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The effect of unit water absorption on long-term movements of masonry

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Abstract

Long-term movements in masonry can be predicted by composite modelling, however, the accuracy of prediction is reduced if the unbonded brick and mortar phases do not reflect the behaviour of the bonded components. It is apparent that the water absorbed by the unit soon after laying produces changes in the behaviour of the bonded components of the masonry especially of the mortar joints, which have reduced creep and shrinkage. This paper presents a study of the transfer of moisture between the brick and mortar components from 30 min after laying of bricks to 120 days. Subsequently, unit water absorption modification factors are developed which improved the accuracy of predicting creep and moisture movement strain of masonry by composite models to within 10% of the measured values.

Keywords: Masonry; Clay brick brickwork; Calcium silicate brickwork; Concrete blockwork; Moisture expansion; Shrinkage; Creep; Composite models

1. Introduction

Time-dependent movements of brick and block masonry can be critically influenced by an interaction between the bonded brick or block and mortar elements of the masonry primarily due to the unit water absorption properties [1–3]. This interaction results from the transfer of moisture between the two elements of the masonry, leading to a reduction in the water content of the bonded mortar, thereby decreasing its potential for creep and shrinkage.

The unit/mortar interaction can significantly affect the prediction of elastic and long-term behaviour of masonry using composite models. A number of models have been developed over the years [3–6], however, experimental verification has been achieved only by a limited number of test data. More recently, Brooks and Abdullah [7–10] developed more universal composite models for all masonry deformations, which were successfully validated on a number of occasions. However, for certain practical situations the accuracy of the models was considerably reduced for masonry built from units having a high water absorption. In those instances, the water absorbed by the unit from the freshly laid mortar meant that the input data obtained from the individual, unbonded brick and mortar samples were not representative of the behaviour of the bonded components in the masonry.

Previous researchers investigating bond strength [11–15] and mortar bed-joint compressive strength [14–16] have shown that there is an influence of moisture transfer between mortar and clay brick unit on those properties. Anderegg [11] suggested that the compressive strength of the mortar bed-joint would increase with an increase in the initial rate of suction, although for mortars with a high OPC content, the compressive strength would be expected to decrease when the 'product combination' involved high absorption bricks. Schubert and Hoffmann [15], however, showed that a reduction in compressive strength occurred even with low unit water absorption properties and that this reduction was independent of the level of initial rate of suction and water absorption, though the amount of moisture transfer was influenced by unit water absorption properties. The condition of the brick (dry or docked) prior to laying, the type of mortar and its water/cement ratio [11] also influence the quantity of water absorbed. The variation in pore structure throughout

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the body of the brick and the interrelationship that exists between the pore properties of the bonded brick and mortar also complicate the relationship.

By comparing the bonded unit and mortar movements with those of equivalent unbonded bricks and mortar prisms, this paper reports a study of the effects of moisture transfer on the long-term movements of Armitage class 'B' engineering brickwork, Fletton clay brickwork, calcium silicate masonry and concrete blockwork. Unfortunately, owing to the presence of an 'enlarged' expansion (i.e., a masonry moisture expansion in excess of the unbonded unit moisture expansion) in the Fletton masonry, the influence of the unit water absorption property could not be isolated for the Fletton brickwork. Modification factors, developed for the Armitage, calcium silicate and concrete masonry were then applied to previously obtained unbonded unit and mortar test data [2,17] before re-estimating the time-dependent strains by expressions given by composite models [7].

2. Experimental procedure

Two series of tests were carried out to investigate the effect of unit water absorption on masonry movement, they being part of much larger test programmes [1,2]. One programme was concerned with the influences of unit and mortar types [1,17,18], while the other programme investigated the loss of pre-stress in post-tensioned walls [2].

Fig. 1 illustrates the 5-stack bonded brick walls together with the loading frames used in the first test series involving Armitage and Fletton masonry [1]. Four walls were constructed from each type of brick (undocked), two walls being monitored for moisture movement strain and the remaining two walls being used to isolate creep of the masonry. The ages at loading adopted for the Armitage and Fletton masonry [1] were 14 and 28 days, respectively. The Armitage masonry was sealed with polythene immediately after construction until the application of the load at 14 days. The Fletton masonry was also sealed with polythene immediately after construction, however, from 14 days it was uncovered and allowed to dry in a controlled environment until the application of load at 28 days.

