TECHNICAL PAPER – TP 005

STABILITY PROBLEMS WITH NATURAL STONE TILES

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INTRODUCTION & SCOPE

Since 2007 the tile market has seen a significant growth in the sale and usage of tiles made from quarried rocks (senso latto – 'natural stone'). The market has also seen the rise and then gradual decrease in the usage of so called stack-stone tiles, which was discussed in Ardex Technical Paper TP001.

In particular the market has seen a gradual increase in the size of the tiles with a length of 600 to 900mm long becoming common, but thinner down to 10mm. Such dimensions create an issue for adhesive dead loading, but another more critical set of problems have appeared, thermal movements and moisture stability.

In this paper we will examine some of the issues related to thermal and moisture stability, using examples of some natural rock tiles that Ardex has seen in the last few years.

TRADITIONAL STABILITY ISSUES

The market is familiar with the peculiarities of some types of rock used for tile and dimension stone. In particular, the problems of warping, grout or silicone picture framing and adhesive show through for marble and limestone, but also the dimensional instability of so-called 'green marble' (*senso stricto* – Serpentinite and Blue Schist) are well known to the industry.

These problems can be minimised by the correct usage of products for fixing the tiles and finishing the installation. In particular the use of non-water based or specialised adhesives and grout eliminate moisture effects for porous and sensitive tiles.

Neutral cure silicones eliminate the Acetic Acid attack on carbonate rocks, but these must also not contain mobile solvent or low molecular weight polymer phases that can migrate and create problems as well.

UNEXPECTED STABILITY ISSUES

We can ask, what are these issues being found as problematic now? It is because some of these stones do not show the problem when used as "ashlars", it is only when the block is cut into thin section slabs for use as tiles that the issue be-

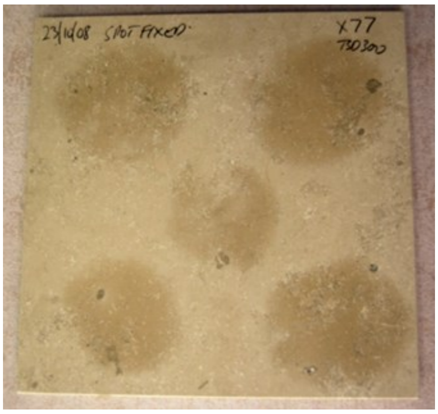

Figure 1. Adhesive show through on spot fixed limestone tiles.

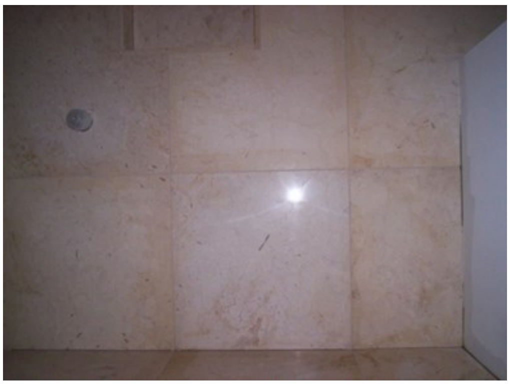

Figure 2. Picture framing on marble tiles either due to adhesive or grout related moisture problems.

comes evident. Also the use of thinner stone and the mesh backing embedded in resins create other issues (see Ardex Technical Papers TP002 and TP013, and Technical Bulletins TB161 and TB228 for other discussions on these and related issues).

The current trend towards cheaper imported tiles, and away from locally quarried quality tiles or higher market end European sourced dimension stone. But in particular to a) black and dark colours and b) unstable rock types have led to a number of other unexpected problems.

Ardex has seen a range of unusual stability issues from tiles made from predominantly imported types of stone. These problems include temperature related warping, moisture related warping and also weathering of unstable minerals and components. Darker colours can create problems with substrate stability (heat transmission), and thermal and moisture instability also can result in premature ageing and stress fatiguing of the adhesive.

The movement problems can be either growth overall due to expansion through the entire tile body, or more commonly differential movements due to one side of the tile being exposed only. The former produces expansion and peaking at the joints, and the latter central cupping/doming and peaking/down curling at the edges and corners of the tiles. Both effects create adhesive de-bonding and loose tiles.

For discussion of movements, it is important to recognise the three dimensional quality of these changes. Traditional moisture movement testing of rock tiles is done in the horizontal X (length) and Y (width) directions with fully saturated samples, but less commonly in the Z direction (vertical axis = tile thickness changes or deflections). Movements in X and Y produce overall growth and shrinkage, whereas Z axis movements create either

