

Introduction

Deterioration of masonry in buildings often results from a combination of chemical and physical causes. The original minerals in a building stone can change chemically with an associated loss of durability. At the same time, mechanical weathering processes can contribute to a physical breakdown of the fabric of the stone with little or no significant change in the composition of the constituent minerals. Physical decay is often the result of temperature and moisture changes in the masonry.

Information is given in this paper on temperature changes recorded on a masonry wall erected in an external exposure area at NBTC and on stone and joint movements caused by the temperature changes (Heiman, 1982). Movements caused by changes in the moisture content of the stone and the performance of joint materials are also discussed.

Wall Construction

The test wall was constructed with sandstone blocks obtained from a demolisher's yard. No information was available on the origin of the stone. Some of the blocks showed signs of surface weathering. Iron compounds were drawn to the external face where they oxidised and gave the stone a rusty colour in the lower two courses of the wall. The iron-stained layer extended to a depth of only a few millimetres below the surface. The unweathered stone below this zone was light grey in colour and was sound and dense.

The wall was approximately 11m long and 1.7m high, Fig. 1. The stone blocks varied in length but were all approximately 450mm high and 150mm thick. They were laid up in 3 courses against a clay brick backing wall, 110mm thick with 230mm x 110mm piers at approximately 2.6m spacing. A 1:1:6 composition mortar was used in the joints and in the grout used to bond the stone to the brickwork. Metal ties were not used. The overall thickness of the wall between the piers was 300mm. The sandstone cladding faced north and on clear days was continuously exposed to the sun from early morning until late afternoon.

Temperature and Moisture Measurements

Four integrated circuit thermometers were installed in a small block of stone in the middle course marked 'A' in Fig. 1. One was placed on the surface and the other three were placed nearby at depths of 10mm, 40mm and 100mm respectively. The holes containing the thermometers were plugged with a filled silicone sealant. A fifth thermometer was placed on a shaded stand near the wall to measure the ambient temperature. The five devices were connected to a chart recorder that enabled the temperatures to be monitored over extended periods of time.

Six pairs of stainless steel gauge studs were glued to the surface of the stone so that strain measurements could be made with a Demec extensometer having a 50mm gauge length. Two pairs of studs were placed at right angles to one another near the surface thermometer. Another two pairs straddled a vertical joint and the other two pairs straddled the lower horizontal joint, Fig.1. Temperature and strain movements were carried out in summer and winter.

Coefficient of Linear Expansion

The expansion coefficients for a piece of sandstone taken from the wall were determined carrying out strain measurements in 3 directions at right angles and at different temperatures within a range of 1°C to 50°C. The graphs of strain plotted against temperature showed a nearly linear relationship in the 'X' and 'Y' directions. The coefficients were both $10.6 \times 10^{-6}/^{\circ}\text{C}$. The graph in the 'Z' direction (at right angles to the face of the wall) was non-linear between 1°C and 22.5°C and practically linear between 22.5°C and 50°C, where the coefficient was $14.6 \times 10^{-6}/^{\circ}\text{C}$.

Measurements of Movements Resulting from Moisture Changes

The stone in the vicinity of Block 'A' was sprayed continuously with a sprinkler for 11 days to determine the amount of surface expansion that resulted from wetting. Prior to wetting there had been no rain for 23 days and the surface of the wall was dry. Strain measurements were made on the stone and across the joints at intervals during the wetting period early in the morning in winter when the ambient temperatures were close to 6°C.

Results of Temperature Measurements

The recorder showed that rapid and erratic, short-term temperature changes occurred during the day while the sun shone on the wall. Appreciable short-term fluctuations occurred as clouds obscured the sun and the wall was intermittently exposed to direct solar radiation, Fig. 2. During one such transition, a 10°C increase in surface temperature took place within 15 minutes and followed a 6°C decrease that took place within 10 minutes. Even on clear, sunny days there were rapid fluctuations in surface temperature although they were of smaller magnitude than those resulting from cloud movements across the sun. These changes were attributed to the effects of air current movements near the wall surface. During the night the wall temperatures decreased steadily until early morning. As soon as the sun shone on the wall the temperatures began to rise rapidly.