A class (ii) $1{:}\frac{1}{2}{:}4\frac{1}{2}$ OPC:lime:sand mortar mix, having a w/c ratio of 0.76, was used in the construction of the four walls. From this mix, individual mortar cubes and prisms ($75\times75\times200$ mm) were cast to determine the compressive strength, modulus of elasticity, creep and shrinkage of the unbonded mortar. All prisms were partially sealed to the same volume/exposed surface area (v/s) ratio of the bonded mortar of the 5-stack masonry. This procedure had been used previously [19] to simulate the rate of external moisture loss from the masonry. Individual clay units were also monitored for moisture movement strain and creep in the header and bed face directions, the bed face creep of the units being obtained from the middle three units of the 5-stack unbonded walls. Table 1 gives details of the unbonded brick and mortar properties. All strains were measured using demountable Demec gauges and 50 mm acoustic/vibrating wire gauges.

The second series of tests [2] investigated masonry constructed from docked (1 min) and undocked Armitage and calcium silicate units and undocked concrete block units. The experimental procedure was different to that of the later series of tests [1] only in that the masonry was cured under polythene for 21 days.

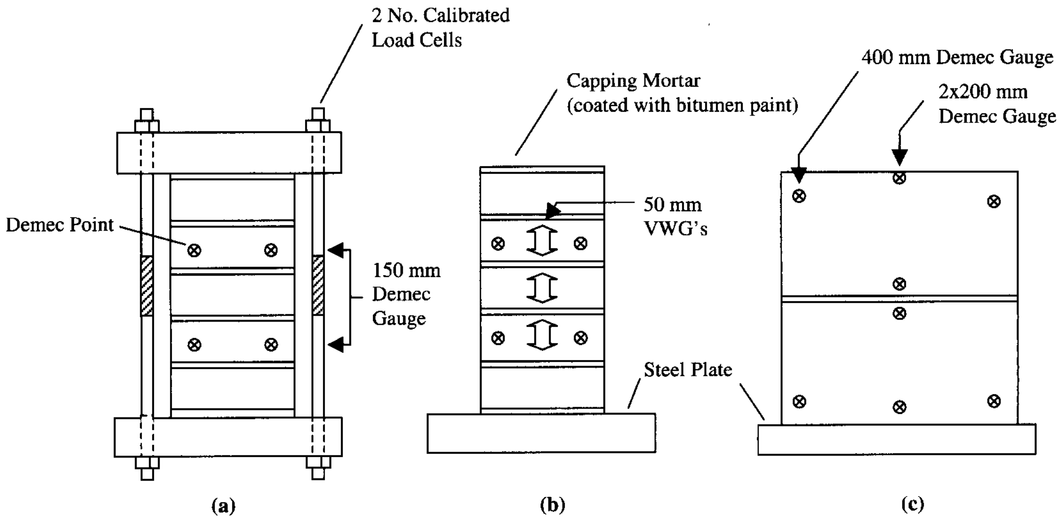

Fig. 1. Masonry walls and loading frames.

Table 1
Unbonded brick and mortar prism details

Test phase	Component type	Compressive strength (MPa)	Modulus of elasticity (GPa)	Absorption		
				24 h soaking (%)	5 h boiling (%)	IRS[a] (kg m^2 min^{-1})
1 [2]	Armitage class 'B' Eng brick	103.0	29.0/17.5[b]	3.7	–	0.27
	Calcium silicate	27.1	15.2/13.4[b]	11.3	–	0.5
	Concrete block	14.9	10.0	8.8	–	8.0
	Mortar prism					
	21 day	11.2	8.2	–	–	–
2 [1]	Fletton	25.4	4.7/8.8[b]	18.9	22.7	1.91
	Armitage class 'B' Eng brick	86.4	27.0/19.0[b]	5.0	6.9	0.48
	Mortar prism					
	14 day	17.5	12.4	–	–	–
	28 day	20.7	13.0	–	–	–

[a] Initial rate of suction.
[b] Bed face/header face.

To monitor the moisture transfer between the Armitage, Fletton and calcium silicate brick and mortar, modified unit water absorption tests were carried out using 17 different two-course bonded masonry couplets (Fig. 2) for each unit type. The weight of one unit of the couplet was recorded before laying and then after assembling the couplets at the following ages: 0.5, 1, 3, 5, 7, 14 and 24 h; 3, 7, 14, 28, 40, 50, 60, 70, 80, and 120 days. To prevent bonding between the mortar and the brick to be weighed, a layer of polythene mesh was inserted. The weight of the masonry couplets was checked before weighing the top brick to ensure no loss of moisture from the couplets during curing. The modified or percentage water absorption (W) at the various times was determined as follows:

$$W = \frac{M_w}{M_b} \times 100,$$

where M_w is the weight of water absorbed by the unit and M_b is the weight of the unit prior to construction of the masonry couplet.

