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Publisher's version / Version de l'éditeur:

Matériaux et constructions. Materials and Structures, 17, 101, pp. 351-357, 1984-09

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THERMAL STRESSES IN MORTAR-TILE SYSTEMS

by Kazumi Yoshikawa and G.G. Litvan

ANALYZED

Reprinted from
Matériaux et Constructions
Vol. 17, No. 101, septembre—octobre 1984
p. 351 - 357

DBR Paper No. 1251
Division of Building Research

Price \$1.00

OTTAWA

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RÉSUMÉ

On a examiné les variations de longueur dans les systèmes composites mortier-tuile de porcelaine et mortier-tuile de pierre (en général $10 \times 3 \times 8$ mm), à des températures variant entre -10°C et 50°C . On a évalué l'effet de la valeur de l'échauffement (1 et $4^{\circ}\text{C}/\text{min}$), des dimensions des échantillons, du rapport entre les volumes des composants et de l'emplacement du point de mesure par rapport à l'interface. Les variations de longueur de la zone interfaciale étaient très éloignées des valeurs théoriques basées sur la prédiction du comportement élastique. Cependant, à l'extérieur de la zone interfaciale qui s'étend à 5 mm dans le mortier et à 3,5 mm dans le matériau composant la tuile, on a obtenu une bonne concordance entre les valeurs mesurées et celles calculées.

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Thermal stresses in mortar-tile systems

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Length changes of mortar-porcelain and mortar-quarry tile composites (typically $10 \times 3 \times 8$ mm) have been examined in the temperature range -10 to $+50^\circ\text{C}$. The effect of heating rate (1 and $4^\circ\text{C}/\text{min.}$), dimensions of specimens, volume ratio of components and location of the measuring point with reference to the interface were evaluated. Length changes of the interfacial zone significantly deviated from the values predicted by assumption of elastic behaviour. Good agreement between measured and calculated values was obtained, however, outside the interfacial zone extending 5 mm into the mortar and 3.5 mm into the tile component.

Glazed and unglazed porcelain and unglazed quarry tile are widely used in Japan as cladding for external wall surfaces of low and high-rise buildings. As these finishes are aesthetically pleasing, fairly durable and maintenance free, they enjoy great popularity. In a small but significant number of cases, however, the tiled wall systems fail in service. Adhesive failure may occur 4 to 5 years after installation or at some later time. Typically, groups of adjacent tiles, sometimes a few sometimes a great many, are dislodged. The composite system (consisting of tiles, plain or modified bonding mortar, and concrete) breaks down owing to dissimilarities of the coefficients of thermal and moisture expansion of the various parts, giving rise to differential movements and stresses. Temperature and moisture gradients, which always exist under field conditions, further aggravate the situation.

A study of stress development at the interface between building elements is of increasing importance, with the trend towards use of large-sized prefabricated assemblies. Stresses exist also at the interface between disperse phases of composites such as cement paste and aggregate [1] or reinforcement and matrix [2], affecting bond strength between components. In spite of the importance of restrained shrinkage and expansion in mortar and concrete, only limited data exist in the literature [3].

In the present study the coefficients of thermal expansion were measured in an effort to clarify the processes limiting durability of composite systems. The effect of changing moisture content will be the subject of a second investigation. Stresses created by changing temperature conditions have been examined by measuring the dimensional changes of composites. But strain gau-

ges can only be installed at the interface, where they seriously alter the interfacial bond, or in the interior of the phases far removed from the stress zone. Measurement of length changes was therefore chosen as the experimental technique because it does not have these limitations.

2. EXPERIMENTAL

2.1. Materials

Normal portland cement and Ottawa sand were used to make mortar with a cement:sand:water ratio of $1:1:0.3$. In some cases it was modified with acrylic resin dispersion with a cement:resin ratio of $1:0.07$. A two-part epoxy resin was used as adhesive. Some of the properties of the porcelain and quarry tiles used in the study are shown in table I.