Damping Effects

The amplitudes of the short-term temperature fluctuations diminished with increasing depth from the surface. At 100 mm from the surface most of the minor undulations occurring at 40 mm had been suppressed and the graph was relatively smooth. In winter the differences between the surface and a depth of 100 mm were less between midnight and 7 am (about 4°C) than around noon (about 13°C).

Temperature Reversals

Two clearly defined cyclic changes occurred within a 24-hour period, namely at about 8 am and 4 pm. In winter between approximately 8 am and 4 pm the stone temperatures generally diminished with increased depth from the surface. At about 4 pm there was a reversal in this characteristic and between about 4 pm and 8 am the surface temperature was lower than the internal temperatures which increased with depth. In summer with earlier sunrises and later sunsets, the two reversals occurred respectively earlier and later than in winter. Just prior to the afternoon reversal the stone at a depth of 100mm was still increasing slowly while the surface temperature was decreasing rapidly, Fig. 3. This temperature lag in the interior of the wall had a restraining influence on the strain movements at the surface and the changes in strain about 4 pm were smaller than those occurring between say 8 am and 1 pm on a clear sunny day when the temperatures at the surface and internally were all rising steadily.

Seasonal Changes

The highest surface temperature recorded on the wall was 46°C at noon on the 21st February when the corresponding air temperature was 40°C. However the daily differences between surface and ambient temperatures were much greater in winter than summer. For example at 2.15 pm on the 23rd July the surface temperature was 37.5°C when the air temperature was 17°C. There were also bigger differences between the surface and interior temperatures in winter than summer. On the 28th July the temperature at a depth of 100 mm was 19.5°C when the surface temperature was 33.5°C, whereas on the 21st February the temperature at a depth of 100 mm was 34.5°C when the surface temperature was 45.5°C. The ranges between the daily maximum and minimum surface temperatures were also greater in winter than in summer and were 30°C and 22°C for the two dates just mentioned. When the wall was exposed temporarily to direct sunlight and then partly shaded as clouds passed over the sun, the amplitudes of the rapid short-term fluctuations of temperature at the wall surface were also substantially greater in winter than in summer.

The darker the surface the greater the amount of solar radiation that is absorbed by the wall. The two lower rusty-coloured courses absorbed more heat than the upper light-coloured one. However higher surface temperatures

can be attained than those measured on the test wall. There are a number of sandstone buildings in Sydney where the effects of urban pollution and lack of maintenance have resulted in the stone becoming black. Surface temperatures in excess of 70°C have been recorded in summer on dark facades facing north and west.

Strain Measurements

There was a non-linear relationship between temperature changes and strains measured on the stone and across the joints. Both expansions and contractions were measured and they occurred in an irregular manner. The surface expansion of the stone resulting from the rising temperature was restrained by the effects of the temperature differential through the wall; restraint being provided by the cooler internal stone and the brick backing which was always in the shade and had a lower coefficient of expansion, (approx. $6 \times 10^{-6}/^{\circ}\text{C}$). In the morning, expansion of the adjacent blocks of stone usually resulted in contraction across the joints. Later in the day as the whole wall expanded this movement was often reversed. The largest contraction measured across the vertical joint took place between 7.30 am and 2.30 pm on the 18th July when the strain difference was 1747 microstrain. The largest measured expansion on a horizontal joint occurred on the same day between 11.30 am and 4.30 pm when the difference was 919 microstrain (Fig 4).

On the 27th July there was a steady and rapid rise of surface temperature until about noon during which period the sky was clear and the sun shone on the wall. The sky then became overcast and within 15 minutes the surface temperature dropped from 32°C to 25°C. It continued to fall more slowly until about 1.30 pm when it stabilised for a while at about 19°C, Fig. 2. Accompanying these changes, there were sudden and erratic changes in strain which would have been associated with marked variations in surface stresses.

Movements Caused by Moisture Changes

Even after prolonged rainfall, the wetted zone of a sound sandstone of low porosity is unlikely to penetrate far below the surface if wetting occurs only on the external vertical face and the joints are in good order. Significant expansion is therefore likely to be confined to a shallow surface layer. The magnitude of the stone and joint movements are given in Table 1. The joint movements were greater than those caused by temperature but with natural rainfall, movements of this magnitude would occur infrequently in the Sydney climate.

