

## A THEORETICAL RECONSIDERATION OF CERTAIN ASPECTS OF BRICK EXPANSION

R BOWMAN Experimental Scientist  
CSIRO Division of Building Research, Melbourne, Australia.

**ABSTRACT** Studies of advanced ceramics and other materials have identified several mechanisms which might contribute to brick growth, commonly referred to as moisture expansion. The major mechanisms that theoretically might contribute to permanent brick expansion and certain phenomena occurring on desorption are discussed. The survey is somewhat speculative and is intended to provoke a lively discussion of the subject. It will hopefully initiate further investigations of brick expansion and lead to improved methods of examination and assessment.

### 1. INTRODUCTION

Insights obtained from studies (1-7) of the fracture mechanics of advanced ceramic materials have identified the need for a reconsideration of the topic of moisture expansion, since it appears that moisture activates at least two mechanisms which contribute significantly to total brick expansion.

Acoustic emission studies (5,6) have indicated that thermally induced microcracking occurs on cooling porcelain, due to radial tensile stresses associated with quartz particles. This microcracking which must contribute to expansion occurs (8) prior to the divergence of the thermal expansion curves of brick specimens cooled in air and under vacuum. While such microcracking can occur in the absence of water vapour, crack growth studies (3,4) have confirmed that fracture occurs more readily in corrosive environments.

It has long been accepted (9) that moisture expansion is due to chemical reactions between moisture and body constituents such as amorphous aluminosilicates, amorphous silica and glass. With the knowledge that other mechanisms (10) also contribute to total brick expansion, it is necessary to determine the potential extent and duration of their contribution so that an optimum conditioning treatment can be agreed upon for the assessment of past expansion and for the prediction of future expansion (11).

The assessment of past expansion and the prediction of future expansion of aged bricks generally requires that the bricks are refired. Since it is rarely possible to completely reverse brick expansion by desorption unless sufficient heat is applied to heal microcracks as well, it can be argued that we should not call the total expansion that a brick undergoes moisture expansion. Several other aspects pertaining to cracking, expansion and refiring are discussed in this paper to provide an alternative frame of reference to promote a reconsideration of moisture expansion.

### 2. A RE-EVALUATION OF THE DEFINITION OF MOISTURE EXPANSION

A simple definition of moisture expansion is that expansion caused by the chemical adsorption of water vapour on the internal amorphous silicate surfaces that may be present in a clay product (12). The predominant part of this expansion is due to a reaction with the highly disordered aluminosilicate structures derived from the breakdown of clay minerals. Reaction with glassy phases (also amorphous), formed by partial melting of body components at the

higher firing temperatures, amorphous silica and  $\gamma$ -alumina may also contribute to the expansion but to a lesser extent. The situation is not necessarily the same when bodies are expanded in an autoclave under a pressure of steam.

It should be made clear that the physical adsorption of water, which can be removed by a vacuum or heating to 110°C, does not play a role in moisture expansion (12). However, it has also been reported (8) that a shrinkage equivalent to about 3% of the total expansion was recorded when a specimen which had been exposed to the atmosphere for approximately 2 years was subjected to 27 hours in vacuo. This phenomenon can be explained by the reversible dimensional changes a brick undergoes due to wetting and drying (13). As a reversible phenomenon, it is not considered to contribute to permanent moisture expansion, although it is undoubtedly a component of the total measured expansion. It is significant that no shrinkage was observed (8) when a sample which had been exposed to the air for only a few weeks was held in vacuo for 72 hours. This suggests that this reversible expansion would not occur prior to the testing of bricks for moisture expansion.

