THE NEED FOR ESTABLISHING A MOISTURE EXPANSION CONVENTION FOR THE ANALYSIS OF TILING SYSTEM FAILURES

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ABSTRACT

Although most ceramic tiles undergo some moisture expansion in service and this may contribute to their lifting from concrete floors, several instances of such failure have been found to be predominantly due to poor tile fixing practices, the use of unsuitable fixatives, and tiling onto inadequately aged concrete slabs. However, the tile alone is often initially held to blame as it is alleged to have excessive moisture expansion. One must determine the expansion that has occurred since fixing in order to assess its contribution to any failure.

This paper will present a constructive approach to the handling and analysis of such failures, covering relevant aspects of site inspections, information gathering and laboratory investigations, and particularly featuring analyses of moisture expansion techniques and results.

INTRODUCTION

The draft ISO standard for determining the moisture expansion of glazed and unglazed tiles has no compliance limits. Instead, it has an informative annex which consists of the following two statements:

'The majority of glazed and unglazed tiles have negligible moisture expansion which does not contribute to tiling problems when tiles are correctly fixed.

With unsatisfactory fixing practices or in certain climatic conditions, moisture expansion in excess of 0.06% (0.6 mm/m) may contribute to problems.'

This paper considers the implications of this annex in the context of tiling system failures. It should be noted that the word 'convention' has been used in the title because of its two principal meanings. we need to convene an assembly to obtain general agreement on the accepted usage of a standard procedure for investigating and analysing differential movement failures, with particular regard to the influence of moisture expansion and the methods used to quantify it. We also need to provide practitioners with better guidance for the specification of tiles. This paper is thus offered as an initial discussion document.

BACKGROUND

Australia and South Africa have a long history of floor tiling system failures, generally referred to as lifting or pop-up failures. Such failures are due to differential movement between the tile and the substrate, and have often been attributed solely to moisture expansion of the tile, without due consideration of other factors. An Australian tile industry floor tiling failure task force analysed 112 case histories (Bowman, unpublished work, 1989) and concluded that there was no single cause for the failures, but it was likely that a combination of different factors had occurred in different failures. Other than structural building movement, the major factors contributing to the failures were summarised as:

(a) concrete drying shrinkage — dependent on the age of the slab at the time of fixing, the drying conditions to that time, the slab thickness, the concrete composition, and site construction practices;

(b) tile expansion — dependent on the age of the tile at the time of fixing and the moisture expansion potential of the tile (itself dependent on the mineralogy and chemistry of the raw materials and the processing of the tile);

(c) poor tile fixing practices — improper application of adhesive, poor bedding of tiles, inadequate preparation of substrate, unsuitable grout jointing, and inadequate installation of movement joints; and

(d) use of unsuitable fixatives.

It was also recognised that failures may often be triggered by climatic and environmental factors which apply further temporary stresses to the tiling system, e.g. stress due to thermal gradients as rapid heating or cooling occurs, high thermal expansion on hot days, and seismic events. Other factors, such as the presence of powdery alumina wash on the back of tiles, or water soluble adhesives on the back of mosaics (for attaching netting), may also be major causes of failure, but such failure types are believed to be relatively uncommon.

Although Bowman (unpublished results) has subsequently investigated over 100 pop-up failures involving Australian tiles, in only about 10% of these has the tile had what might be considered as significant expansion in service — greater than 0.03%. One can thus conclude that the majority of these failures are due to poor tile fixing practices, the use of unsuitable adhesives, and tiling onto inadequately aged concrete slabs.

In the United Kingdom there was an alarming number of pop-up failures in the post-war reconstruction period (late 1940s to mid-50s) coinciding with the greater use of concrete floors and the speeding up of construction due to the greater use of mechanical building aids (R. Harrison, Ceram Research, personal communication). The current low incidence of pop-up failures in the United Kingdom is attributed to:

(a) adequate maturing times for concrete bases (a minimum of six weeks of continuous air drying after concrete curing) before screeding and tile fixing; and

(b) widespread use of separating layer fixing techniques, although these systems are only effective when flexible movement joints are installed at appropriate positions.