Table 1. SURFACE MOVEMENTS CAUSED BY WETTING (MICROSTRAIN)

Wetting Time (hours)	Stone Expansion		Joint Contraction	
	Horizontal	Vertical	Horizontal*	Vertical*
40	182	424	1494	2828
108	525	747	2222	3252
272	566	808	2363	3414

* Mean of Two Readings

Influence of Temperature and Moisture Changes on Building Performance

Stone

The rapid changes in strains and stresses associated with the temperature fluctuations monitored in this investigation highlight the dynamic nature of these processes and suggest they can exacerbate decay particularly when the stone is already weathered. The long-term durability of a sandstone will be influenced by the condition and nature of the matrix binding the quartz grains together. Expansion and contraction of the clay minerals caused by temperature and moisture changes can result in microcracking and a breakdown of the microstructure. Salt attack associated with urban pollution or other forms of contamination can also be accelerated by frequent temperature and moisture changes.

Joints

The maintenance of old masonry buildings in a sound condition depends to a large degree on the prevention of excessive moisture penetration into the fabric and often defective joints provide a ready entry for moisture. In

this context, strong cement mortars are often inappropriate because of their lack of flexibility and tendency to crack. An NBTC survey of deterioration showed that a breakdown of masonry joints often occurred near roof level, on parapets, cornices and other horizontal or sloping projections where rain-water can collect and where there is less restraint to temperature and moisture movements. The strain capacity at rupture of cement mortars or composition mortars is around 200 microstrain, but as has been shown, temperature and moisture movements can far exceed this value and suggest that mortar joints in the situations just described could be inappropriate. (In a subsequent field investigation carried out on a sandstone parapet on an office building, a contraction of 84000 microstrain was measured across a vertical joint. This movement occurred over a 7-hour period when the surface stone temperature increased from 26°C to 43°C.

Mason's putty consisting of a mixture of slaked lime, whiting and linseed oil was used to point some of the joints in this building. It is considered to be more flexible than composition mortars but it still showed extensive cracking. Where large temperature or moisture movements may occur, the repointing or repairing of damaged joints with cementitious mixes or mason's putty is unlikely to overcome the problem because they are often not flexible enough to accommodate these movements. The covering of horizontal or sloping surfaces with sheet flashings and the use of flexible sealants may be more effective.

Flexible Sealants

Elastomers such as polysulphides, polyurethanes and silicones have been used to fill joints. Polysulphides and polyurethanes are available in one-part and two-part preparations. Silicones are one part materials but they are frequently used with primers.

The maximum extension or contraction of an elastomeric sealant such as a silicone should not exceed 25% of the joint width. The narrower the joint width the less movement it can accommodate. No joint should be narrower than 6 mm. The choice of a suitable width-to-depth ratio will also have an important influence on the joint performance. The ratio should never be less than 1:1, and should be constant along the length of the joint. Control of the depth of the sealant is achieved by the prior insertion of a compressible back-up rod or strip usually made of expanded polyethylene or polyurethane. The backing rod should act as a bond breaker so that stress in the sealant acts only in one direction. When joint failures occur, they are often the result of unsatisfactory preparation of the joint surfaces. It may be necessary to grind and widen the joint with an angle grinder to remove loose and decayed stone and to expose sound material followed by the cleaning and removal of dust and loose debris with oil-free, compressed air before application of the primer or sealant. Where moderate movement is expected an oleomastic sealant may be more appropriate than an elastomer because a primer is not needed and also staining of adjacent stone associated with the use of silicones is avoided. However its deformation characteristic is less than a silicone (10% against 25%). An oleomastic may develop surface cracks with time but the sealant below the surface skin can still remain plastic.

The use of a low-permeability flexible sealant in salt-contaminated stone runs counter to accepted practice in that the permeability of the joint material should be greater than that of the adjacent stone so that the salts are encouraged to migrate into the joints. A low permeability sealant will cause salts to accumulate in the adjacent stone rather than in the joint and decay of the stone can result. It is easier to replace a decayed joint than to repair damaged stone. Nevertheless in the case of joints where large movements are likely, the use of an flexible sealant rather than a porous composition mortar may still be the lesser of two evils in that there could be less likelihood of ready penetration of rain-water via cracks in the joints.

