Unreinforced solid dense concrete block walls constructed using thin joint technology

A. N. Fried
BSc (Civ) Eng, MSc, PhD, CEng, MICE, FBMS
School of Engineering, Kingston University, London

E. Marrocchino
PhD
Dept. of Earth Sciences, University of Ferrara, Italy

C. Bradsell
BSc (Hons)
School of Engineering, Kingston University, London

Prof. John J. Roberts
BSc(Eng), PhD, CEng, FIStructE, FICE, FBMS, FIMgt, MICT
Faculty of Technology, Kingston University, London

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Synopsis
The transverse lateral load capacity of masonry built using solid dense concrete blocks with thin joint mortar is up to 4.0 times that of similar blockwork constructed using conventional mortar. Both the mortar properties and the constituents of the parent material forming the block alter the joint strength resulting in enhancements to tensile flexural bond strength. Testing on two block types and one mortar has been undertaken and verifies the trend. Essentially when thin joint technology is employed, in conjunction with solid dense concrete blocks, the masonry behaves more as a concrete plate than conventional blockwork.

Introduction
Masonry construction has been utilised by man for thousands of years as evidenced by its use in building the Tower of Babel[1] in about 2200BC. In erecting that structure, the writer informs us that brick instead of stone and tar instead of mortar were used, implying masonry construction was well established at the time. Over the last 4000 years basic masonry construction has hardly altered although changes in materials, the building process and to the philosophy of masonry construction have occurred.

Variations include the use of concrete blocks as an alternative to clay bricks and natural stone. Modern production line procedures used in the manufacture of masonry units have revolutionised this aspect of the industry enabling greatly increased production rates to be achieved. The use of ready mixed and retarded mortars as alternatives to traditional site produced mortars have eliminated the need for site mixing of mortars and increased building rates. Formal design procedures embedded in codes of practice have replaced 'rule of thumb' and traditional methods of construction, and most recently the use of thin 'glued' joints in masonry walls is being examined as an alternative to conventional mortar in some applications.

The use of codified design procedures for structural masonry developed during the second half of the 20th century for a number of reasons. A better understanding of the physical behaviour of masonry walls since the early 1950s has enabled thinner and more efficient walls to be produced so including these advances in codes of practice produced economies, but in addition codes have improved the confidence of designers in using this material structurally putting masonry on a par with steel and concrete as a building material. Importantly, the codification of masonry has enabled part of the market share lost to steel and concrete earlier in the century to be regained.

Unreinforced masonry design in the UK is currently undertaken in accordance with BS 5628: Part 1:1992[2], a limit state code which enables vertically and laterally loaded wall elements to be readily designed. Vertically loaded wall panel capacity is determined by evaluating the characteristic compressive strength of the masonry as a combination of unit compressive strength and geometry and mortar designation and substituting this into a formula which allows for wall slenderness and the effects of load eccentricity. The capacity of predominantly laterally loaded walls is ascertained using simple bending theory in which the tensile flexural strength of the masonry depends for clay bricks on water absorption and mortar type and with concrete blocks on their strength, thickness and again the mortar designation. As one would expect, both vertical and lateral load capacity of walls is dependant on the properties of the units and the mortar type. BS 5628: Part 1:1992 includes data on a wide range of clay bricks and concrete blocks and on conventional mortar but there is no reference to using thin joint mortar.

With conventional mortar, joints are usually 10mm thick and to bond two courses of units together, mortar is placed on the tops of the lowest row of units currently in a wall and the next row is then bedded into this wet mortar paste by hand to form horizontal joints. Perpend or vertical joints between adjacent units are formed by placing mortar on the ends of each unit with a mason's trowel just before it is placed. With thin joint masonry, the finished product looks similar to walls formed using conventional mortar but with narrower joints. Placing mortar is undertaken in two ways. With either solid dense concrete or Aircrete (Autoclaved Aerated Concrete) blocks, mortar is placed using a form of comb not unlike those used to grout tiles in place. Perpend joints are filled by initially placing units on their ends and applying glue mortar using the comb. These units are then lifted and positioned by hand onto an existing course of units which has had thin joint mortar applied to its top surface using the comb system. Full coverage across joints is assured but there is the possibility of spillage down the face of the units as blockwork is usually rendered or below ground. With brickwork, mortar is applied using a pump which delivers two beads of mortar about 50mm apart. The pump is hand held and the nozzle drawn along the centre line of the bed joints of the most recently placed course of bricks releasing two lines of mortar. When units are bedded into these they squash the beads to an overall width of about 70 – 90mm but the system is designed so no mortar squeezes out onto the brick face as glue mortar is very difficult to remove from the face of brickwork. As with blocks, units are initially placed end up and the mortar pumped onto their perpends so ensuring bond in both directions when placed.