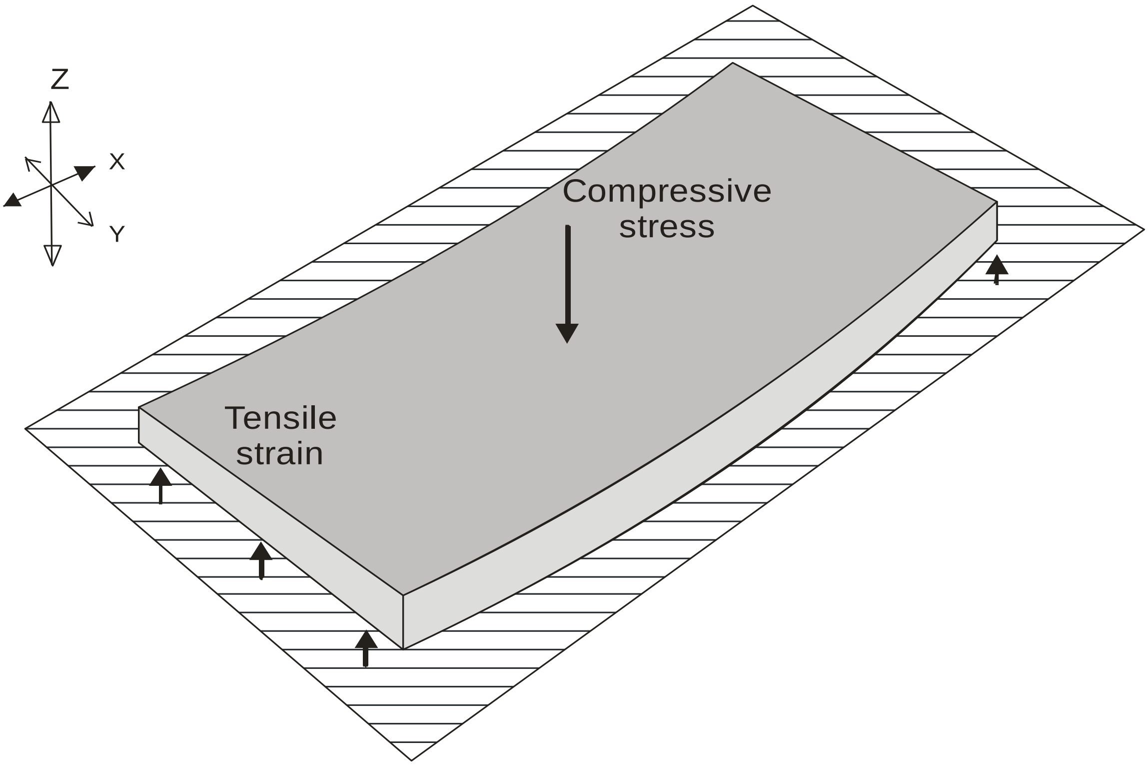

Figure 3. Schematic diagram showing the three strain axis and how they relate to a tile. The X-Y in horizontal plane for length and width changes, and Z in the vertical plan representing thickness changes or vertical deflections. The positions of tensile strain and compressive stress applied by the tile to the adhesive (and also underlying substrate) for a rear face expansion are shown (edges lifting). The positions are reversed for front face expansion (centre lifting). The cross-hatched area represents the tile adhesive bed.

very slight vertical expansion of the tile, but obviously larger bowing and cupping movement due to differentials. The later can be visualised as the tile developing a parabolic shape as shown in Figure 3, and the amount of change difference front-back necessary to create warping is relatively small.

The methodology of measuring warping is described in the method BS/EN 14617-12 Agglomerate stone test methods—Part 12 Determination of dimensional stability. Ardex has adapted this standard to create its own method of testing.

The Ardex method uses dial gauges located in varying positions on the tile surface as shown in Figure 4b, but the approach is visualised in Figure 4a below where the deflection is measured against a straight edge.

Tile Thickness

Traditional 'ashlar blocks' are thick and heavy tiles, used for structural as well as their decorative properties. Such large formats had their own kind of stability, even when made from suspect rock types. The reason being, that the thicker tiles are more resilient to deformation and take longer to be affected by either moisture or thermal effects. However, such large tiles are hard to fix, hard to transport and require specialised constructions. As a result the same types of rocks are being cut into thinner slices, for example from 10-40mm thick, with a common thickness of 12-15mm. The result of this is to remove the inertia to movement that thicker rock has, and allow more rapid and proportionally larger movements to occur. The thinner tiles

