THE EFFECT OF COMPRESSIVE STRESS ON THE EXPANSION OF BRICKWORK AND ITS IMPLICATION IN BUILDINGS

BY

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DECLARATION BY CANDIDATE

I, Vivian Reginald Boardman, hereby declare that the work presented in this thesis is my own and that it has not been submitted for a degree of another University.

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SUMMARY

The restrained moisture expansion of bricks manufactured at two factories in the South Western Cape were investigated to determine what effect restraint would have on their moisture expansion, the stresses that such restrained bricks could cause in a reinforced concrete framed building and measures that should be adopted to prevent the cracking of buildings when expansive bricks are used.

The properties of the two clays, before firing, were examined and their specific gravity, particle size distribution, mineralogical composition by X-ray diffraction and chemical composition were determined. After firing of the clays, the mineralogical composition was again determined by X-ray diffraction analysis. The internal structures of fired bricks, both before being exposed to moisture and after long periods of moisture expansion, were examined under a scanning electron microscope, without however finding any difference between the expanded and non-expanded material.

The effect of firing temperature on the moisture expansion of these clays was determined using steam at atmospheric pressure to accelerate the expansions. The water absorption, porosity and bulk density of the clays fired at different temperatures was also established.

Bricks were fired in the laboratory at controlled temperatures and fired bricks were collected from one of the brick factories. The physical properties of the fired bricks were determined.

The moisture expansion of both loaded and non-loaded bricks exposed in a fog room and on the roof of a building was investigated. Special attention was given to the expansion of bricks under restraint and it was found that the expansion

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could seldon be stopped by restraint, but that in most cases the moisture expansion was reduced by restraint. It was found that some bricks continued to expand indefinitely, even when stressed close to the long-term ultimate strength of the bricks.

The stresses developed at the junction of a column and beam in a framed reinforced concrete building were examined in detail with the aid of a computer. It was found that even very minor expansions of brickwork would cause stresses in the reinforcement beyond its yield strength with resultant cracking of the concrete.

Measures that could be taken at the brickworks and on the building site to prevent damage from moisture expansion is discussed, as well as the provision by the designer of the building of open joints in the brickwork to take up the expansions.

The final conclusion is that restraint of expansive brickwork cannot prevent damage to structures.

CONTENTS

SYMBOLS

a	=	Dimension as defined
A_s	=	Area of tension reinforcement
A_s'	=	Area of compression reinforcement
A_{sc}	=	Total area of longitudinal reinforcement in columns
A_v	=	Cross-sectional area of inclined bars
d'	=	Depth to compression reinforcement
E_B	=	Modulus of elasticity of brickwork
E_c	=	Modulus of elasticity of concrete
E_s	=	Modulus of elasticity of steel
f_{cr}	=	Permissible stress in concrete in compression due to bending
f_{ct}	=	Permissible stress in concrete in tension
f_{sc}	=	Permissible stress in compression reinforcement
f_{st}	=	Permissible stress in tension reinforcement
g_k	=	Characteristic ultimate dead load per unit area
h	=	Overall depth
h_f	=	Thickness of slab
H_{NL}	=	Ordinate to left hand side of node
H_{NR}	=	Ordinate to right hand side of node
L	=	Span

L_N	=	Sum of half the length of element on each side of node
M	=	Bending moment due to ultimate loads
M_d	=	Bending moment due to service load
N_d	=	Axial load on member
p_1	=	Proportion of total reinforcement in terms of gross section
q_k	=	Characteristic distributed imposed load per unit area
R	=	Reaction
v	=	Shear stress
V	=	Shearing force
w	=	Total distributed service load per unit area ($= g_k+q_k$)
w_b	=	Unit load of brick wall
w_s	=	Unit load of slab + unit load on slab
x	=	Depth to neutral axis
z	=	Lever arm
σ_e	=	Modular ratio

CHAPTER 1

INTRODUCTION

The irreversible moisture expansion of some types of bricks at ambient temperatures has caused much damage to structures. This problem has been reported from many countries and is very severe in parts of Australia. Expansive brickwork is also found throughout South Africa, being particularly bad in the South Western area of the Cape Province[1, 2] and occurring with various degrees of severity elsewhere[3]. Besides Cape Town, Pretoria has had a number of cases of costly damage because of the moisture expansion of brickwork, but in the majority of cases the expansion has only caused minor damage of an unsightly nature without the structure requiring expensive repairs.