To monitor the moisture transfer between the concrete block and mortar, a single unit was capped with mortar and covered with glass instead of another block to keep the total weight within the capacity of the scales. Otherwise the procedure was identical.

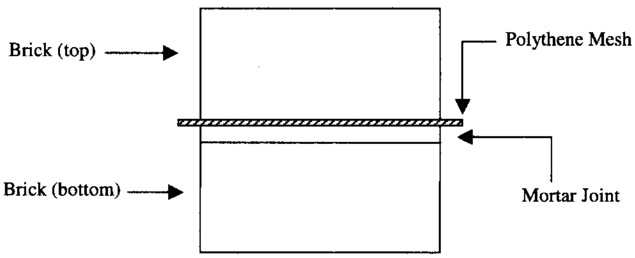

Fig. 2. Bonded masonry couplet for modified water absorption tests.

All types of masonry were stored in a controlled environment of 21 ± 1°C with a relative humidity of 65 ± 5%, after curing under polythene sheet.

3. Discussion of results

3.1. Moisture transfer

The pattern of moisture transfer to and from the Armitage and Fletton bricks during the curing period and the following period of drying is shown in Fig. 3. Initially, moisture was rapidly absorbed by the brick

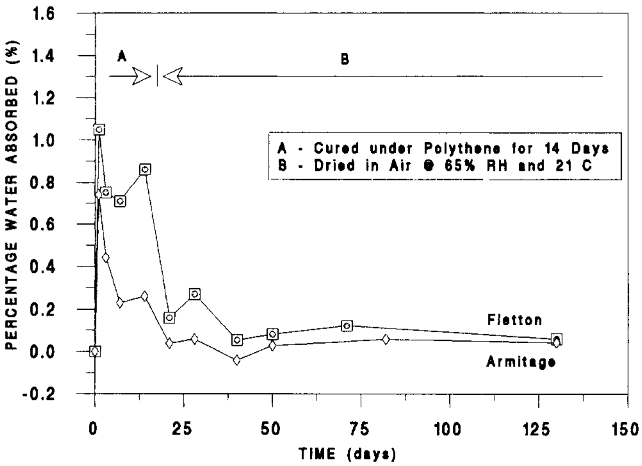

Fig. 3. Percentage moisture absorbed by different units in series 1 tests [1].

from the mortar joint, however, the situation then reversed due to the moisture being taken up by the mortar since no moisture can be lost to the outside in the sealed system. From 14 days, after the polythene was removed, moisture was then lost to the atmosphere from both brick and mortar element. The higher level of percentage water absorption of the Fletton brick is a reflection of its high standard water absorption and initial suction rate (Table 1).

Fig. 4 illustrates the pattern of moisture transfer for the Armitage clay brick, calcium silicate brick and concrete block of the second series of tests [2]. Initially, during the period of curing, the behaviour is similar to that of the first series of tests, but when the masonry was exposed to drying, the concrete and calcium silicate units exhibited further shrinkage due to the removal of natural moisture existing in the units before bedding with mortar.

The initial pattern of moisture transfer has been observed before [12,14] and is an indication that the mortar is hydrating and is no-longer plastic. Sneck [12] commented that the reverse of flow to the mortar was assisted by the blocking of pores in the brick by a cementitious material thus reducing the suction force of the brick. Similarly, the suction force of the mortar is influenced by its pores, which fill up as the process of hydration continues [20]. The transfer of moisture is, therefore, based on a conflict between the capillary suction force of the brick and mortar pore structure.

3.2. Time-dependent deformations

To isolate the time-dependent movements of the bonded unit and mortar of the masonry so that they could be compared with the movements of the equivalent unbonded unit and mortar prism, the following procedure was adopted. The deformations of the bed-joint mortar in the masonry were determined by subtracting the deformations of the bonded units in the masonry from the overall deformation of the masonry. The strain in the mortar was then calculated from

$$\varepsilon_{\text{mortar}} = \frac{(g \times \varepsilon_{\text{masonry}}) - ((g - m \times n) \times \varepsilon_{\text{units}}))}{m \times n}, \quad (1)$$

where g is the gauge length of the Demec gauge used to measure the overall strain of the masonry (mm), $\varepsilon_{\text{mortar}}$ the strain of the mortar (μs), $\varepsilon_{\text{masonry}}$ the mean strain measured on the masonry (μs), $\varepsilon_{\text{units}}$ the mean strain of the units (μs), m the mortar joint thickness (mm) and n is the number of mortar joints over which the Demec gauge spans.