2.2. Equipment

A DuPont Model 1090 Thermal Analyser (TA) with Model 990 Mechanical Cooling Accessory (MCA) and a Model 941 Thermomechanical Analyser (TMA) were

TABLE I
PROPERTIES OF TILES AND MORTAR

	Quarry tile	Porcelain tile	Mortar
Water absorption (%).	5.13	1.14	15.04
Young's modulus (GPa).	52.5	57.7	33.7
Coefficient of thermal expansion ($4^\circ\text{C}/\text{min.} \times 10^{-6}$).	4.734	4.374	12.62

Fig. 1. — Illustration of specimen geometry.

used. Length changes of the specimen, resting on a quartz plate, were registered by movement of a probe of 0.5 mm diameter. To ensure good contact the probe was loaded with a 2 g weight. The rate of temperature change controlled by the TA was based on the signal provided by a thermocouple on the surface of the specimen. The cooling element of the MCA surrounded the TMA heater in the cell. An insulated aluminum collar was placed on the top of the cooling element to prevent condensation and minimize temperature fluctuations.

2.3. Sample preparation

The composite specimens were fabricated by casting mortar against tiles, conditioned at 100% RH, whose surfaces were ground smooth to provide a well-defined interface. After two months' curing in a fog room, the specimens were cut to exact dimensions with a metallographic blade-saw, then dried at 90°C for 48 hours and stored over $Mg(ClO_4)_2$ in a desiccator until tested.

Prism shaped specimens (fig. 1) were used. Height (h) was 12 mm in Series 1 S and 2 Cp, and 10 mm in

subsequent experiments. Depth (d) was 3 mm, except for Series 1 S and 2 Cp, in which specimens 6 mm deep were also used. Width (w) was 12 mm in Series 1 S and 2 Cp, and 6, 8 or 10 mm in Series 3 S. When the effect of the volume ratio of the components was studied (4 and 5 Cp), specimens with $w=6, 7, 8$ and 10 mm were tested. The specimens in 6 and 7 Cp had $w=8$ mm; in Series 8 Cp, $w=6$ mm.

2.4. Procedure

Specimens of known dimensions were placed in the TMA and the temperature of the cell was increased at constant rate (1.4 or 5°C/min.), specified by the program, to +60°C, followed immediately by cooling to -20°C at the same constant rate. Each run consisted of five temperature cycles. Only length changes occurring between -10 and +50°C in the last three cycles were tabulated. These could be read to 0.01 μm and temperature to 0.01°C. The test program was designed and the results evaluated by the statistical methods of randomized complete block design [4].

3. EXPERIMENTAL PROGRAM AND RESULTS

The effects of the various factors investigated in the eight series of experiments are shown in table II.

In Series 1 S and 3 S single materials were used and in the rest, composite specimens.

Table III shows the layout of the factors and their levels, together with measured values. To illustrate the method of tabulation, consider specimen No. 3. The probe was positioned 2 mm from the centre of the specimen (factor A, level 2), on the mortar surface (factor B, level 1), and the cell was heated at 1°C/min.

TABLE II
FACTORS AND LEVELS INVESTIGATED

Series	Symbol	Factor	Level						
			1	2	3	4	5	6	7
1 S.	A	MPLC (mm)	0.5	2.0	3.5	5.0	—	—	—
	B	Material measured	Mo	Po	—	—	—	—	—
	C	Heating rate (°C/min.)	1	4	—	—	—	—	—
	D	Depth of specimen (mm)	3	6	—	—	—	—	—
2 Cp.	E	Material measured	Mo	Po	—	—	—	—	—
	F	MPLI (mm)	0.5	2.0	3.5	5.0	—	—	—
	G	Heating rate (°C/min.)	1	4	—	—	—	—	—
	H	Depth of specimen (mm)	3	6	—	—	—	—	—
3 S.	I	Bonding material	Mo	Ep	—	—	—	—	—
	J	Material measured	Mo	Po	Qu	—	—	—	—
	K	MPLI (mm)	5.5	4.5	3.0	—	—	—	—
	L	Width of specimen (mm)	6	8	10	—	—	—	—
4 Cp.	M	MPLI (mm)	2.0	0.5	0.5	—	—	—	—
	N	Volume ratio (Mo/tile $\times$ 100)	20	60	—	—	—	—	—
	O	Type of tile	Po	Qu	—	—	—	—	—
5 Cp.	P	Volume ratio (Mo/tile $\times$ 100)	500	250	167	—	—	—	—
	Q	MPLI (mm)	2.0	0.5	0.5	—	—	—	—
	R	Type of tile	Po	Qu	—	—	—	—	—
6 Cp.	U	MPLI (mm)	3.5	2.5	1.5	0.5	0.5	1.5	2.5
7 Cp.	W	MPLI (mm)	3.5	2.5	1.5	0.5	0.5	1.5	2.5
8 Cp.	X	MPLI (mm)	0.5	0.5	1.5	2.5	3.5	4.5	—