No clear theory has as yet been developed on the mechanism of this moisture expansion, mainly because the glasses and other substances that are formed when the clay is fired remain amorphous as they expand. The unorganized nature of the atomic structure of amorphous substances inhibits the study of their microstructure with the laboratory tools developed for the study and understanding of crystalline materials. What has been determined is that the amorphous substances that are formed when certain clays are fired have the capability of binding water in their structures with resultant expansion of their volume. It has been found that such amorphous substances only release minor amounts of this water in dry atmospheres even at high ambient temperatures. These amorphous substances do release this water when heated to temperatures above 300 ℃,[4] but in most cases the original dimensions are never regained.[5] Therefore fired clay bricks in buildings will continue expanding over long periods whenever they are moist and will only reduce slightly in

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dimension because of loss of water during exceptionally dry periods.

From a study of the damage caused by expansive brickwork in many buildings, it was realized that the forces of expansion were probably high, but whether they were high enough to cause the crushing of fairly strong bricks as was observed in a number of walls was unknown. Such walls were invariably exposed to the weather and direct sunlight. It was not known whether stresses caused by thermal expansion, after some stress had been induced because of moisture expansion of the bricks, was not perhaps the cause of the crushing failure of the bricks.

Laboratory work was undertaken to determine whether stresses high enough to cause the crushing of strong bricks could arise from moisture expansion alone or whether high stresses in expanding brickwork could inhibit moisture expansion. Certain properties of the clays before and after firing were determined to get a fuller picture of the materials from which the bricks were made.

A theoretical model of the cracked frame of a building was analysed to assess the role that the moisture expansion of the brick walls had played in the formation of the cracks. Recommendations are made as to what steps can be taken to reduce the cracking of buildings in which expansive bricks are to be used.

CHAPTER 2

EXAMPLES OF DAMAGE TO STRUCTURES

Bricks that undergo irreversible moisture expansion expand along all three axes. The forces that they can exert are high, as shown later by the crushing of well-fired hard bricks with crushing strengths up to 55 MPa. If in the design of a building, allowance is not made for the moisture expansion of the bricks, when these are known to expand, damage to the building will result. Many structures have been inspected where the expansive brickwork has caused various types of cracking and some typical failures are described hereunder.

2.1 Crushing of brick against concrete steps

Figure 1 shows how a brick of fairly high strength at the end of a brick retaining wall of about 20 m in length has been crushed because of the forces developed due to the expansion of the bricks. Soil is retained by the brick wall to about the height of the crushed brick. The courses of brickwork above the crushed brick have moved horizontally disrupting the concrete to some extent. At the other end of the wall it was noted that the end portion, also against a flight of concrete steps, had been rebuilt.

2.2 Disruption of top of sloping boundary wall

This wall was on the boundary of the property and formed a side wall of a building with a saw-toothed roof. There were three sloping sections of wall, two of which had been previously repaired at their ends and the middle section, 16,9 m in length, was about to be repaired. The disruption to the top of the middle section of the wall is shown on Figures 2 and 3. The wall had grown in height and the top