Fig. 5 compares the moisture movement strain and creep of the unbonded mortar prisms with the corresponding movements of the mortar bed-joint of the Armitage masonry as given by Eq. (1). The shrinkage of the mortar bed-joint is 25% less than the shrinkage exhibited by the unbonded mortar prism at 160 days. The lower shrinkage can be attributed to the time of start of shrinkage, which was actually after laying the units, due to absorption, whereas measurements only started at the age of 14 days. Thus, pre-shrinkage occurred. On the other hand, for the unbonded prism, which was cured under polythene, the actual start of shrinkage was at the age of 14 days. From Fig. 5, the effect of unit absorption is also seen to reduce creep of the mortar joint, but only by 5% at 160 days.

In the second series of tests, the effect of water absorption of the units on the shrinkage of the mortar joints during curing was monitored, as well as during storage. In addition, the influence of docking or pre-soaking the units prior to laying the units was investigated [2]. Figs. 6–8 show the effect on the shrinkage of

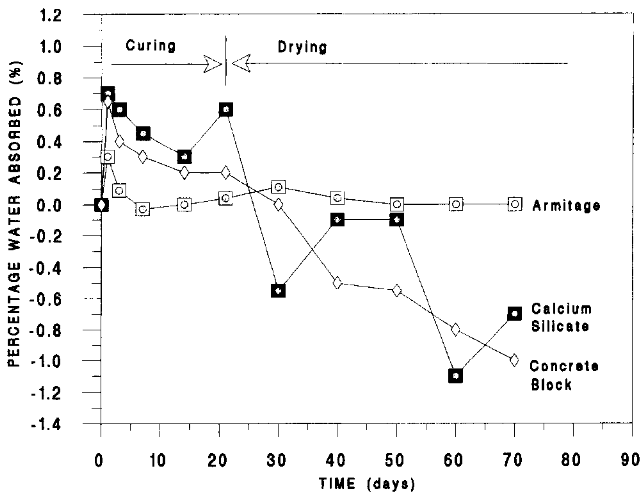

Fig. 4. Percentage moisture absorbed by different units in series 2 tests [2].

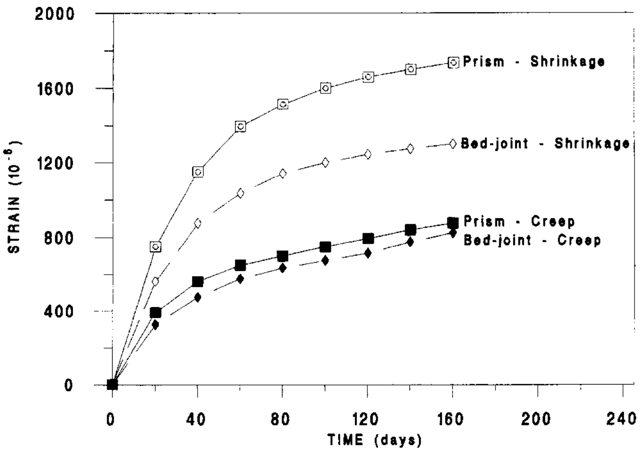

Fig. 5. Comparison of mortar prism and mortar bed-joint movements for the Armitage masonry from the age of 14 days – series 1 tests [1].

mortar during curing and on the subsequent dry storage for the Armitage, calcium silicate and concrete block masonry. The trends shown in Figs. 7 and 8 again demonstrate that appreciable shrinkage occurs during curing due to unit absorption so that the results confirm the reduction in shrinkage of the mortar bed-joint as compared to that of the unbonded mortar prism. This is in fact due to pre-shrinkage during the period of curing.

The effect of docking the units on the shrinkage of the mortar of the masonry is also illustrated in Figs. 6–8, where it is apparent that the practice of docking can reduce the unit absorption but not eliminate it. The influence of docking obviously depends on the duration of the docking process.

Fig. 9 gives the unit absorption modification factors developed from the two test series, which apply to unbonded units and mortar prisms from the start of drying. The modification factor is defined as the ratio of deformation (creep or shrinkage) of the bonded phase to the deformation of the unbonded phase. It can be seen that while moisture transfer due to unit absorption results in the reduction of the deformation of mortar, it causes an increase in the deformation of the unit, which is an irreversible moisture expansion. No attempt has been made to relate the factors to water absorption, because further test results are needed to establish more firm trends. For the re-prediction of long-term deformations shown in the following, the actual factors as plotted in Fig. 9 for the unit absorption have been used.