Although the permanent expansion of a product is commonly termed moisture expansion, it is appropriate to consider what other mechanisms might contribute to the measured expansion of bricks whose datum is established immediately after leaving the kiln, before being left to lie on the ground in exposed external conditions. The measured expansion might be expressed as

$$e_M = e_{ME} + e_{TS} + e_{AL} + e_{SE} + e_{SA} + e_{FD} + e_{RE} \quad (1)$$

where  $e_M$  = measured expansion,  
 $e_{ME}$  = expansion due to moisture expansion,  
 $e_{TS}$  = expansion due to relief of thermal stresses,  
 $e_{AL}$  = expansion due to externally applied loads,  
 $e_{SE}$  = expansion due to salt expansion,  
 $e_{SA}$  = expansion due to salt attack,  
 $e_{FD}$  = expansion due to frost damage, and  
 $e_{RE}$  = reversible expansion due to physically adsorbed water.

In laboratory studies of natural moisture expansion, the conditions are such that one can normally assume that  $e_{AL}$ ,  $e_{SE}$ ,  $e_{SA}$  and  $e_{FD}$  will be negligible. In such cases the measured expansion will be principally due to a combination of moisture expansion and relief of thermal stresses.

There are always thermal stresses present in heterogeneous ceramic products due to the different thermal expansion coefficients of the phases present, as a result of phase transformations and due to crystalline anisotropy. The residual stresses are particularly dependent on the effects of the firing cycle and grain size on the microstructure. The crystalline phases of silica (quartz, cristobalite and tridymite) cause the severest thermal stresses in most silicate ceramics due to the volume changes which accompany their inversions and conversions, as well as the differences in expansion between the glass and crystalline phases. There are generally three types of fracture associated with quartz grains. They are fracture through the quartz grains (internal), fracture at the grain matrix interface (peripheral), and fracture extending into the glassy phase (matrix) (14).

Acoustic emission analysis has been used extensively to study thermally induced microcracking (5,6), as well as the propagation of existing cracks under mechanical stress (7). Acoustic emission and the total expansion (10) have been measured on the same bodies, but there does not appear to have been any attempt to use acoustic emission to study the thermally induced microcracking and subsequent expansion of bodies cooled in vacuo. Stevens and Holland (8)



performed a number of experiments to separate moisture expansion from thermal movement during the cooling of specimens. They found that there was negligible expansion of specimens which had been cooled from 800°C in vacuo, when they were maintained in vacuo at room temperature for 400 hours. It is thus evident that a vapour capable of initiating cracking is required for the relief of residual thermal stresses. As such the expansion due to the relief of thermal stresses could be considered to be expansion due to environmental stress corrosion.

Stress corrosion cracking occurs in most brittle materials due to the presence of water vapour interacting with the crack tip. The significance of this reaction and the deleterious effect it has on properties is most pronounced in oxide ceramics and silicate glasses, and consequently the phenomenon has been well studied (1). The structure of a structural clay product is too complex, too poorly crystalline and subject to too many variable characteristics to permit studies which could reliably ascertain how much expansion is due to stress corrosion and how much is due to moisture expansion. Nevertheless, the distinction between the mechanisms is important because the expansion due to moisture expansion is theoretically more readily reversible on reheating than expansion due to the relief of thermal stresses.

Expansion due to externally applied loads,  $e_{AL}$ , is primarily a function of the texture of the ware and the loads which might be applied (2,15). Compact vitrified bodies, with a large vitreous phase and relatively fine grain size, behave as perfectly elastic bodies in that there is no permanent residual deflection if an applied loading is removed. Such ware ruptures in a brittle manner without any appreciable plastic flow. Porous bodies with a heterogeneous texture and large grain size behave differently in that the deflection-load relationship is a straight line only for very weak loads. This material no longer has a defined characteristic modulus of elasticity and if the load is removed at any point, there is a permanent residual deflection. This phenomenon repeats itself with successive loadings, each operation resulting in further permanent residual deflections. This behaviour is attributed to the heterogeneous texture of the ware which prevents the coarse grains from reengaging in their former positions after they have been displaced. Porous products of finer grain size behave in a manner intermediate between the two preceding cases.