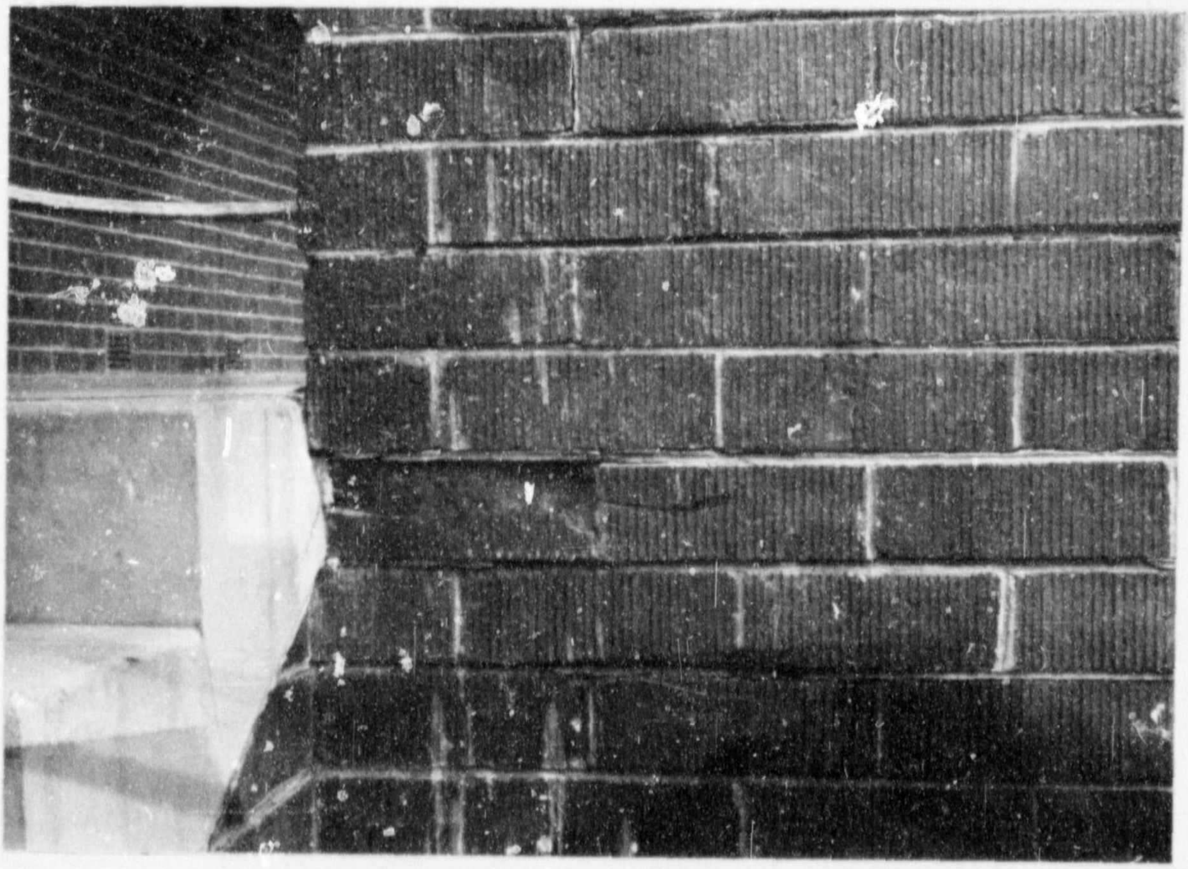

FIGURE 1.   Crushing of brick against concrete steps

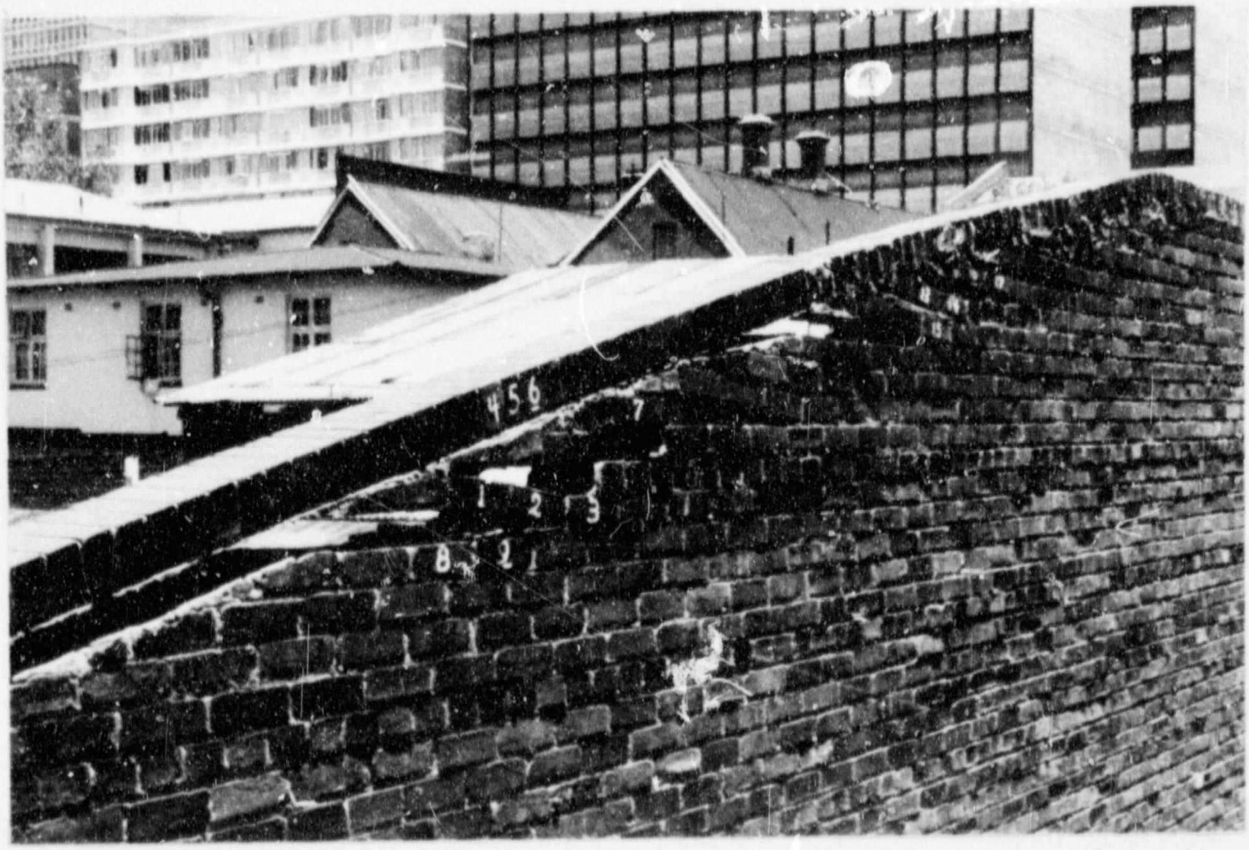

FIGURE 2. Disruption of top of sloping wall

FIGURE 3. Disruption of top of sloping wall

FIGURE 4. Upward buckling of top brick courses

FIGURE 5. Crushing of bricks in wall

sloping header course had expanded more than the other bricks, while strongly restrained at its bottom end and partially restrained at its top end. The expansion movement of the header course was up the slope and combined with a greater horizontal expansion of the upper courses at the highest part of the wall caused the disruption shown. No bricks were observed to have crushed in this wall. A number of bricks about 1,3 m up from the bottom of the wall were selected and Demec measuring disks were fixed to each brick at 203 mm centres horizontally, as described in Appendix B. When the epoxy resin had hardened Demec readings were taken. The mortar round each brick was drilled out in turn and a second Demec reading was taken immediately on removal of each brick from the wall. The bricks were capped with the capping mixture described in Appendix C before being remeasured. Most of the bricks had increased slightly in dimension over a period of 7 days while awaiting capping.

Each brick was loaded in the compression testing machine so that its length was reduced by the same amount as the brick had expanded immediately on removal from the wall. The loads required differed widely, being from 10 kN to 27 kN. These loads meant that horizontal stresses from 1,5 to 3,6 MPa were on the bricks in the wall at the time of removal. Bricks that had a similar medium-fired appearance had been selected for removal, but there were bricks in the wall which appeared to be very well-fired as well as bricks which were perhaps under-fired. Therefore the bricks in the wall would have had a wide range of elastic moduli, which meant that stresses in individual bricks would depend as much on the properties of adjacent bricks as on their own properties.