S=Single material; Cp=Composite; Mo=Mortar; Po=Porcelain; Ep=Epoxy; Qu=Quarry; MPLC=Measuring point location with reference to centre of specimen; MPLI=Measuring point location with reference to the interface; MPLE=Measuring point location with reference to edge of specimen.

(factor C, level 1). The specimen was 6 mm deep (factor D, level 2). The error column, e , contains no factors. Expansions of this specimen, measured when heated under the described conditions from -10 to 50°C in three successive cycles, are listed in the same row of table III. (Columns labelled f in subsequent tables contain no factor; they are used when there are more than two levels in the lay-out.)

The analysis of variance (ANOVA) for Series 1 S is shown in table IV. Symbols $e-1$ and $e-2$ represent the error variance due to experimentation and sampling, respectively. Symbol (e) represents the adjusted error variance used for computing the F ratio. The significance of the factor is determined by comparing the F ratio with the values of the F distribution tables.

According to table IV the effect of the monitored material type (Factor B) is significant at the 1% level. (Following convention, if the F ratio exceeds the 99% point it is tagged with a double asterisk and if it exceeds the 95% point, with a single asterisk. Dagger superscripts indicate 90% confidence limit.) The effect of depth of specimen (Factor D) is significant at the 5% level, and that of the heating rate (Factor C) at the 10% level. In Series 6, change in length of specimen was determined when the temperature of the composite, equilibrated at -10°C , was raised to 50°C . Conditioning at each temperature required 4 hours after which there was no observable change in length. The results of subsequent runs are given in tables V to XIII.

TABLE III
SERIES 1 S: LAYOUT AND TEST RESULTS

Col. ... Spec.	Factor					Length change ($\mu\text{m}/10\text{ mm} \cdot 60^{\circ}\text{C}$)		
	A	B	C	D	e			
	1-3	4	5	6	7			
1.	1	1	1	1	1	9.53	9.06	9.03
2.	1	2	2	2	2	3.45	3.44	3.38
3.	2	1	1	2	2	8.16	8.08	7.93
4.	2	2	2	1	1	3.66	3.66	3.73
5.	3	1	2	1	2	8.38	8.11	8.12
6.	3	2	1	2	1	3.80	3.74	3.66
7.	4	1	2	2	1	7.86	7.90	7.82
8.	4	2	1	1	2	4.08	4.19	4.12

TABLE IV
SERIES 1 S: ANALYSIS OF VARIANCE

Source of variation	Degree of freedom	Sum of squares	Mean square	F ratio
A.	3	0.669,9	0.223,3	—
B.	1	126.362,7	126.362,7	603.16 (**)
C.	1	1.435,7	1.435,7	6.85 (+)
D.	1	1.733,4	1.733,4	8.27 (*)
$e1$	1	0.168,3	0.168,3	—
$e2$	16	0.038,1	0.002,4	—
(e).	(4)	(0.8382)	(0.209,5)	—
Total.	23	130.408,2	—	—

$e1$, experimental error; $e2$, sampling error; (**), 1% level of significance; (*), 5% level of significance; (+), 10% level of significance.

