A STUDY OF THE CRACKING BEHAVIOUR OF FLOOR TILE CLAYS

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INTRODUCTION

Surveys of dust-pressed floor tile manufacturing losses have been carried out by CERAM Research at four UK tile factories. These surveys demonstrated that losses due to cracking were high and variable and constituted a major manufacturing problem.

Losses ranged from 4-15% with some designs showing losses as high as 50%. (TABLE 1) The results were compatible with the average annual loss of 15% found in a detailed raw material analysis also carried out by CERAM Research in 1979 as part of an energy audit.

Table 1. Floor tile process loss

Factory	Cracking (%)
A	7.8
B	14.3
C	3.7
D	8.1

The factors responsible for these cracking losses were clearly unknown and although the cracking had only been observed after firing it was suspected that the stresses responsible had been introduced earlier in the process and could be related to the properties of the individual clays used. These losses represent several million pounds annually to the UK floor tile industry and their removal would represent a significant improvement in productivity for the industry.

The objectives of the research were therefore:

* To identify the factors responsible for the losses

* To apply this knowledge to reduce the losses

The research had the following stages:

(i) Determination of the point in the manufacturing process at which cracking actually occurred. This would be achieved by monitoring the progress of the tiles from pressing through drying and on to firing.

(ii) A study of the influence of the properties of the raw materials on cracking losses. Some 12 to 15 clays are used in the UK covering ball clays, china clays, marls and fireclays.

(iii) Recommendations in terms of preferred raw materials and processing in order to reduce cracking losses.

MONITORING OF BUNGS OF TILES

At two factories bungs of tiles were followed from the press, through loading on to the kiln cars, drying and firing. These bungs were carefully noted as to position and orientation on the trucks. The bungs were carefully examined for faults:

(i) Between drying and firing.

(ii) At the conclusion of firing.

Inspection of the faults arising at drying gave an under estimate of the total. Bungs placed at the corner of a truck could only be examined on two sides of the tile while bungs on the edge of a truck permitted only inspection of one side.

After firing the percentage cracking losses from factory to factory varied from 7.1% to 14.3%. Although difficult to confirm it was suspected that a considerable proportion of these losses were due to cracking at the drying stage. No significant correlation was obtained between the location of cracking damage and the position of the tile in the kiln.

Observations through ports in the sides of kilns using a water-cooled kiln periscope demonstrated that cracking in the edges of tiles had always occurred before red heat. No mineralogical changes have occurred at this temperature, only loss of water. This suggests very strongly that the cracks can be ascribed to drying.

In plastic making there is an excess of water when the piece is shaped, such that individual particles are separated by water. During drying excess water is removed and shrinkage to the extent of several per cent takes place to the stage where all particles are touching. As tiles are closely bunged in drying the edges of the pieces dry more quickly than the centres. The edge is brought into tension and if this exceeds the mechanical strength of the piece the edge splits.

At first sight it is difficult to invoke the same mechanism for the cracking of dust pressed tiles since the water content of the compact is less than the void space between particles. There appears to be no mechanism by which such a compact can contract during drying since all particles are already in contact.

To investigate this point further the size changes of tiles following ejection from the press and during uniform drying were determined. It was found that red and brown tiles did in fact exhibit a steady contraction during drying. (FIGURE 1). However, a further significant finding was that the grey and buff bodies showed an initial contraction followed by an expansion and then a final contraction to the dry state. (FIGURE 2). In this case under non-uniform drying a situation can be envisaged where the edges are trying to expand at the same time as the centre is contracting thereby again putting the edge of the tile into tension.

