methyl cellulose and certain grades of polyvinyl alcohol in proper amounts are mixed with the hydraulic cement composition.

Ericson (1965) claimed that many years of practical experience and extensive laboratory testing have established that addition of a water-soluble cellulose ether to mortar imparts to the composition the following desirable and valuable properties:

1. A considerably improved plasticity or pliability. This effect is particularly marked when the mortar is lean or when it is necessary to use a sand gradation which is not the most suitable for the purpose.
2. An increased adhesion to brick or stone surfaces and therefore tighter joints.
3. A reduced or minimized separation of water, depending on the amount of cellulose ether added.
4. A reduced water requirement (up to 10 %) and hence an increased strength and a more rapid drying of the building.
5. A reduced capillary absorption by the base. Sufficient water is retained by the mortar for its complete and adequate binding or setting.
6. A reduced tendency to shrinkage and cracking.

Conclusions

Viscosity modifiers of cellulose derivative type improve adhesion to absorbent bases. These additives give the mortar a stickiness which may help to improve the bond strength. The amount of additive is in the region of 2—3 per cent of the weight of the mixing water.

Viscosity modifiers do not seem to improve the bond strength to non-absorbent materials.

These admixtures give mortar special water retaining properties which delay the drying of the mortar and make possible new methods of work with thin layers of mortar.

Bond strength may change with time owing to many factors. The adhesion of fresh mortar is usually improved by the chemical reactions occurring successively during the hardening of the mortar. With mortars containing cement, the final strength is attained after only a couple of months. Lime-cement mortar hardens on the whole in the same way as cement mortar, but carbonization of the lime part of the mortar is a slow process and successive improvement may be counted upon during a long period of time. This is true to an even greater extent of pure lime mortar.

When the mortar has been applied, a gradual loss of water occurs in the mortar. Instead of the water, the mortar becomes full of pores. During this drying phase, cracks usually appear in the mortar, depending on the composition of the mortar. Such cracks usually occur if the mortar is rich in binder. Tests made at the PML have shown that mortar with a ratio of 1:3 or fatter cracks with rapid drying of a relatively thick layer of mortar (Fig. 74). Mortar exposed to suction in two directions may crack in this way during an early phase of the hardening process. Stress in the mortar during this phase may be so great that cracks occur in ceramic wall covering (Figs. 75 and 76). This should diminish the bond strength between mortar and base.

During the process of drying and by chemical reactions between binder, water and carbon dioxide, changes take place in the volume of the mortar. The successive shrinkage is greatest and continues longest in cement mortar. Pure lime mortar shrinks very much when the mortar is plastic, but cracks can be eliminated when the mortar is compressed, but after that shrinkage in lime mortar is very slight.

The PML had measured shrinkage in mortar on semicylindrical test pieces 500 mm long (Fig. 77). If
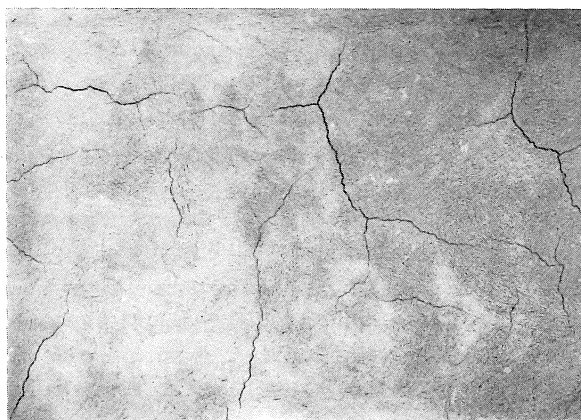
Figure 74. Drying-cracks in a mortar rich in binder. $1/3\times$.

the changes in volume occurring while the mortar is plastic are ignored, the free shrinkage of the mortars used in the test was between 0.10 and 1.50 mm/m. But mortars are seldom allowed to shrink freely, since, almost without exception, they are used in combination with other material. If longitudinal changes differ in mortar and the base material, stresses arise in the contact zones, and they may successively lead to ruptures if the bond strength is inadequate.

The Siporex Central Laboratory at Södertälje, together with the PML, made tests to determine the stresses that may arise between rendering and aerated concrete. These tests, which were made with the help of strain gauges, showed that aerated concrete is compressed as the mortar shrinks. When the mortar was removed, the aerated concrete expanded and the stresses ceased. The shear strength increased with increasing E-modulus in the rendering, and with increasing thickness of the coat. Tensile stress in the

Figure 75. Cracks in cement
mortar 1:3 applied between dry
aerated concrete and dry glazed
whiteware wall tiles.

Figure 76. Drying cracks
in the mortar have
caused cracks in the wall tiles.
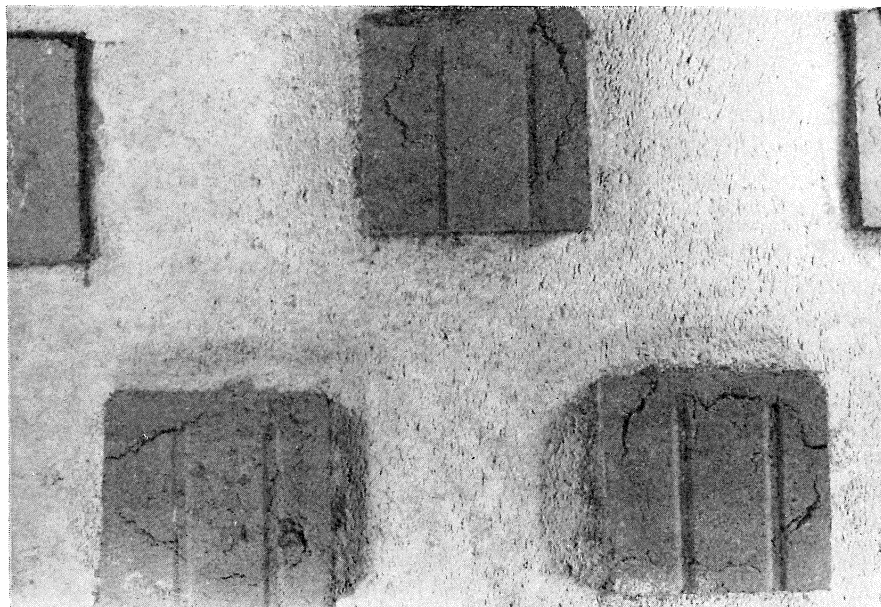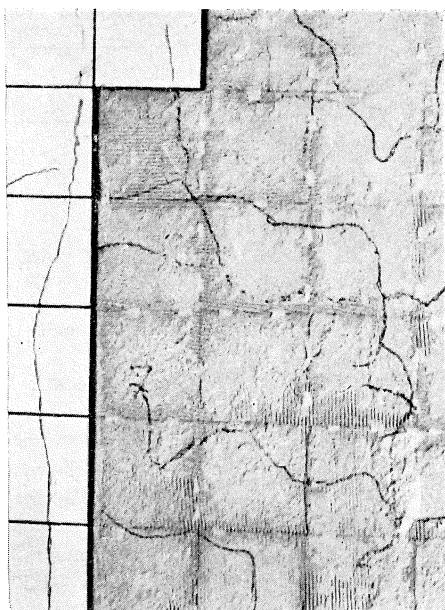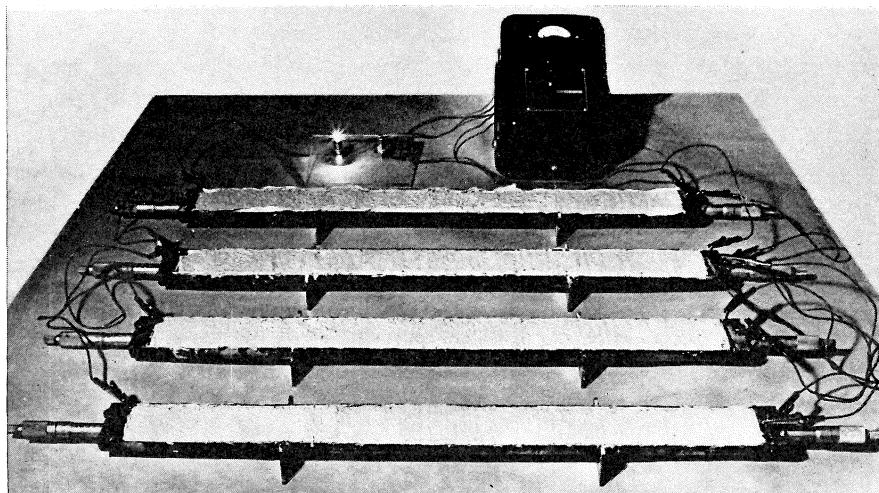

Figure 77. Apparatus to measure
the free shrinkage of mortar.
Electric contacts facilitate
reading off while the mortar is
plastic.

rendering layer was almost as great as the tensile strength.

In the process of moistening and drying, the stresses in the contact surface alternate, and fatigue may eventually lead to failure of the bond.

The alternation between freezing and thawing may also lead to a weakening of the adhesion of the mortar, especially if differences in the diffusion of the mortar and the base give rise to a concentration of moisture in the contact zone.

During the summer of 1954, a two-floor house of aerated concrete was built in Stockholm in the same yard as the PML. The walls were divided into fields, which were rendered with a series of different types of mortar. Masonry cement and lime-cement with different admixtures were used as binders. The PML determined the bond strengths of the various mortars after 3 months and after 1 year. The results consistently showed that the bond strength had increased between the two tests. This was probably due to a successive increase in the strength of the mortars themselves. It is now twelve years since the building was erected, and the mortars in the different fields are still intact. Unfortunately, no bond strength determinations have been made during recent years. (Fig. 78.)

References to the literature

Palmer and Hall (1931) devoted a special paper to durability and strength between mortar and brick. They subjected two-month-old, moisture-saturated test units to alternate freezing and thawing fifty times, followed by drying. The results show that the freezing and thawing tests did not affect bond strength to any great extent as far as the lime-cement mortar used (LC 1:1:6) was concerned.

Palmer and Parsons (1934) studied fifteen different mortars in combination with six different bricks. The test-pieces were subjected to repeated moistening and drying for a year, after which they were exposed to 35 cycles of alternate freezing and thawing. After each fifth cycle, the test pieces were allowed 18 days in which to dry.

Before the freezing tests, failures occurred in three mortar/brick combinations. Cement mortar 1:3 and three different types of masonry cement survived the 35 freezing cycles with all six types of brick. Pure lime mortar was damaged at an early stage, while lime-cement mortar 1:1:6 gave almost as good results as the pure cement mortars.