Relatively little has been published about the phenomenon of salt expansion. However, it is known (16) that the absorption of very small quantities of a salt solution into the pores of a ceramic material, which is then dried, may result in an irreversible expansion approximately equal in magnitude to moisture expansion. A mechanism for this expansion still has to be postulated. The expansion produced is not determined solely by the quantity or type of salt introduced but also by the manner of its introduction; a series of small absorptions each followed by drying produces a greater effect than does a single absorption of the total amount. If the salt is then extracted, the size of the piece remains unaltered. Moreover, the effect of firing temperature is opposite to that for moisture expansion; the harder fired the piece, the greater the expansion caused by the absorption of the salt despite the decrease in the available pore volume. Very easy-fired pieces sometimes contract. Although the salt expansion of a piece fired at a low temperature is small compared with its moisture expansion, a piece fired at a high temperature may have a salt expansion much greater than its moisture expansion. It was also reported that there were negligible expansions of salt-treated porous glass compacts but definite size increases with salt-treated crystalline materials.

Conversely, it has been shown that lower fired bodies are more susceptible to salt attack than higher fired bodies. Salt attack is characterised by damage resulting from the crystallization of soluble salts in brick pores. Good



correlations have been observed (17) with both cold water absorption and Rockwell Hardness with respect to resistance to salt attack. As firing temperatures are increased, the cold water absorption decreases, the Rockwell Hardness increases and the salt attack resistance increases. Increases in porosity due to additions of combustible materials increases the cold water absorption but does not significantly affect the salt attack resistance. Thus products having a high susceptibility to salt attack would be expected to have a low susceptibility to salt expansion, and vice versa.

The existence of subcritical events during the stressing of ceramic materials before failure has been clearly demonstrated (7) by acoustic emission data. It is also well established that subcritical crack growth in vitreous systems is the origin of static fatigue effects, and that this phenomenon is environment dependent (1,3,4). There is, however, little available information on the response of ceramics in environments other than water or water vapour. Slow crack growth measurements have been made (4) on a number of different ceramic materials and the results indicate the influence of pH of aqueous solution and the differences in performance between different materials. At low crack growth rates, the influence of gross corrosion becomes evident, in particular the leaching of the glass phase in debased materials.

The influence of corrosive environments on the expansion of ceramic wares has not previously been adequately considered. The observed phenomenon of salt expansion may possibly be related to the presence of a leaching phase. However, there is another family of surface-active materials that influence fracturing, termed surfactants (18,19). These are proving especially useful in oil reservoir flooding, drilling and hydraulic fracture, while they hold implications for several other areas. Many possible mechanisms for surfactant strength reduction have been proposed, but the theoretical approach is impeded by the measurement of certain parameters being beyond our current analytical capabilities. However, it appears that highly adsorptive surfactants produce the best results.

Surfactant-induced crack branching was first observed in crack propagation tests using natural and synthetic quartz immersed in a variety of dilute aqueous solutions of various surfactants. In these studies it was observed that there was a high incidence of multipath cracking in the fluorochemical environments associated with certain solutions, and that there were significant reductions in the stress required to initiate and propagate a crack in quartz compared to levels required in the ambient atmosphere. On the other hand, distilled water produced only moderate strength reductions and cracks propagated in the presence of the ambient atmosphere or distilled water rarely displayed branching.

Although highly basic or acidic solutions may affect crack propagation, the effect was not apparent at the nearly neutral pH values used in the studies. When the number of charged surface sites on the crack surfaces of each sample and the number of adsorbable species in each environment were compared, it was evident that there were fewer available adsorbable species than charged sites in the distilled water, while there were significantly more adsorbable species than charged sites in the powerful surfactants. The greater the degree of adsorption, the greater the reduction in surface energy of the quartz. If surface energy is reduced, the stress required to propagate a crack is also reduced. Another process which could be at work is the hydrolytic weakening of silanol bonds.

The physical mechanism of weakening appears to be reduction of the surface free energy of the materials by adsorption of the surfactant on the test material, although the mechanism that produces the branching effect is not clearly understood. However, it has been suggested that the presence of surface active



chemicals has the effect of increasing the velocity of crack and fracture propagation. The major difficulty in delineating a mechanism for this effect is determining the important chemical and hydrodynamic parameters: it is difficult to know the precise chemical environment at the crack tip.