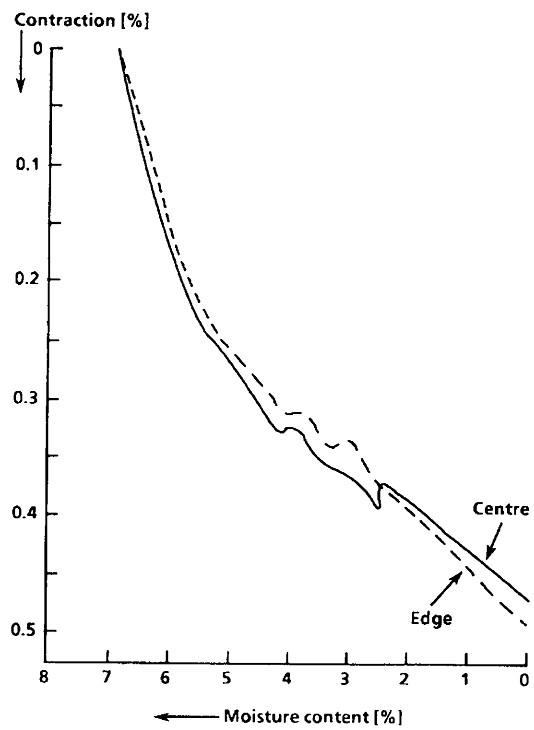

Figure 1. Drying contraction of red tile

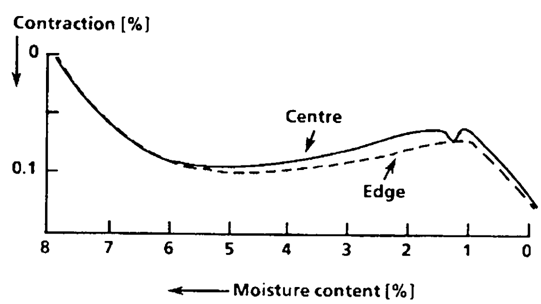

Figure 2. Drying contraction of buff tile

DRYING OF BUNGS OF TILES

Since stress development in the tiles is a consequence of non-uniform drying and the setting up of moisture gradients, the drying of bungs of tiles in a drier at 110°C was monitored. At selected intervals the tenth tile from the bottom of each bung was removed and pieces were cut from positions A and C (FIGURE 3) for measurement of moisture content. The difference in moisture content increased over a five hour cycle to approximately 3% for the red tiles and 4% for the buff tiles (FIGURE 4). This translates to maximum size differences of approximately 0.1%. (FIGURE 5). However, maximum stress for the two bodies occurs at different points in the drying cycle depending upon the size change characteristics. On this evidence therefore it was concluded that only by a better understanding of the properties of individual clays would it be possible to reduce the high level of production losses.