Ryder (1963) studied the effect on bond strength of freezing newly-built brickwork. In these tests, small brickwork panels were used (see Fig. 4). The panels

Figure 78. Testing the tensile bond strength by drilling grooves in different fields of rendering.

Table 54. Freezing tests on small new-built brickwork panels (Ryder, 1963)

Mortar type	Air content %	Ratio Frozen : Normal
Activated LC 1:1:6	—	0
Aerated C 1:6	18	1.0
Aerated C 1:8	19	0.8
Masonry cement M 1:4.5	18	0.5
Masonry cement M 1:6	18	0.1

The figure shown in the last column is the ratio of the average failing load of the frozen panels to the average failing load of the panels built with the same mortar and stored at a normal temperature without prior freezing.

were built in pairs at normal room temperature with soaked, porous brick and were then stored at this temperature for 24 hours. One panel of each pair was then transferred to a cold room maintained at a temperature of —5° C, and was kept in this room for 24 hours. After 28 days the transverse strength of the panels was determined (Table 54).

The results show that the panels built with aerated cement mortar were not seriously damaged by early freezing. The two masonry cement mortars were similar in strength and air content to the corresponding aerated Portland cement mortars, but it appears that the bond strength of the panels built with these

masonry mortars was appreciably reduced by freezing, whereas the panels built with the aerated Portland cement mortars suffered virtually no loss in bond strength.

The masonry cement contained a very fine mineral filler in addition to an air-entraining agent.

Panels built with lime-cement mortar without air-entraining agent suffer extensive damage if they are frozen within 3 days of being built.

Copeland and Saxer (1964) found that the curing of mortar is important for tensile and shear bond. Their findings indicate that the structural bond of hydraulic cement mortars to the base is greatly influenced by curing conditions. Damp curing equivalent to periodic rewetting of the masonry for a few days is essential to the development of the optimum bond of the mortar. The storage of specimens after 14 days, from 28 days to 6 months, has minor influence on the bond.

Pilny and Stuck (1959) concerned themselves with problems of the adhesion of mortar to Ytong, an aerated concrete. The tests were made on account of damage to an 18-month-old house, from which the rendering had fallen from the outsides of the Ytong walls. They studied the longitudinal changes in Ytong and mortar, and in prisms of Ytong, rendered on two sides with lime-cement mortar. Measurements were continued for about six months, during which time the test specimens were allowed to dry slowly. After drying at 110°, the mortar was sawn from the Ytong

prisms and then, by the longitudinal changes occuring in the mortar and the Ytong, the direction of shear stresses in the contact surface could be determined.

Pilny and Stuck came to the conclusion that the stresses which may arise between mortar and Ytong are never so great that they can be responsible for loosening of mortar, if the rendering is done properly on moistened Ytong with a spatterdash coat.

Conclusions

The studies suggest that the durability of bond between mortar and different base materials depends greatly on what happens during the first phase when the mortar is drying and hardening. All the factors mentioned earlier in connection with the composition of the mortar and the absorption of the base are of importance. The work of bricklaying and rendering is also of great importance for the durability of the bond. Rapid drying may impair the results. It is therefore important that brickwork and mortar are kept damp during the first few days of the hardening of the mortar. Frost during the early phase after the application of the mortar may cause bond failure. Otherwise the results imply that bond strength increases with time.

Successive alternate contraction and expansion at all changes in humidity and temperature may eventually lead to fatigue, and failure may occur in the contact zone between mortar and base.

A series of test pieces was made for microscopic studies of the contact zones between mortar and base. In the tests, the mortars were applied between a plate of glass and a ceramic tile (see Fig. 15). After 28 days in constant conditions, the test pieces were sawn in two. A thin section was made of one half, and a polished specimen was made of the other. A casting of the polished surface was made with the help of a special mass (Fig. 79). This cast could then be studied in the microscope with oblique illumination and vertical illumination, which showed up air gaps and voids. I have used this method earlier to study the effects of air-entraining agents on the distribution of pores in concrete surfaces (Högberg, 1959).

In the first tests, an investigation was made of the adhesion between cement mortar 1:3 and cement mortar 1:6, with and without air-entraining agents, and glazed whiteware tiles, some dry and some wetted, but with dry surfaces. The results are shown in Fig. 80 and Table 55.

As shown in Fig. 80, the glazed whiteware tile was lacking in half of the test pieces. Adhesion between mortar and tile was often very poor, and the ceramic tile loosened in an early phase of the production of the thin sections.

Studies in the microscope showed that the adhesion of the cement mortars to the non-absorbent plate of glass was good (Fig. 81). During the preparation of the thin section, however, the plate of glass loosened in the combination cement mortar 1:3 and wetted tiles. Fissures were also observed in the contact zones between mortar and glass with cement mortar 1:3 (Fig. 82).

Adhesion to dry, water absorbent tiles was satisfactory only with cement mortar 1:6 without air-entraining agents. The other dry tiles loosened during the preparation of the thin sections. The contact be-

Table 55. Bond between mortars and glazed whiteware tiles and glass

Backings	Cement mortar C 1:3		Cement mortar C 1:6	
	Without AEA	With AEA	Without AEA	With AEA
Tile, dry	o	o	+	o
Tile, wetted	+	+	+	o
Glass/(Tile, dry)	+	+	+	+
Glass/(Tile, wetted)	o	o	+	+

+ = good bond   o = no bond

tween cement mortar 1:6 and dry tiles was not fully satisfactory (Fig. 83). The mortar had tentacular contact with the tile.

With wetted tiles, the preparation of thin sections was successful except with cement mortar 1:6 containing air-entraining agents. The adhesion of cement mortar 1:6 without additives was satisfactory (Fig. 84). Adhesion was poor with cement mortar 1:3 with air-entraining agent. There were long air gaps along the contact zone (Fig. 85).

Detail studies of contact zones sometimes show that binder paste adheres to the base material and that an air gap is present, which indicates that a rupture has occurred between the binder paste and the rest of the mortar (Fig. 86).

Another series of test pieces was made with lime-cement mortars. In these studies, the mortar was made with glass balls as aggregates to facilitate studies in the microscope (Table 56).
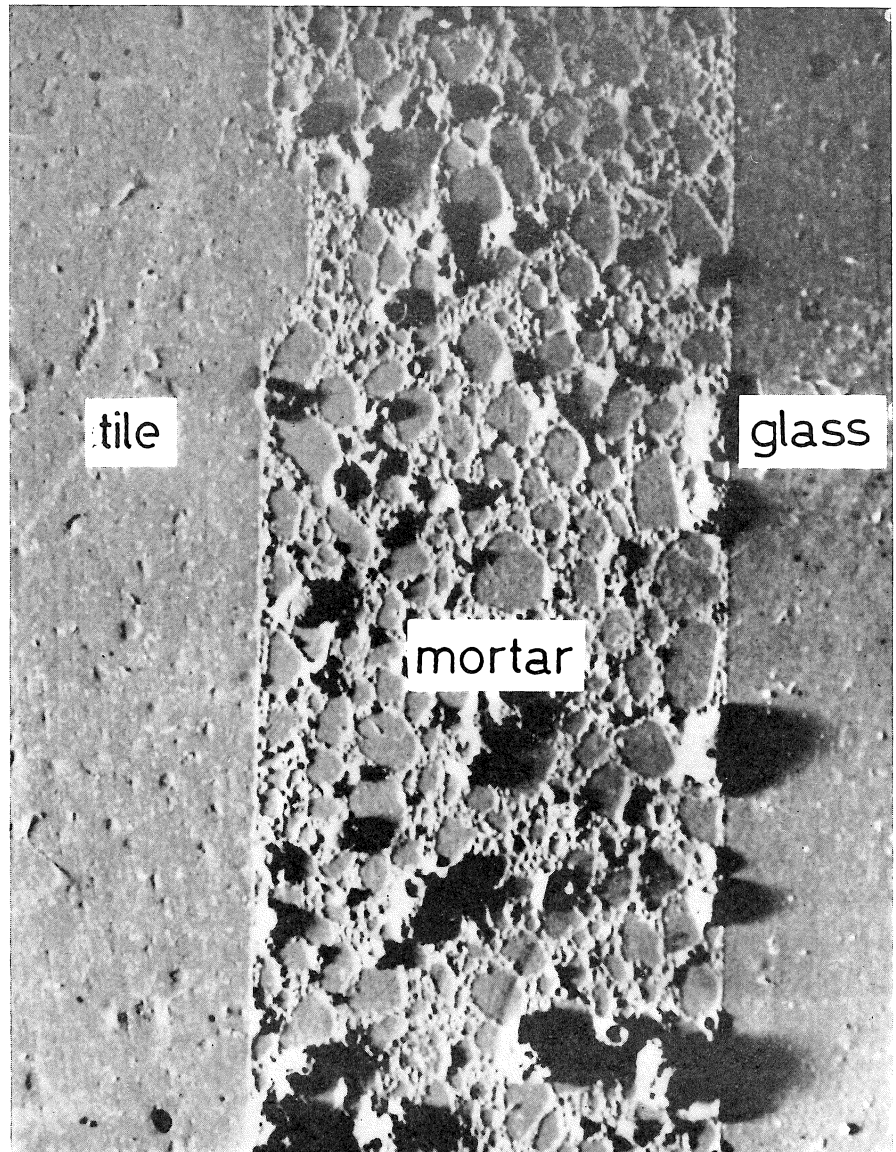
Figure 79. An elastic impression removed from a brightly polished surface of cement mortar between a glazed whiteware wall tile and a glass plate. 5 ×.
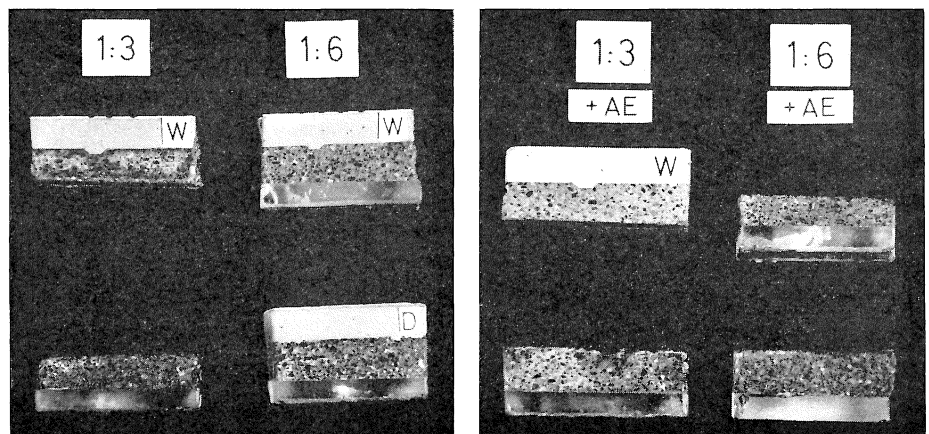