Thin joint mortar technology utilises a cementitious mortar but with polymers included to bond units together. In accordance with EC6[3] thin joints should be under 3.0mm in thickness but this is insufficient to allow for variations in block size and 5.0mm is a practical minimum with normal unit tolerances and has been adopted in this programme. Thin joint mortar offers two main advantages to designers. Firstly, when used in conjunction with light and thermally efficient Aircrete (Autoclaved Aerated Concrete) blocks they reduce the joint volume considerably. Heat flow through masonry walls formed using Aircrete blocks is predominantly through the mortar joints so reducing joint thickness will improve thermal resistance. Secondly, the nature of the mortar and constituents of the material forming the block significantly enhance bond strength to the point where in

Fig 1. (below) Rear elevation of wall not showing reaction frame

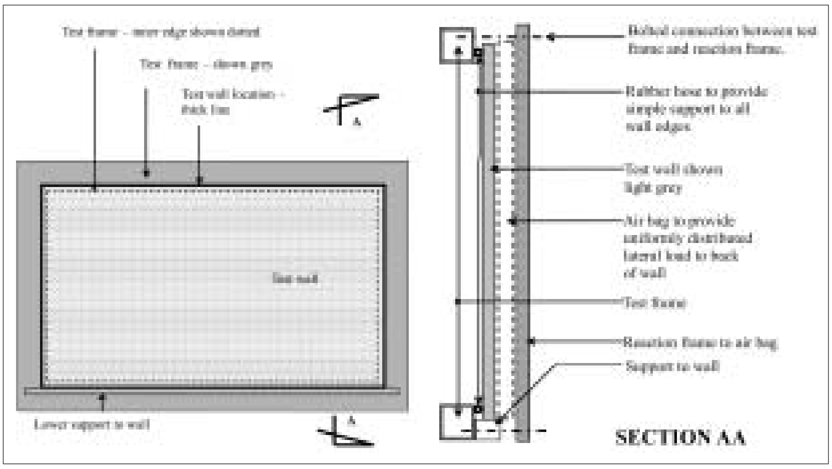
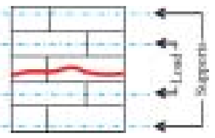
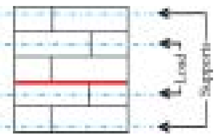
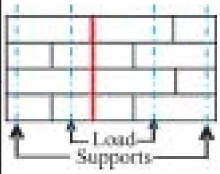


Table 1. Summary of wallette test results

Specimen type	Test format and typical failure position	Average strength at failure[1] (N/mm^2)	Std deviation (N/mm^2)	Charac. strength (N/mm^2)	Failure mode
Grey B-wallette		1.31	0.15	1.06	Predominantly through the unit
Yellow B-wallette		0.76	0.08	1.65	Along mortar joints but with some tearing away of unit
Grey P-wallette		1.78[2]	0.19	1.47	Vertical in all but one case and always through two units and two joints
Yellow P-wallette		1.21	0.10	1.07	Vertical in all cases and always through two units and two joints

[1]Six specimens tested unless noted otherwise.
[2]Five specimens tested

many instances, it exceeds block unit modulus of rupture (UMOR). Consequently wall panels formed using thin joint masonry have lateral capacities dependant on the UMOR, not the tensile bond strength of the joint. Lateral load capacity of walls built using thin joint technology in conjunction with solid dense concrete blocks or bricks with high UMORs will be considerably higher than if the walls had been built using conventional mortar whereas the enhancement in Aircrete walls will be marginal as this block is weak.

Thin joint glued masonry is currently widely used in industry in association with Aircrete blocks to reduce their thermal transmittance but the technology is rarely associated in the UK with solid dense concrete blocks or brickwork. New markets for this material could include unreinforced masonry basement walls, prefabricated masonry and corridor walls in schools, hospitals, universities and government buildings, paint finishes not being necessary if fair faced blocks are used.

