CHAPTER - 1

INTRODUCTION

1. INTRODUCTION

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 and Ngowi, 2003). Ancient dry-stack masonry consisted of robust construction and the huge structural elements were both material and time consuming construction process. 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 could provide construction with smaller sections but, due to its technological production process, construction remained expensive and not affordable for the majority of poor people. The sophisticated construction has provided infrastructures 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.

Political stability followed by formation of democratic government systems based on vote, has increased all over the world in recent years. This fact allows the majority of people to claim basic rights including decent shelter. For example, in South Africa, the new democratic government set on its agenda, a large scale provision of free house for the majority homeless. With the agenda set by politicians, challenge remains on researchers and businessman to develop and commercialize cost-effective housing systems.

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. The 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 worldwide research on dry-stack systems has not yet established a standard code for a rational design. One challenge is that each dry-stack system is unique therefore each system requires its own standard. The usage of Hydraform dry-stack system developed in South Africa is currently legalised by an Agrément Certificate. This document presents basic guiding information of the construction methods and illustrations of constructions using Hydraform product but does not provide information for rational design.

Since the introduction of the product in 1988, a lot of testing has been done proving the suitability of the system. So far, little attention has been given for a systematic handling of information to allow a rational design. To attract interest of the construction sector, design and construction procedures of dry-stack masonry should be as close as possible to those used on conventional masonry. In fact, an official document showing Hydraform block unit compressive strength grades, flexural capacity, shear resistance and testing methods is required.

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 research work is a contribution towards a development of relevant information and systematizing it in a manner that it can be used for a rational structural design. To meet the goals, several tests were carried out and information analysed. In addition, test results from previous researchers were accessed re-analysed and presented in a rational manner for structural design.

1.2 Research Methodology

Prior to all other activities, a literature review was done on conventional and dry-stack masonry. Aspects regarding to masonry manufacturing, testing, construction technology and structural behaviour of masonry were reviewed. Objectives to be met were then set. Those consisted of testing dry-stack block units and masonry walls to compressive loading. Composite dry-stack reinforced concrete beams were tested for flexural strength.

Due to the interlocking mechanism of the blocks, additional steel bearing platen was designed and prepared in laboratory workshop. Testing began with the evaluation of unit compressive strength. Results were collected, analysed and compared to expected results. Differences and similarities were carefully analysed. During the test result analysis, attention was also given to the failure mode.

After the unit testing and analysis, masonry wall was tested to in plane compressive loading. Test results were collected and analysed together with the failure modes.

Prior to composite dry-stack reinforced concrete testing, structural model was established and existing methods of analysing similar structures of conventional masonry were used to predict values to be achieved with the experimental test. The test rig was designed, tests carried out and data collected. The data was compared to the available methods of analysis. Differences and similarities were careful analysed together with the failure mechanism and then correct methods of analysis established for dry-stack system.

1.3 Outline of the Research Work Report

This research work report consists of six chapters, namely the introduction, Hydraform dry-stack building system, block unit compressive strength, masonry compressive strength, dry-stack masonry/reinforced concrete composite beams, conclusions and recommendations. Detailed calculations and test results are given in appendices.

The first chapter describes the background of this investigation, the research methodology and outlines the work covered in this work.

The second chapter describes the Hydraform dry-stack building system. Block types, method of production and mix design are reported. The construction method is also described in this chapter. Opportunities and issues using Hydraform system are reviewed here.

Chapter 3 reports a testing of Hydraform block units under compressive loading. Methods used in compressive testing of conventional block units are reviewed. Three different testing methods of testing Hydraform dry-stack units are discussed. Test results are analysed with the failure mechanisms and a standard method of accessing the block unit compressive strength is proposed.

Chapter 4 deals with the evaluation of Hydraform masonry strength under in-plane vertical loading. Mean compressive strength of Hydraform dry-stack masonry panels from previous work are re-analysed and transformed to characteristic compressive strength. Additional prism tests are carried out to support the failure mechanism behaviour.

Chapter 5 discusses the design philosophy of dry-stack masonry/reinforced concrete composite beams under flexural loading. The design philosophy used for conventional masonry is reviewed and its applicability to the dry-stack masonry checked. Recommendations are made for a flexural design of dry-stack masonry/reinforced concrete composite beams.

Conclusions and recommendations drawn from this research work are presented in chapter 6.

Appendix - A presents the block unit compressive test results. The step by step theoretical analysis of dry-stack masonry/reinforced concrete composite beams is presented in appendix - B. Live projects using Hydraform dry-stack system are presented in Appendix - C.