Figure 80. Test pieces made of cement mortar with and without air-entraining agent between a glazed whiteware wall tile and a glass plate. During the preparation of thin and polished specimens, some wall tiles and glass plates have detached from the mortar. D=dry tile. W= wetted tile.
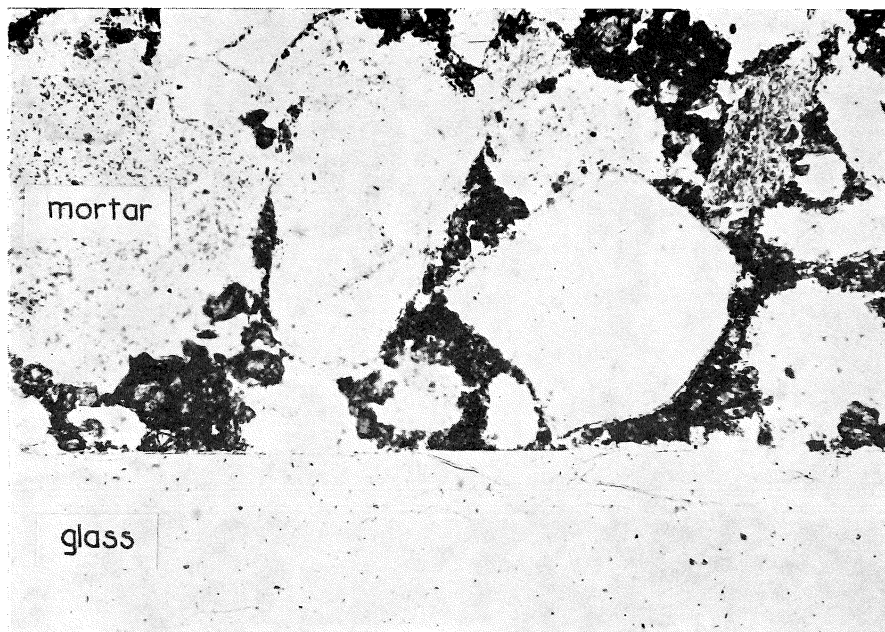
Figure 81. The adhesion between the cement mortar and the plate of glass is good. 75 ×.
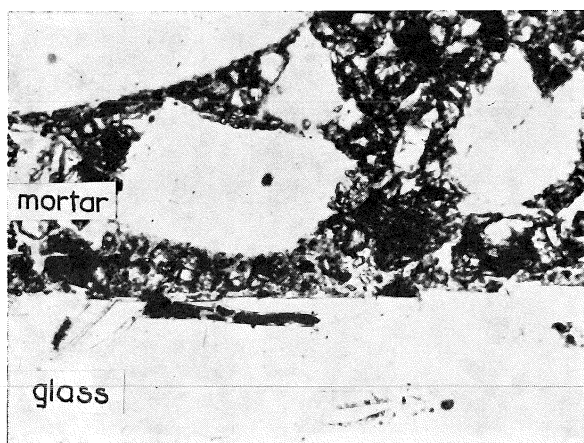
Figure 82. Cracks in the glass plate at the contact with cement mortar 1:3. 100 ×.

Table 56. Bond between lime-cement mortars and clay bricks or aerated concrete

Base material	Lime-cement mortar			
	LC 35/65/400 1:3 by volume		LC 35/65/800 1:6 by volume	
	Without AEA	With AEA	Without AEA	With AEA
Clay brick, dry	o	o	+	o
Aerated concrete, dry	o	o	+	+

+ =good bond   o=no bond

Table 57. Bond between lime-cement mortar and glazed whiteware tiles treated with cement paste

Backings	Lime-cement mortar			
	LC 35/65/400 1:3 by volume		LC 35/65/800 1:6 by volume	
	Without AEA	With AEA	Without AEA	With AEA
Tile, dry	—	o	+	—
Tile, with thin coat of cement paste	+	+	+	+

+ =good bond   ——=poor bond   o=no bond

Table 58. Influence of the addition of cellulose derivative on bond between lime-cement mortars and different backings

Backings	Lime-cement mortar	
	LC 35/65/400 1:3 by volume With cellulose derivative	LC 35/65/800 1:6 by volume With cellulose derivative
Aerated concrete, dry	+	+
Sand-lime brick, dry	+	+
Clay brick, dry	—	+
Tile, dry	—	+
Tile, wetted	o	o
Tile with thin coat of cement paste	+	+

+ =good bond   ——=poor bond   o=no bond

Figure 83. Surface impression photographed in vertical illumination. The contact zone to tile contains voids, while the contact of the mortar with glass is much better. 5 ×.

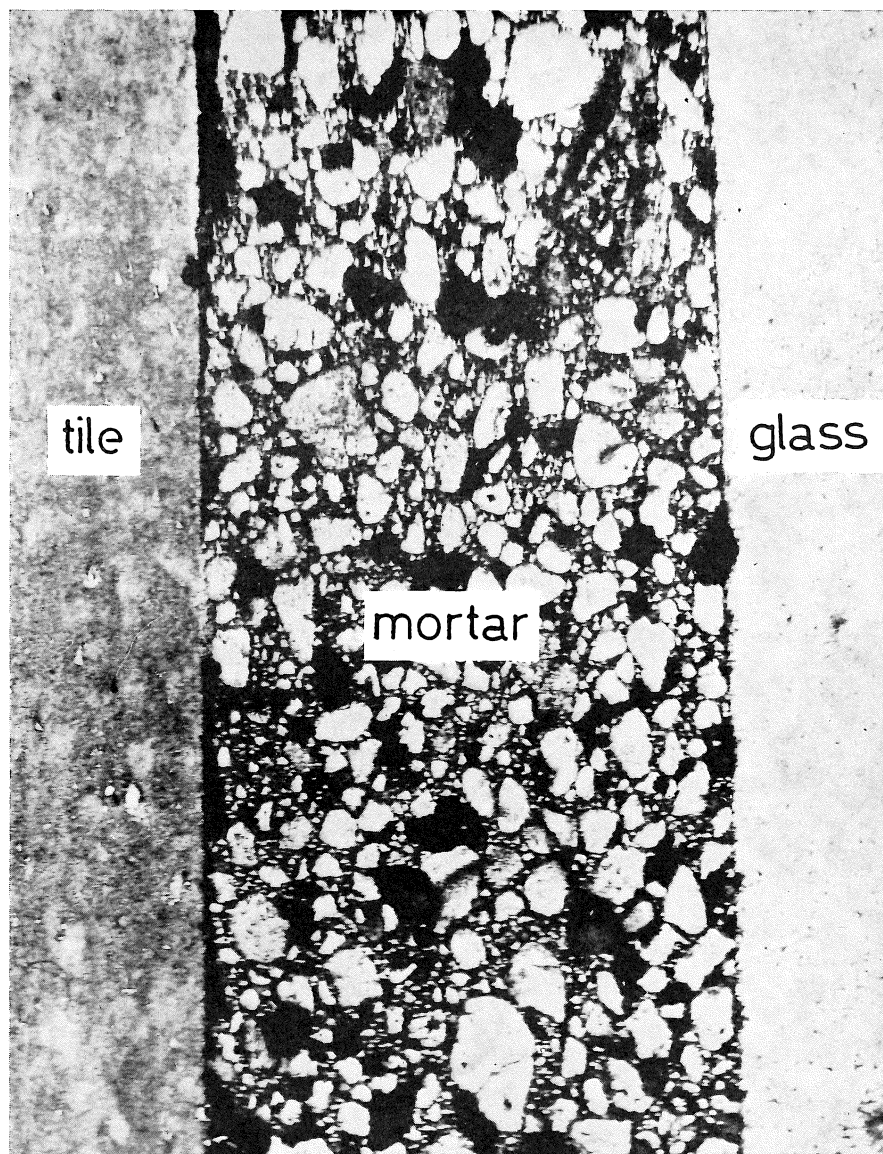This part of the investigation, like tests made earlier, showed that adhesion is poor between water absorbent material and mortar 1:3 by volume (Table 57).

In the same series, test pieces were also made with tiles coated with a thin layer of cement paste. This treatment gave good adhesion with all the mortars studied (Fig. 87).

It could be seen in the microscope that no cement paste had penetrated into the tile. The layer of binder paste was in very good contact with the tile, but small drying fissures were present in the layer itself, although they probably had no great effect on the bond strength (Fig. 88). Contact between mortar and binder paste was usually satisfactory, but not so good as between binder paste and tile (Fig. 89).

A cellulose derivative was also used as an additive in lime-cement mortars. The dose used was 20 g per kg mixing water (Table 58).

The results imply that the addition of a cellulose derivative to lime-cement mortar 1:6 gives good adhesion except to wetted tiles. When using lime-cement mortar 1:3, there is a tendency for a film containing cellulose derivative to form in the contact zone between the mortar and very water absorbent materials. Shrinkage cracks appear in this layer (Fig. 90).

