Physical and Chemical Interactions of Brick Masonry Materials

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Abstract. Brickwork masonry construction is an ancient craft, but the introduction of newer materials and tighter design specifications has led to potential problems. The quality of individual masonry components is controlled by various Standards which include physical and chemical tests. However, these components often show subtle interactions within the wall, which may alter their properties significantly. This paper considers a number of physical and chemical interactions which can have adverse effects on the aesthetic or structural aspects of masonry. These effects should be recognised when drawing up building specifications and Codes of Practice.

1 INTRODUCTION

The main emphasis of this paper is on brick/mortar interactions, but plasters, paints, renderings and cavity insulating materials are also briefly considered.

Research on mortar appears to have been a neglected field in comparison with concrete research, for example. However, a great deal of new work on mortars has been initiated in recent years. The following report reviews the "state of the art" at the present time.

Many of the author's observations are based on experience of the behaviour of brickwork in the United Kingdom, whose climate can include hot, dry summer spells and driving rain plus freeze/thaw cycling during winter months. It will be shown that the weather conditions prevailing at the time of building can have an important influence on the physical properties of the masonry components. This in turn may lead to such problems as: efflorescence on facing brickwork or on internal plastered walls; reduction of bond between bricks and mortar or rendering; frost-failure of mortars; chemical attack on mortar, renderings and plaster; paint failure.

Virtually all the interactions considered are promoted by WATER. During the long evolution of brick masonry, it became recognised that good building design should incorporate features to shed rainwater from structures in order to protect the brickwork by avoiding saturation of the walls. However, some of these lessons were apparently forgotten in more recent years and many costly failures resulted. It is hoped that the specific effects described in the following sections will help to emphasise the necessity for care in the design of brickwork and in the specification and use of the individual building materials.

If brickwork is to maintain the supremacy which it holds in many fields of building, it will be more than ever necessary to understand potential problems and to devise the appropriate material Standards and Codes of Practice to ensure sound, economic buildings with the low maintenance costs traditionally conferred by brick masonry.

2 PHYSICAL INTERACTIONS

2.1 Bricks and Mortar

2.1.1. Water:cement ratio of mortar

Dry porous bricks rapidly absorb a large proportion of water from mortar during the bricklaying operation. A joint research programme carried out by a number of British Brickmakers showed that typically around 50% of the water was removed from the mortar bed after 15 minutes, and about 70% after 6 hours (Figure 1). This 6-hour take-up was practically independent of the brick absorption value or suction rate. In practice, the bricklayer makes some allowance for this factor by adjusting the water content of the mortar (consistency) to maintain workability. However, site control is variable and it should be noted that mortar cubes cast in metal moulds and used for quality control checks will have higher water:cement ratios than mortar in the walls.

Conversely, the absorption rate of <u>wet</u> bricks is very much reduced, and unless brick stacks are protected from rain on site, they may take up large and variable amounts of water. In extreme cases when the bricks are almost saturated, the mortar does not stiffen so readily, and in winter building conditions is prone to frost damage. Saturated brickwork is also liable to

give efflorescence problems, as discussed later.

In summary, the water:cement ratio of the mortar in the wall is markedly affected by the physical state of the bricks, and particularly by their water content. It is recognised that the water:cement ratio of the mix has an important bearing on the subsequent strength of the mortar.

2.1.2. Bond strength between brick and mortar

Laboratory experiments with brick couplets and triplets jointed with mortar have demonstrated that maximum bond strength is obtained at an optimum initial-suction rate of the bricks. In most cases this optimum value does not coincide with the high "natural" initial suction rate of the dry bricks nor with total (or near-total) saturation. In order to achieve the best bond-strength, it is necessary on site to partially wet dry bricks in a controlled manner and to prevent by suitable storage conditions, saturation or near-saturation of the bricks.

Another possible approach is the incorporation of water-retentive additives in the mortar mix, a procedure which has shown some promise in laboratory trials.

2.1.3 Pore-size distribution in mortar

During the winter periods of 1976/7 and 1978/9, Britain experienced severe weather conditions characterised by a high frost incidence allied with frequent periods of heavy rainfall.[2] Widespread frost-failures of mortar were reported in addition to some brick spalling. The pore-size distribution within ceramic bodies is an important factor in determining their frost resistance, so it was decided to measure the same parameter in a range of mortar compositions. Samples of various mortars were cast into cubes (using metal moulds) and mortar from the same batches was used to construct small panels of brickwork. After 30 days curing time, mortar specimens were cut out of the bed-joints of the panels and together with the cube samples were tested for total porosity, density and pore size distribution. Results of these are shown in Table 1 and Figure 2.