This paper reports on a testing programme undertaken to ascertain the tensile flexural strength of two types of solid dense concrete blocks and one mortar type. As masonry flexural strength is highly dependant on mortar/unit bond whereas vertical compressive strength is less so, particularly with thinner joints, testing focused on flexural not compressive strengths. Furthermore, only glued blocks were examined as the potential market gain with this product was considered more promising than with brickwork. It should be noted however, that the constituents of the mortar were not made available by the manufacturers.

Pre-testing information

Testing included two walls (Fig 1 and section AA) and 24 wallette specimens (Table 1) all constructed using solid concrete blocks built using thin joint mortar. All blocks were 440mm long × 100mm wide × 215mm deep. Half of the specimens (one wall and 12 wallettes) were constructed using a 'grey' block of strength $20N/mm^2$ and density $1700kg/m^3$ whilst the remainder were built using a 'yellow' block of strength $14N/mm^2$ and density $1400kg/m^3$. Walls measured 2.65 × 1.75m and the wallettes were either 1.5 units long × 5 units high (665 × 1095mm) when tested about an axis parallel to the bed joints or 2.5 units long × 4 units high (1100 × 875mm high) when tested about an axis perpendicular to the bed joints as shown in Table 1. All specimens were built by an experienced mason at a brick/block producer in the Midlands in order to assess the potential of the process for prefabrication demonstrated by then transporting the specimens by lorry to Kingston University in SW London. The walls were supported vertically while in transit between metal supports on the lorry as 'toast in a toast rack', but without any additional support. Six wallettes were strapped together with 20mm thick sheets of polystyrene in-between each specimen and the batch placed on and secured to a wooden palette using canvas straps. Walls and wallette palettes were unloaded by slinging canvas straps beneath them and craning them from the lorry. A fork lift truck lifted them into the laboratory for storage prior to testing which took place at a mortar age exceeding 28 days in all cases. Thin joint mortar achieves its strength much quicker than conventional mortar and at 28 days was assumed to be at or very near maximum strength.

Testing undertaken

Wall testing

Fig 1 and section AA indicates a schematic view and section of the wall testing rig with a wall in place. All round simple support for the wall was provided using rubber hose attached to the bearing face of the test frame. The base of the wall was supported on a metal bearer designed to enable the wall to move laterally without restraint. Loading to the wall was uniformly distributed and provide by an air bag of similar area to the wall. Pressure was supplied by a pump and a data logger enabled the deformations of the front of the wall to be continuously monitored. One quarter of the wall was instrumented with Linear Variable Differential Transformers (LVDTs), their locations being shown in Fig 2 and Fig 3. The support frame is extremely rigid comprising stiffened 300 × 300 UC158kg/m and unlikely to move relative to the wall.

Wallette testing

The wallettes were tested in accordance with BS EN 1052-2:1999[4] *Methods of Test for Masonry – Part 2*.