Conclusions

The investigation showed that appreciable movements can take place at joints in sandstone masonry as a result of temperature and moisture changes.

Rapid short-term temperature changes in the stone were caused by cloud movements across the sun and were greater in winter than in summer. They tended to damp out with increased depth from the surface.

Temperature differences between the air and the wall surface and between the surface and the wall interior were greater in winter than in summer.

Appreciable temperature gradients occurred with increased depth from the surface. During the afternoon as a result of temperature lag the surface stone could be contracting while the interior stone was still expanding.

There was a non-linear relationship between temperature changes and surface strains, part of which was the result of restraint arising from temperature differentials within the wall. Differential shear stresses can be set up because of these changes and if the outer layer of stone is weathered and the interior stone is sound, the stresses can increase the rate of deterioration of the surface layer.

Movements caused by temperature and moisture changes are likely to exceed the strain capacity of mortar joints in locations where there is reduced restraint such as at horizontal members at roof level. Because of insufficient flexibility, excessive shrinkage and inadequate adhesion, mortar joints often break down at these places.

Flexible sealants can accommodate more movement than mortar joints and where there isn't significant salt contamination may be more effective in preventing rain penetration. Adhesion failures may occur at the interface between the stone and the sealant where the joint surfaces are not clean or sound.

Reference

Heiman, J.L., "The Influence of Temperature and Moisture Movements on Sandstone Masonry", Technical Record 477, National Building Technology Centre.

