TIME-DEPENDENT PERFORMANCE OF BITUBLOCK SINGLE-LEAF MASONRY

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SUMMARY

Bitublock is a masonry unit which can potentially be composed entirely of recycled/waste aggregates and binding agents from selected waste bitumens. As such, it could significantly contribute to a reduction in material sent to landfill. The performance of Bitublock has been shown to be at least equivalent to concrete block masonry products found in the UK. This paper details for the first time the long-term behaviour of Bitublock masonry. These results have also been used to confirm the successful encapsulation of the recycled material by the bitumen binder. The masonry did not exhibit any enlarged expansion (cryptoflorescence) which results from chemical interaction between the mortar and Bitublock.

INTRODUCTION

The developed world has a major problem – it is running out of space to store all of the rubbish it creates. The current trend for land-filling is simply unsustainable – in March 2005 it was estimated that the UK had 6 years disposal capacity remaining at current rates of tipping (Environment Agency 2005). In Europe, the situation is similar with high prices and taxes levied on material sent to landfill. The EU Landfill Directive has set stringent and demanding targets on all EU countries for reducing material sent to landfill (The Waste Thematic Strategy 2005).

It was therefore decided to research and develop a novel construction unit which could significantly contribute to the UK Government's aims for; recycling; reduction in demand for natural aggregate extraction; reduction in waste sent to landfill; and the 2016 zero carbon new homes target (Communities and Local Government 2006). This novel unit readily satisfies all the physical and strength requirements of current coarse aggregate concrete block units manufactured in the UK but does not incorporate any natural aggregates and does not require any specifically manufactured or synthetic binders. Instead the new unit, Bitublock, will incorporate only recycled aggregates.

Bitublock is a masonry unit composed entirely of recycled and waste aggregates and binding agents from selected commercially available and waste bitumens. Previously, the physical properties of Bitublock units composed of mixtures of incinerated sewage sludge ash, incinerated bottom ash, furnace bottom ash, fly ash, construction demolition waste, crushed glass, soil, rice husk ash, steel slag and compacted at pressures of above 8MPa have been reported (Forth et al 2006, Thanaya et al 2006). This paper provides further details on the optimisation of Bitublock using compaction pressures of 1 to 4MPa. The aggregate materials

used in this investigation were; steel slag (in 2002 the volume of production of metallurgical slags such as basic oxygen steel slag was 1 million tonnes; only a fifth of this was recycled); crushed glass (glass collection has increased to meet the 2006 packaging targets of 60% resulting in an excess of 300,000-400,000 tonnes of green glass) and fly ash (currently 6 million tonnes of fly ash are produced each year in the UK – only 40 to 50% of this is utilised), (Forth et al 2006). However, the paper also reports for the first time the creep and moisture movement strain recorded on 7 course high by 4 brick wide single leaf Bitublock masonry constructed using a Class II; 1: ½: 4 ½ , cement: lime: sand mortar.

Briefly, the manufacturing process of Bitublock involves three processes; mix; compact; and cure. It has been shown previously that one of the main factors affecting the properties of Bitublock is the level of compaction; it is assumed that bonding of the aggregate and the binder is achieved through encapsulation rather than chemical interaction, as is the case with cementitious bound or even clay bound units. However, although this assumption is currently being investigated qualitatively, it was decided to confirm the presence of any quantitative effects. In some clay masonry, an enlarged free expansion has been measured due to cryptoflorescence. This results from the chemical interaction of the brick and the cement mortar and can cause expansions far greater than would be expected from a consideration of the irreversible expansion of individual unbonded clay bricks. Previously, it has been proposed that any enlarged expansion or chemical interaction between the unit and the binder can be identified by the model developed by Brooks (Brooks 1990). Masonry composed of Bitublock units and cement mortar were therefore constructed and time dependent movements (creep and 'moisture' movement strains) were obtained. Composite modelling of the long-term deformations of the masonry was performed to investigate whether the encapsulation of the recycled material by the bitumen binder does eliminate any chemical interaction with the mortar.

The theory and derivation of the models has been presented elsewhere (Brooks 1990) and hence only the prediction equations are presented here.