References to the literature

Voss (1933) introduced the microscopic study of thin sections of the test specimen, which finally resulted in his hypothesis regarding the bond layer.
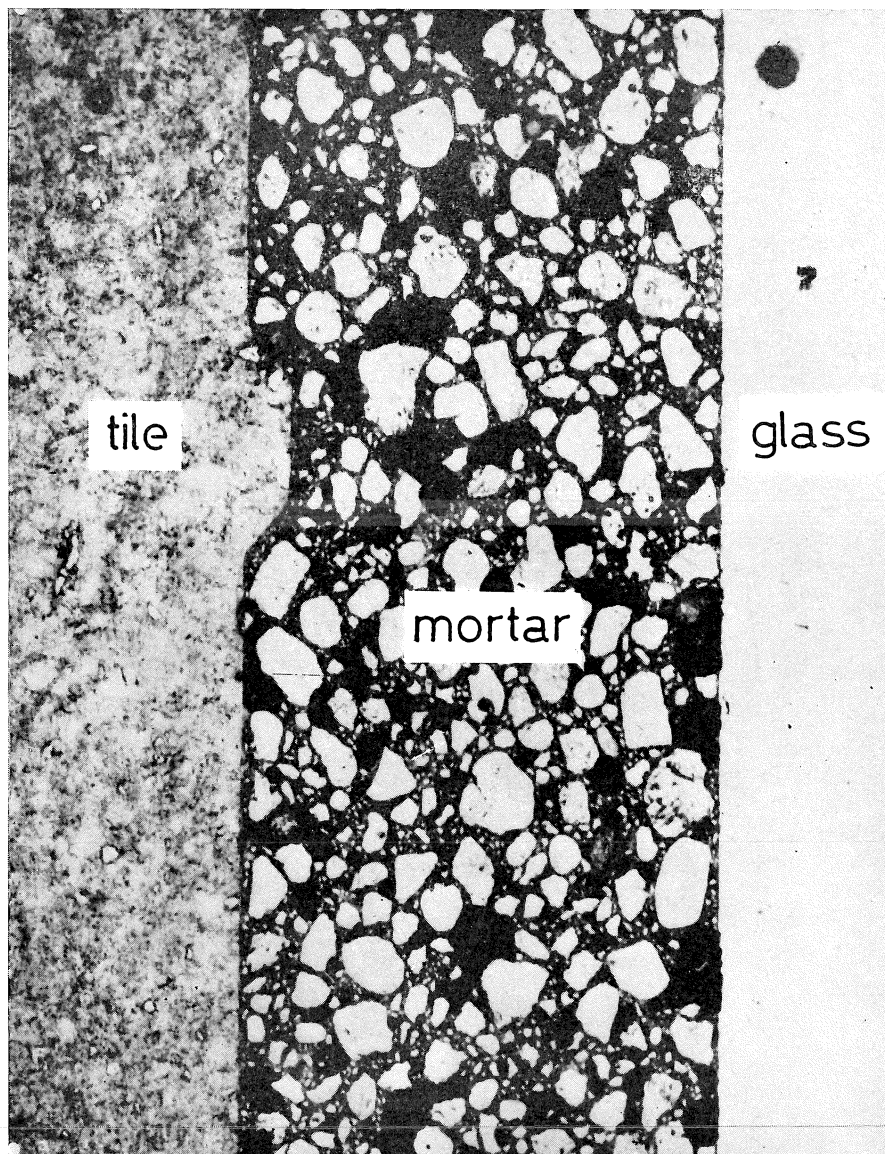
71

Figure 84. Surface impression of cement mortar 1:6. Adhesion seems good to both tile and glass. Fig. 79 and this figure are both photos from the same elastic impression. The figure above is taken in vertical illumination and Fig. 79 in inclined illumination. 5 ×.

In connection with studies of the permeability of brick masonry walls, Voss examined thin sections of actual specimens in the microscope. He chose a few outstanding examples in order to illustrate a general tendency. The photomicrographs of brick and mortar interfaces reveal both continuous "bond layers" and cracks. Mortars with a high content of Portland cement often show that no bond layer is present immediately at the brick surface. A crack approximately 0.01 mm wide has been formed between the mortar and the brick.

Voss observed that, with lime-cement mortar, the contact between mortar and brick is usually good and that the "bond layer" contains highly birefringent material. This birefringence is due, according to Voss,

to the fact that mortars with a high content of lime have a sufficient supply of calcium hydroxide to induce healing within itself, and to experience crystal growth within its voids, e.g. autogenous healing.

In order to obtain a "bond layer", Voss therefore recommends the use of lime-cement mortar. The studies were made on LC 2:1:9, LC 1:1:6 and C 1:3 containing 10 per cent lime.

Staley (1940) made a petrographic study of the bond between brick and mortar in existing walls. The specimens collected represent materials from most parts of the United States. The photomicrographs and surface pictures are from brickwork varying in age from 4 to 187 years.

In these studies in the microscope of specimens

Figure 85. Bad adhesion between a dry glazed whiteware wall tile and cement mortar 1 : 3 containing air-entraining agent. 75 ×.
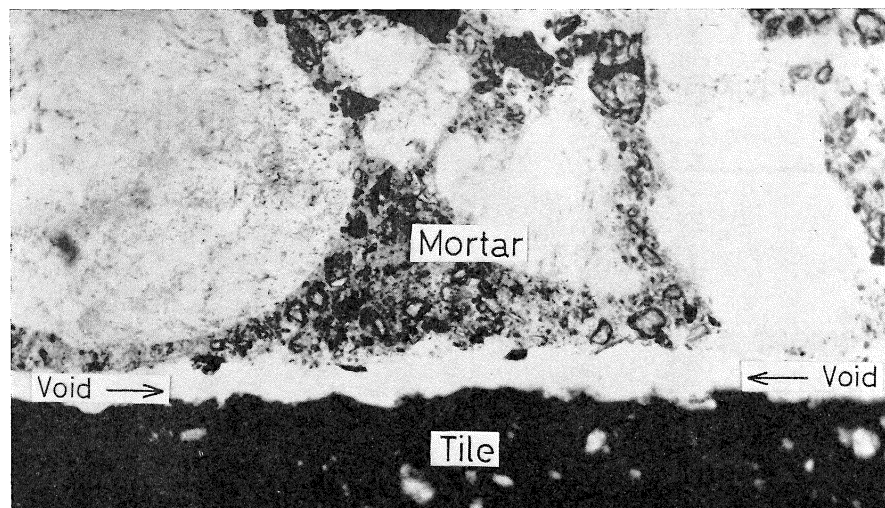
Figure 86. Binder paste (dark areas) adheres to the base material. A rupture has occurred between this layer and the mortar. 75 ×.
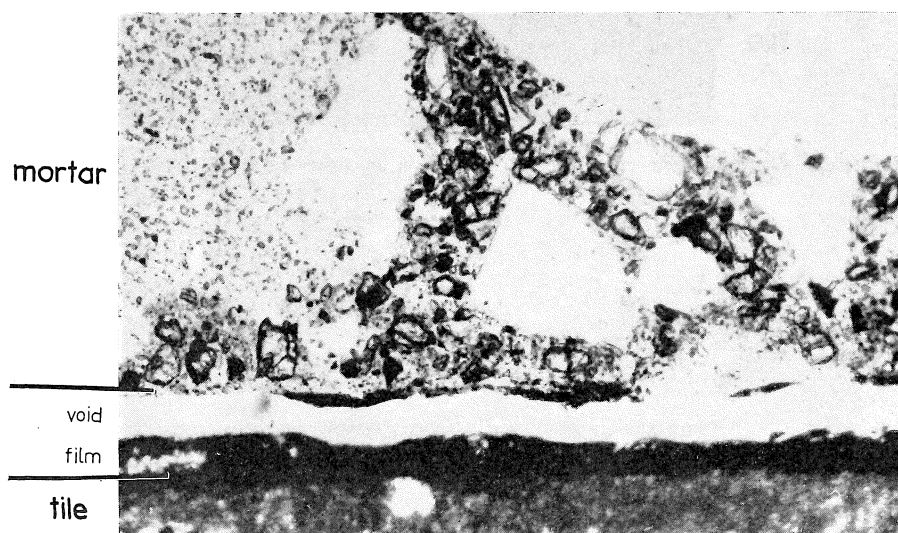
Figure 87. A thin coat of cement paste improves adhesion between a strongly absorbent base and lime-cement mortar. 25 ×.

mortar
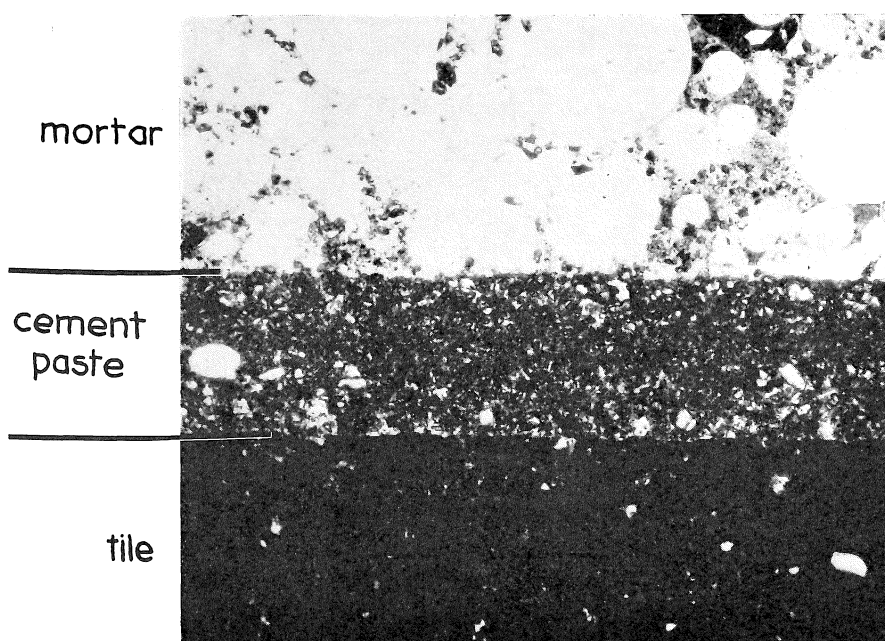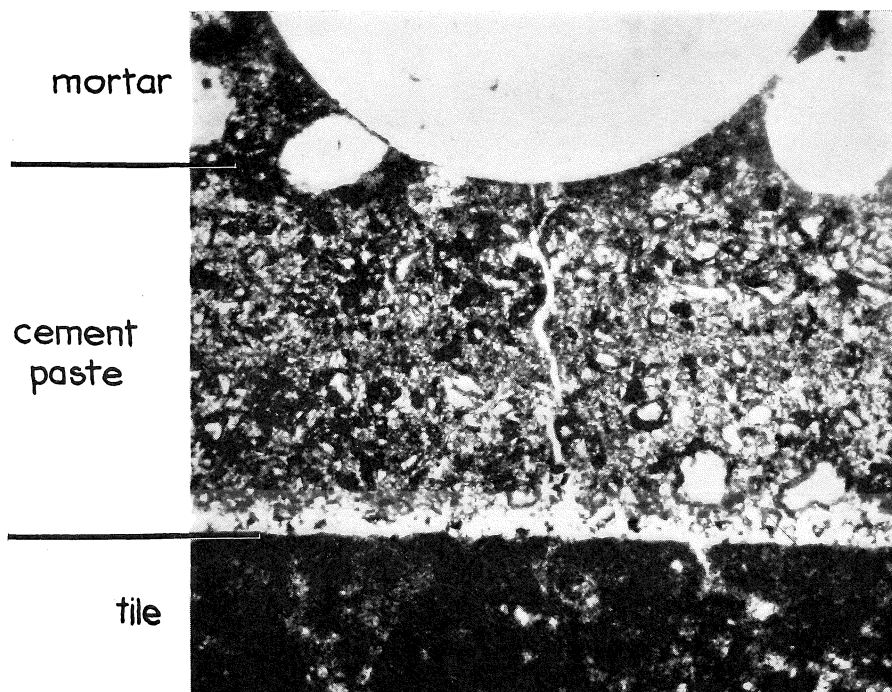
cement
paste

tile

Figure 88. Cracks in the coat of cement paste on an absorbent base. 75 ×.