It is known that fluorine minerals frequently occur in clays and that they readily volatilise as silicon tetrafluoride on firing contributing to air pollution. Such gases are known to cause corrosion in ceramic bodies and it is probable that some of these gases will condense within the cooling ware. Could such pollutants generate a fluorochemical environment conducive to surfactant strength reduction of the thermally-stressed quartz particles?

### 3. PREDICTION OF THE EXPANSION OF AGED BRICKS

Two basic test methods have been proposed for determining the residual expansion of aged bricks. The first involves refiring at a temperature high enough to ensure that desorption occurs before they are submitted to a steaming treatment. The other method involves direct steaming of the aged bricks. It has been stated (20) that the only drawback to the latter method is that the exact age of the bricks needs to be known. However, a close examination of the data presented indicates that there are other limitations, and that extensive developmental work is necessary before a universal relationship can be established. It is felt that while there may be a good correlation between short term natural expansion and steaming at 100°C for a few hours, steaming of bodies that have already taken out much of their natural expansion may result in expansions greater than would be obtained naturally (21).

The former method is based on the assumption that the refired bricks will have been returned to their kiln-fresh state prior to steaming. However, it is well known that the amount of contraction which occurs on reheating is always somewhat less than the total expansion which has occurred. This contraction could be expressed by the equation

$$C_M = C_{ME} + C_{CA} + C_{SC} - e_{TD} - e_{FE} \quad (2)$$

where  $C_M$  = measured contraction on reheating,  
 $C_{ME}$  = contraction related to moisture expansion component,  $e_{ME}$ ,  
 $C_{CA}$  = contraction due to crack annealing and further sintering,  
 $C_{SC}$  = contraction as a result of salt catalysis,  
 $e_{TD}$  = expansion due to thermal displacement, and  
 $e_{FE}$  = expansion due to further expansion associated with recommencement of moisture expansion, relief of thermal stresses, etc.

Several studies have investigated the effects of refiring on the removal of expansion from various silicate products. It has become evident that the extent to which any given heat treatment will return a body to its original dimensions appears to depend not only on the temperature to which it is heated but also on the duration of this heating, and on the temperature at which it was originally fired. In some cases (22) it has proved impossible to remove expansion without heating to temperatures approaching those at which the bricks were originally fired. At these temperatures, further firing shrinkages occur and the two effects become confused.

There have been several thermogravimetric investigations of the kinetics and thermodynamics of dehydration of amorphous silica, silicates and aluminosilicates. However, there have only been a few thermogravimetric investigations of the dehydration of the highly disordered rehydrated aluminosilicate structures with particular respect to the recovery of moisture



expansion. Certain clay minerals, particularly the illites and montmorillonites may regain some hydroxyl water as well as adsorbed water on standing at room temperature after being dehydrated by heating. The temperature at which the dehydroxylation of a clay mineral occurs is related to its structure, exchangeable cations and degree of crystallinity. The amount of rehydroxylation is a function of the firing temperature and the environment to which the fired materials are exposed. The rehydroxylation of heated clays has resulted in the development of new mineral forms which have been found to undergo dehydroxylation at somewhat lower temperatures than during the dehydroxylation of the original clay (23). On the basis of the published literature (24) one might expect that the dehydroxylation of aged bricks should be completed below 800°C. Any further shrinkage obtained by heating above this temperature could be considered to be due to crack annealing and sintering. Acoustic emission studies have shown<sup>5</sup> that microcrack healing of porcelain begins above 850°C.

The presence of soluble salts in specimens could also affect the reactions occurring on refiring. These salts might be expected to act as catalysts (25-27) and to significantly reduce the temperature necessary for sintering to occur. While neither the expansion or damage caused by soluble salts can be reversed by their removal, their presence in specimens which are to be refired, would be expected to result in sintering and a consequent shrinkage,  $c_{SC}$ , which might be either greater or less than any expansion originally due to the salts.