Test results

Grey units

Wall load *vs* deformation results are shown in Fig 4, wallette

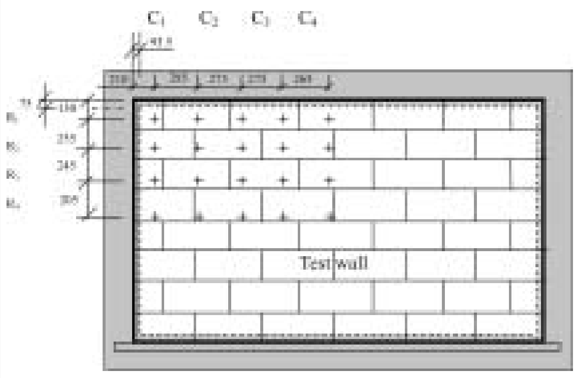


Fig 2. Grey wall – location of LVDTs

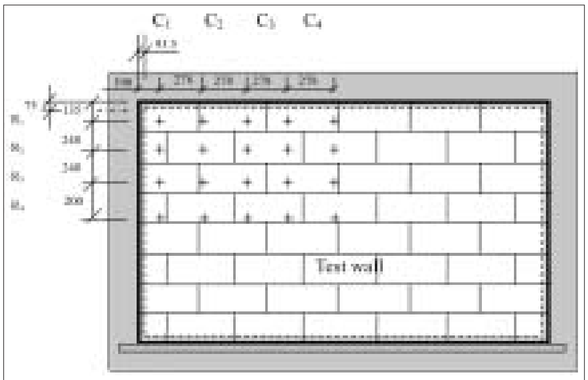


Fig 3. Yellow wall – location of LVDTs

Table 2: Comparison of wallette test results with requirements of Table 3 of BS 5628: Part 1			
Unit type	**Wallette type**	**Characteristic strength - test result (N/mm²)**	**Characteristic value from BS 5628: Part 1 Table 3 (N/mm²)**
Grey units	B-wallette	1.06	0.25
	P-wallette	1.47	0.75
Yellow units	B-wallette	0.63	0.25
	P-wallette	1.05	0.75

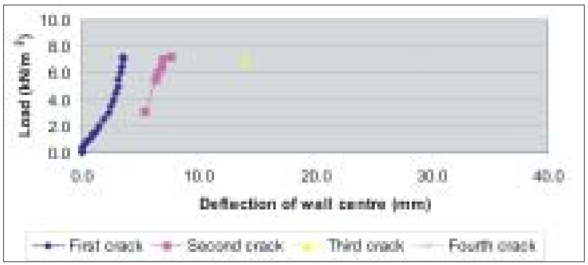


Fig 4. (left) Load vs deflection – grey wall

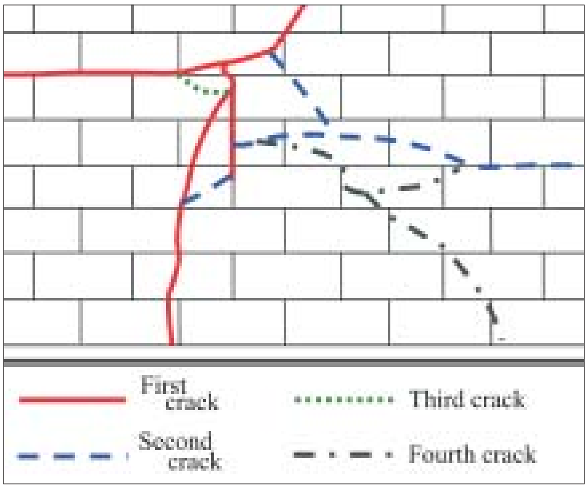


Fig 5. (left) Crack pattern – grey wall

test results are summarised in Table 1 and the wall crack pattern is shown in Fig 5. The initial crack in the grey wall occurred at a uniformly distributed load of 7.2kN/m² and a central deflection of 3.5mm and affected the left half of the wall. The crack occurred instantaneously and immediately the central deflection increased to 5.4mm resulting in a pressure drop. The pressure was then increased and a second crack occurred at the same load of 7.2kN/m² and a deflection of 7.6mm. This crack affected the right hand side of the panel, was again instantaneous and resulted in the deflection increasing to 10.0mm with a corresponding pressure loss. At this point the LVDTs were removed and central deflection was estimated from this point forward. A third and fourth crack occurred at loads of 6.9 and 7.9kN/m², the location of the cracks being as indicated in Fig 5 and with both cracks the wall shifted outwards and there was a pressure loss. Thereafter, increasing deflections occurred under a reasonably constant pressure of 4.2kN/m².

Yellow units

Wall load *vs*. deformation results are shown in Fig 6 whilst wallette test results are summarised in Table 1 and the wall crack pattern is shown in Fig 7. The first crack appeared instantaneously in the wall at a load of 6.0kN/m² and central deflection of 2.02mm as shown in Fig 7 and resulted in the wall moving outwards to a new deflection of 4.96mm. At this point the pressure dropped to 2.9kN/m² but was subsequently increased to 4.0kN/m² when the test was terminated with a central deflection of 12.25mm.

Comparison of wallette results with BS 5628:Part 1 values

Wallette test results are compared with those given in Table 3 of BS 5628: Part 1 assuming a designation (iii) mortar as shown in Table 2.

When failure is about an axis parallel to the bed joints, the characteristic strength of the grey wallettes is 4.24 times that required in the code whilst the wallettes formed using the yellow units were 2.5 times the code requirement. The corresponding ratios when failure is in the orthogonal direction are 1.96 and 1.4.