3.3. Prediction of creep and shrinkage

The derivation of the composite models to predict masonry movements has been presented elsewhere [7] and, as such, only the relevant equations are given here. The elastic modulus (E_{wy}) of masonry under vertical loading, in general form, is

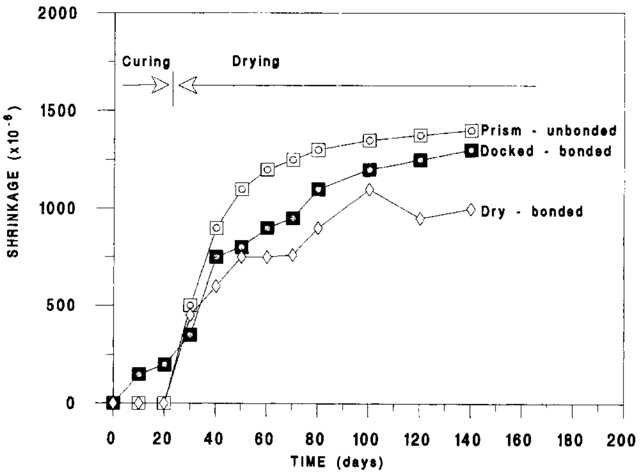

Fig. 6. Shrinkage of mortar in Armitage masonry – series 2 tests [2].

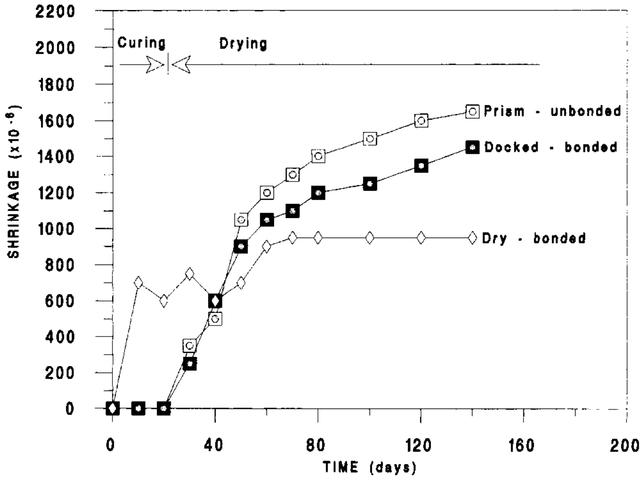

Fig. 7. Shrinkage of mortar in calcium silicate masonry – series 2 tests [2].

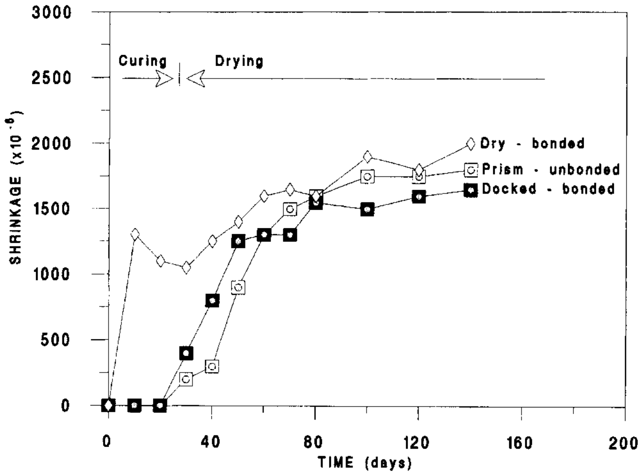

Fig. 8. Shrinkage of mortar in concrete block masonry – series 2 tests [2].

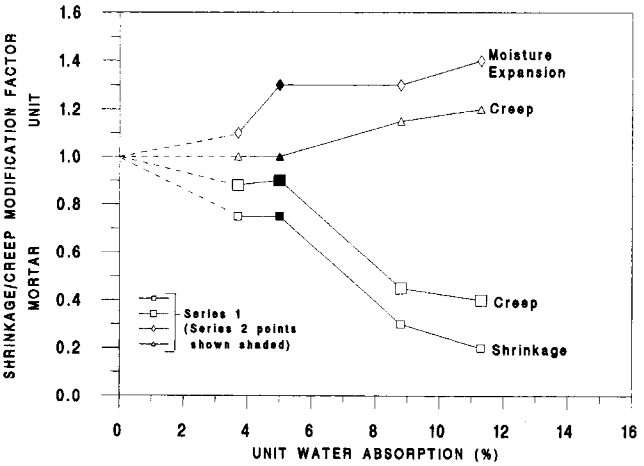

Fig. 9. Shrinkage/creep modification factors for unbonded mortar prism and units.

$$\frac{1}{E_{wy}} = \frac{b_y C}{H} \frac{A_w}{E_{by} A_b + E_m A_m} + \frac{m_y (C+1)}{H} \frac{1}{E_m}, \tag{2}$$

where b_y is the height of unit, C the number of courses, H the height of masonry, A_w the cross-sectional area of masonry, A_b the cross-sectional area of units (bed face), A_m the cross-sectional area of vertical mortar joints, E_{by} the elastic modulus of unit, E_m the elastic modulus of mortar and m_y is the thickness of mortar bed joint.