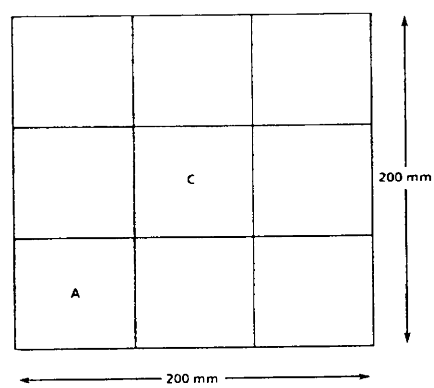

Figure 3. Positions of moisture samples

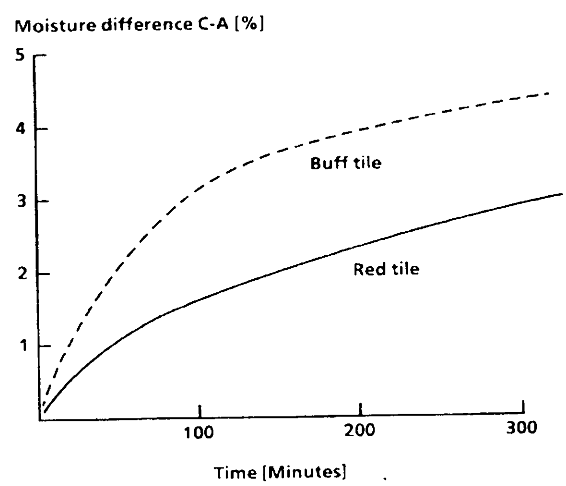

Figure 4. Moisture gradient C-A across tile in bung vs time of drying

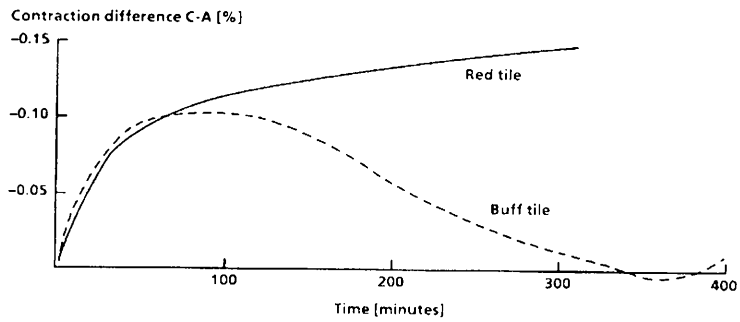

Figure 5. Contraction difference C-A across tile in bung vs time of drying

CHARACTERISATION OF CLAYS

The following twelve clays were examined:

- Ball clays
  - HVAR
  - Sanblend 55
  - Hymod KC
  - GR
- Red clays
  - KI
  - CSM4
  - Copshurst marl
- Core clays
  - Kaolin D'Arvor - France
  - Schmidt 501 - West Germany
  - Schmidt 1001 - West Germany
  - Bosaccio red - Italy
  - HVAPM - UK

and the following properties were determined:

(i) **Clays**

Chemical analysis (XRF)
Mineralogical Composition (XRD)
Differential Thermal Analysis
Particle size distribution

(ii) **Pressed compacts**

Size change on drying
Die spring
Density
Strength
Compaction ratio
Cracking potential

The objective was to relate some aspect of the physical and/or chemical properties of the materials to measured size changes of the pressed compacts on drying.

Granulates of the materials were prepared by spray drying deflocculated slip in a Niro spray dryer and both a 30 T and a 50 T press were used to prepare compacts at different pressures. Linear size changes were determined using bar specimens and a simple dial gauge assembly. The dial gauge was accurate to 0.002 mm on specimens 100 mm long.

Standard procedure was to place the specimens into polythene bags immediately after pressing until required. The specimens were then allowed to dry in air at room temperature with measurements of moisture content and size taken at suitable intervals.

Pieces formed by pressing expand on ejection from the die. This expansion is known as die spring. It is time dependent and the dryer the piece the more rapid the rate of expansion. The magnitude of the expansion also depends upon the moisture content of the compact and the pressing pressure. This die spring can be incorporated into the size change curves by taking the size of the die as the reference (zero point). Alternatively, when considering size changes as the source of stress the size of the specimen after ejection and on completion of die spring can be taken as the reference.

The size changes occurring with individual clays pressed at 8% moisture content and 15 MNm^{-2} pressure are compared in figure 6:

Essentially there are two types of size change curve -

* some clays exhibit a continuous shrinkage on drying;

* others show a contraction, expansion, contraction sequence;

which reflects the size change behaviour shown by commercial tiles.

The red clays - K1, CSM4, Copshurst Marl and Boscaccio clay tended to contract continuously after drying. The kaolin and ball clays displayed a pronounced period of expansion.

