Structural Behaviour of Dry Stack Masonry Construction

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ABSTRACT: Interlocking mortar-less or "dry-stack" masonry construction refers to a technique of building masonry walls, in which most of the masonry units are laid without mortar. Soil-cement dry-stack system is one of cost-effective construction. Savings up to 27% compared to conventional mortared masonry have been reported (Ngowi, 2005). Hydraform dry-stack construction system was introduced in 1988 in South Africa by Hydraform Africa (Pty) Lda. After nearly two decades, the system is currently being used over 40 countries worldwide. Current application of dry-stack construction extends from rural community houses, urban and suburb several applications in medium-sized social and commercial buildings such as schools, hospitals, offices, shops and stores. The intense research work has so far provided a basic understanding of the structural behaviour of dry-stack construction and the system is now more competitive. This paper highlights the structural response of Hydraform block units and walls under compressive testing.

1 INSTRODUCTION

1.1 *General*

Interlocking mortarless or "dry-stack" masonry construction refers to a technique of building masonry walls, in which most of the masonry units are laid without mortar. A limited amount of mortar is allowed for starter and top courses. The structural use of dry-stack masonry relies on mechanical interlocking mechanism between units. The interlocking mechanism provides the wall's stability, self alignment and levelling.

Dry-stack construction has existed in Africa for thousands of years. The Egyptian pyramids and the great Zimbabwean ruins, a capital of Shona kingdom, are live examples of ancient dry-stack construction (Uzoegbo & Ngowi, 2003).

Ancient dry-stack masonry consisted of robust construction and the huge structural elements were both material and time consuming construction process. On that time, interest on dry-stack masonry had been lost and attention was focussed on researching and applying industrialized materials such as fired clay brick, cement, concrete, steel and panels of various types.

The industrialized materials were expensive and not affordable for the majority of poor people. Infrastructures were provided in city centres and other points of economic and political interests. The majority of poor people living in suburbs and countryside remained homeless. In order to provide shelter for themselves, they had to opt for precarious materials which in many cases were unable to give them safety and comfort.

Renewed interest in dry-stack construction is seen in the last two decades. Among others, soil-cement dry-stack system is one of cost-effective construction since soil is the most available construction material in the earth. The intense research work has so far provided a basic understanding of the structural behaviour of dry-stack construction and the system is now more competitive than before.

Several dry-stack systems are being used over the world. More than twenty three different dry-stack systems are currently being commercialised (Ngowi, 2005). The current application of dry-stack construction extends from rural community houses, urban and suburb applications in medium-sized social and commercial buildings such as schools, hospitals, offices, shops and stores.

The worldwide research on dry-stack systems has not yet established a standard code for a rational design.

The University of the Witwatersrand in collaboration of Hydraform Africa (Pty) Ltd is currently investigating the structural behaviour of Hydraform dry-stack masonry under different applications. This paper summarises the research work so far done with Hydraform dry stack system.

2 HYDRAFORM DRY-STACK INTERLOCKING SIYSTEM

2.1 *Hydraform interlocking system*

Hydraform interlocking blocks are produced by mixing soil and cement in predetermined ratios and extruding them vertically under a pressure of about 10 N/mm^2 using a hydraulic powered machine. Full scale and corner blocks are available in the Hydraform system and the block dimensions are shown in figure 1.

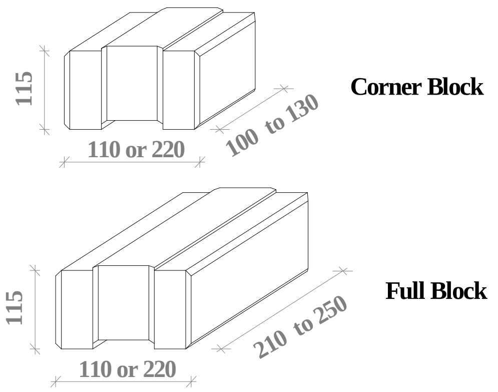

Figure 1. Block unit’s layout.