For the single-leaf wall masonry of this investigation Eq. (2) reduces to

$$\frac{1}{E_{wy}} = \frac{1}{1.157 E_{by} + 0.027 E_m} + \frac{0.142}{E_m}. \tag{3}$$

The moisture movement strain of masonry, S_{wy}, is given as

$$S_{wy} = \frac{b_y C}{H} S_{by} + \frac{m_y (C+1)}{H} S_m + \frac{b_y C}{H} \times \frac{(S_m - S_{by})}{1 + (A_b/A_m)(E_{by}/E'_m)}. \tag{4}$$

For all the masonry of this investigation, the third term of Eq. (4) is small, so that

$$S_{wy} = 0.87 S_{by} + 0.13 S_m. \tag{5}$$

To estimate creep of the masonry, the elastic moduli (E) in Eq. (2) are replaced by the effective moduli (E') for the mortar and brick unbonded samples, and specific creep of the masonry is then given by the following relationship:

$$C_{wy} = \frac{1}{E'_{wy}} - \frac{1}{E_{wy}}. \tag{6}$$

Using the above equations with the basic test data of the unbonded phases [1,2] and the relevant modification factors taken from Fig. 9, the results of the predictions are shown in Figs. 10–17. Figs. 10–13 compare

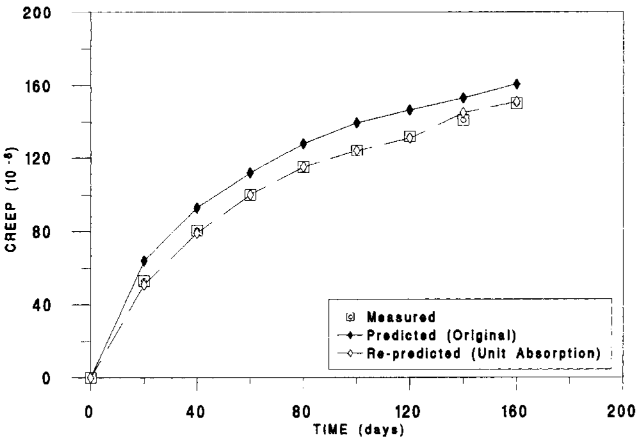

Fig. 11. Measured and predicted creep – time for the single-leaf wall constructed with a 1:0.5:4.5 mortar.

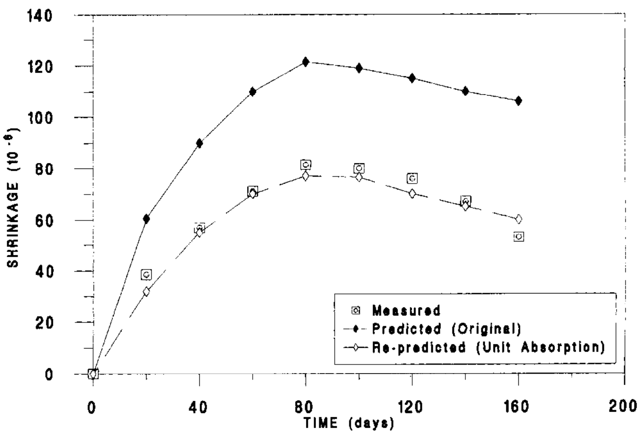

Fig. 12. Measured and predicted shrinkage – time for the single-leaf wall constructed with a 1:3.5 masonry cement mortar.

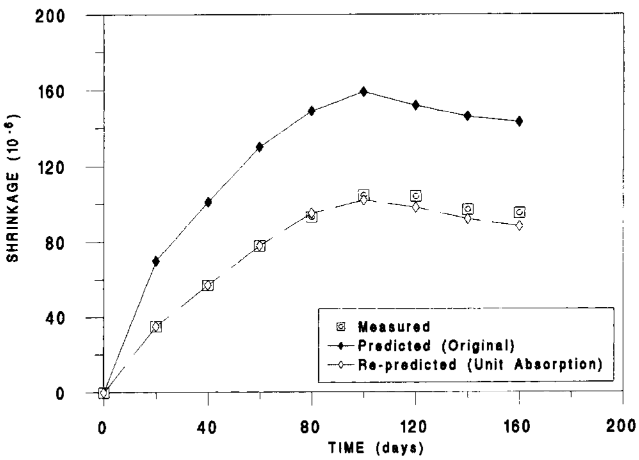

Fig. 10. Measured and predicted shrinkage – time for the single-leaf wall constructed with a 1:0.5:4.5 mortar.