However, in Brazil differential movement tiling system failures predominantly occur with glazed tiles on walls and are generally attributed to poor fixing practices (E. Mas, Ceramica Portobello, personal communication). Thus, when establishing a moisture expansion convention, the implications for tiles used in wall tiling systems must also be considered.

In Australia, the tendency for a greater proportion of locally manufactured tiles to fail has been attributed to either differences in the product as a result of the raw materials used, or to their higher moisture expansion potential due to the relative youth of the product, since imported tiles have had a chance to expand during transportation. However, since there have been instances of imported tiles, domestic tiles of negligible moisture expansion, dimensionally stable stones and terrazzos (which tend to shrink) lifting from concrete floors, there are obvious problems in apportioning responsibility in cases of failure. This situation has been compounded by the absence of a recognised standard for determining the moisture expansion of glazed tiles.

The Australian delegation to ISO/TC 189, Ceramic Tiles, stressed the need for the moisture expansion test to be extended to cover glazed tiles, since most Australian pop-up failures involved glazed tiles, and there was a need to exonerate those which had not contributed significantly to the failure. It had been recognised [1] that some glazed tiles have an expansion in excess of the (EN 155) 0.06% compliance limit required of unglazed tiles (those with a water absorption of between 6 and 10% for pressed tiles and greater than 6% for extruded tiles). However, where these and other tiles with higher moisture expansions have been successfully installed, should there be a compliance limit? ISO/TC 189 has decided no for a number of reasons.

Differential movement failures essentially occur when the rate of the movement between the tile and the substrate exceeds the ability of the adhesive to creep, although the degree of bond achieved is obviously an intrinsic element [2]. Thus, the amount of moisture expansion which occurs once the tile is installed and the kinetics of that expansion are the critical considerations when assessing to what extent the tile may have contributed to a failure. Since the 24-hour boil, which is used to induce expansion in the EN 155 and draft ISO/TC 189 test methods, is incapable of providing such information, there is evidently no basis for a compliance limit. However, what is required is a convention in order to ensure that the informative annex is interpreted and used sensibly, and particularly within the contexts of analysing failures and specifying tiles.

At this time there is scant data on the accelerated moisture expansion behaviour of ceramic tiles using the new ISO draft refiring procedure (a 500°C, 2 h soak which will also be used for conditioning glazed tiles prior to determining crazing resistance). There is also little published data on the natural expansion of individual products, or on the relationship between the expansion induced by a 24 h boiling treatment and natural expansion. The establishment of a convention is thus possibly premature. However, since we have been accumulating such data in Australia, we can offer the following for discussion, with the hope that the CERLABS member laboratories will ultimately have sufficient data to establish an international convention.

In order to resolve the problem of different 'experts' producing reports based on a variety of test methods and kinetic models, a convention should adopt uniform testing and analytical procedures. All possible contributing factors must be considered when establishing the convention to ensure that it is fair to all parties, i.e. manufacturers, merchants, builders, fixers, consumers, etc.

In the event of failure

At the first Qualicer conference, in a paper on the quality assurance of ceramic tiling installations through the use of computer-based expert systems [3], there were flow charts of the process of designing a ceramic floor tiling installation. This philosophy has been adopted in the new Australian tile fixing standard [4], and the same basic data must be sought when determining why an installation has failed. However, in such circumstances the emphasis is slightly different. One has to make an expert assessment of the compatibility of the choices made and the ability of the specified system to perform adequately in the originally planned environment. If the specified bedding system, the anticipated properties of the chosen materials and the expansion joint detailing are compatible with the type of load-bearing structure, its characteristics, the service environment and the expected performance levels, the cause of the failure is probably due to some aspect of structural design, workmanship, some unexpected material characteristic, or construction scheduling.

While a civil engineer is best qualified to determine whether movements have occurred due to structural design, e.g. settlement, creep, applied loads, deflection, or vibration, significant movements should be apparent to the occupant or an experienced investigator. It is generally necessary to remove the tiles and adhesive from lifted or drummy areas to determine the mode of failure and to assess the quality of the workmanship. It is often possible to determine what area of adhesive was spread at a particular time, or whether the tiles were fixed with a twisting action, etc., but there is an understandable reluctance on the part of occupants to permit widespread removal of tiles, unless it has been decided that they will be promptly replaced.