A typical construction method is shown in figure 2. The base course is laid in mortar up to one course above a floor level. The middle courses are dry-stack up to lintel level. The top three courses are normally laid in mortar to form a ring beam at the top of structure. Alternatively, a reinforced concrete ring beam could be cast at the top.

2.2 *Opportunities and issues on Hydraform dry-stack system*

Hydraform soil-cement dry-stack masonry is a cost-effective construction system. The major material component is soil, the most abundant construction material in earth. In many communities, soil is a free material and no relevant technology is required to exploit it. Relevant costs are due to cement and block production machinery. However, cement appears in low quantities. For low rise residential houses, 5 to 10 % cement content by volume of dry mixture of soil and cement should be adequate. With the block making machines being mobile, one machine should be enough to produce blocks for thousand of houses. Block making machine revenue remains on proper planning and management.

Several small local entrepreneurs unable to make business on the industrialised and sophisticated construction systems are now able to run small scale business and create wealth. Job opportunities are created for jobless most of them unskilled people. Communities with low income can make plan to access decent low cost houses.

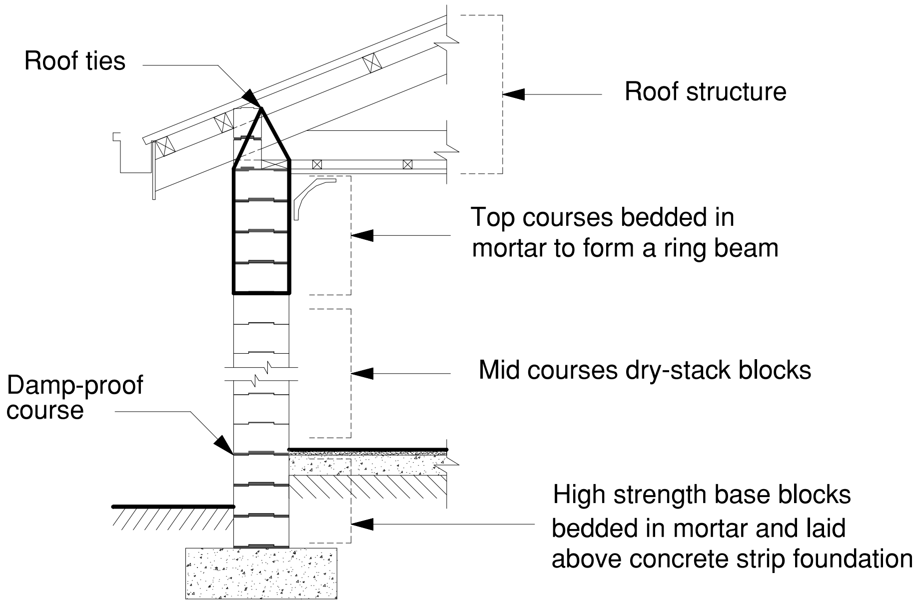

Figure 2. Typical construction detail of Hydraform dry-stack system.

Savings on mortar, faster construction process, low skilled labour employment, cheaper block production, transport savings and more are shown to be the key for the attractiveness of dry-stack system. Cost savings up to 27 % compared to conventional block masonry construction have been reported (Ngowi, 2005).

Shortage of houses, forces people to live in crowded conditions. This fact leads to social instability, crime, unhappiness and anarchy. Epidemic diseases leading to large scale deaths are common in homeless people. Hydraform building system creates for communities, decent houses which are safer and much comfortable. This empowers communities and builds happier, healthy and motivated societies.

In rural communities of low income, the hut is the most type of construction afforded. Huts can also be seen in many suburb poor areas. Hut construction material costs vegetation devastation. Adoption of soil-cement construction can significantly contribute to a health environment.

