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DIMENSIONAL CHANGES OF MASONRY IN RELATION TO
SOUNDNESS OF BRICKS AND MORTARS

BY
T. RITCHIE

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DIMENSIONAL CHANGES OF MASONRY IN RELATION TO SOUNDNESS OF BRICKS AND MORTARS

By T. RITCHIE¹

Cracking of masonry walls is a common problem that reveals the effects of differential movements of the walls of a building or parts of a wall, as well as the effects of differential movements of walls and other components. Cracks may affect the structural stability of walls and the appearance of the building and may also affect the durability of the masonry by allowing excessive penetration of moisture into the wall.

Because of its importance the problem of cracking of masonry has been studied for many years. As long ago as 1832, for example, an investigation of dimensional changes of masonry was made by Lt. Bartlett of the U. S. Engineers (1).² This study was prompted by the practical problem that mortar joints between coping stones "were broken up by fissures which extended from the top to the bottom of the coping." Suspecting that changes in the dimensions of the stones caused the trouble, Bartlett made a series of experiments to relate dimensional changes to variations in temperature. The results of these investigations confirmed that "working" of the stones from temperature changes could be expected to break the mortar between the stones.

Interest in dimensional changes of masonry and their effects has led to many

additional studies, with the result that several causes of dimensional changes, in addition to thermal effects, are now well recognized. The shrinkage of concrete masonry units as they age (2) and the expansion in service of clay bricks (3) may be mentioned in this connection, as well as the expansion that may occur when saturated masonry materials are frozen (4). Chemical reaction between components of masonry, such as that between soluble sulfates in bricks and portland cement in mortar, has also been given as a cause of expansion (5).

Still another mechanism that causes dimensional change in brickwork involves the expansion of mortar containing unhydrated magnesium oxide (6). The possibility of dimensional instability of masonry from this cause is the main subject of this paper. In recent years masonry cement composed, in part, of hydrated lime containing magnesia has come into use in Canada. Such cement, according to present requirements of the ASTM Specification for Masonry Cement (C 91),³ would be considered "unsound" because of relatively large expansion when autoclaved. It was therefore considered necessary to review the autoclave expansion test to determine whether expansion on autoclaving of mortars and their cementing materials offered a means

¹ Building Materials Section, Division of Building Research, National Research Council, Canada.

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

³ Specification for Masonry Cement (C 91 - 60), 1961 Book of ASTM Standards, Part 4, p. 29.

for predicting dimensional changes of masonry.

REVIEW OF LITERATURE

One definition of "sound" as applied to cement manufacturing is "not liable to change in volume," and refers to cement "which contains no free lime or other ingredient which is unstable after the cement has set." In an absolute sense, however, no masonry material is dimensionally stable; in defining "soundness," therefore, a question of degree of instability has to be considered, and this situation has complicated seriously the matter of assessing "soundness" of masonry materials.

Two papers published in 1952 (6,7) describe certain occurrences of cracking of brick walls that were attributed to expansion of mortar because of an increase in the volume of the mortar accompanying the hydration of magnesia. In each of the papers a building having cracked brickwork was described and the cracking was related to "unsoundness" of the mortar. The mortars used in the buildings contained masonry cement prepared by blending portland cement and hydrated dolomitic lime; mortar bars and neat cement bars made of this masonry cement expanded appreciably when autoclaved. It was thought that the amount of autoclave expansion would distinguish "soundness" or "unsoundness" of masonry cements; in one paper (6) it was proposed that autoclave expansion of bars of neat masonry cement greater than 1.0 per cent of the original length of the bar indicated "unsoundness" of the material, and that such cements used in mortar would cause disruption of the masonry. An autoclave test was later adopted in the ASTM Specification for Masonry Cement,³ with a limit of expansion placed at 1.0 per cent.

Autoclave expansion of neat bars of portland cement as a means of assessing

the soundness of cement has been used in North America for many years. The history of the development of the test was described in 1953 (8), along with detailed information on the influence of various factors on the behavior of cementing materials when subjected to the test.

In a paper presented at an ASTM symposium in 1939 (9), proposals advanced for the adoption of the autoclave test for assessment of soundness of masonry mortars were discussed. The adoption of the test was deprecated, however, because studies had shown that although expansion of mortar by autoclave treatment was usually appreciable for those mortars containing magnesia derived from hydrated dolomitic lime, the expansion by autoclaving did not correspond to the dimensional changes of mortar under natural conditions of aging. It was found for the materials studied that magnesia hydrated in mortar joints with no noticeable expansion or harmful effects, whereas the autoclave test produced great expansion or even disruption of the same mortar.