There were some differences between the various mortar mixes, but the outstanding difference was between specimens cast in moulds and mortar removed from the brickwork panels. The latter showed a much higher proportion of coarse pores in all cases, which should be an indication of greater frost resistance. Interestingly, the total absorption of the two classes of mortar was very similar.

The inference to be drawn from these results is very important - if bricks are saturated or near-saturated with water at the time of building, the mortar can be expected to have pore properties similar to those of the specimens cast in steel moulds - and therefore to be less frost-resistant. Subsequent laboratory tests conducted by LBC tend to confirm this proposition. Small panels were built with Fletton bricks (average 24-hour absorption about 18%) using (a) dry bricks and (b) soaked bricks. The mortar employed was 1:1:6 Portland cement:lime:sand and the panels were placed in a deep-freeze cabinet a few hours after building, and frozen overnight. Surprisingly the green mortar in the panels built with dry bricks showed no damage, whereas the joints in the panels incorporating near-saturated bricks displayed typical frost damage i.e. cracking at the brick-mortar interface and spalling of the surface layer of mortar (Figure 3).

2.2. Renderings on Brickwork

The interactions described above for bricks and mortar apply similarly to cement renderings. It is particularly necessary to achieve the correct suction rate for the backing brickwork and again this is primarily a question

of partially wetting the walls before applying the rendering. Too wet a background may result in sliding of the cementitious mix, and poor bond strength. Rendering onto a hot, dry background can also lead to an impaired bond and results in a rapid shrinkage of the rendering coat which frequantly causes hairline craze-cracking. Apart from the undesirable aesthetic appearance of crazed renderings, fine cracks may subsequently allow ingress of rainwater which can lead to structural problems.

2.3 Internal Plaster on Brickwork

Modern gypsum-based plasters tolerate a wide range of background conditions and will set hard even when applied to near-saturated brickwork. However, in the latter case the wet walls feed water through the set plaster and this frequently results in pattern staining on the plaster surface under these conditions. Soluble salts derived from bricks, mortar and the plaster itself form deposits of efflorescence on the surface, which can lead to serious and expensive delays on the decoration of internal walls.

2.4 Paint on Brick Masonry

The main requirement for the successful decoration of fairfaced, rendered or plastered brickwork is a dry background. This is difficult to achieve in new buildings, since the moisture of construction may take up to one year before completely drying out. Interior emulsion paints and many modern exterior masonry paints are more tolerant of moisture than are solvent-thinned oil paints. However trapped moisture can lead to blistering of the paint film and loss of bond.

Painted exterior walls are liable to build up higher moisture levels than unpainted walls due to hindrance of evaporation and under conditions of severe exposure this can lead to serious frost-spalling of the underlying brickwork.

3 CHEMICAL INTERACTIONS

3.1 Bricks and Mortar

3.1.1. Efflorescence problems

Simple cases of efflorescence on facing brickwork may be due to the transfer of soluble salts from the bricks or mortar to the surface of the wall on drying. Hence the soluble-salt levels in the bricks may give some guidance on their liability to produce efflorescence as may the "efflorescence test" included in some National Standards for bricks. However many cases of efflorescence have been observed on exterior facing brickwork when the bricks concerned were known to contain virtually none of the more soluble salts (sulphate of magnesium, sodium and potassium). They did contain some calcium sulphate, which is so sparingly soluble that it produces no efflorescence when the bricks are saturated with distilled water and allowed to dry from one surface (as in the efflorescence test described in British Standard 3921) (3)

The cases of efflorescence noted were associated with very wet building conditions - usually during the winter - and on investigation the salts were found to be composed almost entirely of sodium and potassium sulphates. The only logical source of the alkali-metal cations was the Portland cement in the mortar and laboratory tests in which an aqueous extract of cement was fed through bricks reproduced the efflorescence (Figure 4). Alkalies in Portland cement are extracted mainly in the form of hydroxides, although these react with atmospheric carbon dioxide to form sodium and potassium carbonates. A solution of sodium carbonate was fed through a Fletton brick (containing only calcium sulphate as a soluble salt) and as the solution passed through the brick, a base-exchange reaction occurred:-

$$Na_2CO_3 + CaSO_4 \rightarrow Na_2SO_4 + CaCO_3 \downarrow$$

A heavy layer of white salts formed on the surface of the brick which on analysis proved to be almost pure sodium sulphate.

Most clay bricks contain some calcium sulphate and all Portland cements contain about one percent of soluble alkali (Na_2O equivalent) so this exchange reaction is always likely. In practice it is necessary to prevent undue wetness of brickwork during building to prevent this type of efflorescence.