CHAPTER - 2

HYDRAFORM DRY-STACK CONSTRUCTION SYSTEM

2. HYDRAFORM DRY-STACK CONSTRUCTION SYSTEM

2.1 General

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. Several dry-stack systems are also being used over the world. More than twenty three different dry-stack systems made of concrete or soil-cement hollow and solid block units of different shapes are currently being commercialised (Ngowi, 2005).

Each dry-stack system is unique with regard to structural behaviour. In this report, focus is made to Hydraform dry-stack system. Block unit types, interlocking features, wall construction details and manufacturing process are analysed. Before attention is concentrated to Hydraform system, advantages and disadvantages of dry-stack system in general are presented.

2.2 Advantages and Disadvantages of Dry-stack Masonry

Increase on dry-stack masonry construction seen in the last two decades, reveals existence of relative advantages in comparison to conventional mortared masonry. Dry-stack is a rationalized system, it has simplicity in handling therefore the wall erection is faster. The interlock mechanism assists and allows wall alignment to be completed faster even using local low skilled labour. In dry-stack masonry, quality variation due to mortar joints is eliminated. Erection during cold winter is possible. The non usage of mortar eliminates the curing period and the load of super structure can be applied immediately after construction. Usage of small units in dry-stack masonry does not consume more material but does take more time (Kango-Ho, 1994). Most of dry-stack systems use local aggregates and soil therefore units can be manufactured on site. Savings on transport costs are gained and unit damages during transportation process are eliminated. Demolition of dry-stack masonry is simpler, is conducted by just unplugging the units. This allows the undamaged units to be re-used in future applications. The adoption of compressed block units in dry-stack masonry saves firing energy and is environmental benign.

Dry-stack masonry construction exhibits some disadvantages compared to conventional masonry. Dry-stack systems may be unstable to resist certain types of out of plane loading during construction. This can be overcome by using external temporary bracing or grouting the hollow section at intervals. The usage of hollow system without partial grouting or plastering is restricted. Bond patterns are limited. Traditional aesthetic appeal may be compensated by spray surface treatments. It is difficult to form curve walls with most of dry-stack systems. Hydraform dry-stack system allows curved walls. The absence of mortar in the joints, allow large deformations when out of plane loads are applied.

2.3 Hydraform Block Unit Types

This research work focuses on Hydraform dry-stack construction system. The Hydraform blocks are produced by mixing soil, cement and water in predetermined ratios. The mixture is vertically compressed under a pressure of about 10 MPa on a hydraulic press machine. The blocks rely on interlocking features mechanism consisting of “tongue and groove” kind of interlock in the head and bed faces. Several types of block units are currently manufactured. Figure - 2.1 shows the full scale block used for external walls. It is 220 mm wide, 115 mm high and the length varies from 210 mm to 250 mm. When required, this block may be used for internal walls.

Figure - 2.1: Full scale dry-stack block unit

Figure - 2.2 shows the smaller unit, the corner block used to adjust the walls edges. It is 220 mm wide, 115 mm high and the length varies from 100 mm to 130 mm.

Figure - 2.2: Corner dry-stack block unit

In Figure - 2.3, full scale block unit used for internal partition purposes is presented. It is 140 mm wide, 115 mm high and the length varies from 210 mm to 250 mm. Partition corner block unit is also available.

Figure - 2.3: Full scale partition dry-stack block unit

Conduit block to accommodate reinforcement, electrical and plumbing services and grouting are produced in the Hydraform system. Figure - 2.4 shows full scale conduit blocks to accommodate horizontal reinforcement bars or services. The conduit may not or may be placed at mid section.

Figure - 2.4: Full scale conduit block units

Figure - 2.5 shows full scale and corner conduit blocks to accommodate vertical reinforcement bars and grout material.

Figure - 2.5: Full scale and corner conduit and grout block units

Figure - 2.6 shows Hydraform mobile press-machine used to manufacture the block units. Different block geometries are achieved by a simple mould change.

Figure - 2.6: Mobile block making machine

2.4 Typical Wall Construction Details

Erection of Hydraform wall starts after a concrete strip foundation has hardened. In order to provide wall levelling, the foundation courses are laid on mortar up to one course above ground level. Due to a moisture content below ground level, high strength blocks than those designed for super-structure are recommended for foundation courses. Blocks used on super-structure courses are completely dry-stack until lintel level. The top three courses used above lintel level are laid on mortar to form a ring beam (Agrément SA, 1996). A normal roof structure is tied to the ring beam using galvanized wires to prevent wind uplift. Above doors and windows openings, normal concrete lintels are placed. When fitting, conduit blocks may be used to accommodate electrical and plumbing pipes, otherwise pipes may be chiselled into walls in conventional manner. Depending on client aesthetic choices, the wall's external face may be or may not be plastered and painted. To prevent rainwater penetration on external walls, it is recommended to have them plastered and painted on interior face. Plastering and painting interior walls also improve thermal and sound insulation between house partitions (Rapoo & Buys, 2000). Figure - 2.7 shows typical construction detail of Hydraform dry-stack system.