Modulus of Elasticity (E_{wy}) of Bitublock wall

$$\frac{1}{E_{wy}} = \frac{b_y.C}{H}\left[\frac{A_w}{E_{by}.A_b + E_m.A_m}\right] + \frac{m_{y.}(C+1)}{H}.\frac{1}{E_m} \tag{1}$$

where: E_{wy}= effective modulus of Bitublock wall; b_y= height of block unit; C= number of courses (layer); H= height of wall; E_{by}= elastic modulus of block unit; A_b= cross sectional area of block unit; E_m = elastic modulus of mortar; A_m= cross section area of vertical mortar joints; m_y= thickness of mortar bed joints; A_w = cross-sectional area of masonry.

The dimensions of the Bitublock unit and wall were as follows: b_y = 65mm; A_w = 435x100mm; A_b = 100x100mm; A_m= 33500mm^2; m_y= 10mm. For the 7-course wall investigated, as shown in Figure 9, equation (1) becomes:

$$\frac{1}{E_{wy}} = 0.8426\left[\frac{1}{0.229E_{by} + 0.770E_m}\right] + \frac{0.1481}{E_m} \tag{2}$$

Creep

To model creep behaviour, equation (4) is used however the initial modulus of the individual brick and mortar prism is replaced by an effective modulus (E') to allow for creep. Thus for a unit stress:

Creep for wall: $$C_{wy} = \frac{1}{E'_{wy}} - \frac{1}{E_{wy}} \quad (3)$$

where E'_{wy} and E_{wy} are the effective and initial elastic modulus of wall

Vertical shrinkage

The general expression of the vertical shrinkage (S_{wy}) at any time is

$$S_{wy} = \frac{b_y.C}{H}.S_{by} + \frac{m_y.(C+1)}{H}.S_m + \frac{b_y.C}{H}\left[\frac{S_m - S_{by}}{1+\frac{A_b.E_{by}}{A_m.E_m}}\right] \quad (4)$$

where S_{by} vertical shrinkage of block unit and S_m shrinkage of mortar. For the Bitublock wall investigated, the third term of the equation is small, so that equation (8) becomes:

$$S_{wy} = 0.8426\ S_{by} + 0.1418\ S_m \quad (5)$$

To summarise, the objectives of the current paper were:

- To compare the compressive strength of the Bitublock units compacted at pressures between 1 and 4 MPa with concrete block units commonly used in the UK: 3.5 – 10 MPa (Sear 2005 and British Standard-BS 6073 1981), (it has been found that the compressive strength property is a good indicator of overall block performance) and report the other physical and mechanical properties of the Bitublock units.
- To investigate the creep and 'moisture' movement strain of masonry walls constructed from the Bitublock units.

EXPERIMENTAL DETAILS

Performance Criteria

The Bitublock unit should achieve the following level of performance:

- Compressive strength: ≥ 3.5 MPa at room temperature. This is in line with the compressive strength of concrete blocks commonly found in the UK: 3.5 – 10 MPa (Sear 2005 and British Standard-BS 6073 1981).
- Initial rate of suction (IRS) values shall be equal to IRS values of clay brick found in the UK (0.25-2.0 kg/m^2/min). The IRS is a parameter that can provide an indication of the effect of the unit on the cement mortar. Units with high IRS require very plastic mortar (high water/cement ratio), while units with lower IRS need stiffer mortar (BS3921 1985 and Vekey 2001).
- Possess specific creep (static creep strain per unit stress in MPa) of ≤ 100 microstrain, tested at 20 °C. This target is in line with the specific creep level of concrete blocks currently used in the UK (approximately 100 microstrain). The level of stress of 1 MPa shall be used for the creep test as this is considered representative in masonry experiments (Tapsir 1985 and Forth et al. 2006).

Materials

Bitumen Type and Content

In principal, all types of bitumen (hard/penetration grade or bitumen emulsion) can be used as a binder. However, it is preferable to use a softer grade bitumen as this requires a lower handling temperature. Also, as the samples must be cured in order to improve their resistance to long-term deformation, the use of a harder grade bitumen would not provide a significant improvement to the end product. The type of bitumen used for this investigation was 50 penetration grade bitumen (also referred to as 40/60 pen.) with a specific gravity of 1.03 and a softening point of 47 °C. A range of bitumen contents between 5 and 6.5% was considered.

Table 1. The properties of the aggregate materials.

Materials	Density (gr/cm3)	Water Absorption (%)
Coarse aggregates (CA)		
Steel slag	3.39	1.9
Crushed glass	2.51	< 0.5
Fine Aggregates (FA)		
Crushed glass	2.51	< 1
Filler		
Fly ash Ferrybridge	2.16	-

Aggregate type

For this investigation steel slag, crushed glass and fly ash aggregates have been used. Table 1 provides details of the aggregates used in this investigation.