A more recent study of dimensional changes of brick masonry in relation to the autoclave expansion properties of mortar materials was made in 1955 (10). In this investigation it was found that certain mortar materials and mortars made from them expanded greatly when autoclaved. Brickwork made of the same materials, however, underwent little expansion and showed no evidence of unsoundness under natural exposure conditions. In addition, it was found that samples of mortar and concrete taken from very old structures expanded appreciably when autoclaved, even though the structures had performed satisfactorily and the materials in service had shown no indication of unsoundness.

The use of magnesian lime in mortar in relation to expansion of brickwork was studied in Great Britain because of re-

ports from other countries of defects in buildings caused by its use (11). It was found that the methods used to slake magnesian quicklime in Great Britain usually resulted in the lime's containing unhydrated magnesia, which subsequently hydrates in mortar. A survey of experiences with the use of such lime, however, did not reveal evidence of harmful effects and it was considered that "...magnesium lime mortars, with or without the addition of portland cement, have been and are being used in the construction of buildings of all kinds without giving any significant cause for dissatisfaction" (11).

DOLOMITIC LIMES

Dolomitic lime has been used extensively throughout Ontario for masonry mortar. Much of the lime used by the construction industry in the Toronto, Ontario, area has been obtained from dolomite deposits to the west in the so-called Guelph-Lockport formations (12). Quicklime and normally hydrated lime are supplied from plants at these deposits. When used in making mortar, hydrated lime may be made into a paste beforehand by soaking in water, but frequently it is mixed dry with portland cement and sand. In recent years masonry cements have been prepared from hydrated lime by blending it with portland cement and small amounts of other materials. Such masonry cements, as shown later, are "unsound" by the autoclave test, probably because of the magnesia contained in the hydrated lime.

The possibility that in the Toronto area, where magnesian lime has been extensively used, difficulties may have been experienced with masonry through delayed expansion of mortar has been investigated by a committee concerned with specifications for masonry cement (13). This committee distributed a questionnaire to architects, builders, and

building owners in the Toronto area requesting information on the performance of masonry in relation to the type of mortar used. Problems with masonry, such as efflorescence and rain penetration, were mentioned in some of the replies, but in none was mention made of troubles caused by the expansion of masonry. Such a problem apparently had not been recognized by those who replied to the questionnaire.

The same committee (13) arranged for the examination of several buildings in the Toronto area for which magnesian lime had been used in the mortar. The buildings were examined for indications of unsoundness that might be revealed by displacement of walls, cracking, or bulging; but there was no evidence of distress which could be attributed to abnormal expansion or unsoundness of the mortar, and some of the walls were 20 to 30 years old.

EXPERIMENTAL PROCEDURE

It was the main object of the study to compare the expansion of mortars resulting from autoclave treatment with the dimensional changes of brick masonry in which the same mortars were used. For the autoclave tests, neat cement bars and mortar bars of 10-in. length were used. The bars were removed from the molds at 24 hr, stored in a humid room for another 24 hr, then autoclaved for 3 hr at 300 psi. In some cases the expansion of the bars was too great for measurement by the standard comparator; a vernier caliper was then used.

Small brick piers were used to study dimensional changes of masonry. They were made by stacking bricks one above another with mortar joints between them. A metal mold $\frac{1}{2}$ in. high was placed on the brick, and the mortar joint was formed by overfilling the mold with mortar and then scraping off the excess. On removing the mold, a brick was placed on

the mortar and "worked" into it by a slight twisting movement. The bricks were dipped in water immediately before laying to produce strong adhesion. In or-

such half-bricks were used in each pier, which measured about 6 in. long, 4 in. wide and 18 in. high. Before they were used, the top and bottom bricks were

FIG. 1.—Instrument for Measurement of Length Changes of Brickwork Piers.

der to magnify the influence of the mortar on movements of the piers, "Roman" bricks, which are smaller in height than normal bricks, were used. For convenience the bricks were cut in half and nine

fitted with spherically ended metal pins against which measurements of changes of height of the pier were made. The first measurement was made within 5 min of setting the top brick in place, and subse-

quent measurements followed frequently. The measuring device was fitted with a micrometer head reading to 0.0001 in., arranged as shown in Fig. 1.