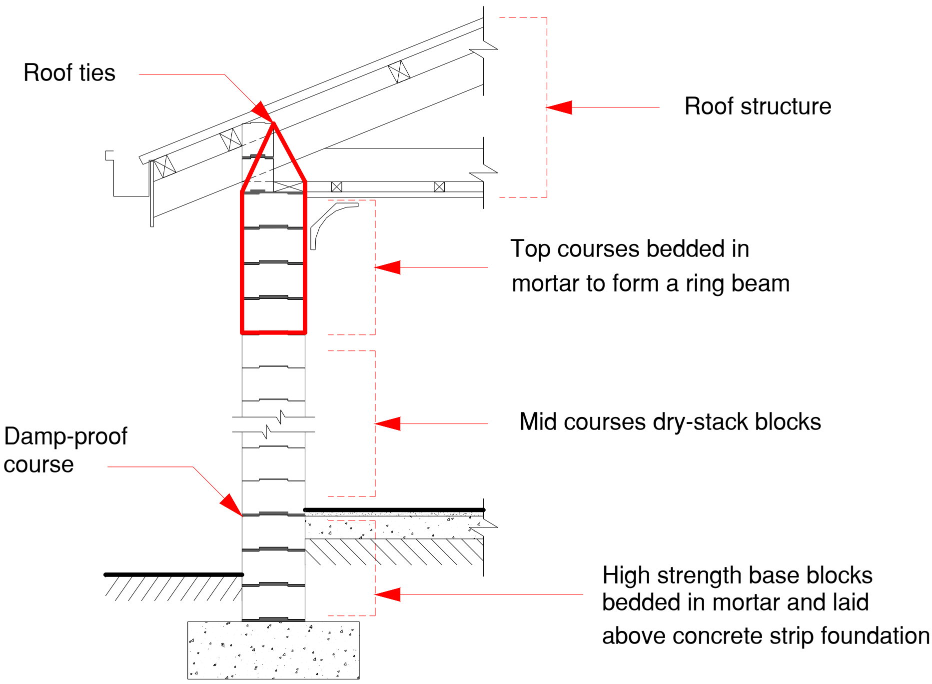

Figure - 2.7: Typical construction detail of Hydraform dry-stack system

2.5 The Manufacturing Process

2.5.1 Soil selection

Soil used to produce block units must be free of organic materials, must not contain harmful quantities of salts and should just contain sufficient clay to bind the blocks so that they may be handled without disintegration immediately after manufacture. The basic requirements of soil are summarized in Table - 2.1. Soil range A is suitable for low strength blocks, up to a nominal compressive strength of 4 MPa. Soil type B is used to produce block units of nominal compressive strength higher than 4 MPa.

Table - 2.1: Basic soil requirements for Hydraform block production

Soil range	% by mass passing the 0,075 mm sieve (silt and clay fraction)		Maximum plasticity index	% by volume of cement content	Estimeted nominal compressive strength [MPa]
	Minimum [%]	Maximum [%]			
A	10	35	15	≤ 7	≤ 4
B	10	25	10	7 - 30	4 - 16

High plasticity is accepted provided that the material has been pre-treated with adequate dosage of lime and additional curing time given (Agrément SA, 1996). Water must be clean and shall not contain harmful quantities of acid, alkalis, salts, sugar or any other organic or chemical materials. Portable water will normally be satisfactory. Depending on the different materials in the design mixture, 5 to 10 % of water (by volume) will produce the optimum moisture content.

2.5.2 Manufacturing, curing and transportation processes

Locally excavated or imported soil is sieved and mixed with cement until uniform material distribution and colour is achieved. Water is added and the wet mixture is loaded to a press-machine. Mixing the component materials can either be done manually using shovels or mechanically using Hydraform batcher. When loaded into machine, the mixture is compressed downwards forming the block unit which is then extruded upwards (see Figure - 2.8).

Figure - 2.8: Block manufacturing, curing and storage activities in block yard

Fresh produced blocks are stacked (not exceeding six courses in height) and immediately covered with polyethylene sheets to prevent moisture expulsion and to protect them from weather harmful effects, as shown in figure 2.9. Blocks must be uncovered and recovered twice a day for watering during a curing period of seven days (Agrément SA, 2006).