Wallette findings

- Comparisons with BS 5628: Part 1 have been made for wallettes used in unreinforced situations.
- With both unit types, the B-wallette strengths are significantly higher than those specified in the code indicating an enhancement in the bond between unit and mortar.
- With the grey B-wallettes, failure was through the unit in four out of six specimens. In the remaining two specimens, whilst failure was along a bed joint, it moved into the units over a significant part of the joint, indicating that the bond strength between unit and mortar was higher or at least equal to the strength of the unit and significantly higher than the BS5628: Part 1 specification.
- With the B-wallettes built from the yellow units failure was always along the bed joints suggesting a de-bonding. However, a close examination of the failed mortar face revealed many small pieces of the unit had been plucked out and were retained in the mortar bed. Behavior intermediate between that of conventional masonry and a plate was being exhibited. When these results are compared to the BS 5628: Part 1 requirement the bond is double that of conventional mortar.
- With the grey P-wallette specimens, failure was always through two units and two perpend joints and vertical in all cases except one. It appears that failure in this direction is initiated by de-bonding in the perpend joints and from this initial crack, failure of the units between cracked perpends (usually vertical) occurs. It should be noted, the bond in the perpend joints will be weaker than in the bed joints where pressure from units above aids bond development during the building process. It is impossible to know if the initial de-bonding of the perpends initiates failure or if this de-bonding is followed sometime later by the units breaking albeit in this latter case with the additional load resistance available from torsional resistance in the bed joints. In any case it appears from the results that the strength of the blocks when flexed horizontally (about an axis perpendicular to their bed joints) is higher than when they are stressed in the orthogonal direction (about an axis parallel to their bed joints) and that P-wallette strengths are nearly double BS 5628: Part 1 values.
- With the yellow P-wallette specimens, failure was always through two units and two perpend joints and vertical in all cases. As with the grey unit it appears that failure in this direction is initiated by de-bonding in the perpend joints and from this initial crack, failure of the units between cracked perpends occurs. Again, it is impossible to know if the initial de-bonding of the perpends initiates failure or if this de-bonding is followed sometime later by the units breaking, in this latter case the load resistance being assisted by torsional resistance in the bed joints as with the grey units.
- The orthogonal strength ratio (flexural strength about an

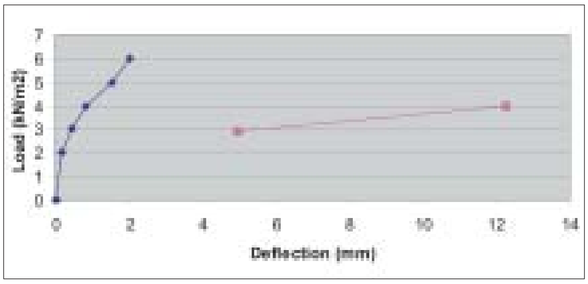


Fig 6. Load vs actual deflection – yellow wall

axis parallel to the bed joints/flexural strength about an axis perpendicular to the bed joints) is 0.33 for both units according to the code. The test results indicate values of 0.72 and 0.60 for the grey and yellow wallettes respectively. Increased orthogonal ratios indicate increased bond, this being most evident with the grey units.

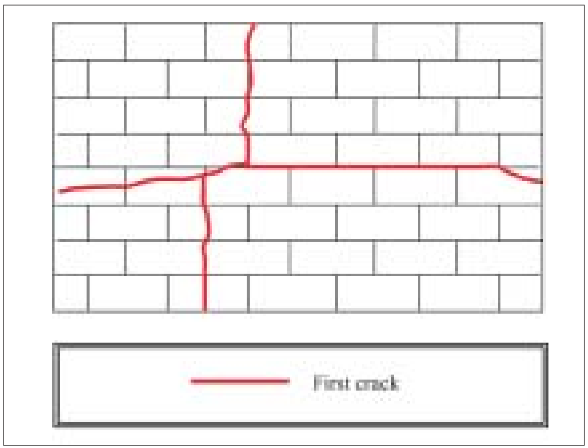
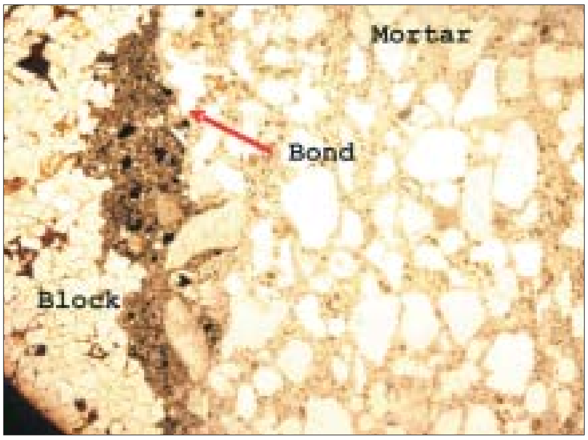