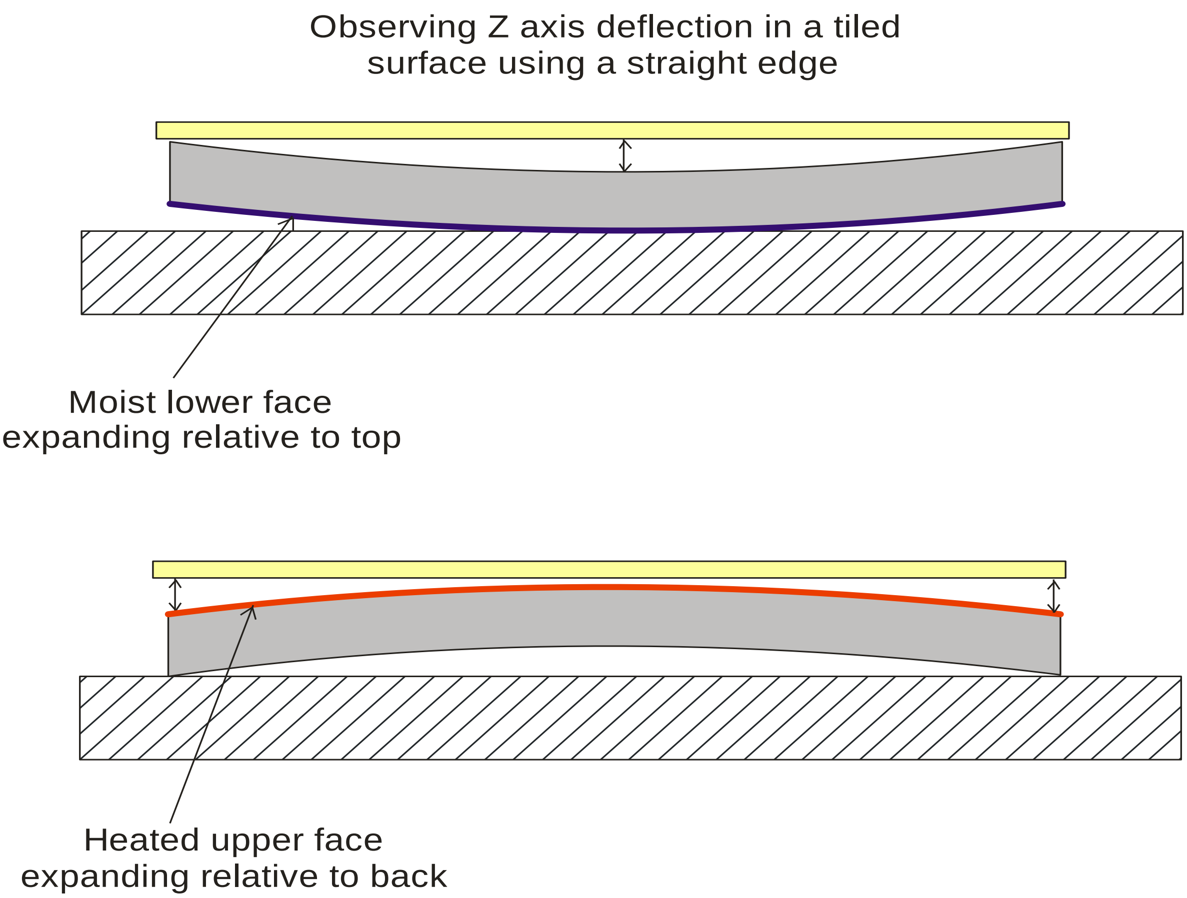

Figure 4a. Schematic diagrams showing the differential movement effects observe in natural stone tiles. The upper face expansion can also occur with moisture sensitive tiles exposed to ponding rain water.

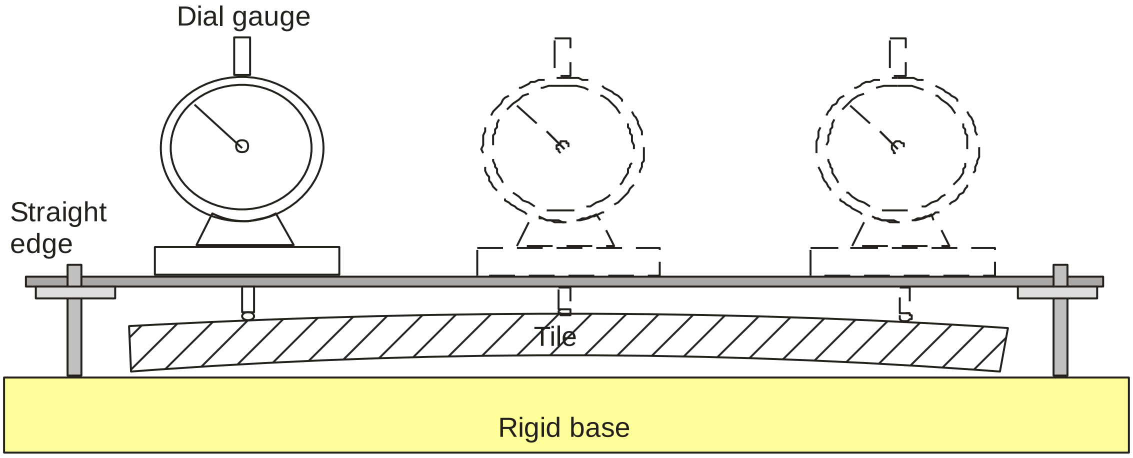

Figure 4b. Schematic diagram of a z axis deflection test. The positioning of the dial gauge is shown for edge and central positions.

are more quickly affected by both moisture and thermal effects.

Thermal Movements in Detail

Rocks have relatively low thermal co-efficients and so act somewhat as insulators. Where the sun falls onto the tile surface, be it outside, or through a large window, the tile surface is heated more rapidly than the tile body. This effect is far more pronounced on dark coloured tiles which are highly effective at absorbing radiant energy. Ardex has measured surface temperatures on dark coloured tiles exposed to the sun slightly in excess of 60^{0}C on warm but not excessively hot days with air temperatures around 30-32^{0}C. The high surface temperature results in the upper layers of the tile expanding relative to the back, and producing differential movement in the tile (this occurs until the tile heats all the way through, which may not occur for thick tiles in the time exposed during the diurnal period).

Surface deg.C	Basal deg.C
18	18
39	27
51	34
62	51
Δ 44^{0}C	Δ 33^{0}C

Table 1- Real test data showing the temperature difference between the front and back of a 12mm slate tile during thermal deformation testing.

Typical rocks used for tiles display expansion co-efficients in the range 4 to 7x10^{-6} mm/mm/^{0}C (Hockman & Kessler 1950—granitic rocks) or more generalised 5 to 10x10^{-6} mm/mm/^{0}C (Nordtest 1997).

Referring back to the live data in Table 1, and a middle range expansion, we can see the differences between faces that the tile could expand by,

Top

7.5x10^{-6} x 44 = 3.3x10^{-4}mm per mm

Bottom

7.5x10^{-6} x 33 = 2.5x10^{-4}mm per mm

That particular tile was 600mm long so,

top expansion = 0.20mm

bottom expansion = 0.15mm.

The consequences of this difference is the underlying rationale for the Nordtest method NT Build 479 (1997-11) where the difference in expansion from 20 to 70 deg.C is used to estimate the thermal stability of a rock tile sample;

The bending tendency is expressed as:

ΔL_O: Change in length on the surface of the test sample

ΔL_U: Change in length on the underside of the test sample

ΔL_b: Difference of change in length on the surface and the underside of the test sample ($\Delta L_O - \Delta L_U$)

This differential creates high flexural strains in the centre of the tile and increasing compression around the edges. There is also a component of shear involved as well. The central strain is converted to a tensile stress in the Z direction. Each time the tile is exposed it heats up and expands, but when no longer exposed then cools down and contracts. This cycle contains a degree of time lag hysteresis and so the tile does not exactly go back to its initial state before the next cycle. This is shown in this graph below.