In investigating differential movement tiling system failures, the mode of failure is often indicative of the cause. Failure at the interface between the fixative and the slab suggests that the slab has been poorly prepared or that the fixative has been improperly applied. The suitability of the surface to directly receive the bedding layer must be assessed with respect to cleanliness, planarity, surface finish, etc. The performance of fixatives can be compromised by the absence of bedding coats, poor mixing, use of excessively thick, thin or discontinuous beds, etc. Shearing through an adhesive or mortar bed suggests that the fixative was unsuitable or defective in some way. Samples should be taken for analysis by appropriate specialists. Failure at the interface between the fixative and the tile generally requires that all aspects be carefully investigated. It will often be necessary to remove areas of apparently sound tiling to assess the uniformity of the bedding system. Where large areas are involved, use of a concrete test hammer (with an appropriate impact force) can provide some differentiation between well and poorly fixed tiles. If properly documented, subsequent hammer testing can be used to monitor deterioration of the system in order to allow programmed replacement with minimum inconvenience and exposure to public liability.

Information gathering

When a pop-up failure occurs, information should be gathered in a consistent and systematic fashion. Tile merchants and manufacturers should distribute preprinted tiling system failure report forms as required. These forms should be user-friendly and should enable the accumulation of some of the data necessary for analysing the failure. In obtaining details of the construction schedule, layout, fixing methods, materials, failure modes, etc., in a systematic way, it should be evident which aspects require resolution when inspected by different parties, and for the agreed details to subsequently be entered into a databank.

The other element of the information gathering process is that of determining the material characteristics. One generally has to rely upon the concrete supplier for indicative shrinkage strain values of laboratory-cured specimens. Little field data is available, and to try to retrospectively determine on-site shrinkage is impossible.

Shrinkage is affected by all the factors which affect the drying of concrete, in particular the water content and the water/cement ratio of the mix, the size and shape of the member, the ambient relative humidity and the amount and type of aggregate [5]. It must be stressed that the values quoted by manufacturers are for concrete mixes where the samples are laboratory-cured under ideal circumstances. While different shrinkages may occur on site, the concrete supplier has no control over the concrete once it is despatched.

AS 3600—1988 Concrete Structures [6] requires that the design shrinkage strain be determined from the basic shrinkage strain, which may be determined by tests or measurement, or taken as equal to a median value of 700 microstrains (0.07%). In the absence of more accurate methods, the design shrinkage strain at any time after commencement of drying shrinkage can be obtained by multiplying the basic shrinkage strain by a shrinkage strain coefficient for various environments and hypothetical slab thicknesses. Gilbert [5] discusses several of the acceptable shrinkage (and creep) models which may be used to estimate movement if the construction schedule details are known.

AS 3958.1 [7] permits adhesive fixing of tiles after the concrete substrate has dried for a minimum of four weeks, since the demand for faster construction schedules has led to the development of fixing systems which are claimed to be capable of coping with the drying shrinkage. While longer air drying of the concrete is preferable (one month for each 25 mm of slab thickness), the kinetics of concrete shrinkage are such that the rate of shrinkage decreases sharply with time. In most instances, the concrete shrinkage between the time of tile laying and any failure of the system is likely to be less than 0.03%, with the majority in the vicinity of 0.01%.

As far as the adhesive is concerned, one can use various analytical techniques to compare the adhesive sample with a freshly prepared sample of the specified adhesive in order to determine whether the specified adhesive was used. Unfortunately adhesive manufacturers rarely indicate the elastic modulus, creep or drying shrinkage behaviour of their products, let alone characteristics such as drying shrinkage. In many fixing environments it will not be possible to achieve the strengths that were obtained with laboratory curing. It should also be recognised that even with optimum fixing, curing and drying conditions, the bond strength is dependent on the surface finish of the concrete, its cleanliness, the sorption characteristics of the tile, etc. When adverse conditions are encountered, the fixer must rely on his own experience and, unfortunately, where new adhesives lack specific guidelines, the ensuing process of trial and error may result in failures.