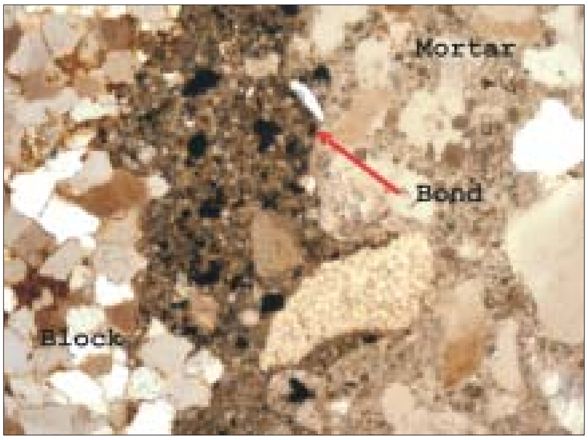
Fig 7. Crack pattern – yellow wall

Wall test results – interpretation

Wall test results are compared to various predictions as indicated in Table 3.

Predicted values of lateral load capacity determined using the method given in Clause 36.4 of BS 5628: Part 1 but using average wallette strengths are higher than the test results for both walls, being 2.3 times the value with the grey wall and 1.73 times that of the yellow wall. This suggests that the method for determining lateral load capacity in the code is not conservative with these materials. Small specimen testing indicated that with wallettes tested about their bed joints those built of yellow units partially debonded along the bed joints as many of the failed mortar joints exhibited parts of the block plucked out and still in the mortar, but the grey unit wallettes behaved as plates, the joint being stronger than the block material. About the axis perpendicular to the bed joints the wallettes made form both unit types behaved conventionally. Using the 'higher' B-wallette test results resulted in non-conservative predictions of wall strength, particularly with the grey wall. As the yield line method, on which the British Standard is based, predicts higher lateral capacities in walls than an elastic plate method would, using this analytical technique to determine the lateral strength





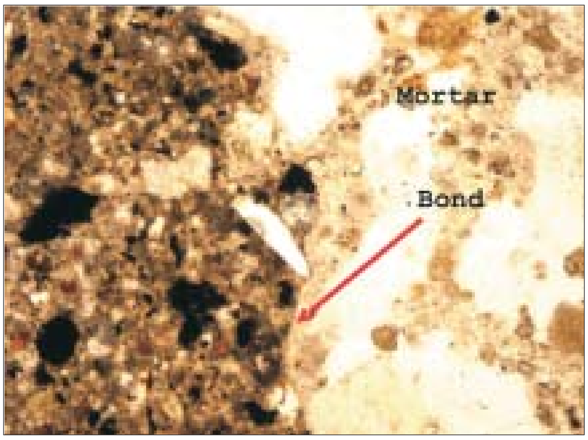
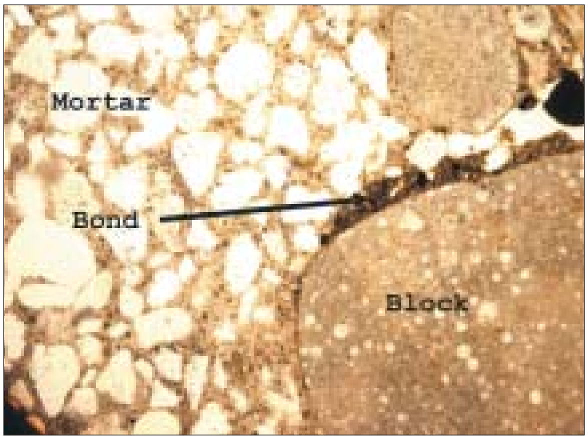
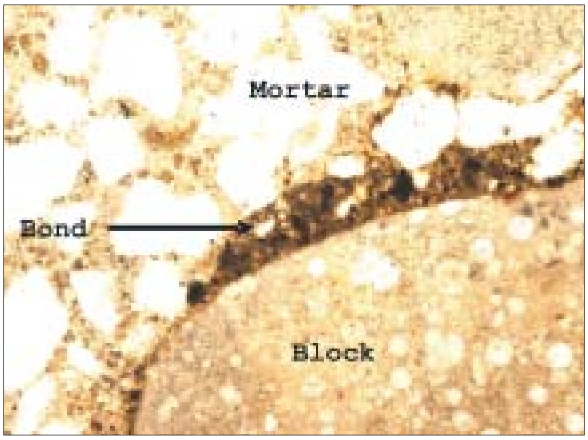