Clay block production requires large amount of energy for heating process. Heating can cost large amount of wood or consume electricity produced by burning coal and expel smoke to atmosphere. Soil-cement construction requires a very low amount of energy in a production process therefore environmental benign.

3 BLOCK UNITS COMPRESSIVE STRENGTH

3.1 *General*

In the evaluation of compressive strength of conventional masonry block units, different codes recommend different procedures. The British Standard (BS) recommends three methods. One consists of capping specimens with mortar and immersing them in water. When the mortar has reached strength of at least 28 MPa, specimens are removed from water, allowed to drain under damp sacking and tested. Other method consists of immersing specimens in water without capping them with any substance. After remaining in water for at least sixteen hours, specimens are removed and immediately tested. The third method described in BS consists of capping the specimens with fibre board and immerse them in water for at least sixteen hours. Specimens are then removed and allowed to drain under damp sacking before testing. A minimum of nine specimens are required for each compressive test (BS 6073: Part 1, 1981). South African Standards specify a testing method similar to that specified in British Standards.

The American Society for Testing and Materials (ASTM) recommends two methods. One consists in capping each masonry unit with a net paste of high-strength plaster and testing at least five specimens. Another method consists in capping the specimen with sulphur and granular material. A mixture of 40 % to 60 % of sulphur and fire clay or other suitable inert material is used to cape at least five specimens before testing (ASTM: Part 12, 1971).

For interlocking masonry block units, there is no existing standard guidelines to evaluate the compressive strength. Each dry-stack system is unique, therefore different types of interlocking mechanism will need different testing procedures. The irregular geometric form of the blocks is not compatible with the conventional method of testing.

3.2 *Compressive testing methods for Hydraform block units*

Three testing methods were considered. The first testing method refers to a shoulder loading of the block units. This testing arrangement was adopted to simulate typical Hydraform dry-stack application. The block on top sits directly on the shoulder of the unit below, creating a 3 to 4 mm interface gape in the central part of the block unit. For in plane vertical loading, the bearing area is reduced to the block shoulders.

The second testing method is the centre loading of full scale and corner blocks. When Hydraform block units are laid on mortar (foundation and ring block courses) it is likely that the vertical load or part of it will be applied on the central region of the block. The roof structure is also likely to rest on the central part of the block unit. This situation is simulated in this method of testing.

To comply with the standard testing of flat specimens in convectional masonry, cube loading test were adopted in Hydraform blocks as the third testing method. 100x100 mm cubes cut from full scale blocks were tested. Each full scale blocks were cut in four parts to form the cubes. Cubes were separated as top or bottom cubes. Top and bottom side of the block refers to how the block is positioned during production process. The bottom side of the block is more compact (dense) while the top side is less compact (low dense). The cube testing was also carried out to investigate the block internal compressive strength due to density distribution.

3.3 *Preparation of specimens*

Specimens were tested under three different humidity conditions, oven-dry, wet and normal. Dry samples were stored in an oven at a temperature of 50 ^{o}C for 24 hours before testing. Wet samples were soaked in water at a temperature of 21 ^{o}C for 24 hours and allowed to be surface-dry for one hour before testing. The normal samples were stored in pallets at normal ambient conditions (NAC) on an open space. Ten block samples were tested to obtain an average compressive strength.

Block units were classified according to the cement volume used as stabilizing agent. The corner blocks cement content was 7 and 10 % and for full blocks and cubes cement content was 5, 7, 10, 15 and 20 %. Test results are represented in Table - 1. The strengths were based on an arithmetic mean of ten samples.