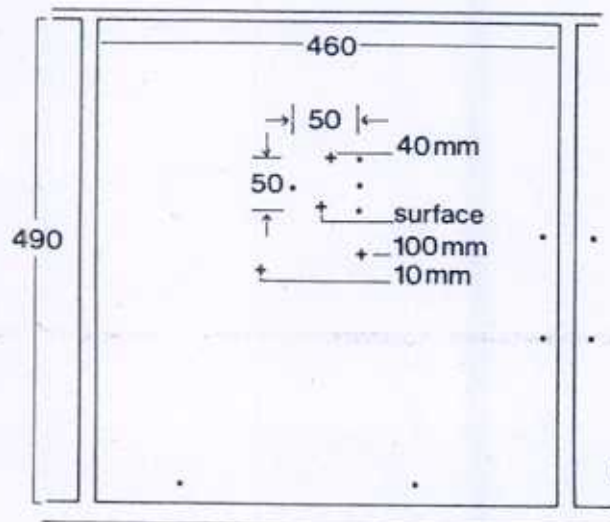
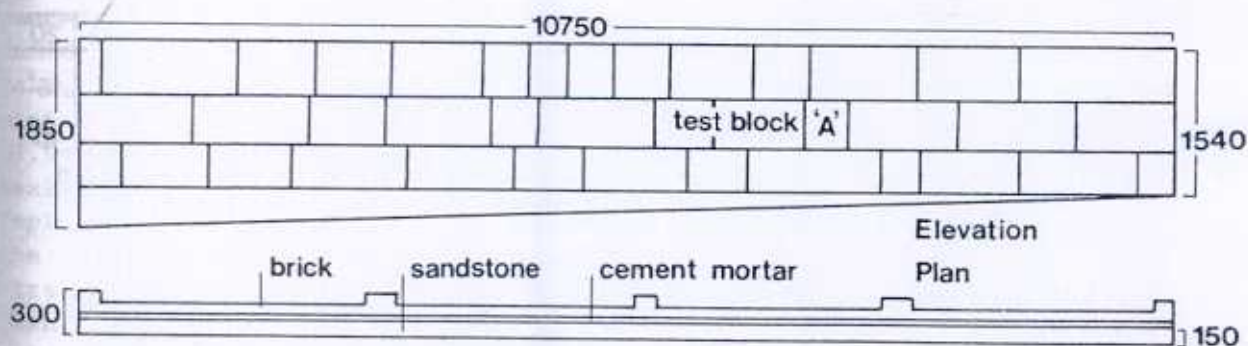
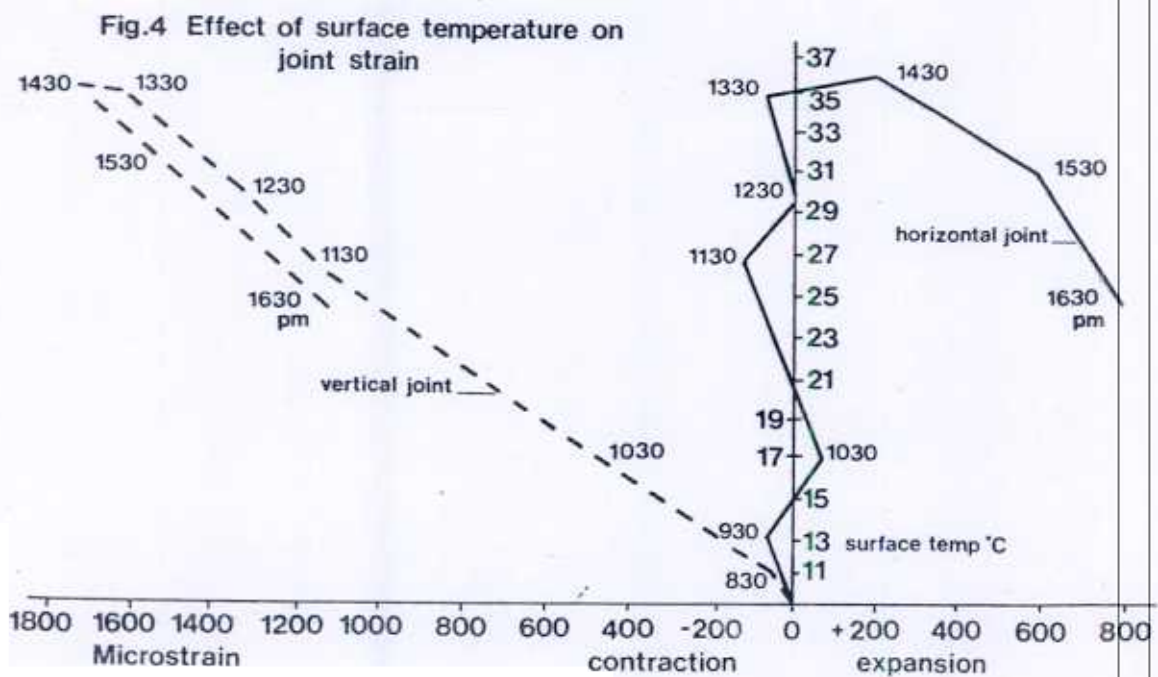
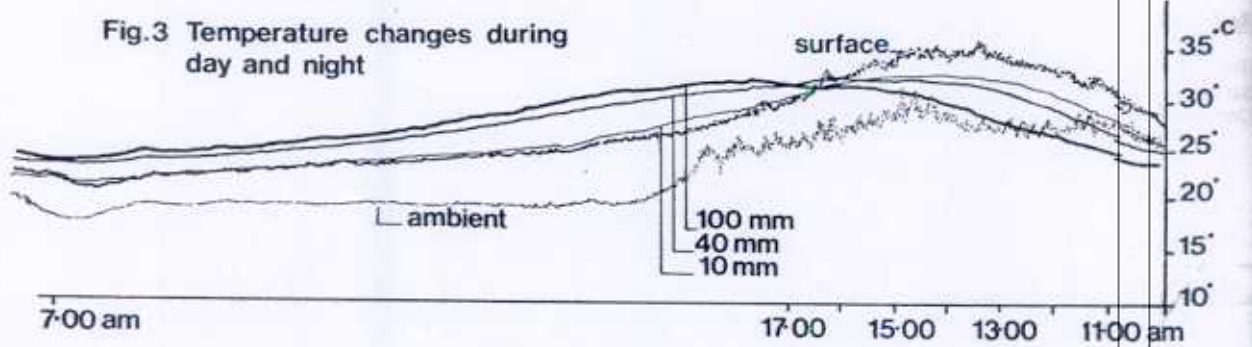
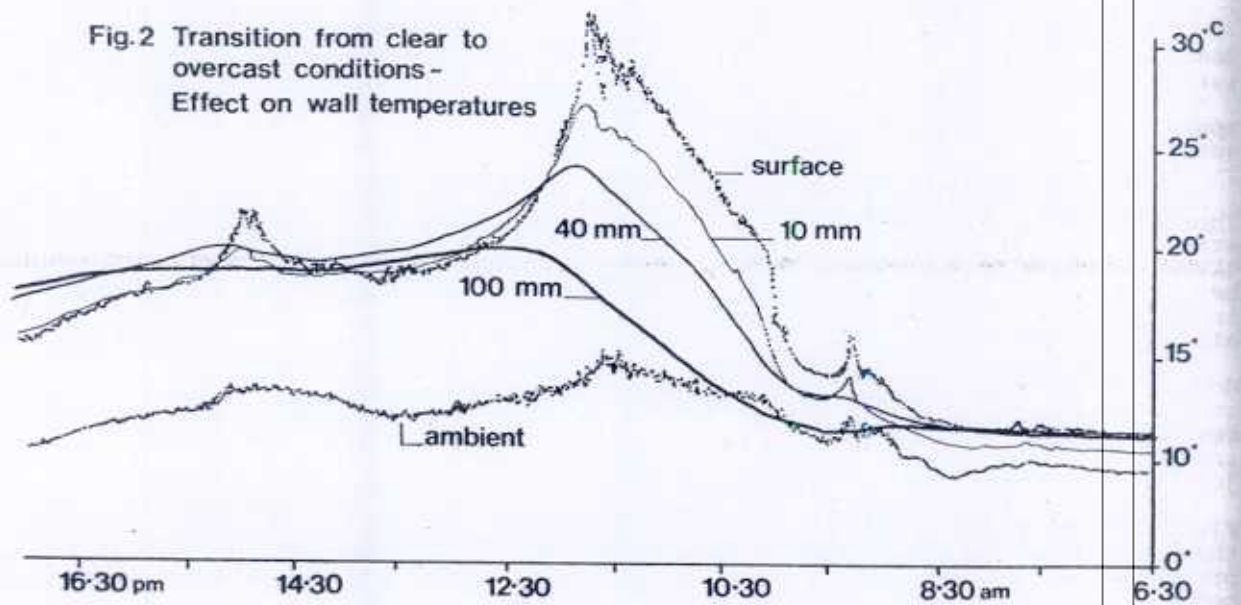