Fig 8. (left) Bed joint – Grey blocks (Metamorphic block material). Top: x5 magnification Middle: x10 magnification Bottom: x20 magnification





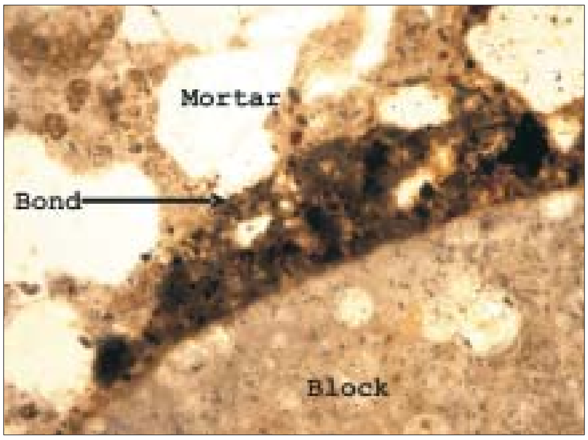


Fig 9. (right) Bed joint – grey blocks (Carbonatic block material) Top: x5 magnification Middle: x10 magnification Bottom: x20 magnification

*Table 3: Test and predicted failure loads of walls**

Unit type used to build wall	Experimental failure load of wall (kN/m²)	Predicted failure load (kN/m²)			
		Average strength of test wallettes	Characteristic strength of test wallettes	BS 5628: Part:1 Table 3 results	BS 5628: Part:1 Table 3 results PSF included
Grey units	7.2	16.59	13.51	4.57	1.09
Yellow units	6.0	10.35	8.79	4.57	1.09