TABLE V
SERIES 2 Cp, LAYOUT AND TEST RESULTS

Col. ... Spec.	Factor						Length change ($\mu\text{m}/10\text{ mm} \cdot 60^{\circ}\text{C}$)		
	E	F	G	H	I	e			
	1	2-7	8	9	10	11-15			
1.	1	1	1	1	1	—	6.36	6.44	6.26
2.	1	1	2	2	2	—	6.44	6.54	6.49
3.	1	2	1	1	1	—	6.91	6.97	6.97
4.	1	2	2	2	2	—	7.28	7.32	7.26
5.	1	3	1	1	2	—	7.77	7.78	7.82
6.	1	3	2	2	1	—	8.23	8.24	8.29
7.	1	4	1	1	2	—	8.46	8.50	8.52
8.	1	4	2	2	1	—	8.22	8.39	8.11
9.	2	1	1	2	1	—	4.95	5.09	5.02
10.	2	1	2	1	2	—	3.88	3.81	3.98
11.	2	2	1	2	1	—	3.89	3.89	3.90
12.	2	2	2	1	2	—	4.54	4.61	4.66
13.	2	3	1	2	2	—	3.55	3.74	3.39
14.	2	3	2	1	1	—	4.09	4.18	4.10
15.	2	4	1	2	2	—	4.23	4.13	4.10
16.	2	4	2	1	1	—	3.74	3.44	3.42

TABLE VI
SERIES 2 Cp, ANALYSIS OF VARIANCE

Source of variation	Degree of freedom	Sum of squares	Mean square	F ratio
E.	1	137.498,7	137.498,7	251.09 (**)
F1-4 (E1) . .	3	13.982,8	4.660,9	8.51 (**)
F1-4 (E2) . .	3	1.683,7	0.561,2	—
G.	1	0.008,0	0.008,0	—
H.	1	0.252,3	0.252,3	—
I.	1	0.001,9	0.001,9	—
$e1$	5	4.078,0	0.815,6	—
$e2$	32	0.242,2	0.007,6	—
(e).	(11)	(6.0239)	(0.547,6)	—
Total.	47	157.747,6	—	—

TABLE VII
SERIES 3 S, LAYOUT AND TEST RESULTS

Col. Spec.	Factor				Length change ($\mu\text{m}/10\text{ mm} \cdot 60^{\circ}\text{C}$)		
	f	J	K	L			
	1	2-3	4-5	6-7			
1.	1	1	1	1	7.94	7.88	7.88
2.	1	1	2	2	7.47	7.54	7.54
3.	1	2	1	2	2.87	2.83	2.70
4.	1	2	2	1	2.62	2.76	2.81
5.	2	2	2	2	2.56	2.56	2.40
6.	2	2	3	3	2.58	2.40	2.44
7.	2	3	2	3	2.62	2.47	2.69
8.	2	3	3	2	2.78	2.84	2.84

4. DISCUSSION

4.1. Effect of depth of specimen

In Series 1 S and 2 Cp the effect of increasing the depth (d) of the specimen had a measurable effect on length changes at the 5% level of significance if the specimens were made of a single material (mortar or porcelain). No such effect could be detected if specimens were composites of the same materials.

TABLE VIII
SERIES 3 S, ANALYSIS OF VARIANCE

Source of variation	Degree of freedom	Sum of squares	Mean square	F ratio
<i>f.</i>	1	41.764,8	41.764,8	467.17 (**)
J J1-2.	1	73.309,6	73.309,6	820.02 (**)
J J2-3.	1	0.140,8	0.140,8	—
K K1-2.	1	0.154,1	0.154,1	—
K K2-3.	1	0.028,0	0.028,0	—
L L1-2.	1	0.073,6	0.073,6	—
L L2-3.	1	0.050,7	0.050,7	—
<i>e</i> 2.	16	0.005,9	0.000,4	—
(<i>e</i>).	(5)	(0.447,2)	(0.089,4)	—
Total.	23	115.527,5	—	—

TABLE IX
SERIES 4 Cp, ANALYSIS OF VARIANCE

Source of variation	Degree of freedom	Sum of squares	Mean square	F ratio
<i>f.</i>	1	3.580,5	3.580,5	11.04
M M1-2.	1	18.179,4	18.179,4	56.04 ^(b)
M M2-3.	1	6.249,6	6.249,6	19.27 ^(b)
N.	1	4.191,7	4.191,7	12.92 ^(c)
O.	1	3.161,0	3.161,0	9.74 ^(c)
<i>e</i> 1.	2	0.648,8	0.324,4	—
<i>e</i> 2.	16	0.068,7	0.004,3	—
(<i>e</i>).	(2)	(0.648,8)	(0.324,4)	—
Total.	23	36.0797	—	—