3.1.2. Chemical attack on mortar

The best known type of chemical attack on mortars is sulphation which may result from the ingress of soluble salts into the joints (the salts may be derived from bricks, groundwater or other sources). In the "classical" form of sulphation[4] the sulphates react with tricalcium aluminate - one of the constituents of Portland cement - to form sulphoaluminates:-

$$3\,CaO.\,Al_2O_3\,12H_2O + 3(CaSO_4.2H_2O) + 13\,H_2O \rightarrow 3CaO.Al_2O_3\,3\,CaSO_4\,31\,H_2O$$
(Ettringite)

or $3CaO.Al_2O_3.12\,H_2O + CaSO_4 \rightarrow 3CaO.Al_2O_3\,CaSO_4.\,12H_2O$ (Calcium monosulphoaluminate).

The reaction products occupy a larger volume than the original reactants which may result in expansion, cracking and disintegration of the mortar joints.

Another type of reaction sometimes termed "acidic" sulphate attack[5] occurs when soluble sulphates react with calcium hydroxide present in the mortar, forming calcium sulphate:-

$$Ca(OH)_2 + SO_4^{2-} + 2H_2O \rightarrow CaSO_4\,2H_2O + 2(OH)^-$$

This is also an expansive reaction which can cause erosion and general softening of the mortar.

Magnesium sulphate is a particularly damaging salt and reacts rapidly with tricalcium aluminate or with calcium hydroxide as described above. Additionally, magnesium sulphate may react with the ferrite phase, or even with the calcium silicate hydrate phase responsible for most of the strength developed by Portland cement pastes:-

$$C\text{-}S\text{-}H + MgSO_4 \xrightarrow{H_2O} CaSO_4.2H_2O + SiO_2\,aq + Mg\,(OH)_2$$

This form of attack can cause disintegration of set mortars.

3.1.3. Crystallisation forces

The previous section dealt with chemical reactions of soluble salts with compounds derived from Portland cement. However, in at least one case expansion and cracking of mortar can be produced by what appears to be simple forces of crystallisation (akin to freeze-thaw action). The phenomenon was observed in the London Brick Company Laboratories during an investigation into the effects of individual sulphates on mortars and plasters. Salt solutions were wick-fed into the underside of mortar (or plaster) plates and the nature of the efflorescence produced was noted (Figure 5) POTASSIUM sulphate caused swelling, curling and deep cracks through the test pieces (Figure 6). Similar tests were carried out using potassium hydroxide solution but in this case only the gypsum-based plaster specimens cracked, implying conversion of potassium hydroxide to potassium sulphate.

Further tests were conducted by feeding solutions of sodium, potassium and magnesium sulphate into gypsum plaster and sand/lime pats cast into Le Chatelier moulds and allowed to harden. The expansive effects were measured over a period of one month (Figure 7).

Potassium sulphate caused the greatest expansion - markedly more than magnesium sulphate even. This is believed to be an important finding, and I am unaware of the publication of any similar observations. Some workers have noted potentially damaging crystallisation forces caused by changes in the levels of water of crystallisation in salts,[6] but since potassium sulphate includes NO water in its crystal structure a different mechanism must be involved.

3.1.4. Iron staining of brickwork

This problem is usually seen on comparatively new brickwork which has become very wet during construction. It is caused by the leaching of small amounts of reduced iron compounds (typically ferrous sulphate) from bricks. These salts are deposited on the surface of the wall during drying and oxidise to form brown stains of hydrated iron oxide. The ferrous salts often run down onto the alkaline mortar joints where it is precipitated and fixed as a deep brown stain.

Fully oxidised bricks do not usually cause this effect. When using bricks which are liable to produce the problem, extra care is needed to keep the walls as dry as possible during and after construction.

3.2. Rendering on Brickwork

The chemical attack mechanisms listed for mortars apply equally to renderings, and in some ways the situation is more critical. It is only necessary to disrupt the thin layer of rendering at the interface with the brickwork in order to destroy bonding.

Furthermore, once rendering is damaged it allows the ingress of rain water to the backing brickwork, with the risk of promoting problems such as sulphation of the mortar joints within the wall.

3.3 Internal Plaster on Brickwork

Deposits of efflorescent salts on plaster surfaces can cause considerable difficulties and delays with decoration. Excessive wetness of the backing wall is a major factor causing these problems, but the actual salts may be derived from the plaster (especially gypsum-based materials); from the bricks; or from the mortar (especially the Portland cement component). The salts are generally sulphates and specific compounds have very different effects:-

Sodium sulphate usually forms a loose, fluffy layer on the surface of the plaster. It may disrupt paint films but rarely affects the plaster itself.