*All predictions exclude Partial Safety (PSF) factors unless indicated

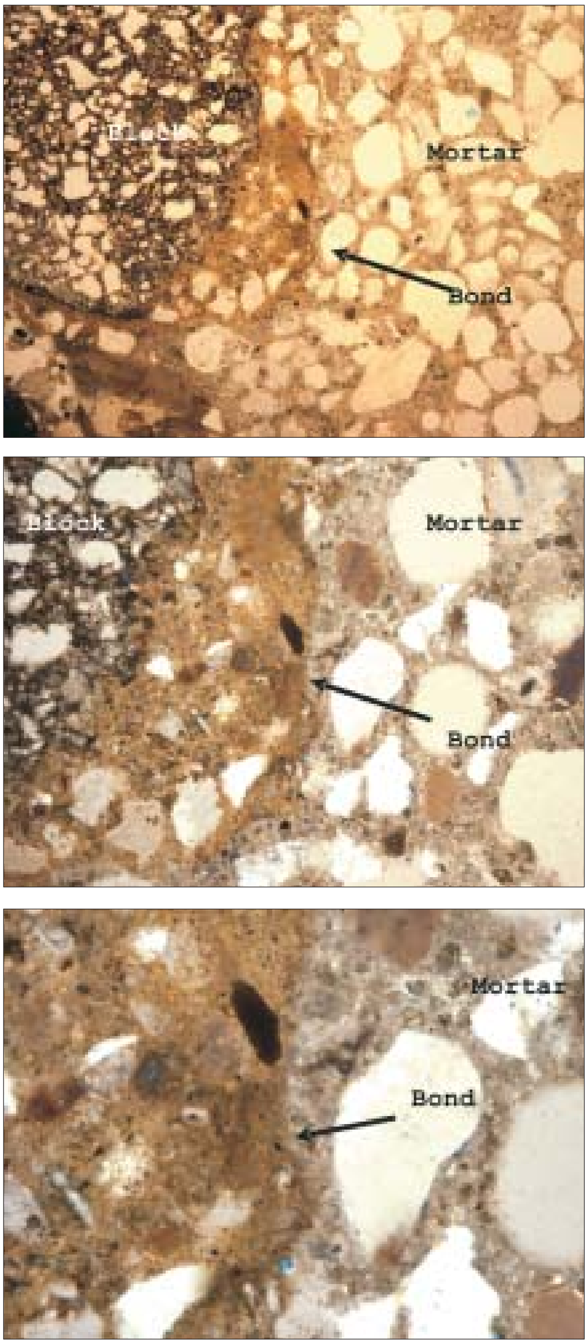


Fig 10. (left) Bed joint. yellow blocks (block mainly chert)
Top: x5 magnification
Middle: x10 magnification
Bottom: x20 magnification

of these walls may not be prudent.

When the characteristic strength of the tested wallettes is used in the Clause 36.4 method, the predicted strength of panels made of grey units is 1.88 times the test value, that of walls built using the yellow units being 1.47 of the strength of the tested wall.

When walls constructed of concrete blocks exceeding 10.5N/mm² in strength in a designation (iii) mortar are assessed in accordance with Clause 36.4 and Table 3 of BS 5628 Part 1, the predicted strength of a wall similar to that tested is 4.57kN/m² if partial safety factors are excluded and only 1.09kN/m² if a $\gamma_m = 3.5$ and a $\gamma_f = 1.2$ are included. Assuming mean strengths are about 1.5 times the characteristic value gives predicted wall strengths of 6.88kN/m², still 0.96 of the strength of the grey wall and 1.14 that of the yellow wall.

Optical microscopy examination

Using optical microscopy, Fig 8 and Fig 9 show the grey blocks consisted of a variety of rock types such as metamorphic (Fig 8) and carbonatic (Fig 9) rock. In both cases, a bond zone, different in each case, as indicated by the variations in colour between mortar and block has developed. Clearly the parent material of the block affects how this forms and is likely to influence the mechanical properties of the joint. Fig 10 indicates the yellow blocks are homogenous and comprised mainly of chert. Again a bond zone indicated by the difference in colour has developed but this zone is unlike those formed with the grey units so the mechanical properties of this interface will again be different.

In summary, the material in the bond interface of both samples was non homogeneous as well as of non constant thickness, both these affects being influenced by the parent material of the block.

Conclusions

- Two solid dense concrete block walls were successfully tested under lateral load.
- 24 wallettes were successfully tested in accordance with BS EN 1052-2:1999. Method of test for Masonry – Part 2.
- Prefabricating the specimens in Nottingham and transporting them to Kingston on the back of a large lorry with associated loading and unloading at either end using cranes and fork lift trucks did not appear to weaken the walls or small specimens.
- The characteristic strength of B-wallettes constructed using thin joint mortar was over 4.0 times that specified for equivalent units with a designation (iii) mortar as specified in Table 3 of BS 5628: Part 1 whilst for the yellow units it was about 2.5 times.
- With thin joint P-wallettes, the characteristic strength of wallettes constructed using grey units was just under 1.5 times that specified for equivalent units built using a designation (iii) mortar as specified in Table 3 of BS 5628: Part 1 whilst for yellow units it was 1.4 times the code requirement.
- Using average wallette test values in the Clause 36.4 method of analysis in BS 5628 Part 1 and excluding partial safety factors, the predicted strengths of the grey and yellow walls is 2.3 and 1.73 times the test values. Because the masonry is not behaving conventionally particularly when flexed about an axis perpendicular to the bed joints, higher B-wallette values have resulted than with conventional behaviour. As the yield line method, on which the British Standard is based, predicts higher lateral capacities in walls say than an elastic plate method would, using this analytical technique to determine the lateral strength of these walls is not prudent
- The flexural strength of these walls will depend more on the unit modulus of rupture than the bond strength.
- Optical microscopy indicates the thickness and nature of the bond zone depends on the parent material of the block, and this will affect the bond strength in the joint.

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