When a mortar is used, it can be analysed in specialist laboratories. The cement/sand ratio can be estimated from the SiO_2, Al_2O_3 and CaO contents and the loss on ignition, although a number of assumptions must be made if the chemical compositions of the cement and sand are not known. The situation is further complicated where blended cements (e.g. containing fly ash), non-siliceous sands, or chemical admixtures are used, since further assumptions must then be made. Cases of improper batching, poor mixing or use of contaminated sand will often be indicated by inconsistent strength or appearance.

However, the main subject of this paper is that of the moisture expansion of the tile. This should initially be determined in accordance with the ISO draft test method, although in some cases further analysis will be required as indicated later. In time, a better test method should be developed, although its adoption will require the accumulation of considerable data before verification by the CERLABS member laboratories. Other tile properties which can be usefully determined are those of thermal expansion and elastic modulus.

The ISO/TC 189 Moisture Expansion Draft Test Method

Establishing an international standard for the moisture expansion of glazed and unglazed tiles has not been easy, but the following points were recognised:

(a) glazed tiles expand in the same way as unglazed tiles [1, 8, 9];

(b) conditioning of the tiles by refiring above the quartz inversion temperature may result in anomalies [9—12];

(c) the EN 155 test method has often been used to assess the moisture expansion characteristics of aged tiles taken from failures [9, 13—15];

(d) the presence of glaze on the tile body during refiring and boiling of the test specimens has little influence on the results [1, 9];

(e) the size of the specimens has little influence on the results;

(f) some tiles shrink and others have negligible moisture expansion and do not require testing, while other tiles which have apparently been successfully used (but not routinely tested or required to be tested according to the existing European Norms) have moisture expansions exceeding the EN 155 compliance limit of 0.06% [1]; and

(g) the significant moisture expansion component is that which occurs after fixing of the tile [9, 13—15].

Accordingly, the ISO draft differs from EN 155 in that:

(a) glazed tiles are included in the ISO test method;

(b) the test method is not restricted to tiles of 6—10% water absorption;

(c) the specified size of the specimens in EN 155 is adopted as the minimum size of specimens;

(d) the number of specimens is reduced from 7 to 5;

(e) the refiring procedure is changed from a 4 h soak at 600°C with a 50°C/h temperature rise to that of a 2 h soak at 500°C with a 150°C/h rise; and

(f) there is no compliance requirement of 0.6 mm/m. Instead there is the informative annex.

INTERPRETATION OF MOISTURE EXPANSION RESULTS

It has previously been stated [14] that natural moisture expansion curves may have very different shapes, and accelerated test methods which use a single treatment to induce moisture expansion do not necessarily indicate the natural moisture expansion potential of a tile. It was also recommended [14] that manufacturers should determine the long-term natural moisture expansion behaviour of their products, as knowledge of the characteristic kinetics indicated by the shape of the moisture expansion curve is fundamental to the interpretation of the accelerated test method result.

In analysing differential movement failures there are several possible scenarios, but once the mode of failure has been defined and the quality of the workmanship and the suitability of the adhesive assessed, one has to relate these to the estimate of past expansion and the moisture expansion potential characteristic (as determined by a standard test method). If on refiring there is negligible shrinkage, where the level of shrinkage is generally assumed to equate to or indicate the level of past moisture expansion, one might assume that the tile has undergone negligible expansion since production. However, the amount of shrinkage is highly dependent on the refiring temperature, and the selection of refiring temperature has been a contentious issue [9, 12]. If the ISO/TC 189 draft test method is to be used, a refiring temperature of 500°C is specified. As this treatment does not induce the same degree of rapid expansion that characterises many tiles when they are first produced, it provides a relatively stable datum for determining the amount of expansion which is subsequently induced. It is generally assumed that the period of initial rapid expansion lasts for one or two days after production, well before the tiles may be fixed, and that the expansion kinetics after this period would be similar to those induced by refiring at 500°C [9]. Thus, neither the estimate of past expansion nor the accelerated expansion contain the rapid initial expansion.