In order to reduce the amount of bitumen needed, (and hence enhance the economics of the mix) and yet still ensure satisfactory bitumen coating, the incorporation of waste aggregates with low absorption properties have been considered for this investigation.

Aggregate grading

The choice of aggregate grading is largely affected by the performance criteria specified above. Previously it has been found that a gap graded distribution of aggregates consisting of about 40 % coarse aggregates (max nominal size of 14 mm; minimum retained 2.36 mm) and 60 % fines (50 % fine aggregates (2.36-0.075mm) and 10 % filler (passing 0.075 mm) was preferable. Table 2 provides details of the aggregate and their proportions.

Figure 1 also illustrates the aggregate distribution and compares it to British Standard 594, (BS594 2003). It can be seen that the fine fraction follows the lower limit of a hot rolled asphalt (HRA) grading. However, the coarser fraction (retained 2.36mm) tends towards the upper limit.

Table 2. Type of mix and aggregate materials used

Mix Name	Coarse aggregates: (40 %)		Fine Agg.: 2.36-0.075mm (50 %)	Filler: < 75µm (10%)
	25 % (14-10) and (10-5)mm	15 % (5-2.36) mm		
SSCF200/24	steel slag	crushed glass	crushed glass	fly ash

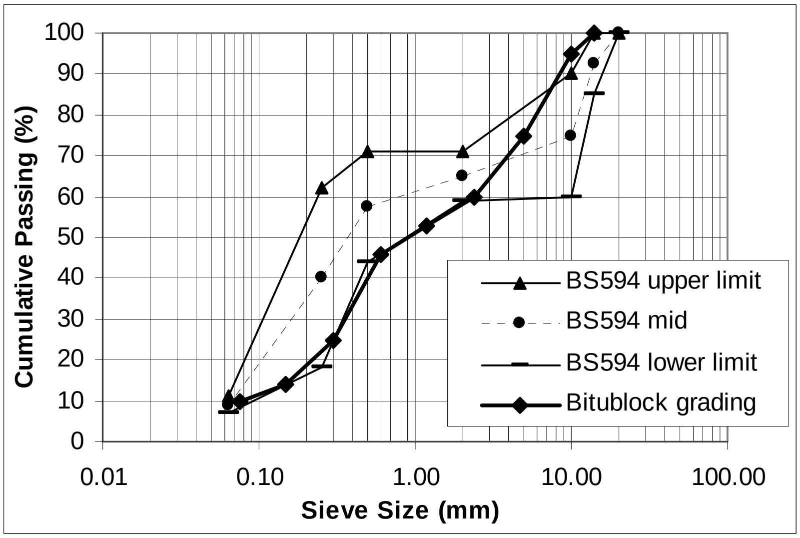

Figure 1. Bitublock grading used in comparison to a hot rolled asphalt (HRA) as specified in the British Standard 594 (BS594), an example case.

Bitublock unit optimisation

The manufacture of Bitublock has been reported previously (Forth et al. 2006). Briefly, to facilitate mixing, the aggregate materials and the 50 pen bitumen were pre-heated at 160-180 °C (Withoeak 1991) for 3 hours. The loose mix was then placed in a mould and compacted. Following compaction, the Bitublock samples were cured in an oven (for this investigation the samples were cured at 200°C for 24 hours). The performance of Bitublock is influenced by porosity and the heat curing regime. A lower porosity (higher compaction) gives improved aggregate interlock which increases the potential compressive strength. However, more efficient heat curing (higher porosity – greater depth of bitumen oxidation / hardening) improves the long-term stability of Bitublock (i.e. reduces the creep potential). In this investigation, the curing regime was fixed and the compaction level and bitumen content were varied. Figures 2 to 4 illustrate the optimisation of bitumen content and compaction level.

Referring to the aggregate grading shown in Figure 1, the minimum bitumen content for road bituminous mixtures recommended by BS594 is 6.5 % by weight of total mixture; this is to ensure adequate coating and durability. With this in mind, the bitumen content was optimised taking the figure of 6.5% as a maximum.

From Figures 2 and 3 it can be seen that a decrease in bitumen content from 6.5% to 5%, corresponds to a decrease in density and an increase in porosity. This is a common trend in bituminous mixtures as the mixture becomes less workable at lower bitumen contents.