It has long been known (15,28) that the thermal expansion of a heterogeneous aggregate of anisotropic crystals is often difficult to predict and often shows evidence of hysteresis on refiring. When such a material is heated, the grains expand differently in different directions and push each other apart with the resultant formation of open spaces. When the aggregate is cooled again, these openings tend to close but never quite retrace their first movements, leaving some spaces unfilled. There is thus a permanent change in dimensions which may be regarded as expansion due to thermal displacement,  $e_{TD}$ . This expansion is particularly comparable to expansion due to externally applied loads,  $e_{AL}$ , since both expansions are related to the modulus of elasticity of the ware and are dependent on the texture of the ware. The capacity of such samples to progressively dislocate themselves under the action of the forces to which they are submitted provides a perfectly natural explanation for the phenomenon of quartz and cristobalite disappearance. This phenomenon is related to the apparent absence of quartz and cristobalite in the dilatometric curves of ceramic bodies. The reduction of the dilatometric effects of these silica varieties at the time of their inversions is due to microcracking resulting from the thermal stresses associated with the inversions.

Stevens and Holland (8) demonstrated how the initial expansion begins, measurably, at about 400°C during cooling in atmospheric conditions. There must therefore be some secondary expansion,  $e_{FE}$ , which negates some of the contraction resulting from refiring. This expansion is not measured and its magnitude will depend on the datum selected for the measurement.

The hypothetical nature of the above considerations indicate that further investigations are needed in this field, since the refiring of specimens is the primary means of estimating either the potential future expansion of ware or the expansion which has already taken place.

#### 4. SUMMARY

In the author's opinion, moisture expansion does not account for total brick expansion and consultants investigating cases of masonry failure related to brick expansion have not always been aware of all the factors which can cause

brickwork to grow or the bricks in a wall to expand. Various phenomena may contribute to this expansion and need to be considered. Phenomena which might occur on refiring and autoclaving also need to be further studied, in order to establish and improve standard test methods and to better understand the causes of masonry failures.

## 5. REFERENCES

- (1) KINGERY, W.D. 'Introduction to Ceramics', John Wiley and Sons, New York, pp. 768-812, 1976.
- (2) EVANS, A.G. and FABER, K.T. 'Crack-Growth Resistance of Microcracking Brittle Materials'. Journal of the American Ceramic Society, 67, pp. 255-260, 1983.
- (3) HIBINO, Y., SAKAGUCHI, S. and TAJIMA, Y. 'Crack Growth in Silica Glass Under Dynamic Loading'. Journal of the American Ceramic Society, 67, pp. 64-68, 1983.
- (4) BYRNE, W.P.R., HANNEY, M.J. and MORRELL, R. 'Slow Crack Growth of Oxide Ceramics in Corrosive Environments'. Proceedings of the British Ceramic Society, 32, pp. 303-314, 1982.
- (5) KIRCHHOFF, G., POMPE, W. and BAHR, H.A. 'Structure Dependence of Thermally Induced Microcracking in Porcelain Studied by Acoustic Emission'. Journal of Materials Science, 17, pp. 2809-2816, 1982.
- (6) FRIDEZ, J.D., CARRY, C. and MOCELLIN, A. 'Acoustic Activity in a Quartz Containing Porcelain Subjected to Low Rate Thermal Changes'. Ceramics International, 8, pp. 144-150, 1982.
- (7) COOKE, R.G. 'Microstructure and Failure Probability of Coarse Structured Ceramics'. Proceedings of the British Ceramic Society, 32, pp. 171-180, 1982.
- (8) STEVENS, T.J. and HOLLAND, A.E. 'Moisture Expansion of Fired Clay: Experiments in Controlled Environments'. Journal of the Australian Ceramic Society, 8, pp. 1-5, 1972.
- (9) COLE, W.F. 'The Contribution of CSIRO to the Study of the Moisture Expansion of Bricks with Particular Reference to Victorian Bricks'. Journal of the Australian Ceramic Society, (in press).
- (10) CROOK, D.N., CLARKE, L.N. and DONALDSON, R. 'A Study of Fired Kaolinite-Muscovite-Quartz Bodies: 11. Scanning Electron Microscopy, Acoustic Emission and Moisture Expansion'. Journal of the Australian Ceramic Society, 20, pp. 13-19.
- (11) BOWMAN, R. 'The Need for Determining the Relevant Moisture Expansion of a Brick'. Proceedings 11th Australian Ceramic Conference, pp. 425-433, Sydney, Australia, 1984.
- (12) BROWNELL, W.E. 'Structural Clay Products', Springer-Verlag, New York, p. 203, 1976.
- (13) BAKER, L.R. and JESSOP, E.L. 'Moisture Movement in Clay Brickwork: a Review'. International Journal of Masonry, 2, pp. 103-109, 1982.