TABLE X
SERIES 5 Cp, ANALYSIS OF VARIANCE

Source of variation	Degree of freedom	Sum of squares	Mean square	F ratio
<i>f.</i>	1	1.596,5	1.596,5	64.37 (**)
P P1-2.	1	0.084,1	0.084,1	—
P P2-3.	1	0.043,2	0.043,2	—
Q Q1-2.	1	29.799,0	29.799,0	1201.57 (**)
Q Q2-3.	1	9.720,0	9.720,0	391.94 (**)
R.	1	1.349,0	1.349,0	54.40 (**)
<i>e</i> 1.	1	0.000,0	0.000,0	—
<i>e</i> 2.	16	0.344,7	0.021,5	—
(<i>e</i>).	(19)	(0.472,0)	(0.024,8)	—
Total.	23	42.9408	—	—

TABLE XI
SERIES 6 Cp, ANALYSIS OF VARIANCE

Source of variation	Degree of freedom	Sum of squares	Mean square	F ratio
<i>f.</i>	1	19.958,6	19.958,6	324.00 (**)
U U1-4.	3	0.864,9	0.288,3	4.68 (*)
U U2-7.	3	9.320,3	3.106,8	50.44 (*)
<i>e</i> 2.	8	0.492,5	0.061,6	—
(<i>e</i>).	(8)	(0.492,5)	(0.061,6)	—
Total.	15	30.636,3	—	—

Increasing the depth of the specimen resulted in larger mass and, for composites, larger interfaces, but neither the mass ratio of the components nor the position of the interface with reference to the boundaries was altered. Doubling the smallest dimension of the specimen, as was done in these experiments, affected the thermal gradient in addition to increasing the area of the interface.

Because the other parameters remained unchanged while *d* was varied, failure to observe any effect in the composites must be ascribed to the presence of the interface. Most probably the uncertainties introduced in the fabrication of the composite specimen prevent measurement of the effect of *d*, although the possibility that some unknown factor is responsible for the insensitivity of composites cannot be excluded.

4.2. Effect of bonding material

In Series 2 Cp the ability of epoxy and mortar bonding agents to minimize thermal stresses at the interface was examined (Factor I). No significant differences could be detected for the two bonding materials when the temperature was raised from -10 to $+50^{\circ}\text{C}$ at 1 and $4^{\circ}\text{C}/\text{min.}$ rate (table VI). It has to be concluded that the ability of the epoxy used in the experiment to accommodate stresses at the interface is not detectably superior to that of mortar.

4.3. Effect of heating rate

As for the effect of depth, a change in heating rate influenced the length changes of specimens of single materials but not those of composites (Series 2 Cp).

TABLE XII
SERIES 7 Cp, ANALYSIS OF VARIANCE

Source of variation	Degree of freedom	Sum of squares	Mean square	F ratio
<i>f.</i>	1	40.586,0	40.586,0	9019.11 (**)
W W1-4.	3	0.984,1	0.328,0	72.89 (**)
W W2-7.	3	33.600,8	11.200,3	2488.90 (**)
<i>e</i> 2.	16	0.071,5	0.004,5	—
(<i>e</i>).	(16)	(0.071,5)	(0.004,5)	—
Total.	23	75.242,4	—	—

TABLE XIII
SERIES 8 Cp, ANALYSIS OF VARIANCE

Source of variation	Degree of freedom	Sum of squares	Mean square	F ratio
<i>f.</i>	1	3.760,4	3.760,4	358.13 (**)
X X1-4.	3	12.197,3	4.065,8	387.22 (**)
X X3-6.	3	1.036,9	0.345,6	32.91 (**)
<i>e</i> 2.	16	0.168,1	0.010,5	—
(<i>e</i>).	(16)	(0.168,1)	(0.10,5)	—
Total.	23	17.162,6	—	—

In Series 1 S the dimensional changes of mortar and porcelain were larger at 1°C/min. than at 4°C/min.

Temperature rate sensitivity could be interpreted as an indication that at higher rates the temperature range traversed by the interior of the specimen is reduced. In cyclical heating, lowering of the temperature of the specimen may commence well before the interior can reach the upper temperature limit if the lag between interior and exterior is sufficiently large. This effect is proportional to heating rate, and the larger length changes at 1°C/min. than at 4°C/min. support this assumption.