Figure - 2.9: Block stacking and covering process

After curing, blocks are ready to be used and are stored in non covered pallets as shown in Figures - 2.8 and 2.9. Blocks manufactured outside the site are delivered by trucks in pallets.

Because soil-cement blocks are heavy, the transportation process may be expensive, for this reason, block production on site should be the first choice.

2.6 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.

Hydraform can also be seen as a successful machinery making and selling company delivering over forty countries worldwide. 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.

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 (Uzoegbo and Ngowi, 2004).

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, job opportunities and decent houses which are safer and comfortable than those living in currently. 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. The devastation is even more due to high rate of replacement of this material in a given house. 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. These stages constitute environmental hazards. Soil-cement construction requires a very low amount of energy in a production process therefore environmental benign.

Lack of design codes and limited information on the structural behaviour of the dry-stack system have limited the application of this system to low rise structures as non-load bearing structures. Usage of dry-stack construction as load bearing structures requires more investigation on structural behaviour and development of codes of practice. The actual usage of Hydraform dry-stack system is officially authorized by Construction Products Approvals Certificate since there is no established standard for this construction system. The absence of codes of practice has negative impact since the designers have no relevant information to opt for this system. The University of the Witwatersrand with the collaboration of Hydraform Africa (Pty) Ltd is currently investigating the structural behaviour of Hydraform dry-stack masonry.

CHAPTER - 3

BLOCK UNITS COMPRESSIVE STRENGTH

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, see Figure - 3.1. For in plane vertical loading, the bearing area is reduced to the block shoulders.

Figure - 3.1: Hydraform blocks stacked to form a wall

To allow shoulder loading during the testing process, an additional steel bearing platen (simulating an upper block) was used as sketched in Figure - 3.2. To simplify the shoulder testing, the additional steel bearing platen may be supplied during the machine purchase as part of tolls.

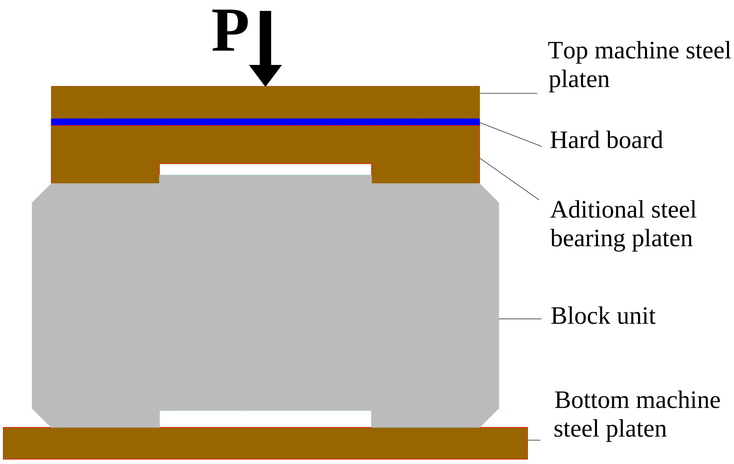

Figure - 3.2: Shoulder loading of full and corner blocks

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. A hard board was used to uniformly distribute the load as sketched in Figure - 3.3. This testing method does not require the fabrication of a special steel bearing platen for the load application.

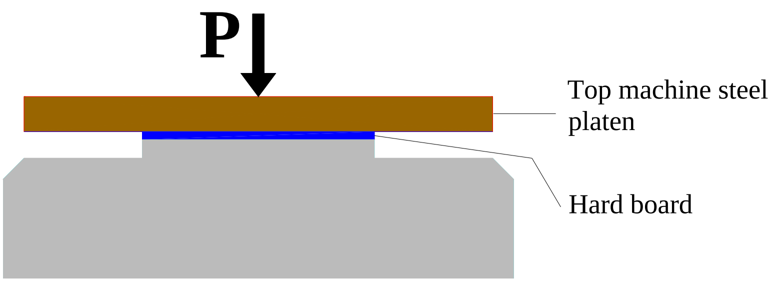

Figure - 3.3: Centre loading of full and corner blocks

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, as shown in Figures - 3.4, 3.5 and 3.6. the cube test gives the standard strength of the material.