MORTARS

A well-graded natural sand was used in the mortars. Two mortars were made from masonry cements prepared in the Toronto area from normally hydrated dolomitic lime. In one of them the proportions by volume of lime and portland cement were equal; the other contained two parts of lime to one part of portland

TABLE I.—AUTOCLAVE EXPANSION OF NEAT CEMENT AND MORTAR BARS.

Cementing Material	Autoclave Expansion, per cent of length (average of 3 bars)	
	Neat Ce- ment Bars	Mortar Bar
Masonry cement (portland cement:limestone).....	0.01	0.1
Masonry cement (1:1 port- land cement:hydrated lime).....	5.5	2.1
Masonry cement (1:2 port- land cement:hydrated lime).....	10.0	4.7
Mixture of 1:1 portland ce- ment:lime paste.....	0.3	0.1

cement. Appreciable expansion of neat bars and mortar bars of these materials took place in the autoclave so that these masonry cements would be classed as "unsound" by the specification for masonry cement.³ Another masonry cement, of the type made by intergrinding portland cement clinker and limestone, was also studied. It was "sound" as judged by the small amount of expansion in the autoclave test. The fourth mortar was composed of equal parts by volume of portland cement and of lime paste made by slaking a high-calcium quicklime. The autoclave expansion of bars of this mixture was small. The amount of expansion of neat cement bars and of mortar bars

of the four materials is shown in Table I. In three cases the expansion of the mortar bars was less than that of the neat bars; the reverse occurred with the masonry cement of portland cement and limestone.

BRICK PIERS

Clay brick was used with all four mortars to construct piers, but concrete brick was used with only one, that containing the portland cement:limestone type of masonry cement. Water absorption properties of the bricks were determined by immersing them for 24 hr; the average for the clay bricks was 10.2 per cent of the dry weight, while that for concrete bricks was 4.9 per cent.

The piers were constructed and stored under three conditions. The first set of piers was kept in a laboratory that had no special control of temperature or humidity; these varied over the year from about 59 to 87 F, and from about 17 to 55 per cent relative humidity (RH). The second set of piers was kept in a laboratory maintained at 50 per cent RH and 73 F. The remaining set was stored at 10 per cent RH and 73 F. Changes in the vertical dimension of the piers for measurements made in the two years following construction are shown in Fig. 2 expressed as percentage of the original height. The type of brick and mortar used and the conditions of storage are indicated on the graph.

All piers shrank immediately after the initial measurement of height. Thereafter the sets of piers behaved differently; for some, shrinkage continued, while for others initial shrinkage was followed by expansion.

Piers of "Unsound" Masonry Cement Containing 1:1 Portland Cement:Hydrated Lime:

The initial shrinkage of the three piers was recovered in a relatively short time. Continuing expansion took place gradu-

Fig. 2.—Changes in Height of Piers.

ally in the pier stored at 50 per cent RH, so that after two years the height of this pier was 0.077 per cent greater than the original height. The pier stored at 10 per cent RH also expanded quickly, following the initial shrinkage, but after about six months slight shrinkage took place; thereafter little change in height could be detected. In two years the height had increased by 0.023 per cent. The pier stored under uncontrolled conditions was intermediate in expansion, compared with the others; after two years its height was 0.053 per cent greater than the original.

Piers of "Unsound" Masonry Cement Containing 1:2 Portland Cement:Hydrated Lime:

The piers stored at 50 per cent RH and under uncontrolled conditions recovered the initial shrinkage over a period of about 6 months; after that slight and gradual expansion took place until at 2 years the pier stored at 50 per cent RH was greater by 0.023 per cent of the original height, while that stored in uncontrolled conditions was greater by 0.016 per cent. The pier stored at 10 per cent RH recovered its initial shrinkage in about 3 weeks; the height then remained fairly constant for about a year, at slightly more than the original. In the second year slight expansion occurred, so that at 2 years the height of the pier was 0.011 per cent greater than originally.

Piers of "Sound" Masonry Cement Containing Portland Cement and Limestone:

Following the initial shrinkage of these piers there was a very gradual recovery, and at 2 years their height was almost the same as the original, being less by amounts of 0.002, 0.005, and 0.008 per cent of the original height.

Piers of Mixture of 1:1 Portland Cement: Lime Paste:

After the initial shrinkage of these piers the height remained fairly constant for about a year, when gradual but slight expansion took place. At 2 years, the piers were 0.019, 0.022, and 0.030 per cent shorter than the original height.

Piers of Concrete Bricks and "Sound" Masonry Cement:

The pier stored at 50 per cent RH continued to shrink for about 6 months fol-

TABLE II.—DIMENSIONAL CHANGES OF SECOND SET OF PIERS.