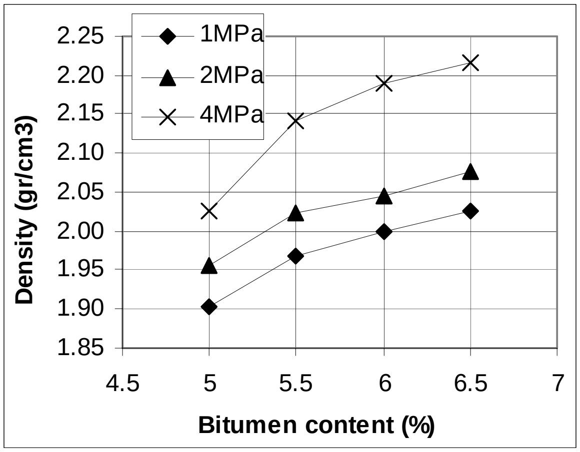

Figure 2. Bitumen content vs. density.

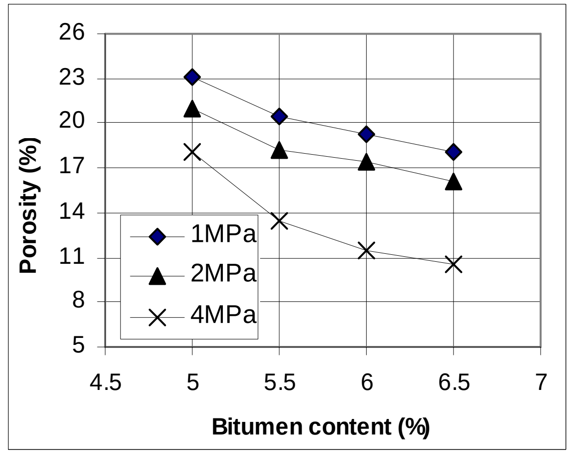

Figure 3. Bitumen content vs. porosity.

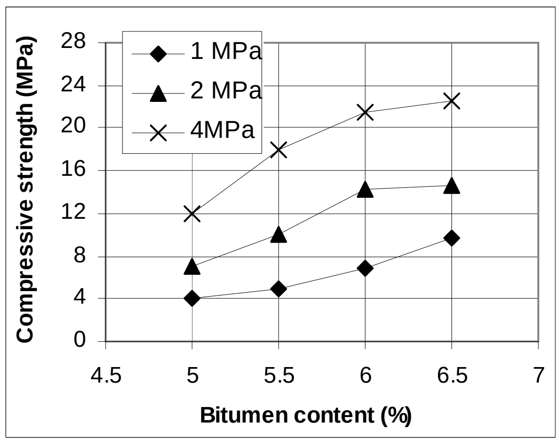

Figure 4. Bitumen content vs. compressive strength.

As expected, a reduction in compaction level also corresponds to a decrease in density and an increase in porosity. The compressive strength trends shown in Figure 4 are in line with the trend identified for density. However, for units compacted at 2MPa there is little improvement in compressive strength beyond 6% bitumen content. It has been shown previously that further increases in bitumen content (higher than 6.5 %) can enhance the density and hence the compressive strength. However, by observing the satisfactory degree of coating of the aggregates; the surface texture of the units and the stability of the samples during handling, together with the insignificant improvement in compressive strength of samples with over 6% bitumen content compacted at 2MPa, it was decided not to optimise the bitumen content further on this occasion. For the remainder of this investigation it was therefore decided to fix the bitumen content at 6 % and the compaction level at 2 MPa. The compressive strength of these units still exceeded the compressive strength of concrete blocks commonly used in the UK (3.5 – 10 MPa). Also, a 0.5 % reduction in the bitumen content and a slightly higher porosity is expected to improve the long-term stability of the unit (this is considered in the next section). The initial rate of suction (IRS) of these optimised units (6 % bitumen content; 2MPa compaction level) was 0.35 kg/m^2.min; the 24-hr water absorption value was 5.5%.

Long-term stability of the Bitublock units

Prior to monitoring the time-dependent properties of the Bitublock units, the samples were stored in a controlled environment of 62% ± 1% relative humidity and 21.5°C ± 0.5°C. The

samples were between 3 and 4 weeks old when they were tested. At this age, the volume stability of the unloaded samples was found to be very stable (i.e. the samples did not exhibit any expansion / shrinkage).