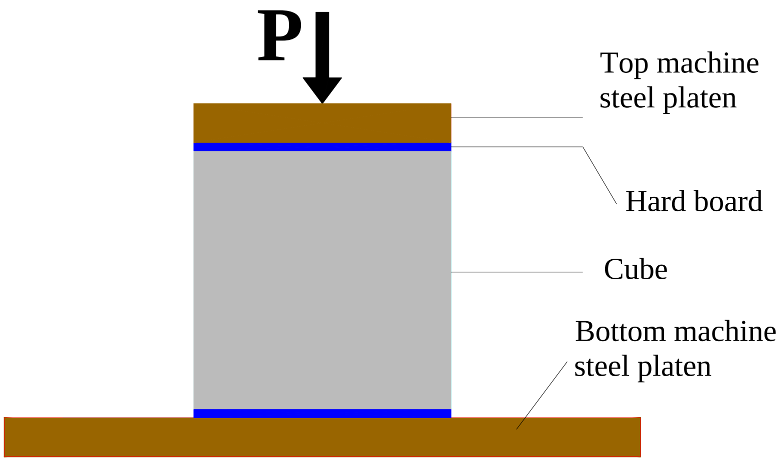

Figure - 3.4: Compressive loading of cubes

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 blocks are extruded vertically under a pressure as previously discussed and shown in Figures - 2.6 and 2.8. The bottom side of the block is more compacted (dense) while the top side is less compacted (low dense). The cube testing was also carried out to investigate the block internal compressive strength due to density distribution.

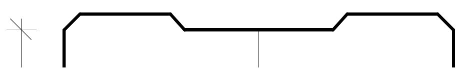

Figure - 3.5: Cube positions within a full block

Figure - 3.6 bellow shows photo of tested specimens (corner block, full scale block and cubes cut from a full scale block).

Figure - 3.6: Test Specimens

Compressive testing for all three methods were carried out using a Tinius Olsen Model 4330 machine which has a capacity of 600 kN and is equipped with a fixed bottom loading platen and a ball seated on top loading platen (see Figure - 3.7).

Figure - 3.7: Tinius olsen testing machine

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 - 3.1 and graphically in Figures - 3.11, 3.12 and 3.13. The strengths were based on an arithmetic mean of ten samples.

3.4 Failure Mode for Unit Compressive Test

Cube compression tests indicate a failure mechanism characterised by vertical and x-cracks similar to those observed for concrete cube compressive tests. The cube under vertical compression contracts on vertical direction and expands transversally on horizontal direction due to Poisson’s effect. The horizontal expansion induces tensile stress and beyond the material’s capacity vertical cracks start to open and progress until the cube fails. At the support edge points, cube material is restrained against the transversal expansion by friction in the top and bottom machine platens resulting in x-cracks, as shown in Figure - 3.8. Similar to concrete and conventional masonry, compressive block strength is attained in a cube testing.

Figure - 3.8: Cube failure mechanism

When loaded at shoulders, block units' failure mechanism is similar to that of cube, characterised by horizontal expansion of the material accompanied by vertical and/or x-cracks, as shown in Figure - 3.9. As shown later trough the test results, shoulder testing also gives the block unit full compressive strength.

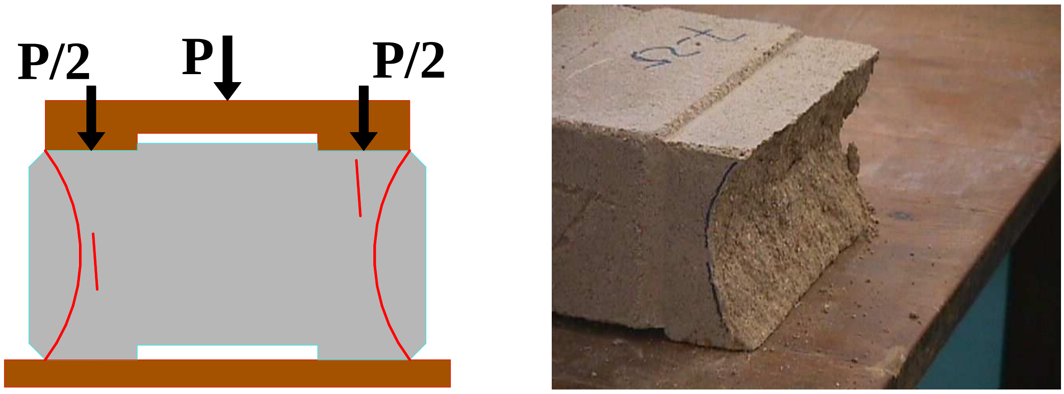

Figure - 3.9: Block unit failure mechanism on shoulder testing

When loaded at centre, the block unit shows a failure mechanism characterized by vertical cracks running along the edge of interlocking groove (see Figure - 3.10). The block fails at a lower load by shear before it can develop its full compressive capacity.