mortar
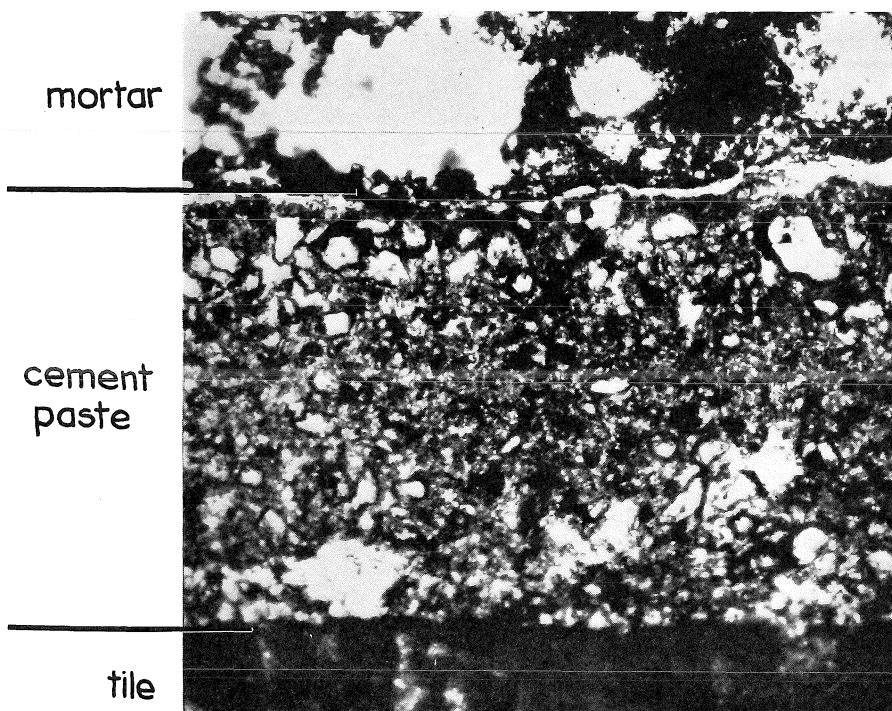
cement
paste

tile

Figure 89. The contact between the cement paste and the tile is good. The contact between the cement paste and the lime-cement mortar is not as good. 75 ×.

Figure 90. A film of cellulose derivative has formed in the contact zone between an absorbent base and a lime-cement mortar containing an admixture of cellulose derivative. 75 X.

mortar   film of cellulose derivative   tile
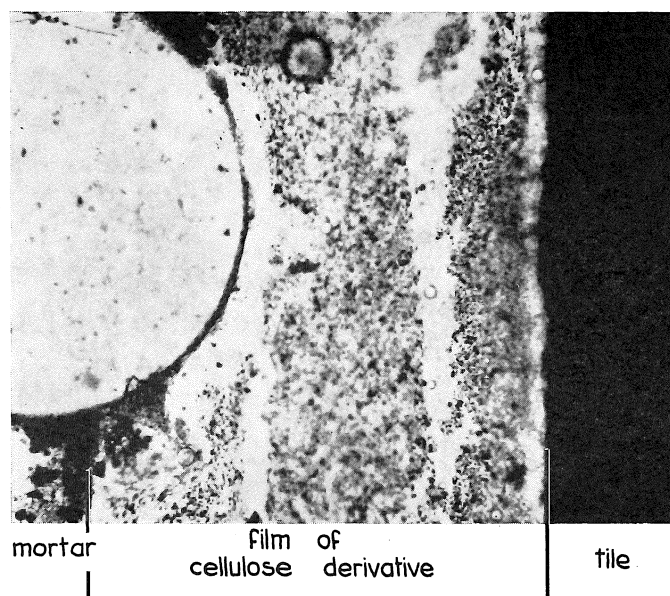
taken from leaky walls, Staley found proof that the leaks were mainly between mortar and brick. At the interface, hydration and carbonation of the matrix surrounding voids at the brickline are much further advanced, which suggest the effect of running water in this zone. In the microscope, the extent of the hydration and carbonation can be seen as a highly birefringent area. Staley considers that it is possible to determine in this way whether the voids have been sealed or open for the transport of water. Like Voss, Staley found examples of autogenous healing in lime-rich mortars. In a specimen 109 years old, Staley found a strip along the brick line with a mass of calcium carbonate crystals. There may have been a crack there at one time, now filled up.

Staley explains the circumstance that lime-rich mortars have an intimate and continuous bond and cement-rich mortars a tentacular bond in the following way. When a brick is laid in lime-rich mortar, the suction of the brick tends to densify and fill voids in the mortar at the interfacial layer. Lime particles which are in solution and suspension in the mixing water are carried to the surface of the brick and there deposited, leaving a layer of crystals at this plane which will carbonate and increase the strength and extent of the bond. The harsher-working cement-rich mortars do not possess the "fatness" necessary to gain full benefit from the suction of the brick since they

are non-plastic. The result is a tentacular contact by fingers of mortar adhering to the brick.

Conclusions

The studies made in the microscope of thin sections of the contact zone between mortar and base supplement the determinations of the tensile bond strength. A high value of tensile bond strength need not mean that the extent of the bond is also excellent. The use of the microscope provides the only means whereby the characteristics of the bond in existing walls can be studied. The investigations made by the PML of the adhesion of fresh mortar give some idea of whether bond strength will be good or not, but it is not until thin sections have been examined in the microscope that a satisfactory picture of the bond strength of the hard mortar can be obtained. On test pieces made in the laboratory, rather certain knowledge of the contact zones between mortar and base can be gained with one or two thin specimens. In order to measure the adhesion of a mortar, a very large number of thin specimens is required, for the variations in the samples used may be very great.

Thin sections examined at the PML have, on the whole, confirmed and complemented the results obtained in the determinations of the tensile bond strength and the studies of the adhesion of fresh mortar.

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BOND MECHANISM

The investigations made by the PML have shown that adhesion between mortar and base material is established at the same moment as the fresh mortar comes into contact with the base.

If the base is non-water absorbent, a film of water and binder is squeezed in the contact zone at the first moment.

If the base is water absorbent, water is drawn from the mortar.

Bond to non-water absorbent materials

When the fresh mortar comes into contact with a non-water absorbent material, a film of water and binder is pressed out in the contact zone. This phenomenon is illustrated here in a series of pictures, in which a plate of glass is laid on a mortar surface and compresses the mortar, whereby a fluid phase emerges from different places in the mortar and finally covers the whole contact surface (Fig. 91).

One important question in the study of adhesion is whether the adhesive wets the adherend. The adhesive in this case is binder paste, and the water the solvent. The PML has studied whether the surface tension of the water is altered by the addition of binder. The binder paste was filtered and the filtrate was dropped on to surfaces of glass and vitreous ceramic tiles. Compared with distilled water, the drops containing ions from the binder had largely the same contact angle (Fig. 92).

The results thus suggest that the water-binder film pressed out wets non-water absorbent surfaces of masonry materials.

When the water-binder film comes into contact with the non-water absorbent surface there is first a physical bonding by wetting, and then chemical bonding occurs successively. The results obtained show that the tensile bond strength to a perfectly smooth surface of a non-water absorbent material may be very high, in spite of the fact that no deep anchoring of the binder paste in the base has taken place.

The bond strength depends on the water/binder ratio.

If the water content of the binder paste increases, the tensile bond strength is impaired.

Bond to water absorbent materials

What happens in the contact zone when fresh mortar comes into contact with a water absorbent material is not, unfortunately, as easy to study as was possible with a non-water absorbent sheet of glass.

Painting porous surfaces stops the suction of the material. Kopinski (1960) has tried to explain what happens when a porous material is primed. He considers that the material used must penetrate into the capillaries of the base, and not remain like a film on the surface. Binders with small molecules, linseed oil, both boiled and raw, for example, can penetrate into the capillaries and stop further suction. Priming agents based on binders with large molecules cannot penetrate deep into the capillaries (Fig. 93).

The large molecules remain on the surface and partly block the openings of the capillaries. They are poorly anchored in the base material.

Experience of priming can be partly transferred to the problems of adhesion between mortar and water absorbent materials. Saturating a water absorbent material with water reduces its suction. This gives the same bond mechanism as with a non-water absorbent base material. The results of the measurements of the tensile bond strength suggest that this is the case.
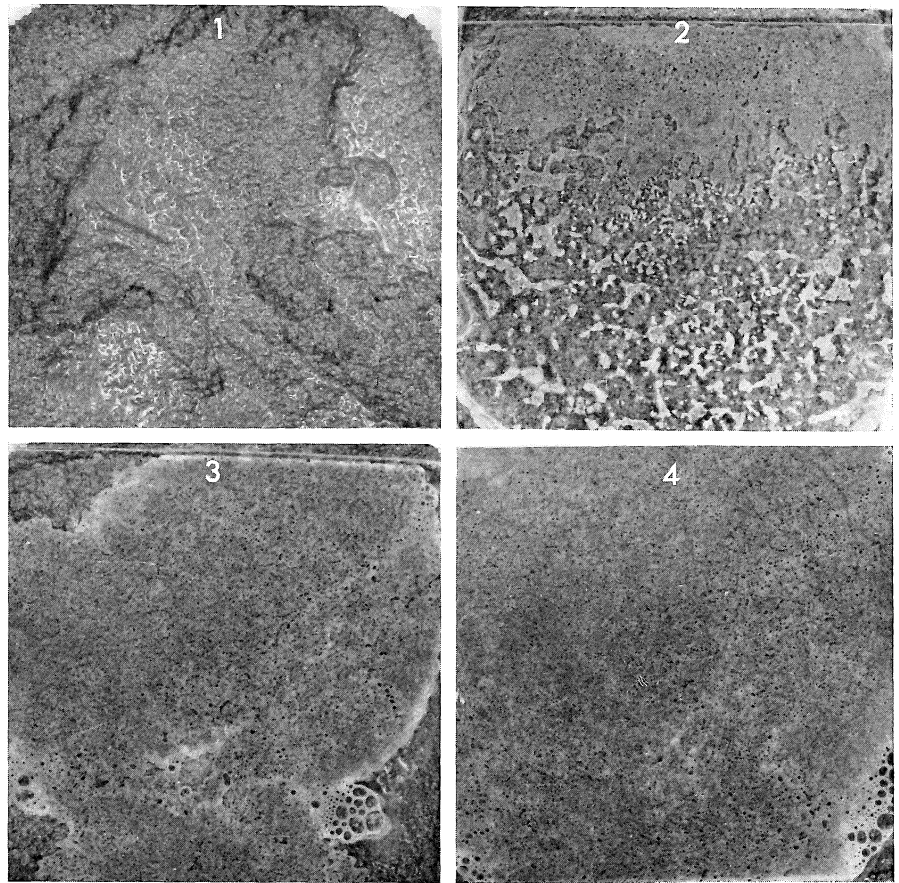
Figure 91. A film of water-binder grout successively spreads out when a glass plate is pressed on fresh mortar. This film gives good adhesion.
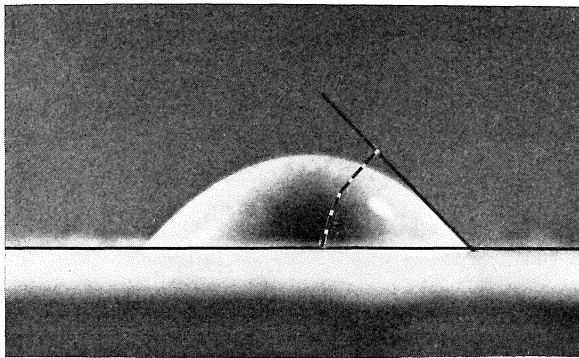
Figure 92. Drop of a filtered binder grout on a plate of glass.
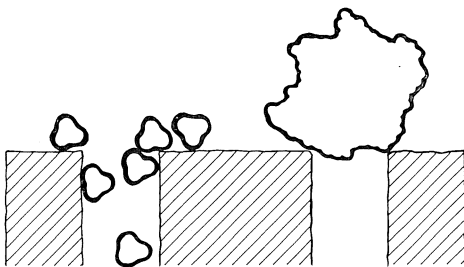
Figure 93. Binder with big molecules do not penetrate into the capillary openings. According to Kopinski (1960).