3.4 *Remarks from test results*

Table - 1 summarises test results from the experiments. The corner block units cement content was 7 and 10 % and for full scale block units and cubes, cement content was 5, 7, 10 and 20 %.
The compressive test results below, led to relevant aspects, unique for Hydraform dry-stack block units. By cutting a full scale block into top and bottom cubes, different strengths can be seen for the same block unit. The bottom part of the unit is much stronger. The shoulder block

unit test results reveal same strength as the bottom stronger cube. The block unit exhibits very good resistance behaviour compared to the top (weaker) cube. The masonry wall is built using full scale and corner block units and not by the isolated top cubes. The above complex test findings made it difficult to decide which testing procedure could be adopted as standard to access Hydraform block unit compressive strength. Based on the moisture content influence on the block unit strength, associated to the real application of Hydraform system, the author suggests that both the full and corner block unit shoulder testing as well as bottom cube can be used to access the Hydraform unit compressive strength. The strength is referred to wet specimens. Wet strength is approximately 60 % of the normal strength.

Table 1. Compressive strength test results.

Description	Mean Strength [MPa]			
Blocks Designation	% of Cement Content	Wet Specimens	NAC Specimens	Dry Specimens
Corner Blocks	7	4,5	5,9	8,3
	10	8,4	12,7	15,2
Full Blocks	5	3,1	6,1	6,7
	7	4,8	8,2	8,7
	10	9,0	13,6	15,5
	20	13,8	20,2	20,0
Top Cube	5	1,8	2,5	3,2
	7	3,5	5,3	7,7
	10	7,6	10,1	12,4
	20	10,9	17,3	17,2
Bottom Cube	5	2,8	4,7	5,3
	7	4,6	7,3	9,2
	10	8,6	12,9	14,2
	20	14,4	18,5	21,1

In many codes of practice for structural use of masonry, conventional block unit grades are based on their compressive strength. This fact has effect in allowing the manufacturing industry to produce only standard grades of units allowing a rational design procedure. With design, manufacture and construction narrowed to standard grades of material, quality, safety and regulated construction can be achieved. Similarly, it is convenient to standardize Hydraform dry-stack block units in grades of their compressive strength. Table - 2 suggests the nominal compressive strength for Hydraform block units.

Table 2. Hydraform block unit compressive strength

Cement Content [%]	Nominal Compressive Strength of Block Units [MPa]
5	3,0
7	5,0
10	8,0
15	10,0
20	12,0
25	14,0

4 COMPRESSIVE STRENGTH OF DRY-STACK MASONRY PANEL

4.1 *General*

Characteristic compressive strength of masonry is an important parameter for design of walls subjected to in-plane uniformly distributed loading. Its laboratory determination for conventional masonry is highly discussed in many codes of practice. In the absence of laboratory tests, standardized values of characteristic compressive strength provided in codes of practice may be used. For dry-stack masonry there is no laboratory testing method or standard values of characteristic compressive strength yet. In this paper, the author presents recent research and laboratory testing data on Hydraform dry-stack masonry panels. Recommendations were made towards a standard determination of characteristic compressive strength.

4.2 *Hydraform dry-stack panels testing*

Dry-stack wall panels were constructed in laboratory using block units of different grades. Four dry-stack wall panels constructed with 5MPa, 9 MPa, 12 MPa and 23 MPa units were considered. The construction method followed the description in the manufacturer’s manual. The first course of blocks and the top three courses were laid on mortar. The end vertical strips were also laid on mortar. The mid section of the panel (over 70 % of the all panel area) was plain dry-stack, see figure - 3. Each wall panel was 3,0 m long, 2,5 m height and 220 mm thick and was constructed on a Macklow-Smith machine platen that was mounted on a hydraulic Ram. A 3 m span steel beam was used to spread the load at the top of the wall. The spreader beam consists of a 305x305x118 mm H-section. Axial compression load was applied at a rate of 2 kN/min.