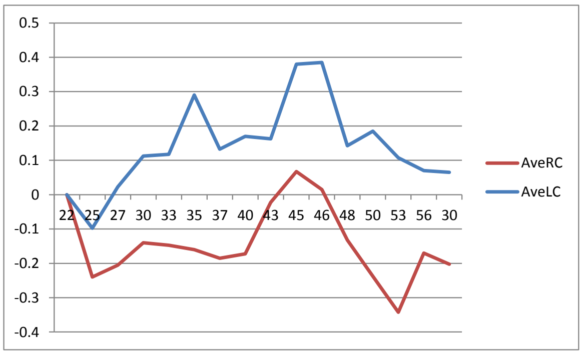

Figure 5. Temperature vs deflection for a stackstone slate tile showing hysteresis where the deflection has not returned to its previous point at the same temperature on the cooling cycle.

This cyclic effect can, over time, stress fatigue adhesives. If it occurs before the tile adhesive has developed high strength (for example less than 24-48hrs old), the adhesive can shear cohesively and the tile becomes drummy. If the rock is 'strong enough', that is has a high compressive strength, but more critically a high E-modulus, then combined with large Z direction movements, it can exert very high strains that exceed the nominal tensile strength of most cement based adhesives and cause cohesive failure within the adhesive. The effect of

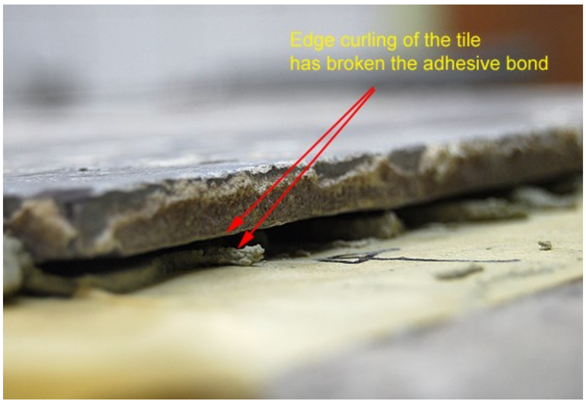

Figure 6. A tile which warped upwards on the test heating cycle and broke the adhesive bond.

thermal movement by high E-mod tiles was discussed by Silva et.al. (1999), where they showed that significant strain was developed at the tile edges leading to high stress concentrations. In finite element modelling of tile systems, Bowman & Banks (1994, 1996) showed that thermal stress can develop across a tiled surface and the concentration point was in the grout lines (which crush). (The same effect occurs with moisture movement as well).

This description is the normal expected deformation for heated tiles with doming of the tile as the upper face expands. However, Ardex has also seen the inverse case occur with some tiles where the edges curl upwards. The reason for this is not clear, but in the worst case seen to date, the tiles deformed purely due to heated air temperatures and not direct sun exposure. The final case is where the tile deforms asymmetrically and develops odd shapes. Models of warping are shown in Figure 7 below from Scherer (2006).

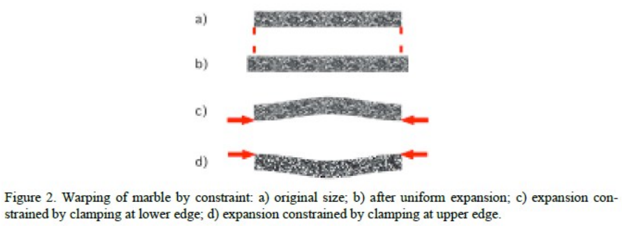

Figure 7. Models of rock tile deformation showing how restraint effects the deformation. Case c) can be modelled as restrained by adhesives on the base with weak grout or sealant in joints, whilst d) could be related to a strong epoxy grout (Scherer 2006).