If a water absorbent material is treated with a cement-rich binder paste of low viscosity, the paste should, being very fluid, become firmly anchored in the porous base material. The water in the paste is drawn into the capillaries while the particles of binder suspended in the water are usually so large that they fasten in the capillary openings. In this way, the cement-rich binder paste adheres firmly to the base material. The water which penetrates into the base contains ions from the binder, but these ions probably do not give deep anchorage of the binder paste.

A fluid priming mortar, rich in cement, used instead of binder paste, a so-called spatterdash coat, also gives good adhesion to water absorbent base materials.

If the same high water/binder ratio as in the binder paste and the priming mortar is maintained, but more sand is added to the mortar, adhesion remains satisfactory.

A mortar with a high water/binder ratio usually adheres better to a water absorbent base material than a mortar with a lower water/binder ratio. The binder paste in a mortar with a high water/binder ratio is very fluid and is easily drawn to the contact

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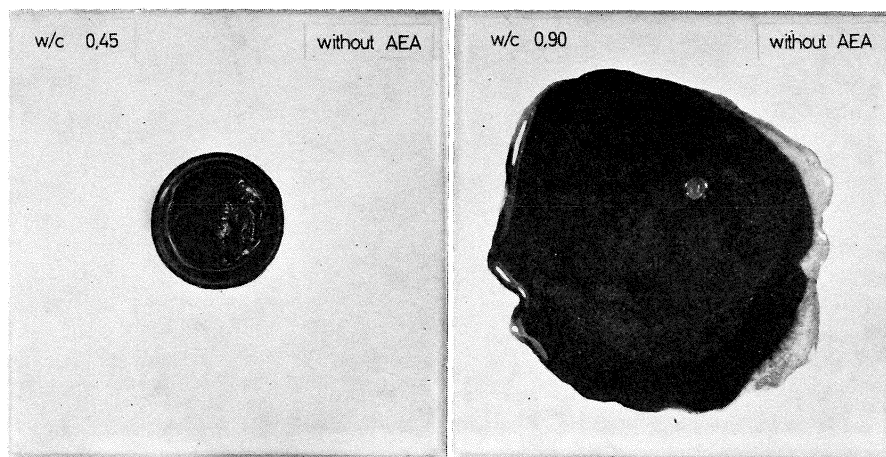
Figure 94. Binder pastes from cement mortar 1 :3 and 1 :6 on the glazed surface of whiteware wall tiles. The same amount of binder paste is poured on the tiles. The paste from cement mortar 1 :6 shows bleeding.

zone. Much of the water in the binder paste is drawn into the absorbent material, thus reducing the suction of this material.

Thus, a mortar with a high water/binder ratio must be chosen if good adhesion to a water absorbent material is required. A mortar with fluid consistence gives a higher water/binder ratio than in a stiffer mortar. The water/binder ratio rises with increased content of sand in the mortar.

A fine-grained binder needs more water than a coarse-grained. Thus lime requires more water than Portland cement. Lime mortars have a higher water/binder ratio than corresponding cement mortars. Additives such as air-entraining agents reduce the water/binder ratio.

Why is adhesion to a very absorbent base material poor in mortars with a volume ratio of 1 :3, such as are used traditionally? In my opinion, it may be due to the following.

Mortar of a ratio 1 :3 contains rather a lot of binder, and the water/binder ratio is low. The viscosity of the binder paste in the mortar is relatively high (Fig. 94). When the mortar is exposed to strong suction, the layer of mortar nearest the contact zone that loses water first. The initially low water/binder ratio becomes still lower, and may reach the critical point where this layer becomes a congealed layer unable to adhere to the base material. If, owing to loss of water, the binder paste stiffens, it will not be made plastic again by the water passing the contact zone from the parts of the mortar farther away. No interruption of the flow of water from the mortar to the base material seems to occur. Strong suction reduces the water/binder ratio to very low values for mortars with volume ratios of 1 :3 and 1 :6 (see Figs. 25, 45, and 48 B). Mortar 1 :6 has binder paste of low viscosity,

which facilitates the flow of water in the mortar, so that no drying of the binder paste occurs in the actual contact zone between mortar and base material.

Good water retentivity in a mortar has been considered essential by many research workers to ensure good adhesion to an absorbent base. The present investigation has shown that the best adhesion to a very absorbent base material is obtained with mortars from which water flows easily. This might give the impression that these results are contradictory, but this is not necessarily so. Good water retentivity, according to the ASTM method (see Fig. 67), means that the mortar is still plastic after one minute's suction.

If, for example, comparison is made between a cement mortar and a lime mortar which have lost the same amount of water by suction, the cement mortar may be quite stiff, while the lime mortar is still plastic. It is important for adhesion that the mortar remains plastic and does not stiffen too quickly when it loses water.

Influence of admixtures

Air-entraining agents

The tests have shown that air-entraining agents impair adhesion, particularly highly to water absorbent base materials. Air-entraining agents give rise to a large number of bubbles in the mortar. The walls of these bubbles, which consist of a thin film of binder, probably wet the base materials less effectively than the other parts of the binder paste. According to experience gained with gluing techniques, this should give poorer adhesion. The investigations have shown, however, that a binder paste containing bubbles from air-entraining agents gives the same tensile

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Figure 95. Cement mortar 1 :6 with air-entraining agent has given off about the same amount of water as cement mortar 1 :3 without air-entraining agent. The bad bond with mortar containing air-entraining agent depends probably on this fact.
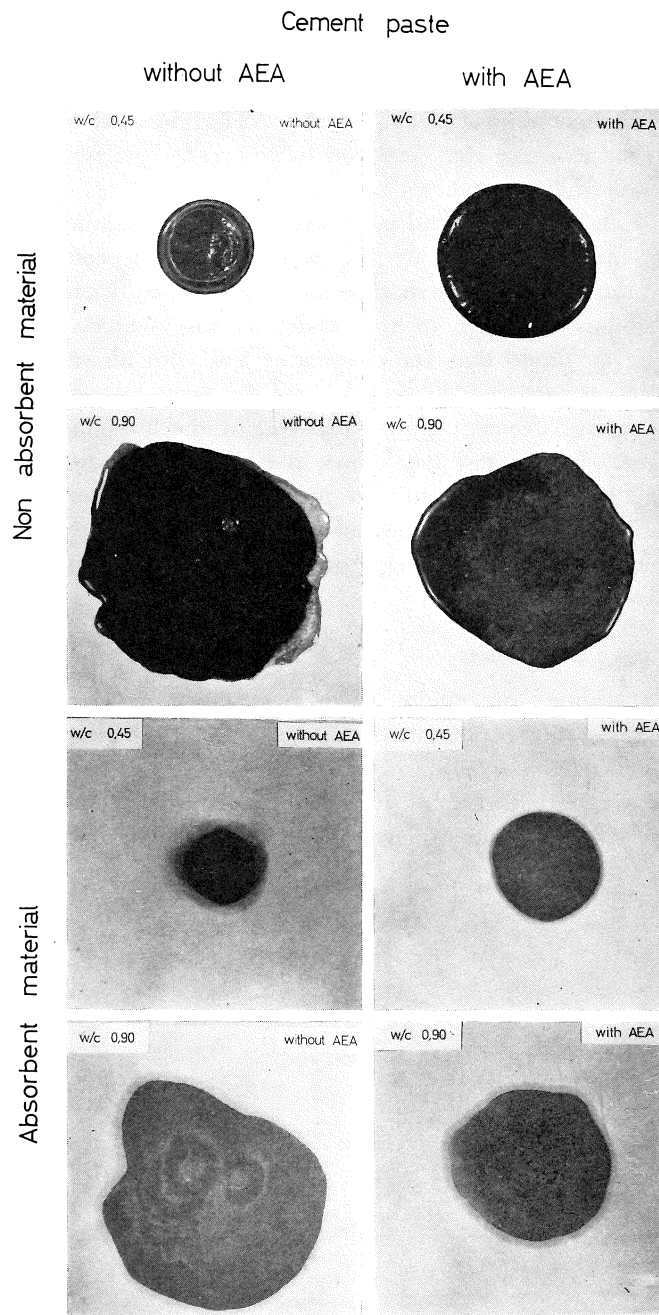
Figure 96. Comparisons between water/binder pastes in cement mortar 1 :3 and 1 :6 with and without air-entraining agent poured on wall tiles.

bond strength to a non-water absorbent material as a paste without such admixtures. This may be because the bubbles are pressed against the non-absorbent material, and the film of binder around the bubbles thus comes into better contact with the base material.