The main fact demonstrated was that a wall that had been built at least 20 years ago still had a permanent horizontal stress in it from the moisture expansion of the bricks.

2.3 Upward / .....

2.3 Upward buckling of top courses of brickwork in a long boundary wall.

The three top courses of brickwork in the middle of a 225 mm thick boundary wall of about 60 m length had buckled upward about 150 mm under the horizontal compression developed because of moisture expansion. Bricks in many of the courses below this inverted 'V' had been crushed. Figures 4 and 5 show this wall where it had failed. The bricks were judged to be of medium strength.

The failure took place at about the middle of the wall because the shear strengths of the horizontal mortar joints on each side of the failure were greater than the cross-sectional strength of the wall. The stresses had been induced by the elastic suppression of a gain in length due to the moisture expansion.

2.4 Cracks in garden wall

In a 110 mm garden wall, vertical cracks had occurred starting two courses below the top of the wall and continuing downwards 3 to 4 courses before tailing away. These cracks had apparently been caused by the more rapid expansion of the top two courses with respect to the courses under them. These cracks were approximately 0,7 mm wide by 230 to 400 mm long, spaced at approximately 1,2 m intervals. When inspected again about 4 years later, it was noticed that the cracks had all closed indicating that with time the lower bricks had apparently caught up with the expansion of the top bricks.

2.5 Displacement of top courses of boundary wall

In a 220 mm wall of about 60 m in length built on slightly sloping ground, a step of three courses was formed in the top of the wall about 36 m from the higher end. The top three courses of brickwork had pushed over the courses below them

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at the step for a distance of a couple of inches. This indicated that the relatively free expansion of the top three courses was far more than the expansion of the lower restrained courses. This was a wall that had been standing for many years by appearances.