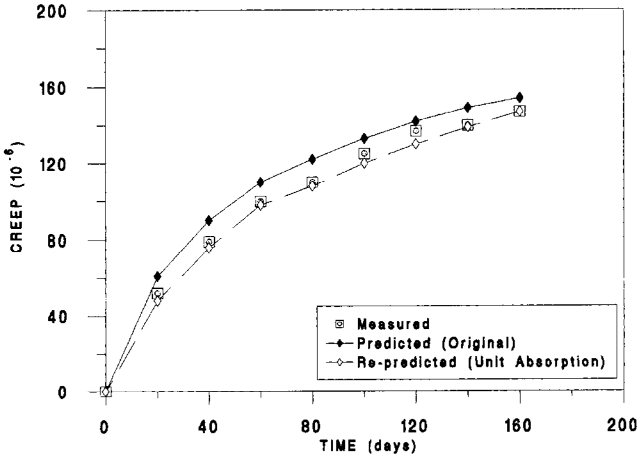

Fig. 13. Measured and predicted creep – time for the single-leaf wall constructed with a 1:3.5 masonry cement mortar.

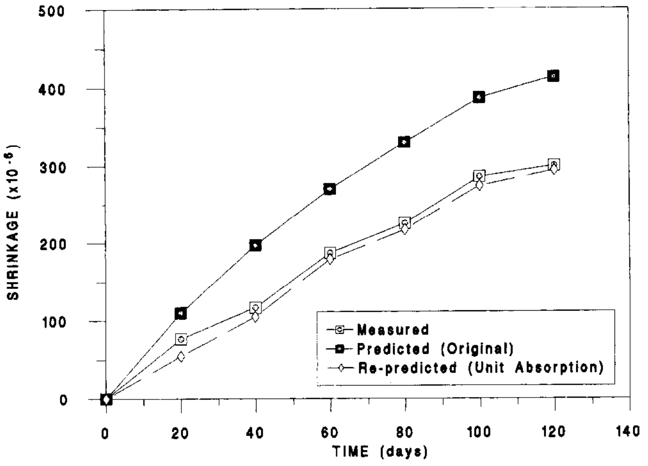

Fig. 14. Measured and predicted shrinkage – time for the calcium silicate diaphragm wall.

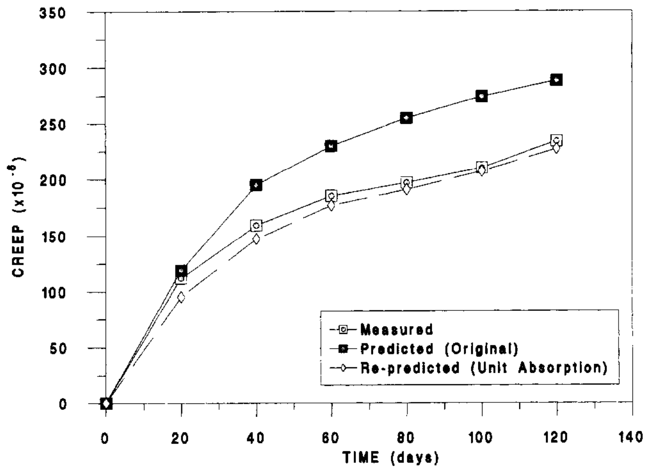

Fig. 15. Measured and predicted creep – time for the calcium silicate diaphragm wall.

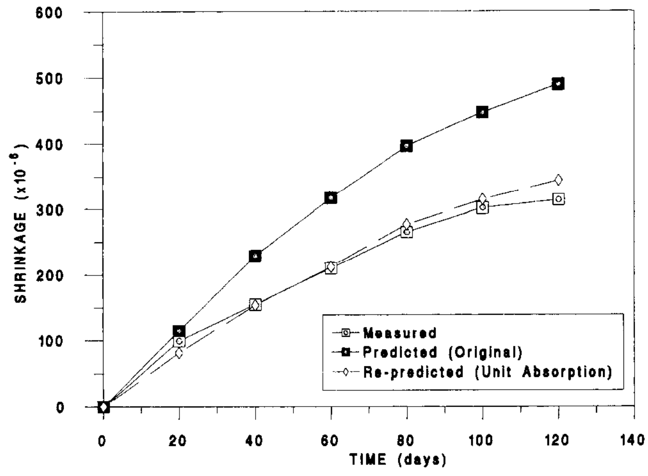

Fig. 16. Measured and predicted shrinkage – time for the calcium silicate fin wall.