Mortar Composition, by volume ^a		Autoclave Expansion of Mortar Bars, per cent	Dimensional Change of Pier After 1 yr, per cent of original height
1:3	L:S.....	^b	-0.012 ^c
1:2:9	C:L:S.....	3.3	-0.016
1:1:6	C:L:S.....	2.1	-0.013
1:½:4½	C:L:S.....	0.5	-0.016
1:3	MC:S.....	0.1	-0.014

^a L = lime, C = portland cement, S = sand, and MC = masonry cement (portland cement:limestone).

^b Not determined; probably very high.

^c (-) indicates shrinkage.

lowing construction, after which the height remained fairly constant; at 2 years shrinkage was 0.051 per cent of the original height. Considerably greater shrinkage took place in the piers stored at 10 per cent RH and under uncontrolled conditions, and at age 6 months shrinkage of these piers had exceeded 0.07 per cent. After about 1½ years the pier stored at 10 per cent RH began to recover its earlier shrinkage and at 2 years its shrinkage was about 0.05 per cent of the original height. The pier stored under uncontrolled conditions, however, continued to shrink and at 2 years the change in its height was 0.087 per cent of the original height.

FIG. 3.—Change in Length and in Autoclave Expansion of Mortar Bars Stored Under Various Conditions.

Open circles: Mortar containing 1:1 portland cement and hydrated lime.
 Solid circles: Mortar containing 1:2 portland cement and hydrated lime.

ADDITIONAL PIERS

It appeared probable, for reasons discussed later, that expansion of the clay bricks had a significant influence on the dimensional changes observed in the piers, in the same way that shrinkage of the concrete brick had undoubtedly influenced the results. A second series of piers was therefore constructed using a different clay brick. In these piers lime mortar, cement-lime mortars, and a masonry cement mortar were used. The lime was a normally hydrated dolomitic lime, the same as that used to prepare the "unsound" masonry cements of the first piers. The mortars containing lime covered a wide range of autoclave expansion, depending on the proportion of lime in the mix. Mortar prepared from "sound" masonry cement of the portland cement: limestone type was also used; its expansion on autoclaving was slight. The autoclave expansion values of the various mortars are shown in Table II.

Piers were constructed and stored in a room maintained at 50 per cent RH and 73 F, and measurements were taken of their heights by the method described previously. All five shrank after construction, the amounts being similar for all piers. One year after construction all heights were less than the original by amounts in the narrow range 0.012 to 0.016 per cent. Dimensional changes are given in Table II. There was no indication at 1 year that expansion was taking place.

Further evidence that expansion of the clay bricks of the first piers had taken place was obtained from measurements of dimensional changes of mortar bars of the two "unsound" masonry cements, stored for 2 years at 50 and 10 per cent RH. These mortar bars shrank, although the piers made of them had expanded under the same conditions of storage for the same length of time.

DIMENSIONAL CHANGES OF MORTAR

Mortar bars of the two "unsound" masonry cements were stored under three different humidity conditions to determine the effect on length. On removal from the molds the length of the bars was measured and they were then stored under three conditions of relative humidity: 100, 50, and 10 per cent, at a temperature of 73 F. At intervals over a 2-yr period length was measured again, and some of the bars were autoclaved. Changes during storage and changes in autoclave expansion are shown in the graphs in Fig. 3, each point representing the average of measurements of three bars.

Bars stored at 50 and 10 per cent RH shrank, a large proportion of the shrinkage occurring in the first week; after 2 years shrinkage was about 0.1 per cent of the original length for mortar bars of both cements. Storage at 100 per cent RH, however, caused expansion in the bars, the amount being similar for bars of both cements. After 2 years the bars were about 0.050 per cent longer than their original length, about half of the 2-yr expansion occurring in the first 3 months of storage.

Detailed studies of the long-term length changes of portland-cement mortars stored in air and in water have been reported elsewhere (8), the studies involving cements that varied over a wide range in autoclave expansion. The cements were made into neat bars and mortar bars and the length changes of the bars were measured over long periods of time (10 years or more). Although many of the cements were high in autoclave expansion, nevertheless with few exceptions they had shrunk after 10 years of storage in air (50 per cent RH at 70 to 80 F). Storage in water of mortar bars of all cements caused expansion to take place.