This illustrates that restraint will not only reduce the magnitude of the moisture expansion, but that the expansion can be taken up by elastic compression of a wall. The compressive forces however will be very high as illustrated in 2.3. The top three courses because of more moisture from rain and more radiation heating from the sun would have expanded more than the fourth course but, not this amount unless the fourth course was restrained.

2.6 Horizontal buckling of wall

A 0,7 m high street boundary wall, which had 110 mm brick panels between 220 by 220 mm brick columns spaced at 4 m centres, showed many signs of disruptive expansion. Besides these, the lower 5 courses of the panel in the middle of the wall had buckled sideways to relieve the high compressive stresses. The top three courses of this panel had bowed upwards slightly.

2.7 Boundary wall expanding between two heavily loaded walls

A wall about 2 m high and 9 m long was built on the same line between two heavily loaded walls about 6 m long which supported 5 storeys of a building above them. Although open vertical joints had been provided between the walls, when inspected the walls were very hard up against each other. As can be seen on Figure 6, the corners of bricks had flaked off at the vertical joints and some bricks adjacent to the joints had failed in compression. At the

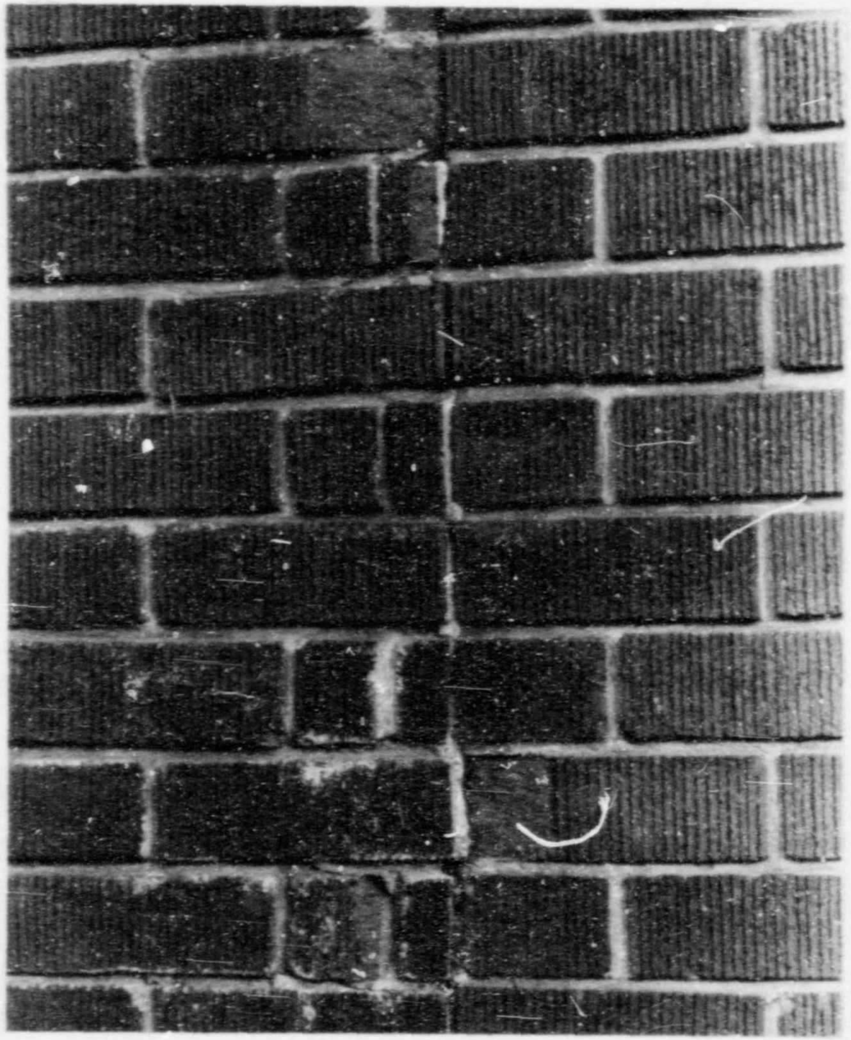

FIGURE 6. Open joint that had closed

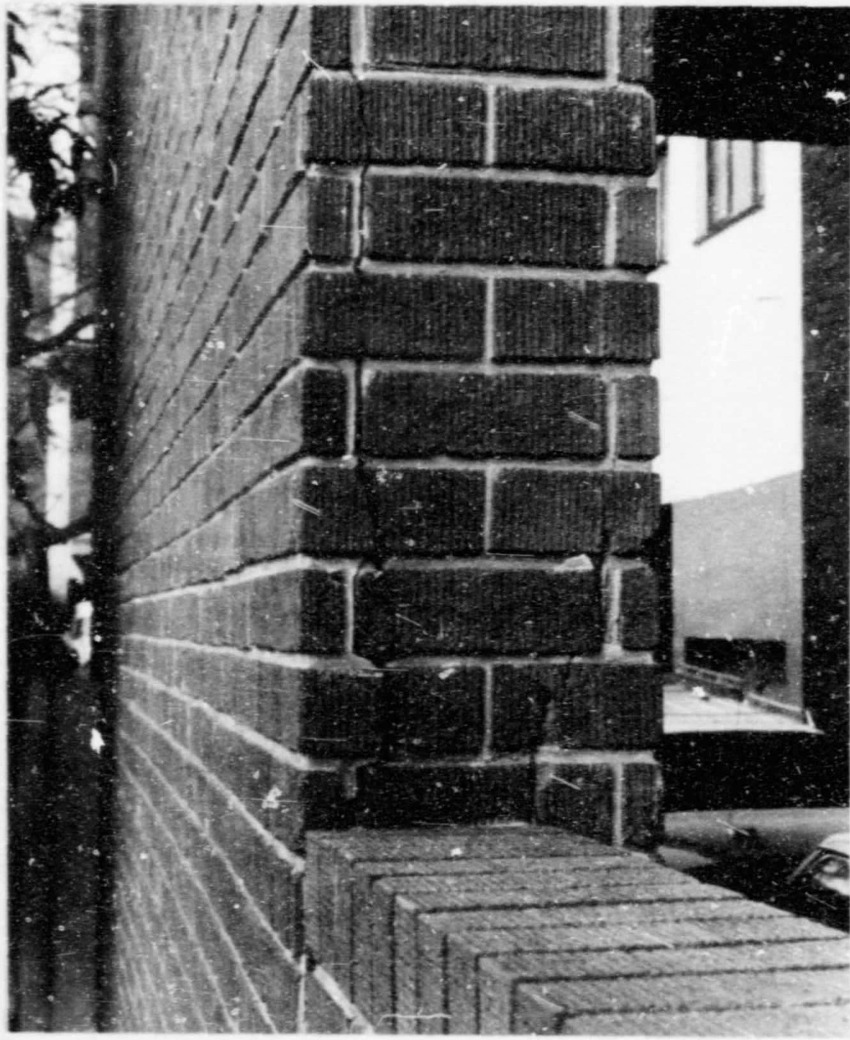

FIGURE 7. Compression damage to wall

FIGURE 8. Vertical crack in column

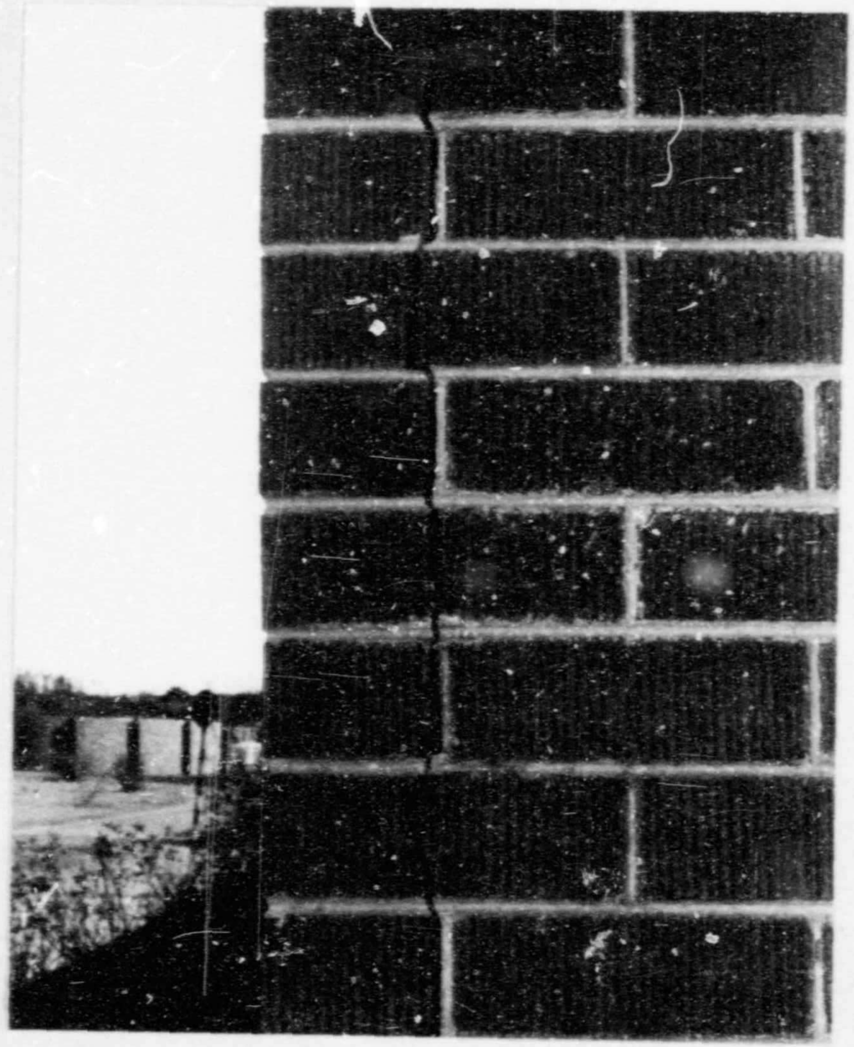

FIGURE 9. Vertical crack at corner of building.

2 m height the walls carrying the heavy vertical loads had been damaged by the top bricks of the lower wall forcing their way slightly into these walls, as shown on Figure 7.