Magnesium sulphate crystallises on the surface of gypsum plasters causing erosion and can seriously disrupt paint films.

Potassium sulphate crystallises mainly within the matrix of gypsum plasters and forms a dark "**glassy**" stain on the surface which appears to be due to the formation of a double-salt with calcium sulphate (probably syngenite $K_2Ca(SO_4)_2$ $2H_2O$).

Higher concentrations of potassium sulphate can cause swelling and even cracking of plaster as described previously. This phenomenon has been observed over mortar joints on internal walls - it should be noted that alkalies derived from cement in the mortar will be converted to sulphates within the plaster.

3.4. Paint on Brick Masonry

Older types of oil-based paints were subject to attack by alkalies derived from the mortar joints of newly-constructed walls, but the development of alkali resistant primers and modern polymer-based paints has largely overcome this problem. Apart from physical disruption by salts migrating from the background, staining is the chief chemical action. White paints are especially sensitive to discolouration and mechanisms which have been identified include staining with traces of iron or vanadium compounds originating in masonry materials. A more unusual cause was the reaction of hydrogen sulphide (evolved from wet bricks which were incompletely oxidised) with traces of heavy metals like lead present in the white paint.[7]

4 DISCUSSION AND CONCLUSIONS

In view of the wide range of the subject matter it has been necessary to deal broadly with the issues concerned, emphasising aspects which are considered to be especially important. Much of the research work mentioned is still in progress.

Mortar rendering and plaster have been treated as individual components of masonry, whereas of course they are compounded from various basic constituents which may themselves interact. Furthermore, the specification for a material like mortar profoundly affects its properties and its ability to withstand the potentially damaging physical and chemical agencies described in the body of this report. The strength, permeability, water retentivity, pore size distribution, chemical resistance and long-term durability or mortar can be altered by varying such factors as cement and lime content, cement specifications, size grading of sand, degree of aeration and bricklaying technique.

Brick masonry construction remains something of an art, and a skilled and experienoed bricklayer instinctively compensates for such factors as the suction rate of bricks, seasonal variations in drying rates and adjustment of the consistency of cementitious mixes.

The emphasis of much of the early research on mortars concentrated on the aspects of workability and ease of use. In climatic conditions such as those pertaining in the United Kingdom, it is necessary to give more consideration to durability. This is becoming increasingly important in view of the high cost of remedial or maintenance work on buildings.

Finally, when considering Standards for individual building components or Codes of Practice for building operations, it is important to bear in mind the ways in which the structural elements may react with one another to affect the overall properties of the whole structure.

References

(1) London Brick Company Ltd. (unpublished research).

(2) "Winter Weather Conditions Since 1956" - report from the Ceramic Research Subcommittee, Structural Ceramics Research Panel, British Ceramic Research Association (1979).

(3) BS 3921:1974. Specification for Clay Bricks and Blocks.

(4) F.M. Lea "The Chemistry of Cement and Concrete."

(5) Mehta, P.K. and Gjorv O.E., "A New Method for Testing Sulphate Resistance of Cements", Journal of Testing and Evaluation, V.2, No.6, 1974 pp 510-515.

(6) Bonnell, D.G.R., and Nottage, M.E., "Studies in Porous Materials with Special References to Building Materials. 1. The Crystallisation of Salts in Porous materials." J. Soc. Chem. & Ind. 1939.

(7) London Brick Company Ltd. (internal report on site investigation).