The autoclave expansion of mortar

bars changes as the bars age (8,9,14). Confirmation of this was obtained on autoclaving the mortar bars whose length changes in storage have been described. The results are presented in Fig. 3, where it may be seen that following 2 years of storage at 100 per cent RH the autoclave expansion of bars of both cements had

bars were prepared from a 1:1:6 mixture of portland cement, hydrated dolomitic lime, and sand. Average expansion of three bars when autoclaved was 3.0 per cent. On removal from the molds at 24 hr, two bars were stored continuously at 50 per cent RH and 73 F. Two other bars were stored for a week under the same

FIG. 4.—Effect of Wetting and Drying on Dimensional Changes of "Unsound" Mortar.

decreased to a value of 0.1 per cent from original values of 2.1 and 4.7 per cent. Autoclave expansion of bars stored at 50 per cent RH also decreased, but not in the same amount. No significant change in autoclave expansion, except possibly a slight increase, took place in bars stored at 10 per cent RH.

The difference in behavior between mortar bars stored at 50 and 100 per cent RH, in which the former bars shrank and the latter expanded, prompted another series of tests to determine whether storage at 50 per cent RH, accompanied by wetting and drying, would produce expansion in "unsound" mortar bars. The

conditions and were then immersed in water for 1 hr; on being removed from the water they were again stored at 50 per cent RH. The procedure of wetting for 1 hr once a week was continued, and the length of the bars before and after immersion was recorded. Results are presented in Fig. 4, the average value of measurements of the two bars of each set being plotted.

All the bars shrank appreciably in the first week, the amount exceeding 0.1 per cent. The bars stored without wetting continued to shrink, but length became fairly stable after about 10 weeks at approximately 0.15 per cent less than the

original length. Immersion of the bars in water caused them to expand, but subsequent shrinkage on drying produced greater decrease in length than that of the bars stored without wetting. After 1 year the shrinkage of the wetted bars was about 0.19 per cent of the original length, compared with 0.15 per cent for bars stored without wetting.

DIMENSIONAL CHANGES OF BRICKS

Shrinkage or expansion of masonry may conceivably result not only from dimensional changes of mortar but also from changes in bricks. The reasons for shrinkage of concrete as it ages are reasonably well understood (2,15); as a concrete unit cures and dries after it is formed, it shrinks and may be placed in a wall while still possessing a large potential of shrinkage. The shrinkage of the piers of concrete bricks laid in "sound" masonry cement mortar (Fig. 2) clearly can be attributed, at least in part, to movements of the bricks.

Clay and shale bricks usually expand as a result of absorption of moisture from the atmosphere after they are removed from the kiln (16,17). The rate and amount of expansion depend on the particular material of the brick, the temperature of firing, and the humidity conditions in which the brick is subsequently stored. In many instances expansion of the order of 0.05 per cent of the original length takes place within 6 months, and has continued for years. The amount of expansion on autoclaving of clay bricks has not been found useful as a basis for estimating their probable future expansion under natural conditions of exposure, owing to the poor correlation between autoclave and natural expansions (17).

Many instances of cracking of brick walls from the expansion of clay bricks have been recorded in recent years (3,18); significantly, these failures appear to re-

semble closely those in which cracking had been attributed in other studies to expansion of mortar.

In an attempt to determine the extent of expansion of the clay bricks used in the first series of piers, four of them left over from the construction and which had subsequently been stored in the laboratory for over a year, were heated to a temperature of 1600 F with the object of restoring them to kiln-fresh condition. The bricks were then fitted with reference plugs for a Whittemore gage and were stored under the following conditions: in air at 73 F and 50 per cent RH; in air at 73 F and 10 per cent RH; in uncontrolled "room" air; and immersed in water. After 10 months the bricks had expanded respectively 0.017, 0.009, 0.022, and 0.047 per cent of the original length, and the expansion was continuing. It is doubtful that these expansions correspond in amount to those which took place in the bricks of the piers for similar conditions. A recent study (19) has indicated the difficulty of restoring ceramic materials which have undergone moisture expansion; the water which has entered the glassy phase of such materials (and thereby caused the expansion) is very difficult to remove and reheating many times to a high temperature is sometimes necessary to restore a material to its condition before moisture expansion occurred.

PERMISSIBLE DIMENSIONAL CHANGES OF MASONRY MATERIALS

In normal service, dimensional changes of masonry materials cannot be avoided; even if they are absolutely stable in all other respects, all materials will respond to temperature changes by expanding or contracting. In addition, as described earlier, some materials by their nature tend to expand irreversibly and others to shrink irreversibly; there may also be short-term expansion or contraction sim-

ply from response to changes in relative humidity of the atmosphere or to wetting and drying of the material. Dimensional changes may also result from chemical reactions or from freezing and thawing. In a sense, therefore, no masonry material is absolutely "sound"; and difficulty may arise when materials undergo dimensional changes too great to be accommodated by the normal methods of construction.