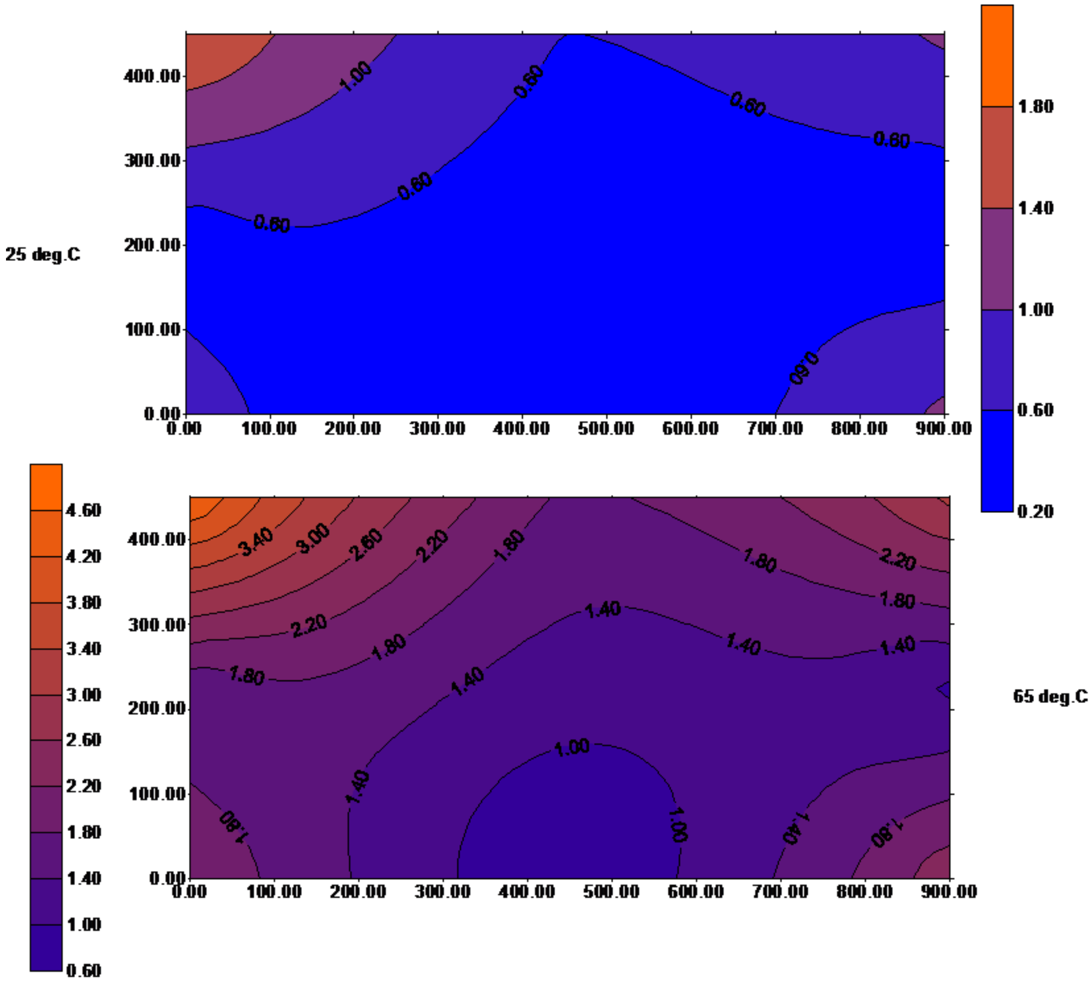

Figure 8. Vertical (Z axis) deflection contour maps for a thermally unstable stone tile exposed to direct sunlight. The contour measurements are in mm. This tile produced unacceptable deflections on a job site in hot weather during the summer months in 2008-09. As can be seen, there was a significant difference in the tile flatness between cool and hot conditions with the tile dishing by >2mm.

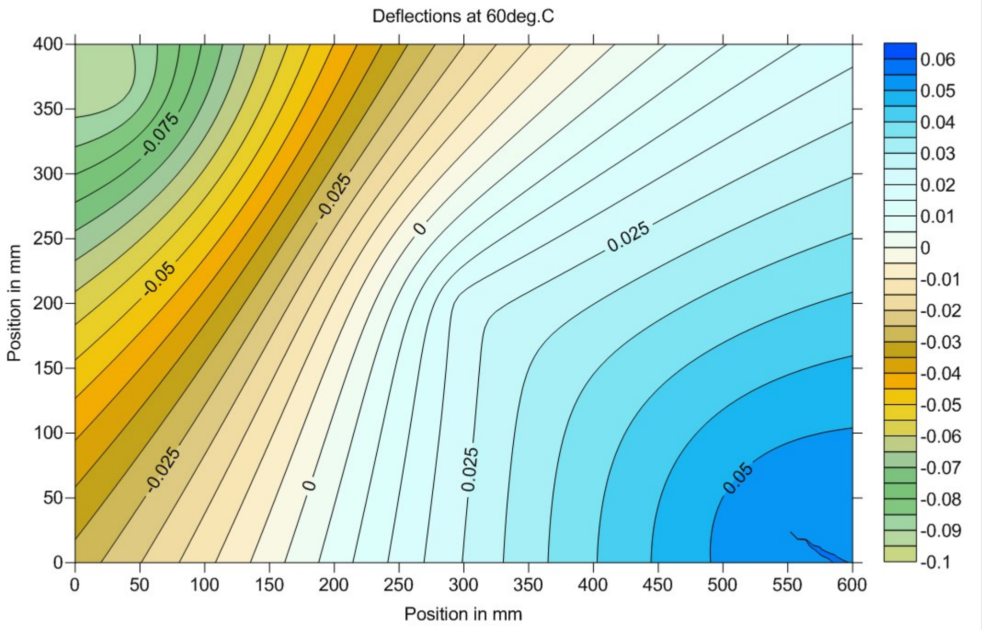

Figure 9. Asymmetric Z axis deflection in a slate tile exposed to heat testing.

Where the tiles are exposed all day to the sun (i.e. E-N-W walls) the tiles will eventually heat through and start to have effects on the underlying materials. Depending on the day time temperature and the darkness of the colour, the temperature rise may exceed the nominal 70^{0}C service temperature for the adhesive. It can also produce durability issues with the substrate over time as well and fibre-cement manufacturers for one, do not recommend external tiling onto their normal sheets (they have specialised systems). This is in part a loading issue, but also a weathering issue which high temperatures accelerate.

The two contour maps in Figure 8 show the measured deflections in a so-called 'basalt' rock tile 900 x 450 x 25mm thick exposed to the sun at Ardex's laboratory in Sydney during March 2009. The vertical Z axis deflections are defined by the contours and colour changes. It can be seen that this tile displayed a range of movement in excess of 2.5mm during the course of the day's sun exposure. This is sufficient to strain adhesive beds and create drummy tiles and lipping issues.