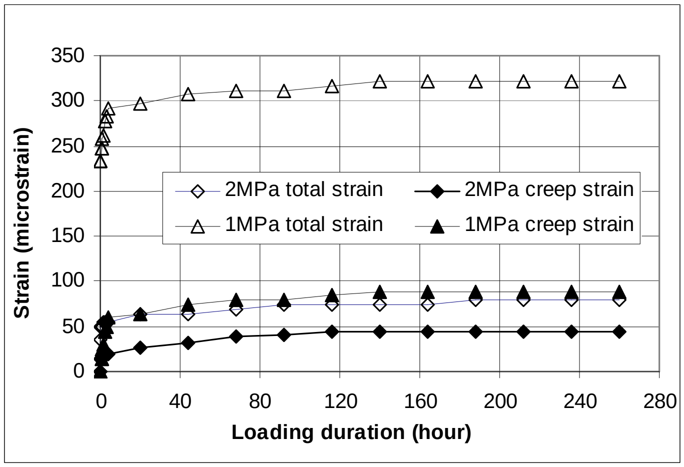

Figure 5. Creep test results of Bitublock units, at 1 and 2 MPa compaction levels.

Figure 5 illustrates the total strain and creep of the Bitublock samples compacted at 1 and 2 MPa. The samples were loaded in a controlled environment using a static dead-weight lever arm machine (mechanical advantage of 4) providing a stress of 1 MPa. Strain measurement was performed using both a 50mm Demec gauge and electrical resistance strain (e.r.s.) gauges.

Figure 5 also illustrates the elastic strain of the samples. A summary of the elastic and time-dependent properties of the samples is shown in Table 3. Although the creep of the units compacted at both 1 and 2MPa were acceptable (in terms of their comparison with concrete blocks), the unit compacted at 2MPa was chosen for construction in the Bitublock walls.

Table 3 Creep performance of the samples

Mix Name	Total Strain (με)	Elastic Strain (με)	Creep Strain [1] (με)	Elastic Modulus [2] GPa)
1 MPa compaction level				
SSCF200/24	321.75	232.65	89.1	4.3
2 MPa compaction level				
SSCF200/24	79.2	34.65	44.55	28.9
[1] creep strain = total strain – elastic strain – shrinkage or expansion. [2] elastic modulus = (1 MPa / elastic strain)				

As mentioned above, the unloaded volume stability of the Bitublock units was obtained from units which were 3 to 4 weeks old (corresponding with the age of the creep samples). Two samples were also later manufactured and monitored from an age of 1 day (after they had cooled to room temperature). The results of these tests can be seen in Figure 6.

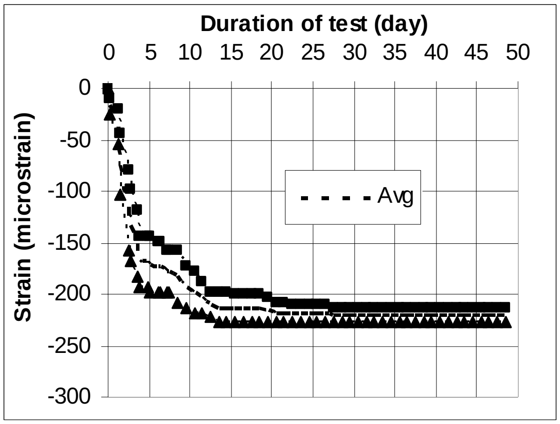

Figure 6. Expansion of Bitublock units.

Figure 7. The prism creep rig.

These results are interesting as they illustrate a behaviour similar to ‘kiln fresh’ clay bricks. This early age behaviour of Bitublock is currently being examined to see whether it is a consequence of water absorption / adsorption. Figure 6 illustrates how stable the Bitublock units are after 15 to 20 days.

Mortar Details

A class II; 1: ½: 4 ½, cement: lime: sand mortar was used throughout this investigation with 7, 14, and 28 day compressive strengths of 5.1, 9.1 and 10.8MPa, respectively. The time-dependent properties of the mortar were obtained from 75x75x200mm prisms as described previously (Brooks and Abdullah 1988), (also see Figure 7 for details of the creep rigs). Readings were taken from an age of 7 days. Prior to this the prisms were cured under plastic.

Figure 8 illustrates the creep and shrinkage of the class II mortar used in this investigation. The behaviour is similar to mortar data measured in other similar investigations. The prisms in this investigation were unsealed. Therefore, for the composite modelling exercise later, this data will have to be modified to take account of the difference in volume / surface area (v/s) ratio between the mortar prisms and the mortar in the Bitublock walls (to compensate for the different drying paths).