2.8 Cracks in vertical column

Figure 8 shows a crack in a vertical column. Elsewhere in the building and in a boundary wall were evidence that these bricks were of an expansive nature. This column was at one side of a driveway into the building and carried six storeys above it. Inside the brickwork was a reinforced concrete column. Just how much the shrinkage and creep of the reinforced concrete column had contributed to the load on the brickwork and how much the expansion of the bricks had contributed cannot be said but the brickwork had obviously had to carry an excessive load which had split it vertically. Brick walls under compressive loads during testing crack vertically in this manner just prior to collapse failure. About 11 years ago this crack was about 0,1 mm wide and is now 3,2 mm wide. Similar vertical cracking of expanding brick clad columns have been observed in other buildings.

2.9 Vertical cracks at the corners of buildings

A type of crack which commonly occurs in the external brickwork of buildings is a vertical crack 110 mm from the corner extending all the way up the building. This crack is caused by the two outer leaves of brickwork at right angles to each other expanding and pushing each other outward. They are no longer able to remain at right angles to each other and one or the other cracks. An example of such a crack is shown on Figure 9.

2.10 Expansion of brick parapet walls

The exposed situation of parapet walls ensures rapid expansion of the bricks in them to judge by the many brick parapet walls that can be observed to have thrust outwards at their corners with associated cracking.

2.11 Vertical expansion of brickwork