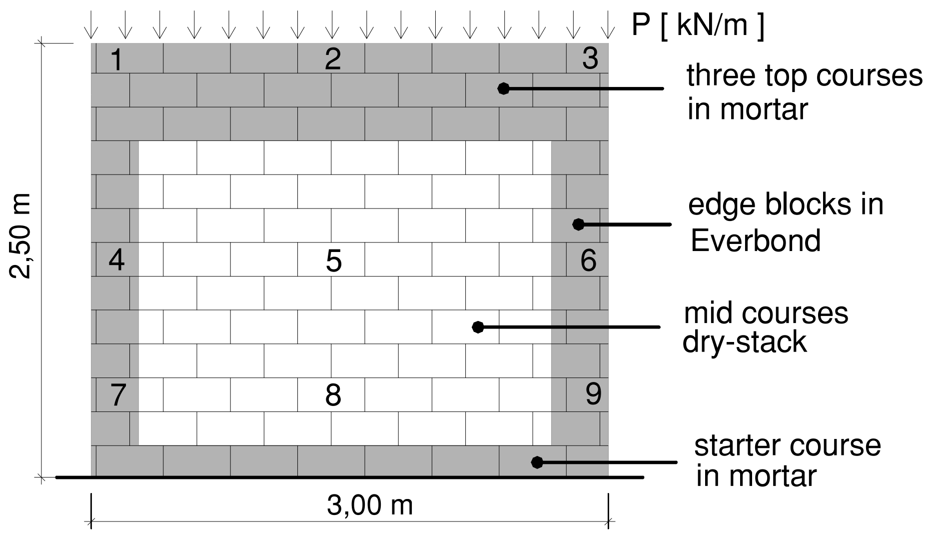

Figure 3. Wall panel construction details and strain gauge positions

4.3 *Test results*

Table - 3 shows test results conducted in the masonry dry-stack masonry panel tests. Similar to conventional masonry, the compressive strength of dry-stack masonry increases with the increase on block unit strength. Consistent proportionality was obtained between the unit strength and the wall strength. The ratio of masonry strength to unit strength decreases with increase in the unit strength and varies from 0,40 to 0,20. The lateral displacement results were not consistent and may need further tests to establish a trend.

Table 3. Hydraform block unit compressive strength

Block Unit compressive strength [MPa]	Ultimate compressive load [kN]	Bearing Area [m2]	Masonry compressive strength [MPa]	Masonry / Unit aspect ratio	Maximum lateral displacement [mm]
5	595	0,3	1,98	0,40	2,30
9	721	0,3	2,40	0,27	10,00
12	938	0,3	3,13	0,26	3,40
23	1360	0,3	4,53	0,20	40,00

Table - 4 summarizes Hydraform dry-stack masonry characteristic compressive strength as function of block unit compressive strength. A procedure similar to that used in conventional masonry was used to transform the masonry compressive strength from testing in characteristic compressive strength for design.

Table 4. Hydraform dry-stack masonry characteristic compressive strength

Unit compressive strength [MPa]	Masonry characteristic compressive strength [MPa]
3,0	1,1
5,0	1,3
8,0	1,6
10,0	1,8
12,0	2,0
14,0	2,2
16,0	2,4

Having a nominal unit compressive strength and masonry characteristic compressive strength systematized in a standard manner, design using Hydraform system becomes more rational and safe. Further research is required to evaluate and present the flexural and shear strengths of plain Hydraform dry-stack masonry.

5 CONCLUSIONS

5.1 *General*

Compressive strength of a block unit is largely used to describe several design properties of masonry wall. Unit compressive testing is important for both quality control and design. Dry-stack masonry is relatively a new technology yet to establish and document testing methods. Challenge relies on a fact that each dry-stack is unique therefore testing method will differ from system to system. This work constitutes an early attempt to standardize Hydraform dry-stack system.

Moisture content of the blocks has significant affect on the block compressive strength. Compressive strength of wet specimens is approximately 60 % of the dry specimens. For design, wet specimens are used as a standard method for evaluation of block compressive strength.

From wall panels testing, it was found that, the wall panel strength of dry-stack systems under vertical load is directly proportional to the strength of the masonry units.

Wall characteristic compressive resistance can be evaluated using a similar approach used to access the characteristic compressive strength of conventional masonry.

6 REFERENCES

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