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ABSTRACT: A series of dry-stack (mortarless) interlocking block wall systems 3 m x 2.5 m were tested under concentric loading. The blocks comprise earth-cement blocks stacked in stretcher bond without mortar. Further tests were conducted on wall prisms consisting of 4 or 8 blocks. A conventional masonry block wall was also tested for comparison.

This paper highlights the experimental set-up and reports the failure loads, typical crack patterns and general structural behaviour of the dry-stack walling systems under in-plane loading. The test results were used as a basis for the development of an empirical model for the prediction of the load capacity of the dry-stack system

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STRUCTURAL BEHAVIOUR OF DRY-STACK INTERLOCKING BLOCK WALLING SYSTEMS SUBJECT TO IN-PLANE LOADING

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ABSTRACT

A series of dry-stack (mortarless) interlocking block wall systems 3 m x 2.50 m were tested under concentric loading. The blocks comprise earth-cement blocks stacked in stretcher bond without mortar. Further tests were conducted on wall prisms consisting of 4 or 8 blocks. A conventional masonry block wall was also tested for comparison. This paper highlights the experimental set-up and reports the failure loads, typical crack patterns and general structural behaviour of the dry-stack walling systems under in-plane loading. The test results were used as a basis for the development of an empirical model for the prediction of the load capacity of the dry-stack system.

Key words: dry-stack masonry units, compressive strength, interlocking features, prism, wall

INTRODUCTION

The technique of dry stacking masonry units in construction has existed in Africa for thousands of years. The Egyptian pyramids and the Zimbabwe ruins, a capital of ancient Shona Kingdom in 400AD, are living examples. Innovative mortarless system has improved with time since mid 1980´s and is now more competitive in many market segments than before. Several institutions in America, Africa and Asia are now involved in the development of this technology. However the emphasis so far has been on the development of dry-stack construction systems while little attention is given to research on the structural behaviour of the systems. Hydraform of South Africa, Azar and Spurlock both of Canada and Haener of USA are among the companies currently developing and marketing dry-stack masonry.

Dry-stack masonry units of different geometry, sizes and interlocking features have been developed. In conventional masonry, mortar is used for bonding the masonry units. Dry stacking relies mainly on the mechanical interlocking features of the units, which assist alignment and levelling and provide stability during construction. Dry stacking reduces the requirement for skilled labour and costly bonding materials like cement and allows floor and roof loadings to be applied immediately upon completion of walls. Dry stacking reduces building costs due to savings in construction time (Uzoegbo 2001). Overall savings of up to 27% compared to conventional masonry have been reported. The savings are mainly due to savings in cost of mortar, the block units and construction time. The University of the Witwatersrand in collaboration with Hydraform Africa Ltd is currently investigating the structural behaviour of a dry-stack masonry system developed by Hydraform. This report presents an investigation of full-scale dry-stack masonry wall constructed in the laboratory using Hydraform blocks and tested under vertical axial load.

MATERIALS

Compressed earth blocks (CEB's) are made by mixing soil and cement in predetermined ratios. The blocks in these investigations were made with 5-20% cement by volume. The required soil properties and cement content are shown in Table 1. The blocks are press extruded vertically under a distributed pressure of about 10 MPa

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using a diesel driven hydraulic block making machine. Curing was done by stock piling in stacks not exceeding 6 blocks in height and covering with plastic sheeting for 24 hours to prevent loss of moisture. The blocks may be used after a minimum curing period of 72 hours (Agrément1996). Tests have shown that the blocks gain over 80% of the 28-day strength in 72 hours under the prescribed curing conditions. This amount of strength gain is considered adequate for normal handling. An experienced operator can produce 220 blocks per hour. The block (see Figure 1) dimensions are 220mm width x 115 height x 220 to 250 mm in length. The units were made in strengths of 5, 9, 12 and 23 MPa . Normal cement:sand mortar (1:3) was used in the construction of the starter course. Glue-like cement based bonding agent with a trade name "Everbond" may also be used in place of mortar. The bonding agent requires only a thin layer to achieve the required bond, thus capable of retaining the same levels at the joints as the un-bonded units.