Fig.1 Test Wall Details

• Demec Gauge Points
+ Integrated Circuit Thermometer

Elevation of Test Block 'A'



THE INFLUENCE OF TEMPERATURE AND MOISTURE ON SANDSTONE MASONRY MOVEMENTS
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An investigation has been carried out to examine the effects of changes of temperature and moisture on a sandstone wall. The temperature measurements were made with integrated circuit thermometers attached to the surface of the wall and at depths of 10mm, 40mm and 100mm. The ambient temperature was also measured. Surface strains were measured on the stone and across vertical and horizontal joints using a Demec extensometer. During the investigation the wall was continuously sprayed with water for 11 days and the effects of the wetting on surface movements were measured with the extensometer. Rapid and erratic short-term temperature changes occurred during the day while the sun shone on the wall. The fluctuations were most marked when clouds passed across the sun and the wall was intermittently exposed to solar radiation. But even on clear, sunny days there were smaller but distinct fluctuations in surface temperatures caused by air movements near the wall. The amplitudes of these fluctuations diminished with increasing depth from the surface. Two clearly defined temperature reversals occurred at about 8 am and 4 pm. Between these times the stone temperatures decreased with increased depth from the surface. At about 4 pm, this characteristic was reversed and between 4 pm and 8 am, the surface temperatures were less than the internal temperatures which increased with depth. Just prior to the afternoon reversal, the stone temperature at a depth of 100mm was still slowly increasing while the surface temperature was decreasing rapidly. The highest surface temperature recorded on the wall in summer was 46°C when the corresponding air temperature was 40°C, but the daily differences between surface and ambient temperatures were greater in winter than in summer. For example on 23rd July the surface temperature was 37.5°C when the air temperature was 17°C. The ranges between the daily maxima and minima were also greater in winter as were the magnitudes of the amplitudes of the short-term fluctuations recorded as clouds passed across the sun. There was a non-linear relationship between temperature changes and strains measured on the stone and across the joints, part of which was the result of restraint arising from the temperature differentials within the wall. In the morning, expansion of adjacent blocks of stone resulted in contractions across the joints, but later in the day as the whole wall expanded these movements were often reversed. During the day, the surface stone moved erratically and expansions and contractions occurred within short time intervals. The joint movements caused by prolonged wetting were greater than those caused by temperature changes, but are likely to occur much less frequently. Movements caused by temperature and moisture changes are likely to far exceed the strain capacity of mortar joints in locations where there is reduced restraint such as on horizontal members at roof level. Joint cracking and rain penetration can occur as a consequence of this incompatibility. Flexible sealants can accommodate more movement than mortar joints and where there is insignificant salt contamination may be more effective in preventing rain penetration.