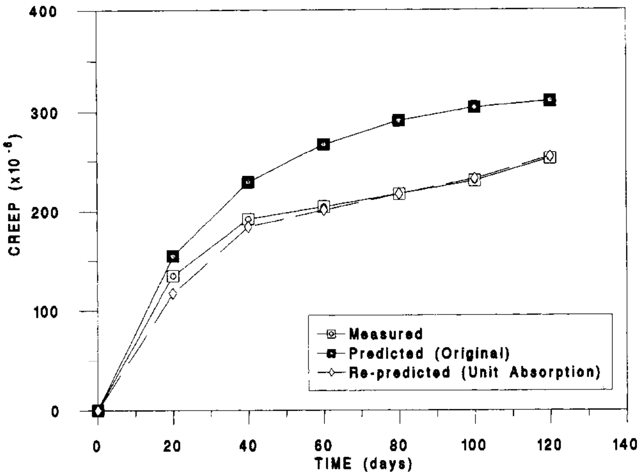

Fig. 17. Measured and predicted creep – time for the calcium silicate fin wall.

these modified predictions with the measured and unmodified predicted movements of Armitage masonry constructed from 1:0.5:4.5 cement:lime:sand mortar and 1:3.5 masonry cement mortar types [16]. Figs. 14–17 compare the re-predictions with the measured and unmodified predicted movements of calcium silicate diaphragm and fin walls [2]. Figs. 10–17 demonstrate that the influence of the unit absorption can be taken into account by applying the modification factors applied to the unbonded mortar prism creep and shrinkage data. Typically, composite model predictions, which originally overestimated moisture movement strain by up to 70%, now predict movements to within 10%. Prediction of creep also improved from original overestimates of up to 25% to estimates now within 5%.

Finally, the deformation of the Fletton masonry should be mentioned, because it suffered from an 'enlarged expansion', as referred to earlier in the introduction. Fig. 18 compares the moisture movement strain of the Fletton masonry with that of the individual bonded and unbonded units, and unbonded mortar prisms. It can be seen that the masonry expansion of 850 microstrain at 160 days was far greater than that of the unit (negligible expansion). The enlarged expansion actually occurs at the brick/mortar interface and so, being outside the gauge length was not measured by the vibrating wire strain gauges attached to the bonded units. The calculation of representative modification factors from a comparison of mortar bed and unbonded mortar prism movements was, therefore, not possible for the Fletton masonry. The enlarged moisture expansion is thought to be caused by cryptoflorescence [1,21] and can be considered as equivalent to a transition zone effect between cement paste and aggregate in concrete.

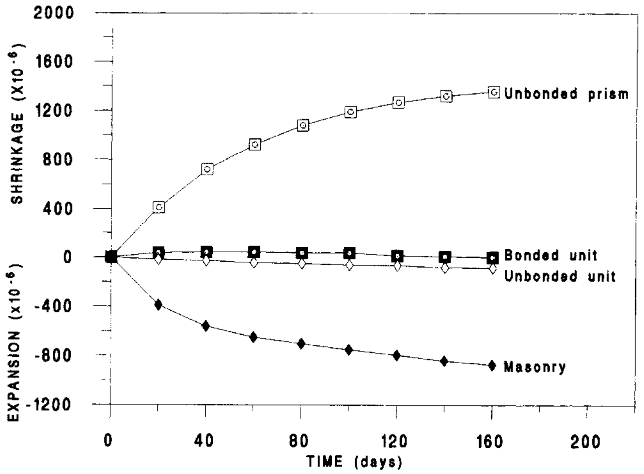

Fig. 18. Moisture movement strain of the Fletton masonry, bonded/unbonded unit and unbonded mortar prism.

4. Conclusions

By comparing different types of masonry, namely, clay brickwork, calcium silicate brickwork and concrete blockwork, it has been demonstrated that significant moisture transfer can occur between the bonded brick and mortar elements of freshly laid masonry. This interaction is a result of the unit water absorption and influences the long-term movements of masonry by reducing the shrinkage and creep of the mortar joints, but by increasing the corresponding deformations of the units.

Comparison of the long-term movements of the mortar bed-joint and unbonded mortar prisms, and bonded units with unbonded units, has allowed modification factors to be derived, which are dependent on the unit water absorption. When these factors are incorporated into composite models, accurate predictions of masonry shrinkage and creep are obtained.

The foregoing conclusions do not apply to those types of clay brickwork exhibiting an enlarged moisture expansion due to cryptoflorescence at the mortar/unit interface.

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