Table. 1 Basic requirements of Soil for CEB's production

Nominal % Compressive Strength (MPa)	By mass passing the 0.075mm sieve		Plasticity Index (maximum)	Cement content (%) (CEM II/A-M 42.5)
	Min.	max		
4	10	35	15	4-7
7	10	25	10	7-10
20	10	25	10	15-20

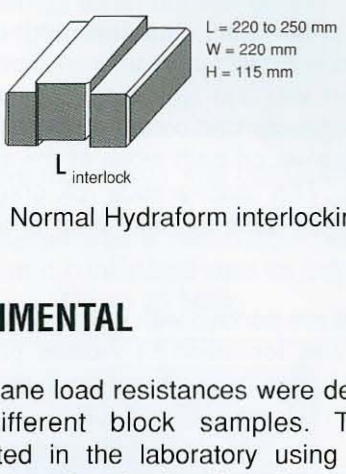


Figure 1. Normal Hydraform interlocking block

EXPERIMENTAL

The in-plane load resistances were determined for wall using different block samples. The walls were constructed in the laboratory using the construction method described in the Hydraform manual. The first course of blocks and the top three courses were bonded by mortar or Everbond. The end vertical strips were also bonded as shown by the shaded area in Figure 2.

Walls measuring 3 m span x 2.50 m height x 220 mm thick were constructed on a Macklow-Smith machine platen that is mounted on a hydraulic ram. The starter course was laid in mortar and cured for three days without load. The rest of the courses were dry-stack, with the units at the edges of the wall laid in Everbond. The last three top courses were also laid in Everbond to maintain level with the dry-stack units. The top surface of the wall was made flat using mortar and checked by spirit level. The structure was tested at 14 days. A 3 m span steel beam was used to spread the load evenly at the top of the wall. Dial gauges were placed in positions indicated in Figure 2. Axial compression load was applied at a rate of 2 kN/min. At each interval the lateral displacement was recorded from the dial gauges and the corresponding load from machine control panel.

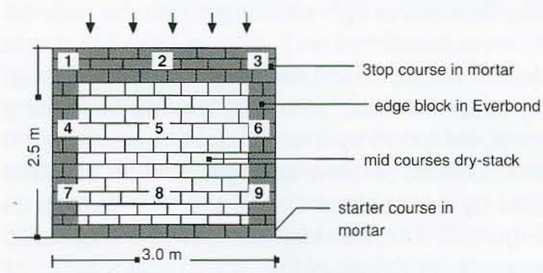


Figure 2. Wall construction details and strain gauge positions.

Tests were also conducted on scaled down models or prisms consisting 4 or 8 masonry units, which were either dry-stack or bonded with mortar and subjected to axial compression as shown in Figures 3 and 4. The axis of the specimens was carefully aligned with the centre of the machine platen before loading at the rate of 2 kN/min. Although the loading was central, the load path to the base is via the shoulders as a result of the design of the blockinterlocking keys.

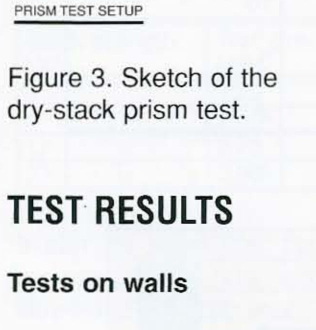


Figure 3. Sketch of the dry-stack prism test.

Figure 4. Testing bonded prism.

TEST RESULTS

Tests on walls

Compression tests on the walls indicate that the onset of failure is characterised by the formation of a vertical crack (less than 3mm) parallel to the axis of loading along the mid section of the wall (see Figure 5). At ultimate state, cracks also appeared on the faces and edges of the specimen (Figure 6). The appearance of the cracks was accompanied in each case by a loud snap and sudden reduction in the magnitude of the load applied, which quickly reduced to zero.

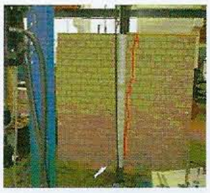


Figure 5. Front view of wall showing failure line

Figure 6. Side view of cracks at top

The main failure plane, as established in the prism tests, was along the vertical joint of the interlocking mechanism as indicated by the vertical cracks in Figure 10. However, failure in low-strength unit walls was characterised by a local crushing of the top courses as shown in Figure 7. The weakest sample (5 MPa) failed in this manner, by crushing of the top 10 courses.

Figure7. Side view of the crushing of the top courses (5 MPa specimen)

The ultimate load at the point of failure including the maximum lateral displacement of each wall is given in the Table 2. The total load capacities for the 3 m width walls are plotted for the various samples in Figure 8.