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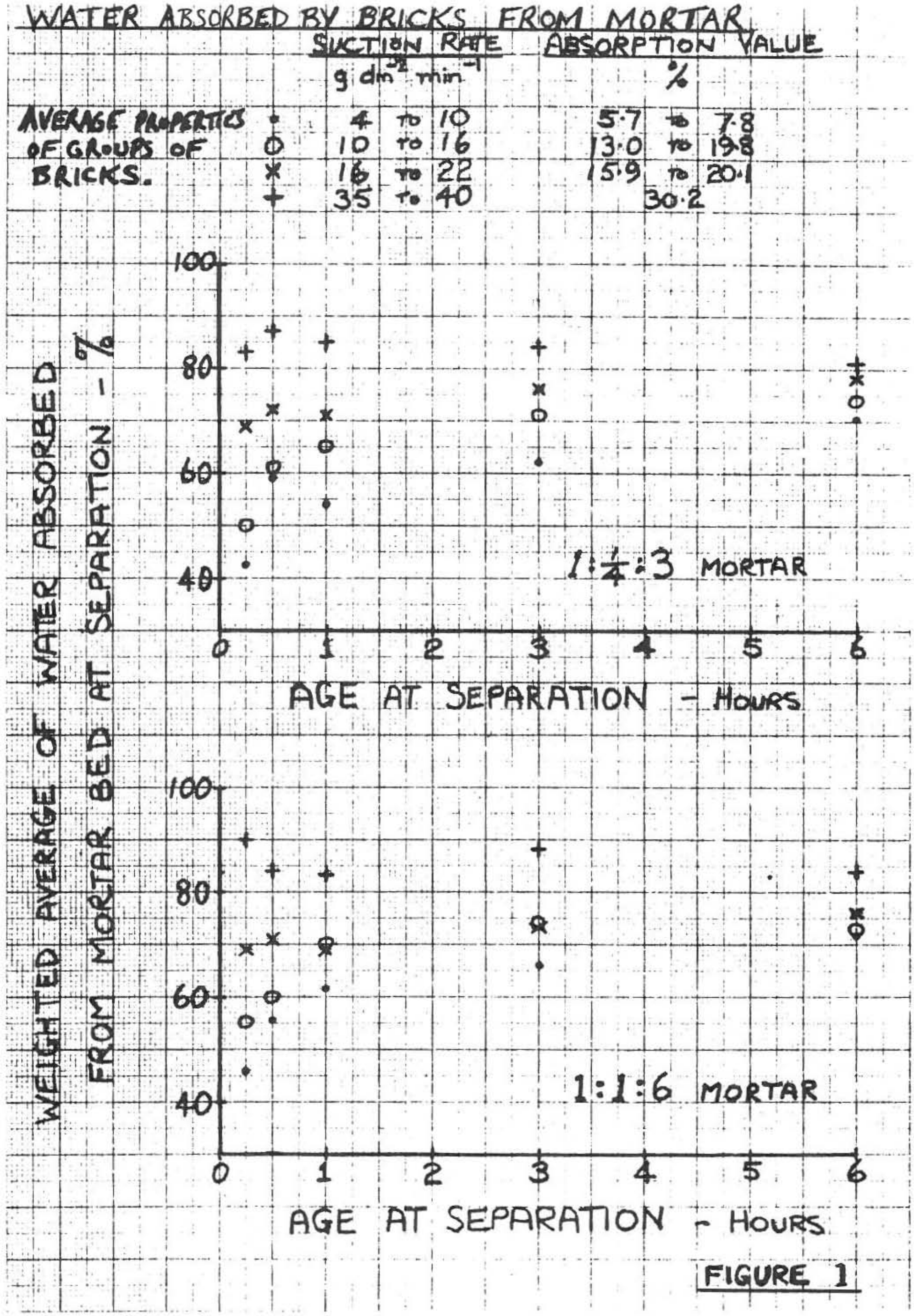

WATER ABSORBED BY BRICKS FROM MORTAR
SUCTION RATE g dm⁻² min⁻¹
ABSORPTION VALUE %
AVERAGE PROPERTIES OF GROUPS OF BRICKS.
• 4 to 10 5·7 to 7·8
o 10 to 16 13·0 to 19·8
x 16 to 22 15·9 to 20·1
+ 35 to 40 30·2
WEIGHTED AVERAGE OF WATER ABSORBED FROM MORTAR BED AT SEPARATION - %
100
80
60
40
0 1 2 3 4 5 6
AGE AT SEPARATION - HOURS
1:¼:3 MORTAR
1:1:6 MORTAR

FIGURE 1

Mortar : Apparent Porosity and Bulk Density

MORTAR (Proportions by Volume)	Sample Taken From			
	JOINT		CUBE	
	Apparent Porosity %	Bulk Density gm/cm^3	Apparent Porosity %	Bulk Density gm/cm^3
Cement:Lime:Sand				
1 (1:¼:3)	26.5	1.955	27.9	1.909
2 (1:1:6)	26.9	1.907	30.4	1.850
3 (1:2:9)	31.7	1.828	31.5	1.832
Cement:Sand				
4 (1:4)	30.1	1.890	31.0	1.839
5 (1:4 aerated)	32.1	1.835	33.1	1.788
6 (1:5 Masonry Cement)	37.2	1.700	38.4	1.651