When masonry is free to move in any direction without restraint, dimensional changes are probably of little consequence, but when restraint is imposed harmful stresses may be set. To some considerable extent, therefore, the design of a structure has a bearing on the effects of dimensional changes of masonry. Not only the amount of dimensional change but also the rate of change should affect the result, as well as the ability of materials, through properties of elasticity or flexibility, to accommodate movement. More study of these factors appears to be necessary. It has been noted (20) that the theoretical expansion that might result from a moderate rise in temperature in a long brick wall might be expected to cause cracking if there were no expansion joints to accommodate the movement. Actual experience has not borne this out, since many long walls exposed to severe temperature changes over many years of service have shown no cracks attributable to thermal effects. "The reason for this apparent contradiction of the theory has not been determined; it may be due to compensating movements of the masonry units and mortar, to the compressibility of the mortar, or to a combination of several factors" (20).

To establish a limit on the amount of movement in masonry or masonry materials that will ensure "soundness" of a structure (freedom from cracking or bulging) does not appear possible at the present stage of the understanding of dimensional changes of masonry.

SUMMARY AND CONCLUSIONS

A brief review of the causes of dimensional changes in brick masonry has shown the importance of dimensional changes in bricks themselves on the behavior of the masonry. Because of their considerable influence the main object of the laboratory study described in this paper—to determine the influence of mortar, particularly that of high autoclave expansion, on the dimensional changes of brickwork—could not be accomplished. The dimensional changes of the first piers studied appeared to be influenced by two factors operating simultaneously, expansion of the clay bricks and contraction of the mortar. The brick expansion would be expected to be equal in amount in all piers exposed to the same condition, but would vary in rate and amount depending on the condition of storage. The behavior of a particular mortar would be expected to be influenced by its composition; the rate and amount of shrinkage of the mortar would also depend on the storage condition. For a certain mortar the period of continuing shrinkage may be prolonged, having the effect of "canceling out" the expansion of the brick over that period, whereas lesser shrinkage in another mortar may be more than offset by the brick's expansion, resulting in a net increase in the dimension of the brickwork.

The possibility of expansion of masonry owing to long-term hydration of magnesia in mortar has been considered. Masonry mortars containing magnesia, introduced in particular by the use of normally hydrated dolomitic lime, have been employed for many years in the Toronto area of Ontario, apparently without having given rise to problems of harmful expansion of masonry. Similar experience has been obtained with the use of dolomitic limes in Great Britain. Few records of instances of damage to brickwork attributed to expansion of mortar from hydration of magnesia are

available, and these few apparently have not taken account of the possibility that damage resulted from the expansion of brick rather than mortar.

Results obtained in this study indicate that the amount of expansion of masonry mortars, when autoclaved, does not provide a useful means of assessing the behavior of mortar under natural conditions of aging. The latter varies with the relative humidity of the air in which the mortar is stored. Factors affecting the amount of autoclave expansion of mortars have been reviewed; and composition of the mortar is important in this regard. Considerable change may take place in the amount of autoclave expansion of mortar bars as they age, but the extent of change depends on the relative humidity of the air in which they are stored.

The problem of establishing limits of movements of masonry to ensure freedom from cracking or bulging has been discussed briefly. No simple measurement of the length changes of individual materials can provide a solution, however, because many other factors influence the results. Not only is the amount of movement of the masonry important, but there is a strong possibility that the rate of dimensional change also has its effect. Conditions of service and the design of a structure are undoubtedly important as well.

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DISCUSSION

MR. W. H. KUENNING.¹—These data are very interesting. Does the author conclude that the kind of disruptive expansion under consideration is always the result of expansion of brick rather than unhydrated magnesia in the mortar, or only in some cases? Are there still factors involved in such expansion which are not completely understood?

MR. T. RITCHIE (*author*).—The evidence available at present indicates that disruptive expansion of brickwork does

not occur because of magnesia in mortar. There is strong evidence, however, that expansion of clay bricks is an important cause of cracking of brickwork. Unfortunately in the few recorded instances of cracking which have been attributed to expansion of mortar because of magnesia in it, information is not available to indicate whether expansion of the brick may have caused, or contributed to, the problem; or if the mortar was indeed involved, whether its expansion occurred from mechanisms not involving magnesia, such as those described in references (4) and (5).

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