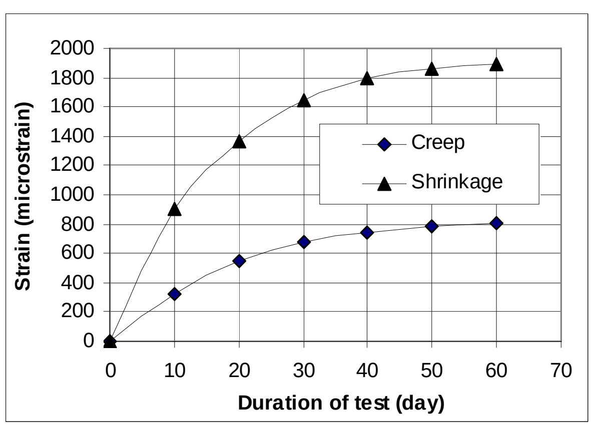

Figure 8. Time-dependent movements of mortar prisms.

Construction and testing of Bitublock walls

The walls were constructed in a controlled environment, with temperature of: 21.5 ± 0.5 °C and relative humidity (RH) of 62±1%. The size of the Bitublock units was 100x100x65mm; the units were approximately 30 days old. Four sets of walls were constructed. Each wall was 4 units wide by seven courses high (Figure 9). The walls were constructed with a class II mortar with joints of between 5 and 8mm thick. Immediately after construction the walls were covered with plastic bags and cured for 7 days prior to being exposed to drying in the controlled environment.

Figure 9. The loaded and control wall.

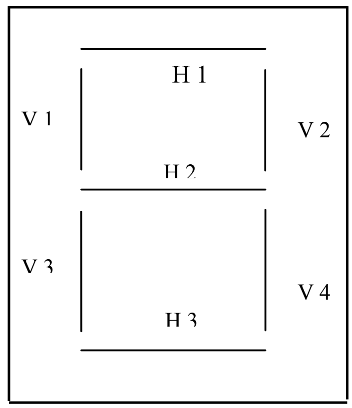

Figure 10. Schematic presentation of the vertical and horizontal strain reading.

Each set of two walls consisted of a loaded wall (to isolate creep) and a corresponding control wall (to obtain expansion / shrinkage deformations). On each side of the walls, vertical strain readings were taken at 4 locations and horizontal reading at three positions (Figure 10).

The strain readings were initially taken twice a day. After two weeks, the strains were recorded once a day and after one month, strains were recorded twice a week. Vertical strain readings were taken using a 150mm Demec gauge; horizontal strain readings were taken using a 200mm Demec gauge (Figure 11). Only the vertical strain data have been reported here.

Figure 11. The Demec gauges and strain reading.

The walls were loaded at an age of 7 days; a stress of 1 MPa was applied to the loaded walls. This stress was monitored and constantly maintained throughout the duration of the tests using 4 calibrated steel tie-rod load cells. (Any load adjustment required was possible by tightening / loosening the nuts on the tie-bars (Figure 12).) For practical reasons, the tests were only performed for 60 days. This was shorter than was envisaged however the data collected was considered sufficient for the purposes of this investigation.

Figure 12. The steel tie-bar load cells and the data logger

DISCUSSION OF RESULTS

Modulus of Elasticity

The average modulus of elasticity of the Bitublock walls was 4.3GPa. The elastic moduli of the unbonded Bitublock unit and the mortar prism samples were 28.9 and 2.0GPa, respectively. (The modulus of the wall is clearly influenced by the modulus of the mortar.) The measured elastic modulus compares well with the modulus predicted using British Standard BS5628-2. For a unit strength of 14.2MPa and a class II mortar, the code predicts a modulus of 4.61GPa.

It is normal practice to apply the load to the walls within 15 minutes. According to Neville 1983, this limits the incorporation of creep within the strain measured on application of the load to acceptable levels. However, in this investigation it was reported that the time for application of the load was between 15 and 30 minutes. The elastic strain will therefore contain some creep and the elastic modulus will therefore be lower than expected. This is confirmed by the prediction of elastic modulus using the composite model (equation (2)). An elastic modulus of 5.64GPa is predicted which is higher than the measured modulus.