Table 2. Wall compressive test results

Type of wall	Ultimate compressive load (kN)	Maximum lateral displacement (mm)
5 MPa units, dry-stack	595	2.25
9 MPa units, dry-stack	721	10
12 MPa units, dry-stack	938	3.4
12 MPa units, bonded	1553	4
23 MPa units, dry-stack	1360	40

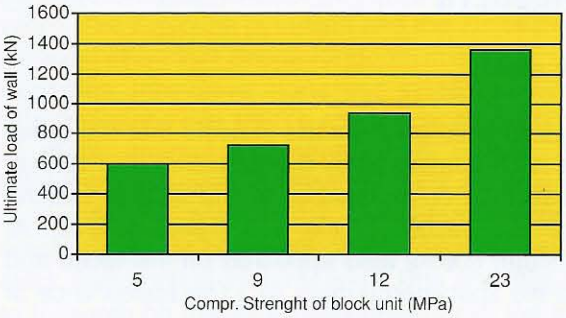


Figure 8. Wall load vs unit strength

Control Wall

A control wall was built with 12 MPa units and class 2 mortar. The structure was tested at 28 days. The mortar strength was 5.6 MPa at 28 days. Figure 9 compares the load capacity of the conventional (units bonded with mortar) walling system with a dry-stack system using 12 MPa units. The tests indicate a 50% increase in vertical load capacity when the blocks are bonded in mortar. The reason for the lower compressive strength in the dry-stack system is because the contact area between units is only 51% of the total cross section. The failure modes were different: compression in the bonded wall and shear in the dry-stack system.

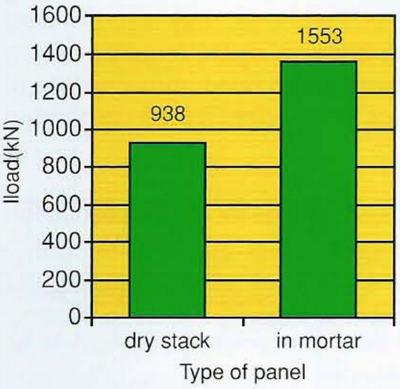


Figure 9. Load capacities of dry-stack and conventional walls (12 MPa units)

Prism test results

In the dry-stack prism tests, four-unit and eight-unit prisms were tested in axial compression. A typical mode of failure observed was the formation of two parallel vertical cracks between the contact area along the interlocking mechanism on both sides of the specimen (see Figure 10). The appearance of cracks was accompanied in each case by loud snap and sudden failure.

For the prisms that are bonded with mortar, the mode of failure observed was formation of x-crack pattern as shown in Figure 11. The results are summarised in the Table 3.

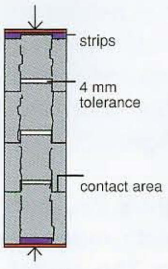
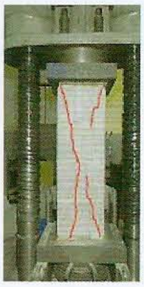


Figure 10. Four-unit dry-stack prismFigure



11. Four-unit prism bonded with mortar

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Table 3 Prism compressive test results.

Type of Prism	Prisms average compressive strength(MPa *)		h/t ratio
	9 MPa specimens	23 MPa specimens	
4unit prism dry-stack	2.85	5.92	2.10
4unit prism in mortar	8.9	17.8	2.20
8unit prism dry-stack	3.1	6.2	4.20
8unit prism in mortar	5.8	11.9	4.45

*based on gross area

The failure mode is in shear along the lines indicated in Figure 10. It follows that the dry-stack block wall did not develop its full capacity in compression.

DISCUSSION AND CONCLUSIONS

Relationship between wall capacity and masonry unit strength

The contact area between the masonry units was 51% of the gross area and this net area was used in stress calculations. The results show that existence of proportionality between the unit strength and the wall capacity (see Figure 8).

The results were used for regression analysis to establish strength relationship between the units and the masonry. The average compressive strength of the dry-stack wall f_{wall} as a function of the masonry unit cube strength, f_{cu} is given as:

$$F_{wall} = \varnothing_m 0.15 f_{cu} + 1$$

Where $\varnothing_m$ safety factor on material = 0.67

The above expression was compared with test results. As shown in Figure 12, a good agreement with test data was achieved with a reasonable factor of safety. The expression is considered valid for block unit strengths in the range 5 MPa to 25 MPa.

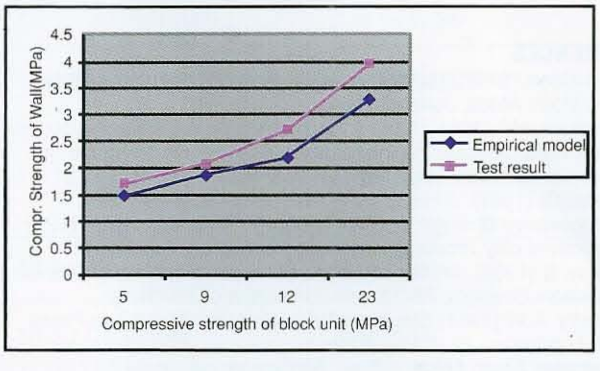

Figure 12. Wall strength vs masonry block unit strength.

The recorded lateral deflection shown in Table 2 implies the presence of out-of-plane forces and stresses. These are however small and are ignored in the above derivation as the interlocking system provides adequate resistance to the lateral forces developed.