On the other hand, when 4 hours of residence time at the temperature extremes (called "static" measurement) was included in the temperature cycles (the difference between interior and exterior of the specimen at the extreme temperatures was essentially nil), the length change of the mortar component was smaller and that of the tile component larger than at the 5°C deg/min. rate (fig. 2). It is concluded, therefore, that either the temperature lag between the interior and exterior of the specimen is not significant (even at a rate of 4°C deg/min.) and rate dependence is due to some other cause, or the temperature lag assumption is valid and the results of the static experiments are affected by another factor (such as plastic flow) operative during the long residency period. No indication of this could be detected in the length change versus time curves.

4.4. Restriction of stress by the interface

On heating of a composite of two materials with different coefficients of expansion, the equalizing influence of the components is quite clear (fig. 2). This is, of course, to be expected. Adopting the multi-layer model for a beam (although the length-to-width ratio is somewhat less than ideal) and changing the temperature by T (consisting of layers of materials with different Young's moduli, E , and coefficients of expansion, α),

Fig. 2. — Length changes of porcelain-mortar (100:60) composite as a function of measuring point, in temperature cycles without (1) and with (2) residency time at extreme values.

Fig. 3. — Comparison of calculated and measured values of length change as a function of measuring point.

the thermal stress, σ , can be calculated by the formula [5] :

$$\sigma_y = E(-\alpha T + \varepsilon + \beta y), \quad (1)$$

where:

$$\varepsilon = \frac{\int_{-c}^c E \alpha T dy}{\int_{-c}^c E dy} \quad \text{and} \quad \beta = \frac{\int_{-c}^c E \alpha T y dy}{\int_{-c}^c E y^2 dy},$$

where y is the coordinate normal to the interfaces, and c is half the width of the beam. The term $(-\alpha T + \varepsilon + \beta y)$ gives the strain produced by thermal stress at the various points of the beam. The calculated theoretical and measured expansions of porcelain-mortar composite specimens are shown in figure 3.

There is general agreement between measured and calculated values, with some deviations occurring at and in the vicinity of the interface. Owing to its higher Young's modulus (57,665 MPa compared to 33,736 MPa for cement), porcelain is less deformed by restrictive stress at the interface with mortar than would be the case if the positions were reversed. This is demonstrated by the difference in the width of the interfacial zone; expansion of the mortar component reaches the value of free mortar at 5 mm from the interface, while for porcelain this occurs at 3.5 mm from the interface (fig. 4).

To analyse the significance of the deviation of the measured values from those predicted by theory, the results of Series 4 Cp (table IX) and 5 Cp (table X) are examined. The slopes of length change, as a function of distance from the interface, were divided by the slope of the theoretical curve and compared with similar ratios in the region of the single component (mortar

Fig. 4. — Length changes of composites as a function of measuring point in relation to length changes of individual components.

or porcelain) of the composite. As a function of distance from the interface, length changes are presented in graphical form in figure 5.

Testing the difference between the populations of data pertaining to the interface and component side of the composite, the variance ratio is:

$$F = \frac{\sum (X_1 - \bar{X}_1)^2 / (n-1)}{\sum (X_2 - \bar{X}_2)^2 / (n-2)} = 5.28,$$

X_i = variable;

$\bar{X}_i$ = mean of sample set;

n = number of observations;

subscript 1 refers to interface;

subscript 2 refers to one component of the composite.

Because the value of the F distribution, $F_4^4(0.05) = 6.39$, is greater than the computed value of F , both sets belong to the same population, i.e., there is no real difference between the variances of the data sets.

Fig. 5. — Comparison of measured and calculated values of length changes of porcelain-mortar-composites in interfacial zone.

Next, the equality of the means of the two sets can be tested:

$$t = \frac{|\bar{X}_1 - \bar{X}_2|}{\sqrt{\frac{\sum (X_1 - \bar{X}_1)^2 + \sum (X_2 - \bar{X}_2)^2}{(n_1 + n_2 - 2)} \left(\frac{1}{n_1} + \frac{1}{n_2} \right)}}$$

$$= 5.46 > t_8(0.01)$$

$$= 3.355, \text{ value of the } t \text{ distribution.}$$

There is a real difference between the means of the ratios of experimentally-determined to calculated slopes in the interfacial and single-component regions of the composite. Calculations for the quarry tile-mortar composite obtained in this series yield the same conclusion.