Time-dependent behaviour

Figures 13 and 14 illustrate the time-dependent behaviour of the Bitublock walls. It can be seen that the moisture movement behaviour of the Bitublock control walls is one of shrinkage (Figure 13). This is not unexpected as the Bitublock units are stable and so the movement of the wall will be controlled by the mortar which shrinks. This trend of overall shrinkage of the masonry agrees with previous findings of research performed on clay brick masonry (although BS5628-3 1995 recommends that all fired clay masonry expands).

Using the unbonded unit and mortar prism data (adjusted for v/s ratio differences) in the composite model expression (equation (5)) yields a slight over-prediction of shrinkage at early ages (Figure 13). However, at later ages the model under estimates the shrinkage of the walls (although the error is less than 20%, which is considered acceptable). Previously it has been shown that the composite model tends to over-predict the shrinkage of clay masonry. This is because the model does not entirely account for the interaction between the mortar and the unit in the masonry resulting from the water absorption properties of the unit. The Bitublock units in this investigation have very low water absorption properties and this interaction would be expected to have less effect. More importantly, the absence of any 'enlarged expansion' (the brickwork / brick expansion ratio is less than unity (Forth and Brooks 2000)) and the accuracy of the prediction indicates there is no chemical interaction between the elements of the masonry and that cryptoflorescence does not appear to be present.

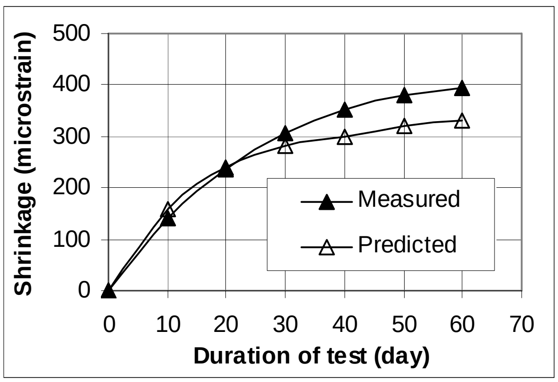

Figure 13. Measured / predicted vertical shrinkage of control walls.

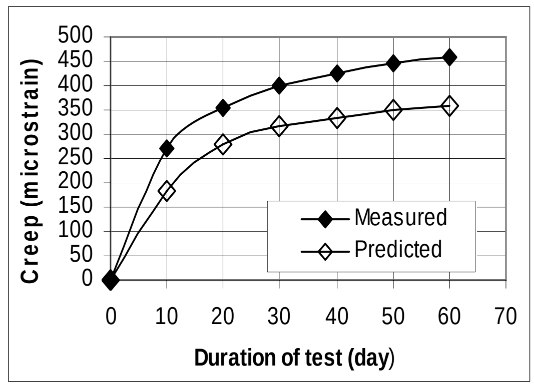

Figure 14. Measured / predicted creep of walls.

The creep-time characteristics of the Bitublock wall can also be seen in Figure 14. As expected the pattern of movement is similar to that seen for the mortar prisms and the unbonded Bitublock unit in Figures 8 and 5, respectively. The level of creep is also similar to that previously measured in concrete block masonry (Forth et al. 1996). Overall the composite model under-estimates the creep of the Bitublock masonry (approximately 25%) however beyond 10 days the measured and predicted creep is very similar.

The 60-day creep coefficient obtained for the Bitublock masonry of this investigation is 2.1. This value is within the range of design values suggested by BS5628-2 1995 (1.5 and 3.0 for clay and concrete block masonry, respectively). However, an exact comparison cannot be drawn as the code recommendations are ultimate values.

CONCLUSIONS

a. The investigation provides further proof of the concept of Bitublock and that the physical and mechanical properties of Bitublock units are at least equivalent to concrete block masonry units used in the UK.

b. This is the first time the elastic and time-dependent properties of Bitublock masonry have been investigated. For the experimental conditions of this investigation, composite modeling using un-bonded unit and mortar deformations gives reasonable estimates of elastic modulus, shrinkage and creep of Bitublock masonry. The use of composite modeling has helped to confirm the apparent absence of any chemical interaction

between the mortar and the unit in terms of what effect this might have on the long-term behaviour of Bitublock masonry. The manufacture of Bitublock is an encapsulation process (its properties are not dependent on chemical binding). The results of this investigation help to confirm that the recycled material used in Bitublock is adequately encapsulated by the bitumen.

c. Overall, Bitublock is compliant with the design suggestions of the relevant British Standards for masonry.

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