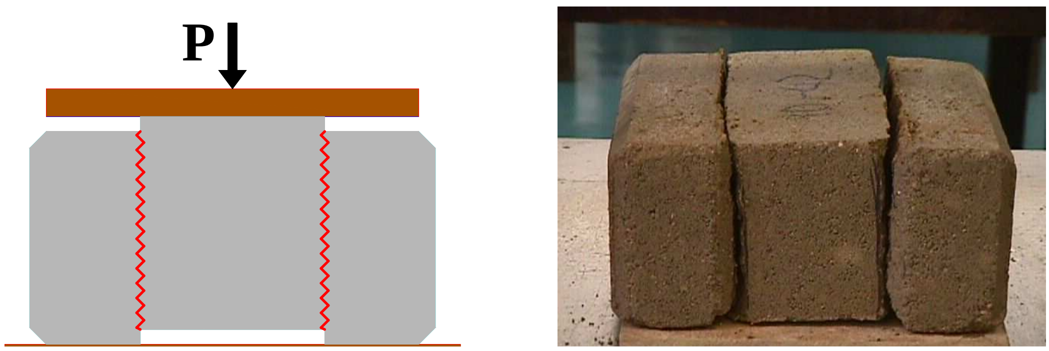

Figure - 3.10: Block unit failure mechanism on centre testing

3.5 Test Results

Table - 3.1 summarises test results conducted in this research work section. 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 %.

Table - 3.1: 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

3.5.1 Wet specimens

Test results of wet specimens (top and bottom cubes and full blocks loaded at shoulders) are represented in Figure - 3.11. It can be seen that compressive strength of cubes from top part of the block is lower than that of bottom cubes. The difference in strength between the top and bottom cubes is attributed to the block production process. The blocks are compressed downwards in the machine therefore the bottom part of the block unit is better compacted than the top part. Strength difference between top and bottom cubes is, in average, equal to 22 %. Compressive strength of bottom cubes is equal to that of full block loaded at shoulders. Knowing that the masonry wall is made by full or corner block units and not using isolated cubes, design should not be based on the weaker top cube, but instead, by the block unit strength. This approach is based on the fact that for all test results, the block unit exhibits very good resistance behaviour. It is also probably that the cutting process to obtain cubes helped to disintegrate the cubes therefore weakened the cube specimens, special the low dense top cubes. Basing the design on the weaker top cube could lead, unnecessarily, for a non economical construction.

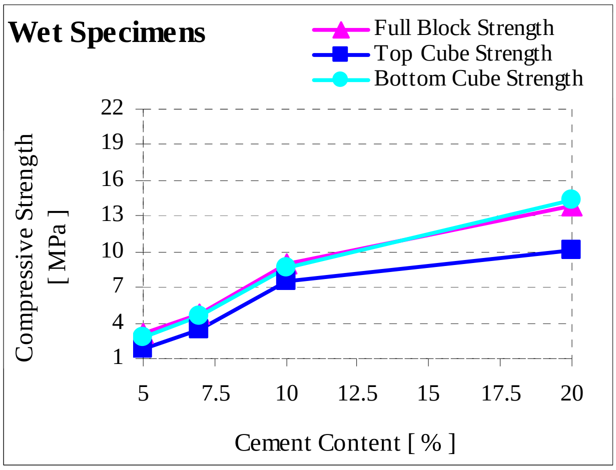

Figure - 3.11: Wet specimens' test results

3.5.2 Normal specimens

Test results on specimens stored in pallets under normal atmospheric conditions are graphically represented in Figure - 3.12. Compressive strength of top cubes is lower than that of bottom cubes. Strength difference between top and bottom cubes is, in average, equal to 22 %. Bottom cubes and full scale block units loaded at shoulders exhibit almost the same strength. Normal blocks were stored in pallets in an open space therefore specimens might have small differences in moisture content which led to small differences in strength. In general, consistence on results can be seen. Good resistance behaviour of the block units compared to those of top cubes is once again seen.

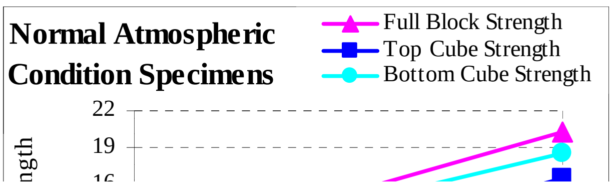

Figure - 3.12: Normal specimens' test results

3.5.3 Dry specimens

Figure - 3.13 represents test results of oven dry specimens. Consistence in test results can be considered achieved. Top cubes are weaker than bottom cubes which exhibit same strength as full blocks. Strength difference between top and bottom cubes is, in average, equal to 22 %. As seen in the wet and normal blocks, for dry specimens the block unit behaves well compared to top cube and no doubt remains in the fact that the design shouldn't be limited to the weaker top cube.