Mortars containing air-entraining agents always give poorer adhesion to a water absorbent base than equivalent mortars without such agents. This may be because the pressure against the bubbles is not the same with a water absorbent material as with a non-

absorbent base. It may also be because the air-entraining agents reduce the water/binder ratio of the mortar (Fig. 95). The admixture affects the water-retaining properties of the mortar, i.e. the mortar does not lose water to an absorbent base so easily. (Fig. 96.) The water retention values of mortar measured according to the ASTM method, are improved by adding air-entraining agents, which implies that the flow values of mortars are not changed very much when they are exposed to suction for one minute. In these cases,

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the retained plasticity does not seem to have contributed to better tensile bond strength. For this reason, care must be taken not to interpret good water retention according to the ASTM method as strong evidence that adhesion to absorbent base materials will be good.

I claim that the bad bond with mortars containing air-entraining agent to absorbent material depends on the fact that these mortars do not give off sufficient amounts of water to the absorbent base material. Fig. 95 shows tha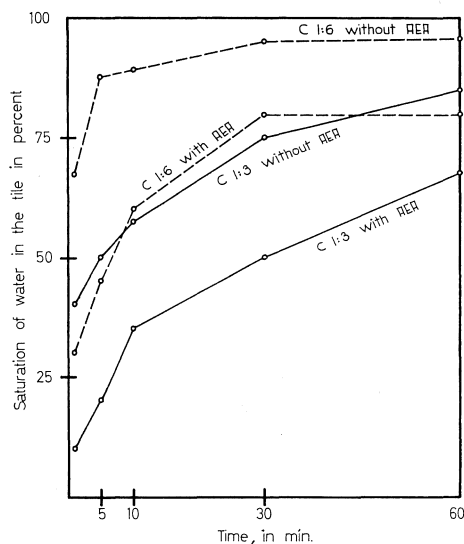t cement mortar 1:6 with air-entraining agent has given off about the same amount of water as cement mortar 1:3 without air-entraining agent. Earlier test has shown that this mortar has bad bond to absorbent base materials. Cement mortar 1:3 with air-entraining agent has less loss of water and may thus give a very bad bond to an absorbent base material.

Viscosity modifiers

An addition of cellulose derivative, which increases the viscosity of the mixing water, has a beneficial effect on the adhesion of mortars to water absorbent base materials. This is due to the circumstance that the mixing water is given such viscosity that only with difficulty it can be absorbed into a strongly absorbent base material. It is also feasible that the large cellulose derivative molecules are drawn to the mouths of the capillaries and close them, thus reducing the suction.

The addition of cellulose derivatives makes mortars sticky, which gives the fresh mortar good adhesion. The particles of binder suspended in the viscous mixing water come into intimate contact with the absorbent base material. Cellulose derivatives prevent a too rapid drying of the contact zone. The danger with this type of admixture is that a film of cellulose derivative may be formed between the mortar and the base material. This would be very risky, since cellulose derivatives are soluble in water. Studies in the microscope have shown that such a film may be formed, but the tensile bond strengths suggest that the inorganic binders have taken over the bonding properties of the hardened mortar.

Cellulose derivatives do not improve the adhesion of mortars to non-water absorbent base materials.

The specific water retaining effect due to cellulose derivatives makes this admixture suitable for mortars that are to be used in thin layers, for without this additive the thin layers of mortar would soon dry up.

CONCLUSIONS AND RECOMMENDATIONS

The studies were designed as comparisons between different combinations of mortar and base materials.

In order to obtain a good mortar bond, two lines may be followed. The purpose of the investigation was to find a single mortar that would suit all combinations of mortar and base material. This is the first line. The other is to adjust the absorbent properties of the base material to the mortar used.

Mortar with good bond independent of the suction of the base material

Studies made at the PML have shown that there are mortars with good bond to both absorbent and non-absorbent base materials. In the first place the correct relation between binder and sand must be chosen, and in the second place the correct composition of the binder. Choice of admixture also affects the results.

Binder

The binders used in the traditional mortars—lime and Portland cement—may give good adhesion to the most common masonry units, such as clay-brick, sand-lime brick, concrete and aerated concrete. Lime mortar, which was formerly used exclusively, usually gives good adhesion, but the tensile bond strength is far too low for the rapid building of today. Portland cement as binder in mortar may give very high values of tensile bond strength, and the extent of the bond may be good, too. But cement mortar does not have the workability a bricklayer demands. In most countries, a mixture of lime and cement of the volume ratio 2:1 or 1:1 is used as binder in mortar.

Masonry cement without lime but with finely ground limestone requires a plasticity improver to ensure satisfactory workability. This agent usually has a deteriorating effect on the tensile bond strength.

Binder/sand proportion

Studies made in different parts of the world on mortar with a ratio of 1:3 by weight between binder and sand have shown clearly that good adhesion is obtained to slightly absorbent base materials, while adhesion to highly absorbent base materials is usually poor. Investigations made at the PML have shown that mortar 1:6 by volume gives good adhesion to both water absorbent and non-water absorbent base materials. This composition gives a high water/binder ratio, which contributes to good adhesion to absorbent base materials. It may be difficult to work with a mortar 1:6 by volume unless the sand is very well graded. This mortar is seldom found on building sites. For this reason, leaner mortars than 1:5 by volume can probably not be recommended.

Sand grading

The sand to be used in mortar should be well graded, primarily to make the mortar workable, but also to improve its strength. A single-grain sand may, however, give mortar with good adhesion to absorbent base materials, but is not recommended, for single-grain sand gives a porous mortar with poor resistance to water penetration.

Admixtures

Additives in the form of air-entraining agents improve the workability and frost resistance of mortars, but they usually impair the adhesion of the mortar to absorbent base materials.

Viscosity modifiers such as cellulose derivatives increase the stickiness of the fresh mortar. They improve adhesion to water absorbent base materials.

Adhesion to non-water absorbent materials is not improved, however.

Universal mortar for good adhesion

In order to obtain good adhesion to both absorbent and non-absorbent materials, a binder consisting of hydrated lime and Portland cement, in which, to ensure satisfactory bond strength, the cement should not be less than 50 per cent of the weight of the binder, and the lime content should not be less than 25 per cent, should be chosen.

The amount of sand in the mortar should be as great as possible in order to obtain a high water/binder ratio. The relation between binder and sand should be between 1:5 and 1:6 by volume. Thus the composition of the universal mortar should be LC 50/50/800—LC 25/75/700.

The mortar should not contain air-entraining agents, which, as a rule, reduce the tensile bond strength. The consistence of the mortar should be as liquid as the working technique allows.

Mortars of these compositions may be used for most purposes. If greater strength is required in brickwork than can be obtained with these mortars richer in binder or possibly richer in cement must be used. Tensile bond strength to non-absorbent base materials will then be somewhat higher, while tensile bond strength to absorbent base materials is impaired. This deterioration of tensile bond strength can be avoided by reducing the suction of the base material.

Improvement of bond by reducing suction of base material

The expressions "slightly absorbent" and "strongly absorbent" base materials are often used without any definition of their meaning. The best way of determining whether a material has capillary suction which may impair the adhesion of mortar is to test the two materials together. The PML has shown that it is possible at a very early stage to determine whether adhesion will be good or not. The test is made in the following way. The base material is covered with a piece of gauze, after which the fresh mortar is applied. One or two minutes later the fresh mortar is removed by the help of the gauze. If only very slight traces of the mortar can be seen on the surface of the base material, adhesion will be poor. Ordinary masonry mortar with a ratio of 1:3 shows signs of poor adhesion to most base materials except concrete and vitreous ceramic materials.
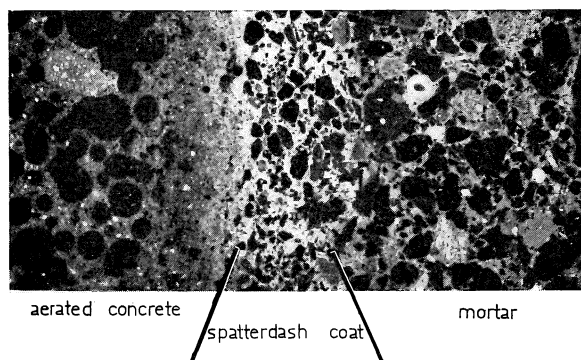
Figure 97. A spatterdash coat nearest the surface of aerated concrete gives a better bond between the mortar and the base material. 10 ×.

Wetting the base material

Water absorbent material may be saturated with water so that capillary suction is reduced. In this way a less-water absorbent material can be obtained, and good adhesion ensured with mortar 1:3 by volume. Rapid immersion in water or brushing over with water is usually insufficient to cause any marked change in the capillary suction. On the other hand, saturation must not be carried so far that a film of water is formed on the surface of the base material.

Water treatment of clay bricks increases the risk of efflorescence on the surfaces of the bricks.

Treatment with cement mortar or cement paste

When aerated concrete is to be rendered, it should be coated first with a spatterdash coat of fluid cement-rich mortar. This coat improves adhesion between the base material and the actual rendering mortar (Fig. 97). The thin, water-rich cement mortar adheres well to the absorbent aerated concrete, and alters, to a certain extent, the suction of the aerated concrete. It also gives a better key for the next coat of mortar.

Rendering a water absorbent material with a thin cement paste has been shown to improve the adhesion of a mortar which, without this treatment, would have stuck badly to the water absorbent material. This mode of procedure is sometimes used when wall tiles are to be set, and the absorbent base is primed with the liquid part of the mortar.

When material is used to which adhesion with mortars recommended traditionally is poor, pretreatment of the base material with a thin cement paste may be resorted to. To obtain the best adhesion, this coat of cement must dry before the next layer is applied.

SUMMARY

Mortar bond, i.e. adhesion between mortar and different base materials, has been studied in a series of investigations in order to elucidate the effects of various factors on mortar bond, and to establish a basis for practical recommendations for obtaining good bond between mortar and masonry units. The studies were made at the Plaster and Mortar Laboratory in Malmö during the years 1955—66.

Since capillary suction in the base material is important for the adhesion of the mortar, the investigations included adhesion to water absorbent and non-water absorbent base materials.

The binder paste in a mortar causes the actual adhesion, the sand is mainly only ballast which, however, affects the properties of the mortar.

The first phase of the investigations was concerned with the adhesion of the binder paste to non-water absorbent and water absorbent backings. In the case of non-water absorbent materials, adhesion declines with rising content of water in the binder paste. The situation is the opposite with water absorbent materials. Adhesion improves with rising content of water in the binder paste.

In most cases, adhesion was measured as the tensile bond strength with the help of Hinderson's apparatus (see Fig. 7).

The adhesion of fresh mortar was studied as follows. A piece of gauze was placed between the mortar and the base material, and after one or two minutes the mortar was removed with the help of the gauze, and the appearance of the base material was studied (see Figs. 12 and 13). Agreement is good between the adhesion of the fresh and the hardened mortar (see Fig. 36). Thus, adhesion seems to be decided when the mortar is applied.