Figure 9 shows a slate tile deflection when exposed to heat testing. In this case the slate was actually bonded to a concrete base, but had developed a degree of de-bonding which permitted warping to occur. Figure 10 shows the results for a stack stone slate which displayed a degree of thermal movement which was relatively consistent across the tile face.

There are only two ways to get around this type of problem, either select light colour rock types that do not heat up as severely, or use rocks that do not display significant thermal movements.

Unfortunately the latter is not necessarily easily determined without testing, and is likely outside the scope of the suppliers range of quality control tests for properties.

The former, using light colours, has advantages for reducing thermal cyclic

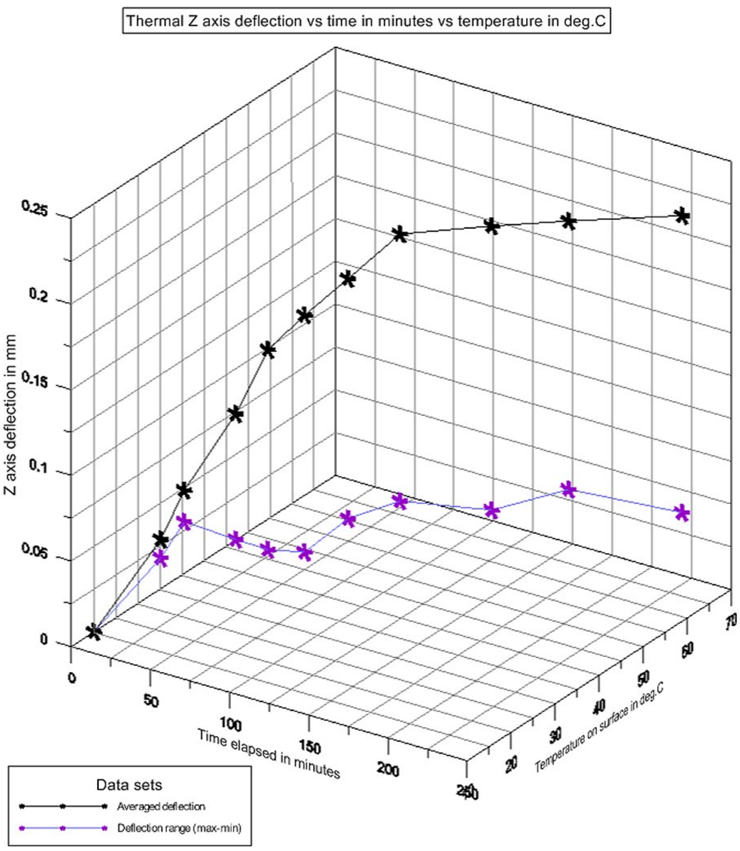

Figure 10. The temperature vs deflection graph for a borderline stable to moderately unstable slate stack stone tile. The deflection in this case was consistent across the tile as shown by the low range, and was ~0.24mm at 65 deg.C.

strains on the underlying materials, and would also no doubt assist in the building thermal efficiency in terms of reduced requirements for cooling. Also, dark coloured paving surfaces can create unpleasant problems for pedestrians in summer.

Moisture Movement in Detail

Movement in stone tiles is a function of the rock's porosity, together with the stability of the constituent minerals and also the matrix. The term matrix really refers more to sedimentary rocks than crystalline igneous and metamorphic rocks and is the binder that holds the particles together. That being said, fine grained volcanic igneous rocks can be composed of a background matrix and crystals as well, and finer grain metamorphic rocks can also display this texture.

Porosity

The rock porosity is a measure of the amount of pores within the rock structure which allows the penetration of water. Non-porous or 'tight' rocks do not allow the penetration of water and are more resistant to moisture related issues. The tightness is a function of the interlocking boundaries of the mineral crystals that make up the rock. Most crystalline plutonic igneous and metamorphic rocks are considered tight, with low porosity, however volcanic equivalents are often highly porous. Sedimentary rocks such as sandstone are also porous, and are well recognised as conduits for artesian water supplies, and also underground oil reservoirs. Limestones such as travertine and caliche are also highly porous.

There are two issues with porosity, the first is that highly porous rock tiles can easily stain or discolour, and the second is that high porosity can lead to dimensional stability problems. With staining and marking, this can either be a permanent or temporary effect. Temporary marking is purely due to the rock being wet, and is a result of moisture in the adhesive, or possibly the substrate. Permanent staining is either due to changes in the rock itself due to the water, or the rock capturing water mobile salts or polymer phases and producing a physical or chemical alteration.

Matrix components

The matrix of sedimentary rocks is usually very fine grained minerals, down to silt or clay size (these are particle size names and range from 0.06 to 63mm), and the composition can vary widely. The most common matrices are the actual clay minerals (i.e kaolin), lime mud, re-deposited silica and in the case of volcanic rocks devitrified glass. The fine grained matrices tend to display a similar affinity for absorbing water which either produces a physical appearance change (staining), or swelling and dimension change with warping. The higher the amount of matrix, the more unstable a rock is likely to be.

These problems do not appear to be a major issue for sandstones bonded with re-deposited silica. The most heavily affected rocks are things such as fine grained sandstone (with clay or fine lime matrices), muddy limestone (travertine etc,) and some light coloured volcanic rocks. Slate, whilst a metamorphic rock can also display this effect because it is composed of aligned clay minerals.

The fine grained matrix absorbs moisture from the adhesive and warps upwards, whilst others change colour and darken, usually in patches producing a blotchy light- dark appearance (see Figures 1, 2, 11 &12). In the case of crystalline marble, the amount of matrix is minimal or non-existent and the effects that occur with these rock tiles are usually show through or shading due to translucence.