Relationship between the strengths of masonry unit, prism and wall

An interesting observation from the prism test is that the 4-unit and the 8-unit dry-stack prisms gave approximately the same compressive strengths. In the bonded prisms, higher strengths were obtained for the shorter (4-unit) prisms. The increased resistance in this case is due to the effect of friction at the platens that provides enhanced resistance due to the three-dimensional stress effect. In the dry-stack system, this effect is neutralised by the ability to adjust and absorb stress.

In order to establish the relationship between the prism strength, wall strength and unit strength the test results were calculated based on the contact area and the results are summarised in table 4 to 6.

Table 4. Relationship between block strength and 8-unit prism strength (*based on net area)

Block strength MPa	Prism strength * MPa	Prism/unit strength ratio
9	6.1	0.67
23	12.2	0.53

Table 5. Relationship between dry-stack 8-unit prism and dry-stack masonry wall
(*based on net area)

Block strength MPa	Prism strength* MPa	Wall strength* MPa	Wall/prism strength ratio
9	6.1	2.1	0.34
23	12.2	3.96	0.32

Table 6. Relationship between dry-stack masonry wall and unit strength (*based on net area)

Block strength MPa	Wall strength* MPa	wall/ unit strength ratio
5	1.73	0.35
9	2.10	0.23
12	2.73	0.23
23	3.96	0.17

It can be seen that the overall strength of the wall increases with the strength of the masonry unit. However, the ratio (wall: unit) strength decreases with increase in the unit strength. This is mainly because the mode of failure is in shear and therefore the full compressive strength capacity is not allowed to develop.

General comparison of dry-stack with Conventional masonry

Hendry (1981) used tests on prisms as a basis for

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determining brickwork design strength in conventional masonry. It was reported that the ratio of wall strength to prism strength is on average 0.9. The ratio of wall strength to masonry unit strength is 0.3 - 0.4. This compares well with the Hydraform dry-stack system where the ratio ranges between 0.2 and 0.35. However the wall: prism ratio indicates a big difference between the two systems. The values obtained for dry-stack system is 0.3 - 0.4 compared with 0.9 for conventional masonry.

Monk (1967) reported on series of experiments conducted by Structural Clay Products Research Foundation in the United States, which examined the effect on the compressive strength of brick couplet specimens in which different bonding materials were used, including dry bonding with brick face ground flat. The specimens with faces ground flat (dry bond) were two times stronger than the specimen bonded with mortar. This was not unexpected as the bricks (98 MPa) used were at least twice as strong as the mortar (44 MPa). Some of the results of those experiments are summarised in the Table 7.

Table 7. Effect of different joint materials on compression strength of brick couplets.

Joint Material	Compressive Strength MPa	Couplet / brick strength ratio
Mortar (1:½:4½) (by mass)	44	0.40
Dry sand	65	0.59
Ground surfaces	98	0.89

Source: Monk, 1967

Similarly Morsy (1968) investigated the effect of bed material on brick prism strength. In these experiments different bed materials were tested including dry bonding. The results were similar to Monk's results, suggesting that brickwork prism consisting of loose bricks, (dry-stack) the bedding planes of which has been ground flat, achieved compressive strength approximately twice as high as those obtained from prism bonded with mortar. The results of these experiments are summarised in the Table 8. It is important to mention that the grinding of the surfaces allowed the full contact between the units. Full compressive load capacity was achieved. The mode of failure is different from the result of the investigations in this report.

Table 8. Effect of different joint materials on the compressive strength of prisms

Joint Material	Compressive Strength MPa	Prism / brick strength ratio
No joint material	37.20	0.93
Mortar (1:½:3) (by mass)	14.0	0.35

Source: Monk, 1968

From Morsy and Monk investigations, one may suggest that the absence of bonding material in dry stacking does not necessarily have an adverse effect on the performance of masonry under compressive load.

Housing construction based on the dry-stack walling system is gaining in popularity particularly in developing countries in Africa, Asia and South America. A typical housing unit using the Hydraform dry-stack units is shown in Figure 13.

Figure 13. Housing unit utilising dry-stack earth-block units.

CONCLUSIONS

The following are the conclusions may be drawn from the investigations:

- Dry stack masonry under uniform compression load usually fails by the development of tension cracks parallel to the axis of loading.
- The compressive strength of the dry-stack walls tested was approximately 0.3 of the nominal compressive strength of the masonry units.
- Interlocking mechanism in the dry-stack units, assist alignment and stability of the wall.
- By bonding the masonry units in mortar, the strength in compression was increased by about 50%.
- Failure is governed by shear in the system investigated; the compressive strength capacity is not attained before failure.

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