TABLE 1

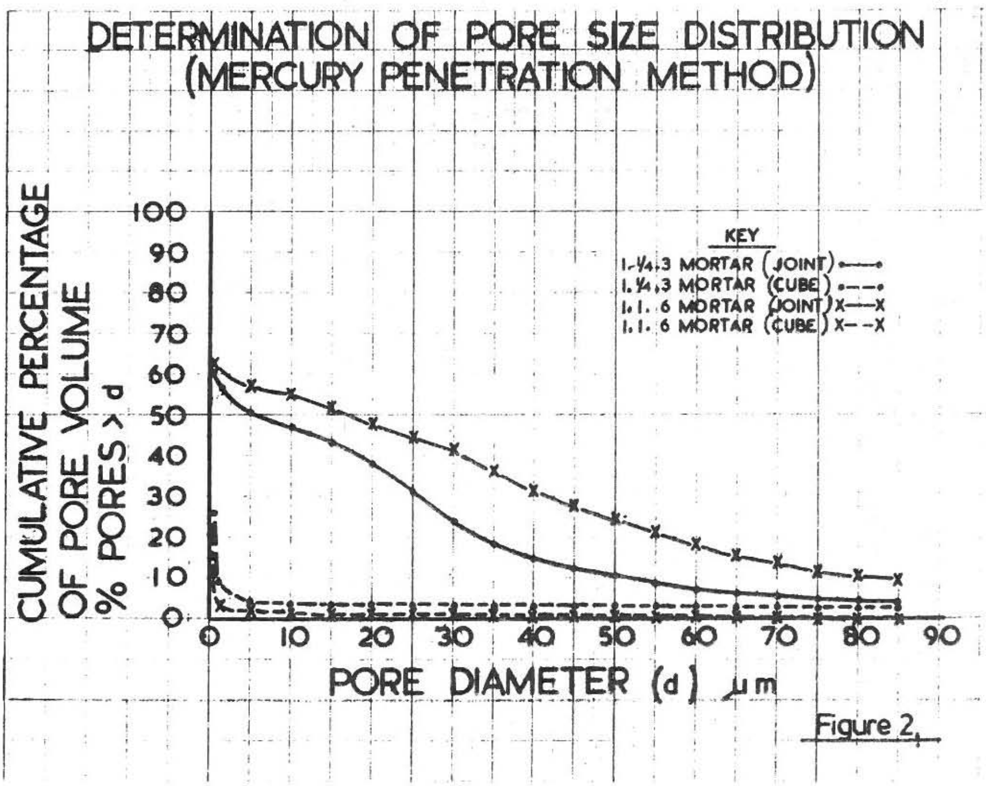
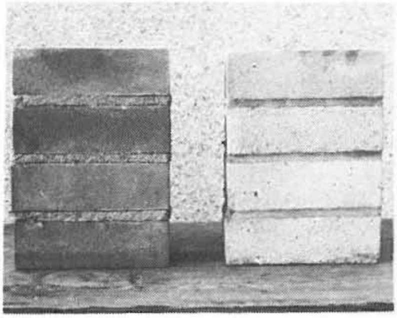
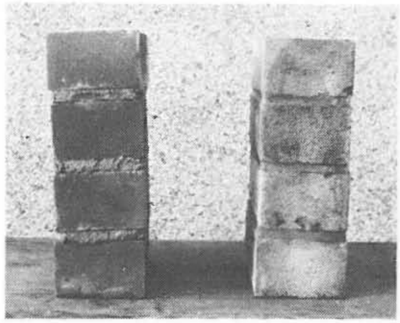


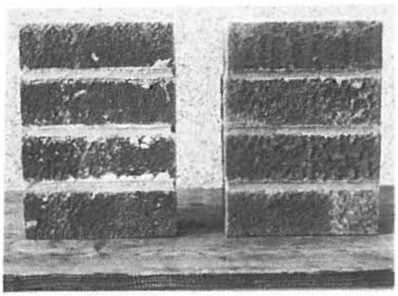
Figure 2.



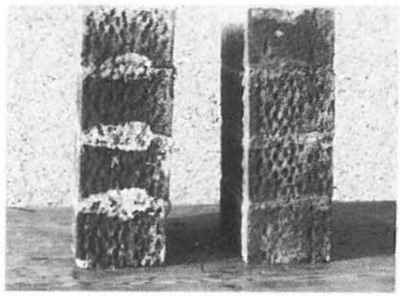
3(a)



3(b)



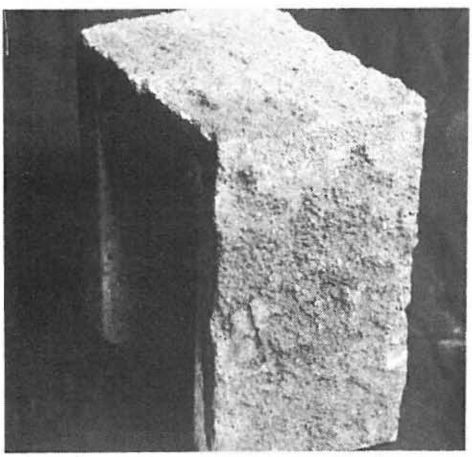
3(c)