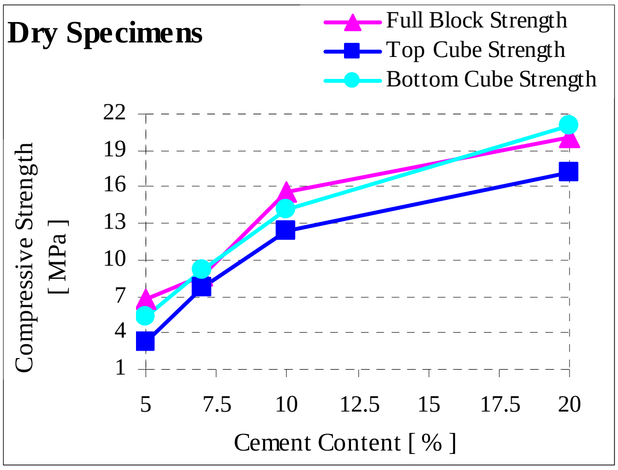

Figure - 3.13: Dry specimens' test results

3.5.4 Moisture influence on block strength

Test results of wet, normal and dry specimens (bottom cubes) are graphically represented in Figure - 3.14. Compressive strength of normal specimens is higher compared to that of wet specimens, but lower compared to that of dry specimens. On average, the compressive strength of normal and wet specimens is respectively 92 % and 57 % of dry specimens. Influence of moisture on the block strength is obvious. Due to the significant influence of moisture on strength, it is recommended that the wet strength be used as the standard strength for soil cement blocks.

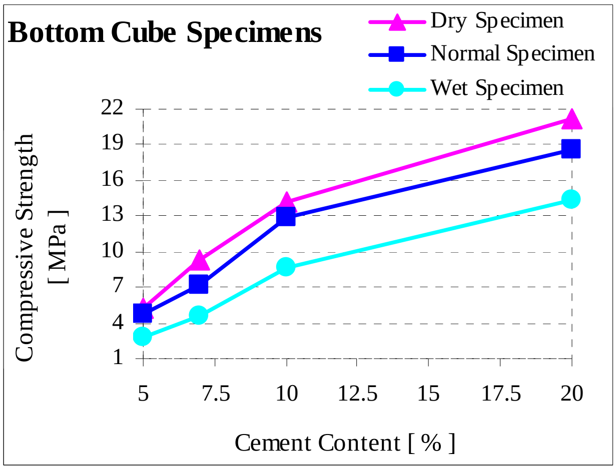

Figure - 3.14: Dry, normal and wet specimens' test results

3.6 Strength Relationship Between Full and Corner Block Units

Strength relationship between full scale and corner block units were investigated for wet and dry specimens. The blocks were made of 7 % and 10 % cement content. Test results shown in Figure - 3.15 reveal the same strength for full scale and corner blocks. Dry specimens are stronger compared to wet specimens. In average, the compressive strength of wet specimens is 57 % of dry specimens.

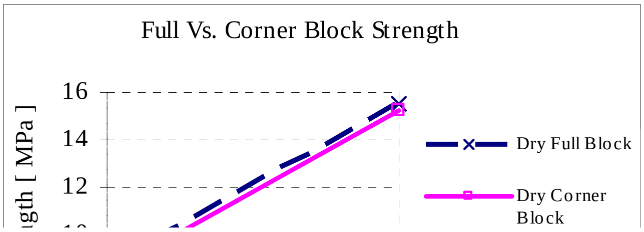

Figure - 3.15: Full vs. corner block unit strength

3.7 Comparison of Results from Different Test Methods

It was shown previously in section 3.5 that cube and shoulder test give the same test results. Comparison between centre and shoulder load capacity was made using full scale block units of 15 % cement content. Only oven-dry and wet specimens were tested in a centre loading. Blocks loaded at centre failed by shear (see Figure - 3.10) at lower load of about 60 % of its cube strength as shown in Figure - 3.16. Loading a block unit at centre does not give its compressive strength. The evaluation of the compressive strength of the units can either be accessed by testing bottom cube or block unit loaded at shoulder. Detailed unit compressive strength test results are listed in appendix - A.