While the estimate of past expansion is a very useful indicator, there is no requirement in the ISO draft test method to determine it since the standard principally relates to new tiles. The test method only determines what may be considered as a characteristic indicator. If one determines both the estimated past expansion and the 24 h boiling expansion, the ratio of these figures should theoretically relate to the age of the product, although such an analysis should be based on the expansion kinetics of the product concerned. It can be estimated [16] that a 24 h boiling induces an expansion equivalent to 36 months of natural exposure, although the exposure conditions can significantly influence the kinetics, e.g. installation in a sauna. Thus, if the past expansion is equal to the induced 24 h boiling expansion, it implies that the product is likely to be about 3 years old. Interpreting such relationships obviously depends on knowledge of the age of the tiles, the time since installation and their exposure conditions. Where these conditions have varied significantly from standard laboratory conditions, one may need to use the Arrhenius relationship to calculate modified exposure times [16]. Such a calculation requires that one assumes an activation energy for the moisture expansion reaction.

Where the natural moisture expansion characteristics of a tile are known, Cole and Birtwistle [17] have shown that the kinetics of the expansion can be described in terms of a logarithmic function of the form:

$$E = m + n \ln (t + k) \qquad (1)$$

where m, n and k are constants, using an iterative technique as demonstrated by Cole and Banks [9]. Such a relationship obviously gives far more reliable predictive and interpretative information than a generalised kinetic model. While the rate and total amount of expansion varies considerably from product to product, making generalisations difficult, McDowall and Birtwistle [18], after studying the relationship between accelerated steam-induced moisture expansion and long-term natural expansion for several brick types, developed the equation:

$$E_t = [-0.1929 + 0.6013 \ln (t + 2.2977)]S \qquad (2)$$

where E_t is the expansion (%) to take place after a prediction period of t months, and S is the value of expansion (%) of kiln-fresh bricks after four hours of steam treatment at atmospheric pressure. This equation implies that the expansion induced by 4 h steaming is equivalent to 4.93 months natural exposure. Zsembery [19] reported that in these bricks, the steam values were approximately equivalent to the first five months of natural growth.

The Brick Development Research Institute (BDRI) subsequently simplified this equation to:

$$e_m = ZS \qquad (3)$$

where e_m is the estimated long-term (5-year) unrestrained expansion (mm/m), and Z is a steaming factor [19]. This equation has been used as the basis for AS 1226.5 [20]. Architects use this estimated expansion to specify the minimum spacing of expansion gaps in brick walls.

The last predictive equation which BDRI derived:

$$E_t = -3.4S + 1.51S \ln (t + 11) + 3.5S^2 - 0.253S^2t + 0.00058S^2t^2 \qquad (4)$$

was based on observed natural expansions over 15 years [21], but has been criticised because it does not lend itself to predictions beyond 15 years [22]. While equation (4) accommodates some unexpected expansion behaviour which occurred between 5 and 15 years, it implies that the expansion induced by 4 h steaming is equivalent to 7.4 months natural exposure, rather than the 5 months previously reported [19]. Freeman and Smith [23] reported good correlation between natural exposure for 4.2 months and 6 h steaming in British bricks. This highlights the differences that exist between products and supports the supposition that the activation energy for the moisture expansion reaction would be expected to vary from body to body and would also be dependent on the processing parameters that an individual body has been subjected to.

Bowman [15] showed that equation (4) could be used to derive:

$$Z = 3.02 - 9.43S \qquad (5)$$

which should provide a better estimate of the steaming factor, Z, than those used in AS 1226.5 [20]. However, equation (5) still suffers from the limitation that one is extrapolating on the basis of a single experimental result (a 4 h steam).