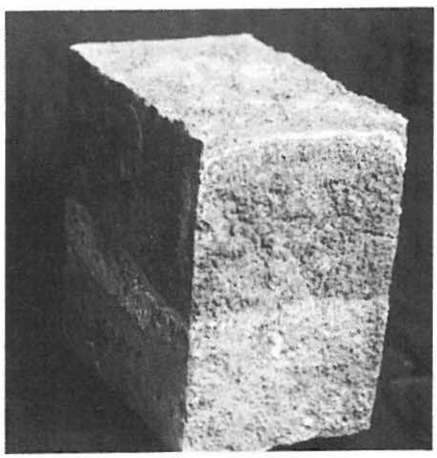
3 (d)

The effect of freezing on newly built Fletton brick panels.
(The left-hand panel in each case was built with soaked bricks, the right-hand panel was built with dry bricks).

FIGURE 3



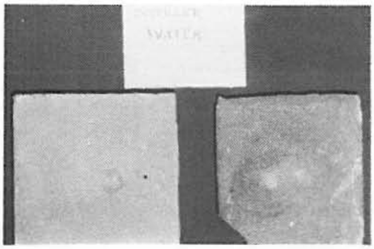
4 (a) Brick After 3 Soaking/Drying Cycles Using Distilled Water.



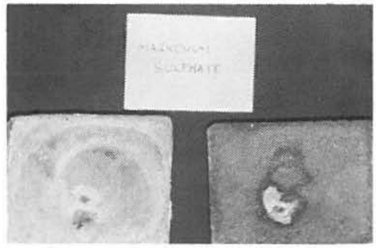
4 (b) Brick After Feeding with an Aqueous Extract of Portland Cement.

FIGURE 4

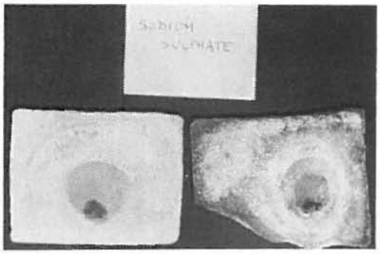
NATURE OF SALTING CAUSED BY INDIVIDUAL SULPHATES



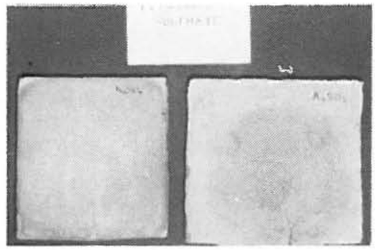
5(a) Distilled Water
Left: Gypsum Plaster Right:Mortar



5(b) Magnesium Sulphate
Left: Gypsum Plaster. Right: Mortar



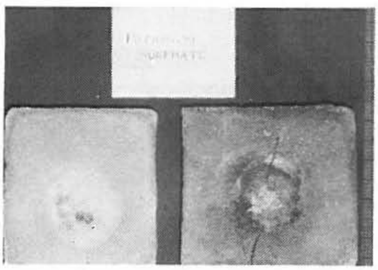
5(c) Sodium Sulphate
Left: Gypsum Plaster Right:Mortar



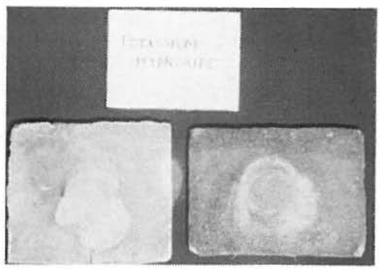
5(d) Potassium Sulphate
Left: Gypsum Plaster. Right: Mortar

FIGURE 5.

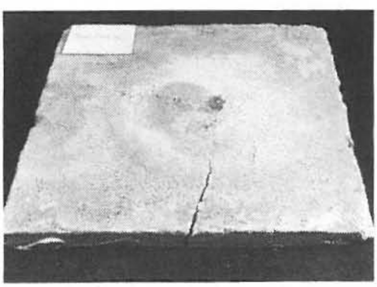
CRACKING OF GYPSUM PLASTER AND 1:1:6 MORTAR BY POTASSIUM SULPHATE



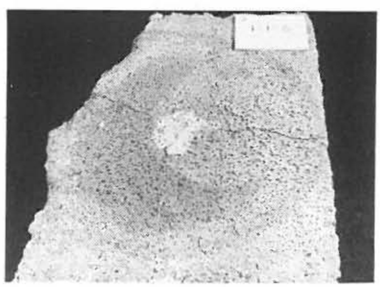
6(a) Left: Plaster Right:Mortar
Specimens fed with K_2SO_4 solution