L'INFLUENCE DE LA TEMPERATURE ET DE L'HUMIDITE SUR LES MOUVEMENTS DE LA
MAÇONNERIE DE GRÈS

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Une investigation s'est conduite pour examiner les effets des changements de la température et de l'humidité sur un mur en grès. Les mesures de la température se faisaient avec des thermomètres à circuit intégré attachés au surface du mur et à 10mm, 40mm et 100mm de profondeur. On mesurait aussi la température ambiante. Les extensions sur la surface et à travers les joints verticaux et horizontaux se mesuraient avec un extensomètre Demec. Pendant l'investigation on arrosait le mur continument avec eau pendant onze jours et mesurait les effets du mouillement sur les mouvements du surface avec l'extensomètre. Des changements rapide, erratique et de courte durée de la température se passaient pendant la journée tandis que le soleil brillait sur le mur. Les fluctuations étaient plus marquées quand des nuages passaient à travers le soleil et le mur était exposée au radiation solaire intermittent. Mais, même les jours du soleil et clairs il y avait de petites fluctuations mais distinctes de température au surface a cause de mouvements de l'air près du mur. Les amplitudes des fluctuations diminuaient avec le profondeur augmentant sous la surface. Deux renversements nettement definis sont arrivés vers huit heures et seize heures. Entre ces heures les températures de la pierre diminuaient avec le profondeur augmentant sous la surface. Vers seize heures, cette disposition s'est renversée et entre seize heures et huit heures les températures de la surface étaient moins que les températures interieures qui augmentaient avec le profondeur. Juste avant le renversement de l'après-midi, la température de la pierre a 100mm sous la surface augmentait lentement encore pendant que la température de la surface diminuait rapidement. La plus haute température enregistrée sur le mur était 46°C pendant que la température correspondant de l'air était 40°C, mais les différences quotidiennes entre les températures de la surface et ambiante étaient plus grandes en hiver qu'en été. Par exemple, le 23 juillet la température de la surface était 37.5°C quand la température de l'air était 17°C. Les rangées entre les maxima et minima quotidiennes étaient aussi plus grands en hiver, aussi bien que les grandeurs des amplitudes des fluctuations de courte durée enregistrées quand des nuages traversaient le soleil. Il y avait un relation non-linéaire entre les changements de température et les extensions mesurées sur la pierre et à travers les joints, dont une partie resultait de la contrainte provenant des différentiaux de température dedans le mur. Le matin, l'expansion des blocs adjacents de pierre a abouti à contractions à travers les joints, mais plus tard dans la journée lorsque le mur entier s'étendrait ces mouvements se sont souvent renversés. Pendant la journée, la surface de la pierre se mouvait irrégulièrement et les expansions et les contractions arrivaient dans de courts intervalles de temps. Les mouvements des joints occasioné par de mouillement prolongé était plus grand que ceux occasioné par les changements de température, mais ils sont enclins à arriver beaucoup moins souvent. Les mouvements occasioné par les changements d'humidité et de température sont enclins à excéder la capacité pour extension des joints de mortier situés où la contrainte est reduite, comme aux membres horizontaux au niveau du toit. Cette incompatibilité peut occasioner des craquements aux joints et de pénétration par la pluie. Les scellages flexibles peuvent accommoder plus de mouvement que les joints de mortier et dans le cas où le contamination au sel est insignifiant peuvent être plus effectifs pour empêcher la pénétration par la pluie.