The mean ratio of the slopes of the measured and calculated length changes versus distance from the interface (range extending from 0.5 to 2.0 mm distance from the interface) is 1.03. Because the calculated value assumes elastic behaviour, good agreement indicates that 0.5 mm from the interface the response of the material to the stresses created by the other component

Fig. 6. — Comparison of measured and calculated values of length changes of mortar-porcelain-composites.

Fig. 7. — Calculated axial stress in mortar component at interface of mortar-porcelain composite.

is elastic. In contrast, within 0.5 mm on either side of the interface the high value (2.12) of the mean ratio of the slopes (calculated:measured) can be explained by viscoelastic behaviour. Owing to difficulties of experimentation, the width of the interfacial region could not be narrowed further, but it is very probable that the zone with viscoelastic behaviour is mainly on the mortar side or in the immediate vicinity of the interface.

4.5. Effect of volume ratio

In Series 4 (table IX) the effect of the volume ratio of the components on length changes was investigated. The results with porcelain-mortar ratios of 100:60 and 100:20 are shown in figure 6 together with calculated values (equation 1). The theoretical values are quite sensitive to change in volume ratio and, significantly, the measured values clearly exhibit a similar trend. Deviation of the measured values from the calculated ones is greatest for the interfacial region, but the experimental points are in general agreement with the predicted values.

When the volume of the mortar component was constant and that of the porcelain component varied, porcelain-mortar ratio = 20:100, 40:100, and 60:100 (Series 5, table X), the theoretical values were found to be quite insensitive to the ratio changes and the differences could not be established experimentally (fig. 6). The axial stress of porcelain-mortar composites as a function of volume ratio of the components created by changing temperature were calculated. A 60°C deg temperature rise in the composite beam was considered, assuming no temperature gradient in either the initial or final state. Axial stress was calculated using equation (1).

Axial stress in the mortar at the interface is plotted as a function of volume ratio in figure 7 for a freely-bending porcelain-mortar composite and for one restrained by a rigid concrete substrate. With decreasing thickness of the mortar layer the axial stress of the mortar increased.

5. CONCLUSIONS

1. Strain in the interfacial zone of mortar-porcelain and mortar-quarry tile composites created by thermal effects shows viscoelastic behaviour.

2. Mortar, porcelain and quarry tile in composites behave elastically outside the interfacial zone.

3. The restrictive influence of components on the strain produced by temperature change can be observed within 3.5 mm of the interface on the porcelain side and within 5.0 mm on the mortar side.

4. The volume ratio of components affects the strain of the composite, particularly in the interfacial zone.

5. Epoxy, used as a binding agent in the experiment, does not reduce interfacial stress.

ACKNOWLEDGEMENT

The valuable assistance of G. Polomark in the thermomechanical measurements is gratefully acknowledged. This paper is a contribution from the Division of Building Research, National Research Council Canada, and is published with the approval of the director of the Division.

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RÉSUMÉ

Contraintes thermiques dans les carrelages au mortier.

— On a examiné les variations de longueur de carrelages mortier-porcelaine et mortier-carreau céramique ($10 \times 3 \times 8$ mm en moyenne) à des températures variant de -10 à 50°C . On a relevé les effets de la vitesse de chauffage (1 et $4^\circ\text{C}/\text{mn}$), des dimensions des échantillons, du rapport entre les volumes des constituants, et de l'emplacement du point de mesure par rapport à l'interface.

Les conclusions ont été les suivantes :

1. Les contraintes thermiques dans la zone de l'interface des carrelages mortier-porcelaine et mortier-carreau

céramique ont révélé un comportement visco-élastique.

2. Le mortier, la porcelaine et la pierre juxtaposés se comportent élastiquement en dehors de la zone de l'interface.

3. L'effet restrictif des éléments sur les contraintes thermiques dues aux variations de température a pu être observé jusqu'à 3,5 mm de l'interface du côté de la porcelaine et jusqu'à 5,0 mm du côté du mortier.

4. Le rapport entre les volumes des constituants modifie la déformation de l'ensemble, notamment dans la zone de l'interface.

5. La résine époxyde, qui a servi de liant au cours de l'expérience, ne réduit pas la contrainte interfaciale.