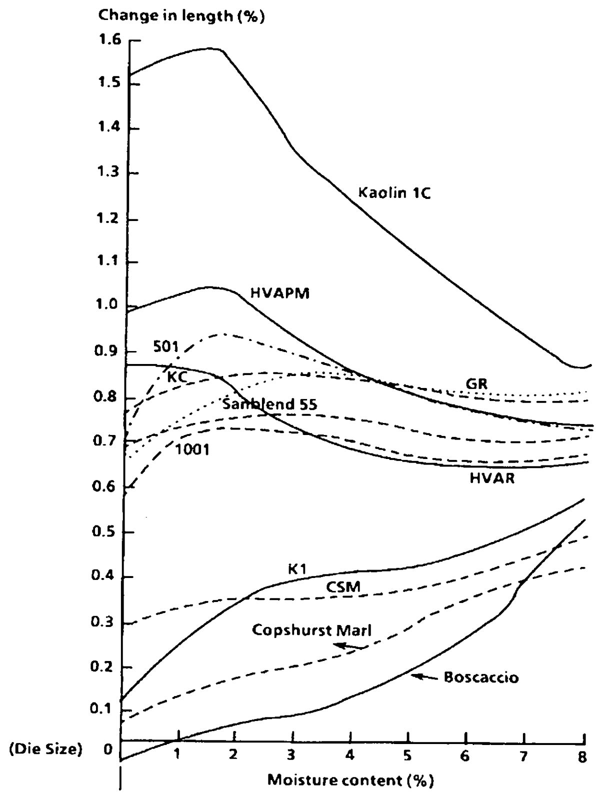

Figure 6. *Size changes on drying of dust pressed compacts*

A simple empirical test with 75 mm diameter disc compacts was used to assess cracking potential. The discs were placed between insulated cylinders and dried only from the edge, thereby simulating the drying of tiles in bungs. The experimental arrangement is illustrated in figure 7.

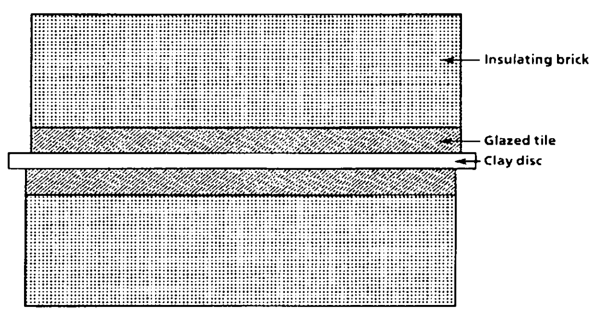

Figure 7. *Empirical drying test unit*

From the results it was apparent that there is no simple relationship between cracking and the extent of the size change. Ball clays HVAPM and HVAR cracked badly (maximum size change approximately 0.25%) - while the red clay CSM4 (size change 0.3%) - and the Boscaccio clay (size change 0.65%) were resistant to cracking. Size change, however, only establishes stress within the compact. Resistance to failure depends upon the strength and elasticity of the compact.

Elasticity was measured as the deflection under 3-point loading using an Instron 1195 testing machine at a cross head speed of 0.1 mm/minute. The results for four clays are shown in Table 2. These show that the good performance of the Boscaccio clay is a consequence of its high strength and elasticity. The success of the CSM4 clays relates to its high elasticity, whereas the ball clays (KI + HVAPM) have both low strength and elasticity despite their relatively low contraction on drying. However, it must be recognised that the stress generated is not simply a function of the total size change. Rapid size changes over narrow moisture ranges will be more likely to lead to stress failure.

Table 2. Factors influencing cracking

Clay	Dry Strength (N/mm^2)	Deflection to Fracture (mm)	Maximum Size Change (%)	Cracking Tendency
Bosaccio	13.0	0.60	0.65	Resistant to cracking
CSM4	5.7	0.69	0.30	Resistant to cracking
KI	8.1	0.40	0.51	Prone to cracking
HVAPM	2.5	0.33	0.25	Very prone to cracking

Figure 8 illustrates a typical sequence of contraction-expansion-contraction as a clay is dried progressively from approximately 8% moisture content. In the first stage (8-6%) noted with certain clays, the tile edges will be under tension and hence will have a potential for cracking. However, during stage II (6-2%, figure 8) the forces at the tile edge will become compressive and cracks will tend to close. Below 2% moisture, in the final stage of drying, the edge forces become tensile again and cracks will re-open. Such sequences of crack movement can be observed in practice.

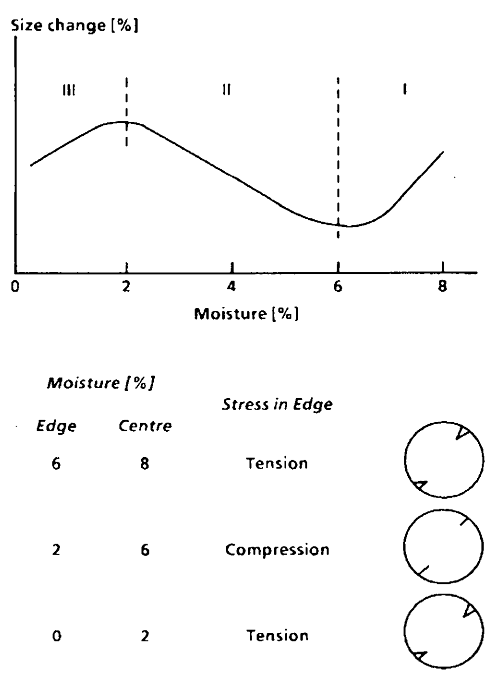

Figure 8. *The development of tensile and compressive forces during drying of a typical floor tile clay*