Warping

Warping is a differential effect with the rock expanding on the wet side relative to

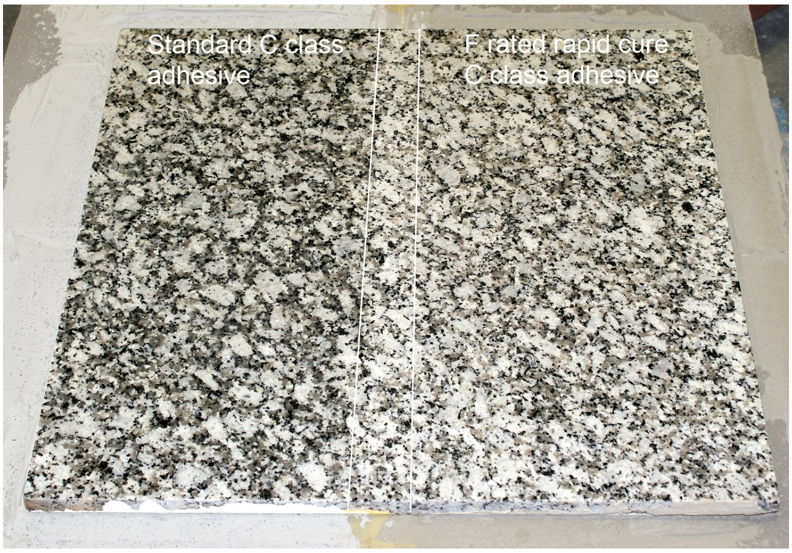

Figure 11. An unusual porphyritic granite (Adamellite) displaying extreme sensitivity to marking. The left side of the tile was bonded with a C2TES1 adhesive and on the right a C1FT adhesive intended for sensitive tiles. The central strip shows the natural colour. As can be seen, shade change occurred even with the F rated fast cure adhesive. This tile requires 100% adhesive coverage to display a consistent colouring.

dry side. Where the tile is not bonded, the warping normally disappears when it dries out, or conversely when it is fully saturated. The moisture source that affects the base side can be from the substrate or adhesive, but also rain and ponded water can effect the upper face as well (see Fig.4a). The measurable effects of moisture warping are shown in Figures 13a and 14a.

A deformable free tile is one thing, but when the tile is glued down that is a different problem. Where the tile bottom contacts a water based adhesive (or wet substrate), the surface can begin to expand and the tile starts to warp into a dish (Figures 13b & 14b). When the adhesive is soft it could accommodate this movement, provided the relaxation occurs before the adhesive hardens (unless it is so great that it cohesively fails the soft adhesive). However, the more common situation is the adhesive dries and has developed a degree of cure before the tile stabilises. This can either lead to compressive stress being applied to the adhesive around the tile perimeter, or excessive tensile strain being applied to the tile centre, cohesively shearing it with resultant drumminess. (Rain onto an unstable tile produces the reverse effect with doming of the tile in centre and down curling at the edges, but results in the same type of ultimate failure).

Figure 12. A mafic rock ('basalt, dolerite or diorite') displaying striping as a result of poor and incomplete contact coverage. The adhesive has altered the properties of the rock changing its porosity.

The issues and consequences are the same as for thermally sensitive tiles, though moisture warping sensitive tiles are far more common than thermally unstable ones.

SOLUTIONS

The solutions to using natural stone tiles made from unstable rock types are not simple. Ideally such rocks should not be

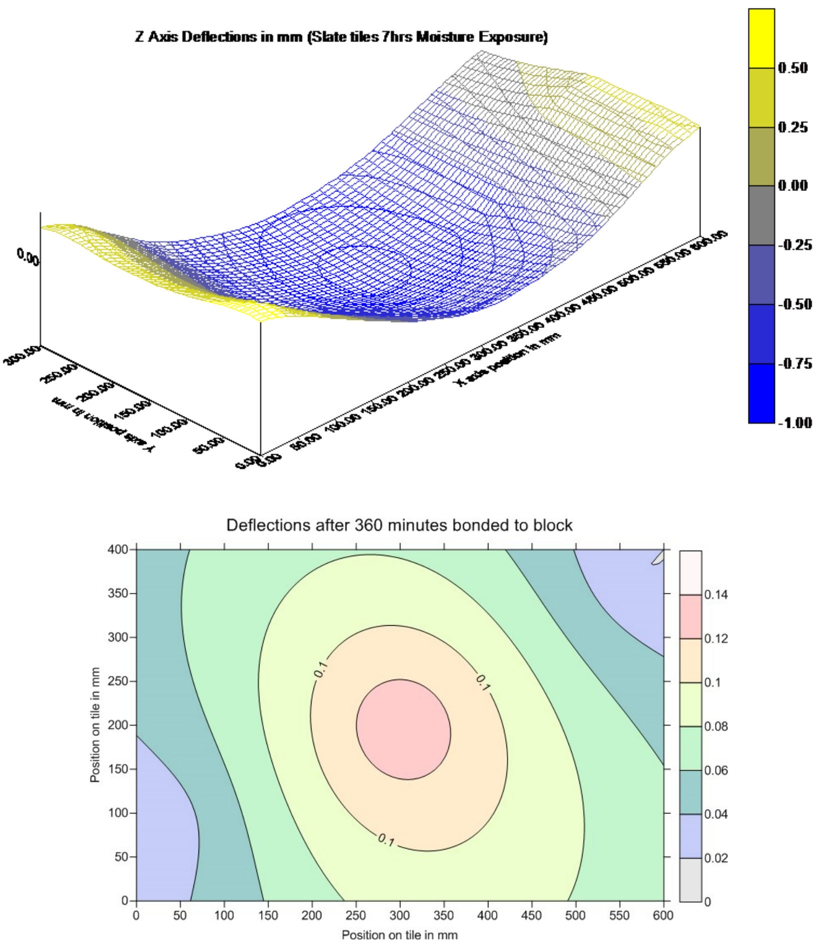

Figure 13a & 13b. Two types of three dimensional representation of the upper surface of a warped slate tile. This upper X-Y-Z plot represents movements measured after 7 hours exposure to moisture on one side of the tile. Both these tiles failed on job sites due to rain related movements.