The contact zone between the mortar and the base material was also studied in the microscope. Thin specimens and polished specimens of various combinations of mortar and base material were studied.

Attempts were made to elucidate step by step how the composition of the fresh mortar affects adhesion. The influence of binder type, water/binder ratio, binder/sand ratio and sand grading was studied. Each section of the report is followed by references to published literature.

The maximum bond strength of a mortar is greatly dependent on the strength of the mortar itself. High bond strength can be obtained with mortar with a high content of Portland cement. The bond area, however, is not dependent on the strength of the mortar. A low bond strength need not necessarily mean that adhesion is poor in itself.

The ratio between binder and sand affects the bond strength. With a non-water absorbent base material, the bond strength is impaired when the amount of sand in the mortar is increased and the water/binder ratio rises in consequence. With an absorbent base material, the bond strength is usually improved when the amount of sand in the mortar increases. The binder/sand ratio and the water/binder ratio are intimately related.

Sand grading affects the water/binder ratio. A single-grain sand gives a higher water/binder ratio than a well-graded sand. The bond strength to absorbent base materials rises with rising water/binder ratio. A single-grain sand, which might be unsatisfactory from other aspects for use in mortar, may give a mortar with satisfactory bond strength to absorbent materials.

The investigations have shown that the mortars used traditionally in the volume ratio 1:3 often have poor adhesion to very absorbent base materials. The results attained suggest that the tensile bond strength of these mortars increases if the base material is

wetted to reduce suction. Wetting has some drawbacks, however. It means extra work, and bricklaying will be made rather more difficult by the low suction of the base material. Wetting also involves greater risk of efflorescence.

Adhesion to absorbent materials can be improved by treating their surfaces with a thin, cement-rich coat, which may be dry before the next coat is applied. A spatterdash coat consisting of a fluid, cement-rich mortar improves the adhesion of rendering to both absorbent and non-absorbent surfaces.

Admixtures in the mortar may affect adhesion.

The addition of air-entraining agents reduces the adhesion of the mortar to both non-absorbent and absorbent materials, but this reduction is especially noticeable on highly absorbent materials.

Viscosity modifiers in the form of cellulose derivatives improve adhesion to absorbent bases. These additives give the mortar a stickiness which may help to improve the bond strength. The amount of additive is in the region of 3 per cent of the weight of the mixing water. Viscosity improvers do not seem to improve the bond strength to non-absorbent materials.

These admixtures give mortar special water retaining properties which delay the drying of the mortar and make possible new methods of work with thin layers of mortar. In traditional mortars, these additives delay the stiffening of the mortar, and thus slow up the work.

The investigations have shown that there are mortars which can be used regardless of the suction of the base materials. Mortar of a ratio of 1:5 and 1:6 by volume between binder and sand have been shown to give the best results. To obtain a satisfactory tensile bond strength, the content of Portland cement must be between 50 and 75 per cent by weight. To give the mortar good plasticity and elasticity, the rest of the binder may consist of hydrated lime. The sand must be well graded. Admixtures such as air-entraining agents, or other types which reduce the tensile bond strength, should not be used.

Working the mortar so that contact between mortar and base material is improved increases the tensile bond strength. Working techniques may have great influence on the mortar bond.

The durability of the bond depends greatly on what happens during the first phase when the mortar is drying and hardening. The strength of the mortar usually improves with time, but adhesion may gradually decline on account of the stresses arising in the contact zone owing to the longitudinal changes taking place in the different materials as a consequence of variations in humidity and temperature.

APPENDIX

The following important conclusions have been drawn from the present investigations.

1. To non-water absorbent materials the bond decreases with increasing water/binder ratio.

2. To water absorbent materials the bond increases with increasing water/binder ratio.

The conclusions are based on the bond of the fresh mortar and the tensile bond strength of the hardened mortar. Studies in microscope of the contact zone between mortar and base material have confirmed the results.

In this section 4 tables have been chosen for statistical analysis of the experimental data. These examples suggest what kinds of statistical considerations precede the conclusions drawn from the tables.

All the tests used here can be found in ordinary textbooks of statistical analysis. Throughout the analysis the asumption has been made that the samples come from normal populations. This seems quite reasonable, considering the nature of the experiments, and in fact, rejecting this hypothesis would normally require more observations than the present experiments afford. Most of the tests used, assume that the samples come from distributions with equal variances, and Bartlett's test has been applied to this hypothesis.

Test of table 6

In this experiment the tensile bond strength between lime-cement paste and glass was observed, and the factor studied was the water-binder ratio. The following result was obtained:

Water/binder ratio	Tensile bond strength, kp/cm^2				
1.00	2.84	2.67	2.93	2.67	3.38
1.25	1.78	2.13	1.78	1.95	2.13
1.50	1.24	1.07	0.89	1.07	0.62

Assuming the three samples have normal distributions, we have to test the equality of the variances, before we can use the analysis-of-variance. Bartlett's test gave no significant deviation, since the test-statistic is $d = 0.47$ and the hypothesis would be rejected only if d is greater than $F_{0.05}(2,106) = 3.09$. Hence we assume homogeneity of the variances. Testing the hypothesis that all the means are equal gives us the following analysis-of-variance table:

	Sum of squares	df	Mean square	F ratio
Means	9.2168	2	4.6084	$F = \dfrac{4.608}{0.057} = 80.7$
Within	0.6847	12	0.0571	$F_{0.005}(2,12) = 8.51$
Total	9.9015	14		

Since the result is highly significant, the hypothesis of equal means must be rejected.

The 95 per cent confidence intervals for the means are the following:

	1.00	(2.71,	3.09)
Water/binder ratio	1.25	(1.76,	2.14)
	1.50	(0.79,	1.17)

With great confidence we can state:

The tensile bond strength decreases with increasing water-binder ratio.

Test of table 20

In this experiment the tensile bond strength between a lime-cement mortar and a glazed tile surface was observed at three different levels of the water/binder ratio.

Mortar	Water/binder ratio	Tensile bond strength, kp/cm²				
LC 50/50/450	1.25	2.31	3.02	2.67	2.49	2.31
LC 50/50/650	1.50	2.40	2.13	1.95	1.95	1.78
LC 50/50/950	1.75	1.07	1.54	1.12	0.71	0.76

We assume normality of the sample distributions and begin with the test of equal variances. The test statistic in Bartlett's test is $d = 0.30$ and testing on the significance level 0.05 the hypothesis is to be rejected if d is greater than $F_{0.05}$ (2,324) = 3.06. Hence we assume the variances to be equal.

Testing the hypothesis that all the means are equal gives us the following analysis-of-variance table:

	Sum of squares	df	Mean square	F ratio
Means	5.9712	2	2.9856	$F = \dfrac{2.986}{0.085} = 35.1$
Within	1.0197	12	0.0850	$F_{0.005}(2,12) = 8.51$
Total	6.9909	14		

With a confidence greater than 99.95 per cent we reject the hypothesis that the means are equal.

The 95 per cent confidence intervals for the means indicate that bond strength decrease when water/binder ratio increases:

	1.25	(2.33,	2.79)
Water/binder ratio	1.50	(1.81,	2.27)
	1.75	(0.81,	1.27)

Test of table 36

In this experiment two kinds of aerated concrete were rendered with and without a spatterdash coat and the bond was observed.

Aerated concrete	Tensile bond strength, kp/cm²	
	Without spatterdash coat	With spatterdash coat
Siporex 0.4	1.7	3.4
	1.2	3.2
	2.2	1.7
	1.1	2.8
	1.0	3.0
Siporex 0.5	1.4	3.0
	1.3	2.8
	1.5	2.8
	0.8	2.6
	1.4	3.2
	1.2	2.6

Assuming normality, we use Bartlett's test and get the statistic $d = 2.48$, which is less than $F_{0.05}$ (3.00) = = 2.60. Hence we do not reject the hypothesis of variance-homogeneity.

We can now use the analysis-of-variance, and we get the following table:

	Sum of squares	df	Mean square	F ratio
Columns	0.2400	1	0.2400	
Rows	13.2017	1	13.2017	$F = \dfrac{13.201}{0.223} = 58.7$
Interaction	0.0416	1	0.0416	$F = \dfrac{0.0416}{0.2228} = 0.19$
Within	4.4567	20	0.2228	$F_{0.05}(1,20) = 4.35$
Total	17.9400	23		

Since 0.19 is smaller than $F_{0.05}$ (1,20) we assume that there is no interaction between the row and the column factors.

This permits us to test the hypothesis that "without spatterdash coat" and "with spatterdash coat" give the same effect to the bond.

Since 58.7 is considerably greater than $F_{0.05}$ (1,20) we have a highly significant deviation from this hypothesis, and therefore we can state that a spatterdash coat improves the bond.

Test of table 44

In this experiment the effect of air-entraining agent was observed.

	Bond strength, kp/cm²							
	With AEA				Without AEA			
Brick dry								
LC 50/50/475	0.4	0.0	0.6	1.0	4.1	3.9	1.8	1.9
LC 50/50/925	1.5	2.0	1.3	1.4	7.1	7.6	5.2	6.0
Aerated concrete								
LC 50/50/475	0.3	0.2	0.4	0.3	1.0	1.8	0.8	0.7
LC 50/50/925	0.2	0.2	0.1	0.2	3.0	1.9	2.4	2.5

Again we assume that the observations from each sample are normally distributed.

Barlett's test gave a significant deviation from the hypothesis of homogeneity of the variances. The test statistic is 2.68 and this is greater than $F_{0.05}$ (7,585) = = 2.05.

Therefore we do not proceed to the analysis-of-variance to study the effect of AEA, but perform four t-tests with the combinations.
Brick-LC 50/50/475, Brick-LC 50/50/925, Aerated concrete-LC 50/50/475 and Aerated concrete-LC 50/50/925. (These tests do not assume equal variances, and therefore they are not identical with the standard t-test.)

Brick-LC 50/50/475.
The two samples are normally distributed and we test the hypothesis that the mean of "with AEA" is greater than the mean of "without AEA". The test statistics is 3.69 and is greater than $t_{0.05}$ (4) = 2.13 and therefore we have to reject the above hypothesis.

The same result was obtained for the remaining three tests:

Brick-LC 50/50/925.
Test statistic = 8.80 is greater than $t_{0.05}$ (4).
Aerated concrete-LC 50/50/475.
Test statistic = 3.08 is greater than $t_{0.05}$ (3) = 2.35.
Aerated concrete-LC 50/50/925.
Test statistic = 26.9 is greater than $t_{0.05}$ (4).

With great confidence we can state that air-entraining agents in lime-cement mortar deteriorate the bond.

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