Since stress in the compacts was the result of size changes on drying, clays of opposed properties were mixed to determine:

* if the size changes could be opposed and thereby the total reduced;

* non-cracking compacts would result.

The approach is illustrated in Figure 9. Whereas clay D contracts by 0.5% on drying, clay A shows an expansion of approximately 0.25%. A blend of 67% clay A, 33% clay D was found to be resistant to cracking.

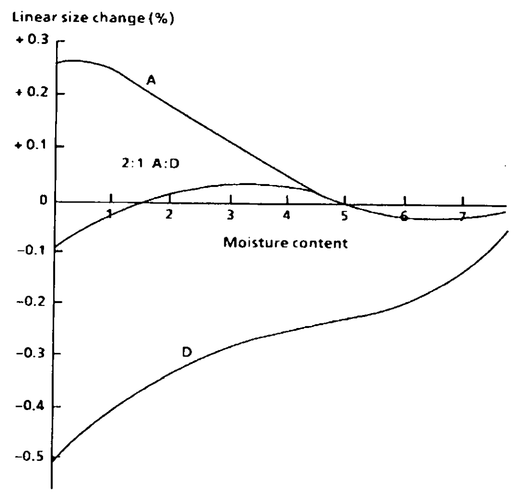

Figure 9. Composite size change on mixing two clays

THE DRYING PROCESS

From a theoretical point of view the expansion occurring with certain clays has been the main point of interest. A simple hypothesis is offered to explain the phenomenon. The removal of water during drying affects the water meniscus within the pore system and macroscopic changes in size are determined by the changing balance of expansile forces due to elastic recovery and die spring versus contraction forces due to surface tension.

To study further the hypothesis of elastic recovery, samples of clay exhibiting expansion on drying were stored over water in sealed containers and allowed to re-absorb moisture. They were then dried again and the sequence was repeated several times. Changes in sample length during this treatment are shown in figure 10. An expansion by 0.25% in the initial drying cycle was followed by further expansion to 0.5% when water was reabsorbed. Subsequent repetitions of the drying/reabsorption cycle resulted in an approximately stable situation, with a permanent expansion of 0.45-0.55% over the original, moist sample size.

For samples exhibiting contraction on initial drying, an expansion of 1.4% was found when water was reabsorbed. Further cycling confirmed a swing of $\pm$ 1.4% on drying and reabsorption of water (figure 11).