6(b) Left: Plaster Right: Mortar
Specimens fed with KOH solution



6(c) Dense Gypsum Plaster
fed with K_2SO_4 solution



6(d) 1:1:6 Mortar fed with K_2SO_4
solution

FIGURE 6

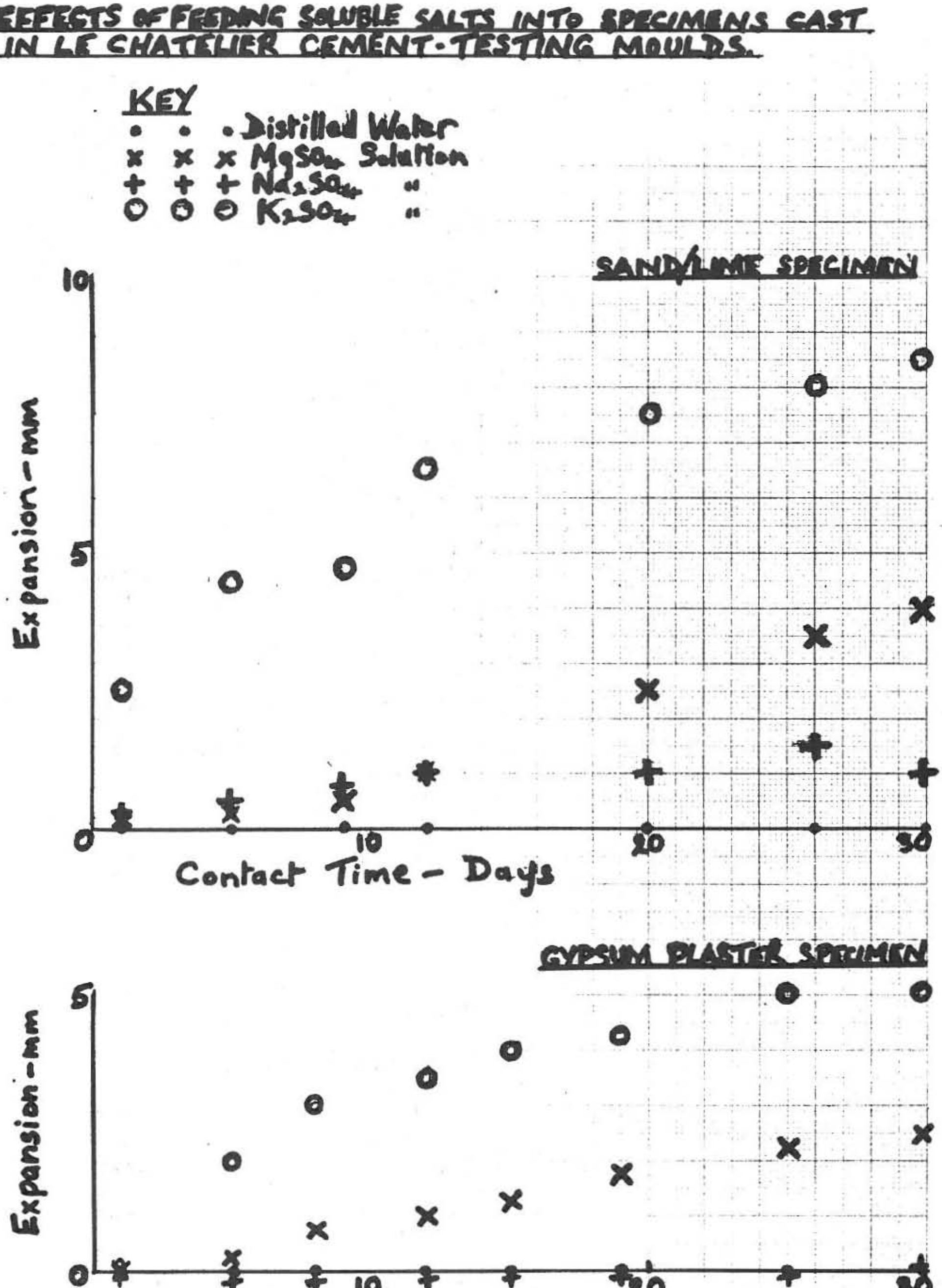

EFFECTS OF FEEDING SOLUBLE SALTS INTO SPECIMENS CAST IN LE CHATELIER CEMENT-TESTING MOULDS.
KEY
• Distilled Water
x MgSO4 Solution
+ Na2SO4 "
O K2SO4 "
SAND/LIME SPECIMEN
Expansion – mm
Contact Time – Days
GYPSUM PLASTER SPECIMEN
Expansion – mm
Contact Time – Days

FIGURE 7.