Because of the vertical expansion of brickwork some failures have occurred which are very difficult to repair. Two buildings have been examined where an outer 110 mm leaf of brickwork had been laid continuously in the vertical direction for the full six storeys plus top parapet wall. The expansion of the bricks tended to become greater, both progressively and accumulatively, the higher they were above ground level.

Cases have also been observed of the faggot bricks, covering reinforced concrete beams, bulging outwards because of the vertical compression. It is considered that this compression is only partially from the expansion of the brickwork, the other cause being that reinforced concrete columns shorten due to shrinkage and creep. The mechanism of this buckling is that the thin faggot bricks against the faces of the reinforced concrete beams between storeys are not adequately fixed (if at all) to the reinforced concrete beams. Under the slowly increasing vertical pressures they initiate outward buckling. One case in which the ties to the concrete beams as well as to the inner leaf of brickwork had been omitted was inspected. Three storeys of the external leaf, containing no openings, had fallen to the ground because this buckling had disturbed the poor seating on the edge of the concrete beam of the 110 mm leaf above the faggots.

2.12 Shearing off of reinforced concrete column by a brick wall

A 220 mm by 400 mm reinforced concrete column at the end of a building was sheared off at its base because of the thrust from a long face-brick wall which was expanding.

These examples illustrate the problems that can be caused by the moisture expansion of brickwork when measures are not adopted that will accommodate the expansions. A false impression should not be gained however, because the majority of brick buildings have been most durable, virtually crack-free structures.