If one arbitrarily assumes that a 24 h boiling treatment is equivalent to 36 months natural exposure, one can use either equation (2) or equation (4) to calculate a steaming value, and use this to obtain the relevant expansions at specific elapsed times. Thus, these equations can be used in the design of tiling systems, although the period during which the tile may be held liable for any failure will depend on local legislation. It should be noted that for the preceding assumption, equation (2) would indicate that when E_{36} equals 0.06% (the EN 155 limit for a 24 h boil), S would equal 0.03%, and that the five-year estimate, E_{60}, would be 0.069%. Substituting the same steam value in equation (4) for the same time intervals causes E_{36} and E_{60} to respectively equal 0.068 and 0.082%. Equation (2) is generally the more convenient generalised equation to use, as the ratio between any two given times is constant. Far better estimates of $E_{\text{legislated t}}$ will be obtained when data is available to calculate a function of the form of equation (1) for the specific product. However, the expansion which will occur in any given time period after installation of the tile, $E_{t2} - E_{t1}$, is more relevant than any estimate of E_t.

Where the natural expansion kinetics are not known, and this obviously applies in the case of a new product, a manufacturer or a researcher might predict the expansion characteristics by the use of a series of steamings at atmospheric pressure (either submitting the same specimens to several cycles, or testing several sets of specimens for different times). This is more appropriate than interpolating on the basis of a single result, as with a 24 h boil, or extrapolating on the basis of a single result, as with AS 1226.5 [20]. In this manner, the effects of expansion of the tile prior to fixing can effectively be discounted. While Australian tile manufacturers have commissioned studies in order to develop a reliable indicative moisture expansion test, obtaining the necessary natural expansion data for correlation essentially requires a protracted commitment.

Most past failures have been assessed on the basis of whether the tiles have had a moisture expansion in excess of 0.06% (the existing EN 155 limit), although various heating treatments have been used to estimate past expansion, and estimates of expansion have been based on steaming and natural re-expansion, as well as the 24 h boil test. There is a dangerous possibility that this benchmark will continue to be applied, as it will discriminate against products which exceed this value without causing problems in service due to their particular expansion kinetics. In this context, how should we use the impending ISO test method?

Failure models

In the light of the previous paragraphs, it is difficult to make generalisations. Perhaps it is more appropriate to initially consider what level of expansion might initiate failure. There are a number of models which have been developed to analyse differential movement failures [2, 13, 24—27], but each makes a set of assumptions and has its associated defects. For instance, Bernett's model [2] recognises that the grout shrinks and creeps, and that a given amount of stress will cause elastic deformation of the tile and grout. Bowman [13] further developed this by recognising both the role of the expansion joint and the discontinuous nature of the adhesive bed (which will often be a characteristic of failures where the tile has a relatively low expansion). However, these one-dimensional models do not recognise the restraint to bending that a thick concrete slab would provide, as in a multi-layer theory [26]. Although it is known that failures are sometimes initiated by rapid temperature changes, this variable is generally not incorporated in the failure models.

As failure is intimately associated with the adhesive layer, one must reflect on the adhesive manufacturer's role. In order to counter differential movement failures, manufacturers have either developed super-strength adhesives, or adhesives with a high degree of elasticity in order that they can effectively creep. The latter group of adhesives can only function as intended if the system is designed and installed so that movement can be accommodated. Furthermore, tiling is sometimes carried out under adverse climatic conditions, such that the intended bond strengths may never develop in the same way as in controlled laboratory conditions. There is a very real danger that international tiling adhesives standards may be developed where the influence of climatic conditions on the workability and curing of the adhesive are overlooked. Product literature is essentially based on standard test methods and, as indicated previously, does not necessarily provide the specifier or the fixer with the necessary data for product selection and application.

It could be considered that external tiling systems should be able to cope with a thermal expansion of 0.03%, allowing for a 40°C temperature change with a coefficient of linear thermal expansion of 8 x 10^{-6} K^{-1}. Such systems should thus be capable of withstanding a higher total differential movement. Where it is known that tiles will be exposed to significant thermal movement, expansion joints are specified at closer intervals. Thus, the specifier tries to design the tiling system according to the anticipated environment, although there are significant difficulties with the management of building information [3]. For instance, while it is known that concrete shrinks, the specifier may not be aware of the rate of shrinkage, and must anticipate the construction schedule, in addition to some material properties, e.g. the modulus of elasticity of the adhesive, and its creep characteristics.