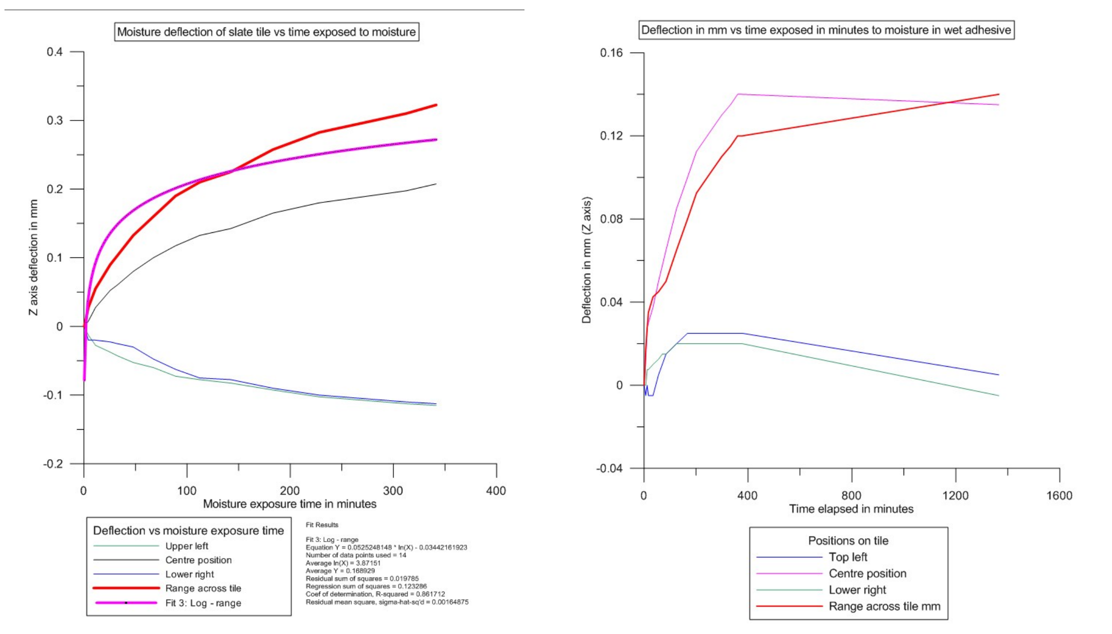

Figure 14a & 13b. Movements measured for a piece of unstable slate tile involved in a de-bonding event. The left graph shows the unrestrained tile movement when exposed to moisture up to 6hrs (peaked at 0.45mm after ~1000 minutes). The right graph shows the same tile displaying warping as a consequence of absorbing water from the C class tile adhesive (C2TES1).

quarried, but realistically that is not commercially going to happen. This means that 'work around solutions' are required, for example using specialised adhesives when these tiles are encountered, but in some cases not using them at all and selecting something else for the job is more appropriate.

In terms of thermal effects, tiles with light colours will not develop such high temperatures and hence reduce potential movements. However, there is no quick check when purchasing these tiles to determine whether they will move, or simply just get hot and sit there.

Moisture sensitive types can usually be identified by a careful examination of the tile for porosity and matrix types, but some types such as limestone and marble are well recognised moisture sensitive types.

Of late, one suggested solution for moisture related problems is to use a stone sealer on all sides, however this requires careful selection of the sealer since many appear to interfere with the adhesive bond leading to later failures. Again, this is something that can only be identified by testing so is not a simple thing to do in the field. Sealing does not do anything about thermal problems.

Some adhesive based solutions to the problem of unstable stone tiles are:

Use high strength non-water based R class polymer adhesives such as ARDEX WA100 epoxy.

Use rapid cure F rated cement based systems which develop a high proportion of their tensile strength in a short space of time such as ARDEX Quickbond +/- Abalastic. Note that these F rated adhesives are not suitable for the most sensitive tiles, as shown by Figure 11 where Quickbond was used and still marked the tile, or where the Z axis movement exceeds 0.4mm.

Another type of specialised F rated adhesive is formulated to suppress free water penetration into the tile surface before they dry. Such adhesives also develop rapid cure as well providing high strength rapidly, for example ARDEX S28N for internal locations.

Use hybrid systems where the tile back is coated with a lower viscosity 100% solids epoxy which whilst wet is laid into a high strength cement based adhesive bed (ARDEX EG15 resin used with ARDEX Optima, Abaflex, STS8, X18 or X77).

Finishing also requires the use of specialised grouts (the use of ARDEX EG15 requires test areas) and also specifically designed sealants to prevent picture framing; ARDEX ST Silicone is used for the latter, but even the most sensitive types can picture frame.

Ultimately though, the old customer protection maxim, '*caveat emptor*' needs to apply when selecting natural stone tiles for any external or critical job. However it should be noted that under consumer protection laws, suppliers and importers of tiles can be held accountable for their products.

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