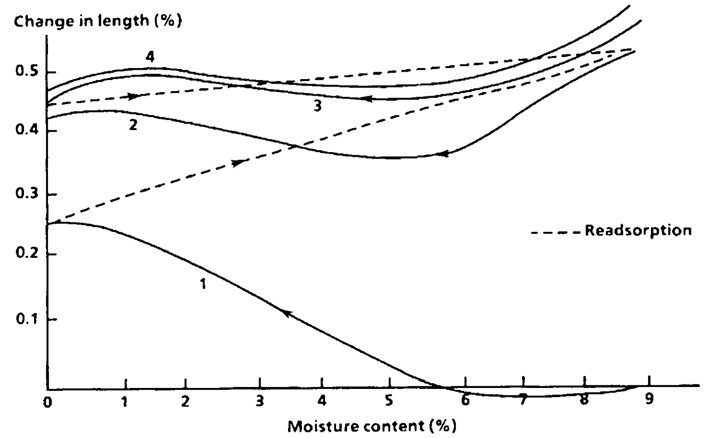

Figure 10. *Effect of readsorption of moisture on clay exhibition phase*

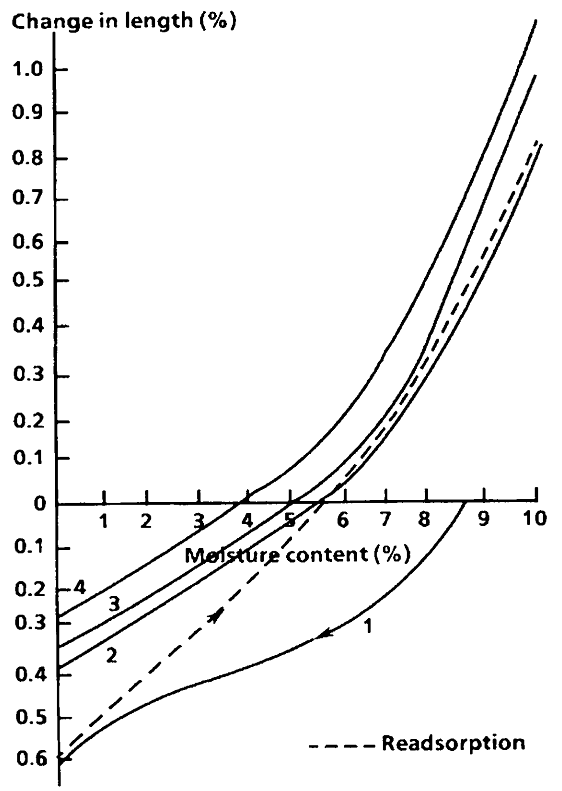

Figure 11. *Effect of readsorption of moisture on clay exhibiting contraction only*

These features can be regarded as supporting the contention that elastic recovery influences size change on drying but the balance between expansion and contraction forces determines whether or not an expansile period is shown in the size change curve.

The water swelling characteristics and high drying shrinkage of certain carbonaceous matter and montmorillonite are well known and could be responsible for pushing the expansion - contraction balance in certain clays in favour of contraction. This was demonstrated by adding bentonite to a clay showing high expansion (figure 12). The bentonite reduced the expansion observed during drying. XRD data demonstrated that the more kaolinitic clays displayed the greater expansile phase eg, Kaolin C and the ball clays, whilst the red clays showing only contraction on drying had the smallest kaolinite phase. It is postulated therefore that all clays compacted at low moisture levels are subjected to four distinct forces that influence size changes on drying:

* An initial contraction arising from an increase in suction pressure as water is removed and the curvature of the water meniscus in the pores increases.

* An expansile force related to the elastic recovery of loaded particles.

* A contractile force due to the high shrinkage of montmorillonite, siliceous gels etc.

* A final contraction due to the formation of solid bridges between particles resulting from the crystallization of soluble salts.

The shape of the size change curve is determined by the relative magnitudes of each of these forces.

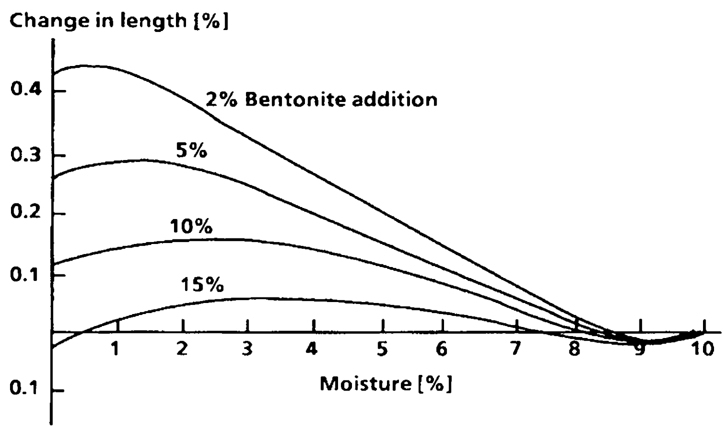

Figure 12. Effect of bentonite additions on size-moisture relationship

CONCLUSIONS

The study has shown that it is possible to classify the drying characteristics of clays based on the four mechanisms identified. Application of the results of these studies by UK industry has resulted in the introduction of different clays and new formulations leading in many cases to a significant reduction in cracking losses.