There is an obvious need to develop improved differential movement models. While these should be supplemented with finite element analyses, advances in this area are dependent on better definition of the various characteristics of all the system components and their interrelationships.

Moisture expansion determinations in the case of a failure

The draft ISO/TC 189 test method should be used as an initial indicator of the extent to which a tile may have contributed to a differential movement failure. Since some existing product standards have a compliance limit of 0.06% when tested according to EN 155, there is a natural tendency to adopt the same limit for the ISO/TC 189 test method (which is very similar to that of EN 155). In most cases, adherence to this limit should prevent failure if the tiles are allowed to age for a few weeks prior to use, and if they are adequately fixed in a suitably designed and executed tiling system.

In analysing failures, the following guidelines might be adopted, where the expansion determined by a 24 h boiling is greater than 0.04%.

1. Utilise both the refiring shrinkage and the induced expansion or natural re-expansion data in assessing the likelihood of tile moisture expansion being the principal cause of a failure.

2. Assume that the shrinkage resulting from a 2 h soak at 500°C indicates the amount of expansion since the originally manufactured tile was a few days old.

3. Assume that a third of the presumed expansion (up to a maximum of 0.02%) will have occurred prior to fixing of the tiles. This assumes that the tile was about two months old when laid.

4. Presume that where there has been good workmanship, suitable adhesive has been used, and functioning expansion joints have been installed on stable concrete, this ideal system should be able to tolerate up to 0.04% expansion in-service over a period of three years.

5. Recognise that where the system has been reasonably designed and installed, lower amounts of expansion can cause failure in shorter time periods.

6. Where the natural expansion, refiring shrinkage and induced expansion characteristics of a tile are well known, a manufacturer may be able to demonstrate that either a refiring shrinkage or an induced expansion in excess of 0.06%, or both, does not indicate that a product has excessive moisture expansion in service.

7. Where such data is unavailable, a recognised laboratory with proven ability may be able to assess whether an implied expansion of 0.04% or greater has caused a failure through the evaluation of the kinetics of the expansion (obtained by the judicious use of various refiring and steaming or boiling techniques) relative to the history of the installation and its components.

Possible advanced analytical techniques

It would obviously be advantageous if manufacturers and analysts were to use the same techniques. In South Africa, Boucher [28, 29] has determined the unrestrained moisture expansion of unglazed split tiles by subjecting them to eight periods of steaming at atmospheric pressure, one of 6 hours, followed by one of 18 hours and six of 24 hours each, following a procedure similar to the South African standard test method for bricks [30]. When plotted against logarithmic steaming time, the expansion curves were approximately linear. Bowman (unpublished results) has obtained linear plots (for logarithmic time functions) when using either a series of steaming or boiling treatments, or a combination of both. If this expansion is expressed as:

$$E_{St} = a + b \ln (t_s + c) \qquad (6)$$

where t_s is expressed in hours of steaming, and a, b and c are calculated constants, then if one arbitrarily assumes that each hour of boiling or steaming is equivalent to 1.5 months of natural exposure, equation (6) can be recalculated as:

$$E_{natural\ t} = d + b \ln (t_n + 1.5\ c) \qquad (7)$$

where t_n is expressed in months, and d is a calculated constant. Such a relationship can be used to interpolate and extrapolate to calculate the unrestrained expansion for any time interval. The major advantage of such a technique would be that the initial expansion which occurs prior to fixing can be eliminated from the estimation. However, it should be noted that long steaming times may unduly influence the determination of the constants, and particularly where calculations relate to short exposure times. Furthermore, additional data must be obtained to produce a better correlation between natural and induced expansions, and for specific tile types and exposure conditions. For instance, a relationship of two months of natural expansion for one hour of steaming may be more appropriate with some tile bodies.

Where manufacturers have intimate knowledge of their product, better correlation can be obtained. Since most data will relate to typical product rather than the small percentage that has a higher expansion potential, the characteristics of the atypical product might only be determined by refiring and measuring the subsequent natural expansion. Cole and Banks [9] have shown that re-expansion data can be used to assess the magnitude of moisture expansion between the time of laying and the time of failure.