CHAPTER 3

LITERATURE SURVEY

Researchers who have studied moisture expansion in various types of clay products have found that, on cooling after firing, a porous ceramic product starts absorbing moisture from the atmosphere and if it is of the expansive type will expand. The suggested causes[5] of moisture expansion are water that is:

(i) capillary condensed in the pores of the fired body, where the expansion can be recovered by heating to 110 ℃.

(ii) physically absorbed on the surface of the pores and which requires temperatures in excess of 110 ℃ to remove,

(iii) chemisorbed on the reactive surfaces of some of the fired products,

(iv) chemically bound by the fired products.

The amount of expansion depends on the chemico-mineralogical composition of the fired product. In the case of natural materials, the investigations have been complicated by the complex mineralogy and the presence of impurities. To simplify matters, moisture expansion has been studied using fired gels and mixtures of gels to simulate fired natural clays[5]. Some polar liquids other than water also cause an expansion[6].

The crystalline minerals, mullite and cristobalite, that form when certain clays are fired have been found to become less

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disordered at the higher firing temperatures, i.e. 1100 ℃ and 1300 ℃ respectively. They and feldspar have little or no moisture expansion[5,7]. Smith[8] considers that, because crystalline materials have a relatively small specific surface and a low surface energy, they do not contribute greatly to moisture expansion. At the Building Research Station, England, it was found, by condensing nitrogen on the internal surfaces, that the internal surface area of three fired clays, viz. Gault, Oligocene and Keuper, decreased markedly with firing temperatures between 800 ℃ and 1050 ℃[9]. The Keuper clay was 28 m^2/g when fired at 800 ℃ and only 0,6 m^2/g when fired at 1050 ℃. The moisture expansion of Gault, Oligocene and Keuper Marl clays fired at various temperatures are given by Freeman and Smith[10] and the 800 ℃ firing temperature in no case gave the highest expansion. For the fired Gault clay it was 1025 ℃, for the fired Oligocene clay 950 ℃ and for the fired Keuper Marl 875 ℃. This casts some doubt on the internal surface area *per se* having a direct relationship with permanent moisture expansion. The substances formed at a particular firing temperature are most important, because the surface energy and reactivity are directly related to these substances. For substances of a given reactivity, the greater the internal surface the greater will be the rate of reaction.

In work done by Cole and Crook[11] on clay mineral mixtures of kaolinite, muscovite and quartz, it was found that little glass was likely to have formed between 1000 ℃ and 1050 ℃ and the moisture expansion phenomena were more likely to be caused by the amorphous products of the breakdown of the kaolinite and mica. However, Cole[12] later reports Schairer and Bowden as stating that melting can be expected to occur beyond 985 ℃ in that part of the ternary system $K_2O.\ Al_2O_3.\ SiO_2$ covering clay compositions, and aluminosilicate glasses will be formed in a ceramic body. The amount of glass will depend largely on the stability of the mica minerals. Such a glass corresponds closely to that of natural obsidian glasses. The hydration of obsidian glass is a very slow process even in geological time, so that if such glasses form this perhaps

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explains why brick expansions will continue for very long periods.

Freeman and Smith[10] postulated that the mechanism causing the expansion in the early stages may differ fundamentally from that acting subsequently. The initial expansion may be caused by release of surface energy following physical adsorption or chemisorption of water. These would be rapid processes. The later expansion might depend more on a slow hydration of some constituents of the fired clay body. From the literature in general, it seems that the moisture expansion of bricks is not a single process, but a combination of a number of processes such as absorption, adsorption, chemisorption and chemical reaction. Also because of the complicated compositions of fired clays, there are likely to exist simultaneously a number of substances which will react with moisture and expand both different amounts and at different rates, so that some reactions will be completed in relatively short periods whereas others will continue for longer periods. After the rapid expansion of the first day or so, perhaps because of absorption, adsorption and chemisorption, the large expansions that take place over the next few years are probably due to chemisorption and chemical reactions of moisture with amorphous aluminosilicates that are relatively reactive materials[12], and the really long-term expansions follow, because of moisture reaction with certain glasses.

Freeman and Smith[10] also investigated whether cooling in a desiccator would affect long-term expansions when compared with cooling under normal humidity conditions and found that they did not, in spite of the large expansions of desiccator cooled specimens on the first day of exposure. They also found a 20% increase in expansion for specimens in storage atmospheres of 65% and 90% relative humidities respectively.