- (14) WARSHAW, S.I. and SEIDER, R.J. 'Triaxial Porcelains - Strength and Microstructural Relations'. Ceramic Microstructures (edited by R.M. Fulrath and J.A. Pask), John Wiley and Sons, New York, pp. 559-571, 1966.
- (15) MUNIER, P., 'Influence of the Texture of Ceramic Products on Thermal Expansion. The Effect of Quartz and Cristobalite Evaporation'. Silicates Industriels, 15, pp. 67-76 and 91-95, 1950.
- (16) NORRIS, A.W., VAUGHAN, F., HARRISON, R. and SEABRIDGE, K.C.J. 'Size Changes of Porous Ceramics Caused by Water and Soluble Salts'. Proceedings 6th International Ceramic Congress, pp. 63-76, Wiesbaden, West Germany, 1958.
- (17) ZSEMBERY, S. and PHILLIPS, D.N. 'Assessment of the Salt Attack Resistance of Fired Clay Bricks'. Journal of the Australian Ceramic Society, 19, pp. 8-11, 1983.
- (18) DUNNING, J.D. 'Surfactants'. Chemtech, 10, pp. 356-359, 1980.
- (19) DUNNING, J.D. 'Surfactants Revisited'. Chemtech, 14, pp. 46-50, 1984.
- (20) ZSEMBERY, S. 'Developments in the Determination of Moisture Expansion of Clay Bricks'. Proceedings 9th Australian Ceramic Conference, pp. 328-338, Sydney, Australia, 1980.
- (21) COLE, W.F. 'Fundamental Causes of Moisture Expansion'. Proceedings 9th Australian Ceramic Conference, pp. 114-119, Sydney, Australia, 1980.
- (22) WATERS, E.H., HOSKING, J.S. and HUEBER, H.V. 'Tests for Potential and Past Moisture Expansion of Ceramic Building Units'. ASTM Bulletin No. 245, pp. 55-59, 1960.
- (23) JONAS, E.C. and GRIM, R.E. 'Differential Thermal Analysis Using Controlled Atmosphere'. The Differential Thermal Investigation of Clays (edited by R.C. MacKenzie), Mineralogical Society, London, pp. 399-402, 1956.
- (24) MACKENZIE, R.L. 'Simple Phyllosilicates Based on Gibbsite- and Brucite-like Sheets'. Differential Thermal Analysis, Vol. I. Fundamental Aspects (edited by R.C. Mackenzie), Academic Press, London, pp. 497-537, 1970.
- (25) HELLER-KALLAI, L. 'Reactions of Salts with Kaolinite at Elevated Temperatures'. Clay Minerals, 13, pp. 221-235, 1978.
- (26) BOSSI, A., LEDFANTI, G., MORETTI, E. and GIORDANO, N. 'Morphological and Structural Effects of NaOH Added to Silica'. Journal of Materials Science, 8, pp. 1101-1109, 1973.
- (27) BARTHOLOMEW, R.F. and KOZLOWSKI, T.R. 'Alkali Attack of Glass Surfaces by Molten Salts'. Journal of the American Ceramic Society, 50, pp. 108-111, 1967.
- (28) AUSTIN, J.B. 'Thermal Expansion of Nonmetallic Crystals'. Journal of the American Ceramic Society, 35, pp. 243-253, 1952.