It was previously suggested [14] that

'Tile manufacturers should benefit from a different philosophy for determining the moisture expansion of tiles, because there is insufficient published data to have sufficient faith in any test method being able to adequately characterise expansion behaviour, such that specifiers can be given a reliable estimate of the expected in-service expansion, or that investigators can later determine this expansion component.

Since manufacturers have the most intimate knowledge of their produce, it would appear preferable that they should be asked to classify their products as being of negligible (<0.02%), low (0.02 to 0.04%), medium (0.04 to 0.06%) or high (>0.06%) moisture expansion potential, based on the likely in-service expansion over a fixed time interval, perhaps a 5-year period commencing 2 weeks after leaving the kiln, since they are unlikely to be laid prior to this. If such classifications were adopted, there would be no need to have a compliance limit within the tile standard, nor a mandatory requirement to test to the standard. While it would allow for improved design of tiling systems, manufacturers of high expansion tiles would need to give the estimated potential expansion. There would, however, still be a need for a recognised standard test method for the purposes of quality assurance, settling disputes, and specification where a purchaser seeks to specify tiles in terms of a maximum permissible moisture expansion. A series of mild expansion inducing treatments would be most likely to yield the most useful information.'

While a longer soak at 550°C would appear preferable [9], the ISO draft test procedure of a 2 h soak at 500°C can be used and should be initially adopted for reasons of consistency. In conducting a series of steamings or boilings at intervals of say 1, 2, 4, 8, 24 and 48 h, one should ensure that the product is relatively stable prior to measurement of the induced expansion. The expansion characteristics can then be expressed as a logarithmic function of time using an iterative procedure to refine the constants. When rewritten in terms of months, the function can be used to indicate the likely in-service expansion over a fixed time interval. In the case of a pop-up failure, the function can be used to calculate the likely in-service expansion [9].

Where a product has a higher than anticipated moisture expansion, intentional aging of that product prior to shipment can ensure that the moisture expansion of the product does not exceed a desired amount over a fixed time. However, explicit documentation may be required to safeguard the manufacturer. If such a tile were involved in a pop-up failure, it would be in the manufacturer's interest for the age of the tile at the time of fixing to be known. Furthermore, if a pop-up failure occurs, it is important that the manufacturer be able to differentiate between a first quality product and one which has been sold as a second quality product due to high moisture expansion. If neither the retailer nor the purchaser can discern that the latter product is being sold as a second due to its high moisture expansion potential, it would create a complex question as to legal responsibility, if it is considered that the moisture expansion of the tile may have contributed significantly to the failure. Such situations need not arise if the long-term natural expansion behaviour of a product range is known, together with its correlation with the expansion induced by accelerated tests. Manufacturers would benefit from comprehensive documentation and a knowledge of the correlation between the natural expansion and that induced by accelerated tests for their product range.

Boucher [28, 29] found that the moisture expansion of tile bodies fired at or above the temperature where sintering starts was directly proportional to their water absorption, and thus that water absorption determinations could be used for factory control of potential moisture expansion. A comparison of the expansion kinetics of a standard production body fired to a range of temperatures might enable better use to be made of quality control data.

RECOMMENDATIONS

1. That a convention be established for differential movement failures which have possibly been caused by moisture expansion of the tile, such that:

(a) the details which are necessary to analyse the failure should be gathered by the means of a user-friendly form;
(b) the ISO/TC 189 draft test method should be used to give an initial indication of the expansion characteristics of the tile;
(c) the determined moisture expansion of the tile, both past expansion and induced expansion, should be considered in the light of the expansion kinetics of the tile;
(d) the expansion kinetics of the tile should be determined by a series of boilings or steamings (at atmospheric pressure) if they are not known, and preferably supplemented by re-expansion measurements;
(e) a logarithmic function should be used to estimate the amount of expansion within specific time intervals; and
(f) caution should be exercised when using system failure models.

2. That further experimental work be undertaken to better define the characteristics of tiling system components in order that better system failure models can be developed, ultimately leading to the production of better fixatives and improved installation techniques.

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