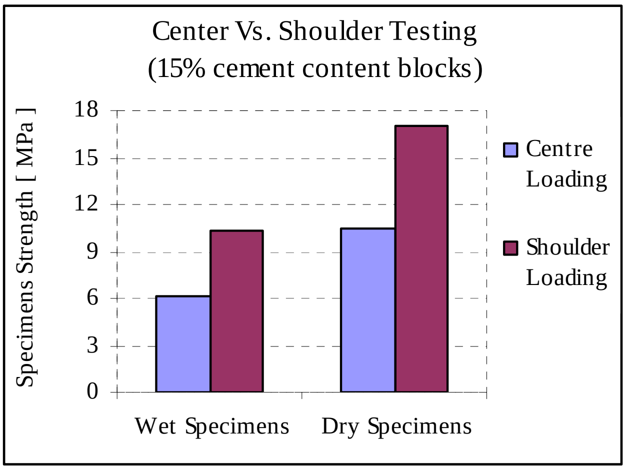

Figure - 3.16: Comparison of results from different test methods

3.8 Remarks From Test Results

The compressive test results obtained from different tests methods shown in Figures - 3.11, 3.12, 3.13, 3.15 and 3.16, led to relevant aspects, unique for Hydraform dry-stack block units. It was found that 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. From the principle used for design, the unit strength should be based on the weaker segment. However, the shoulder block unit test results reveal same strength as the bottom stronger cube. In reality, test results have revealed that the block unit exhibits very good resistance behaviour compared to the top (weaker) cube. Furthermore, the masonry wall is built using full scale and corner block units and not by the isolated top cubes. It is also probably that the cutting process to obtain cubes caused micro-cracks which helped to disintegrate the cubes therefore weakened the cube specimens, special the low dense top cubes. It is known that the strength of the material in a structure is higher than the strength of a cube extracted from it. It is not necessary to limit the unit compressive strength to the top (weaker) cube. Limitation of the unit strength to the top cube could, unnecessarily, lead to non economical construction. For safer construction usage, it is reasonable to consider the strength of wet block unit specimens also similar to bottom stronger cube. To secure safety, cautions measures must be put in place. It is recommended to use corner blocks instead of cutting a full block unit to adjust the masonry wall edges. If for any reason there is a need to cut a full scale block, only the bottom stronger portion should be used on the masonry wall.

The centre loading of a block unit causes shear failure at lower load. The shoulder test leads to a real unit compressive strength, the same given from the bottom cube test. When possible, only shoulder loading should be adopted. Centre loading is likely to occur in the last course of a masonry wall where the slab or a roof structure rests. Improvements on block unit's geometry of last course and/or introduction of accessories are required to guarantee the desired shoulder loading. On the next chapter "Dry-Stack Masonry Compressive Strength", it will be seen that the wall compressive strength is influenced by the block shear failure pattern which is accounted for (safety secured) and affects the wall/unit aspect ratio.

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, as shown in Figures - 3.8 and 3.9. The strength is referred to wet specimens. Wet strength is approximately 60 % of the normal strength. Wet strength bases the design since there are situations where blocks are likely to be permanently wet such as in a foundation block courses.

3.9 Empirical Expressions to Predict the Unit Strength

Cautious examination of Figures - 3.11, 3.12, 3.13 and 3.14, showed a consistent behaviour on test results. The unit compressive strength as a function of cement content can be approximately described using a bi-linear relationship broken at a cement content of 10 %. From that observation, empirical expressions to predict the compressive strength knowing the cement content were developed. The expressions predict block strength for a range of soils described on Hydraform Agrément Certificate and presented in Table - 2.1 of this work.

$$f_{cu} = kt\phi(c-2) \quad for \;\; c \le 10 \qquad (3\text{-}1)$$

$$f_{cu} = kt\left(\frac{1.25c}{\phi} + 4\phi\right) \quad for \;\; c > 10 \qquad (3\text{-}2)$$

Where:

f_{cu} Cube/block unit mean compressive strength;

c Percentage of cement content by volume in dry mixture;

k Loading method factor

$$\left| \begin{array}{l} k = 1 \;\; for \;\; block \;\; units \;\; loaded \;\; at \;\; shoulders \;\; and \;\; bottom \;\; cubes \\ k = 0.78 \;\; for \;\; top \;\; cubes \\ k = 0.60 \;\; for \;\; block \;\; units \;\; loaded \;\; at \;\; centre \end{array} \right.$$

t Humidity conditions factor

$$\left| \begin{array}{l} t = 1 \;\; for \;\; dry \;\; specimens \\ t = 0.92 \;\; for \;\; normal \;\; specims \\ t = 0.57 \;\; for \;\; wet \;\; specimens \end{array} \right.$$

Empirical material factor; for soil-cement blocks

Empirical results predicted using expressions (3-1) and (3-2) were plotted against test results as shown in Figure - 3.17. Agreement between empirical and test results is good.

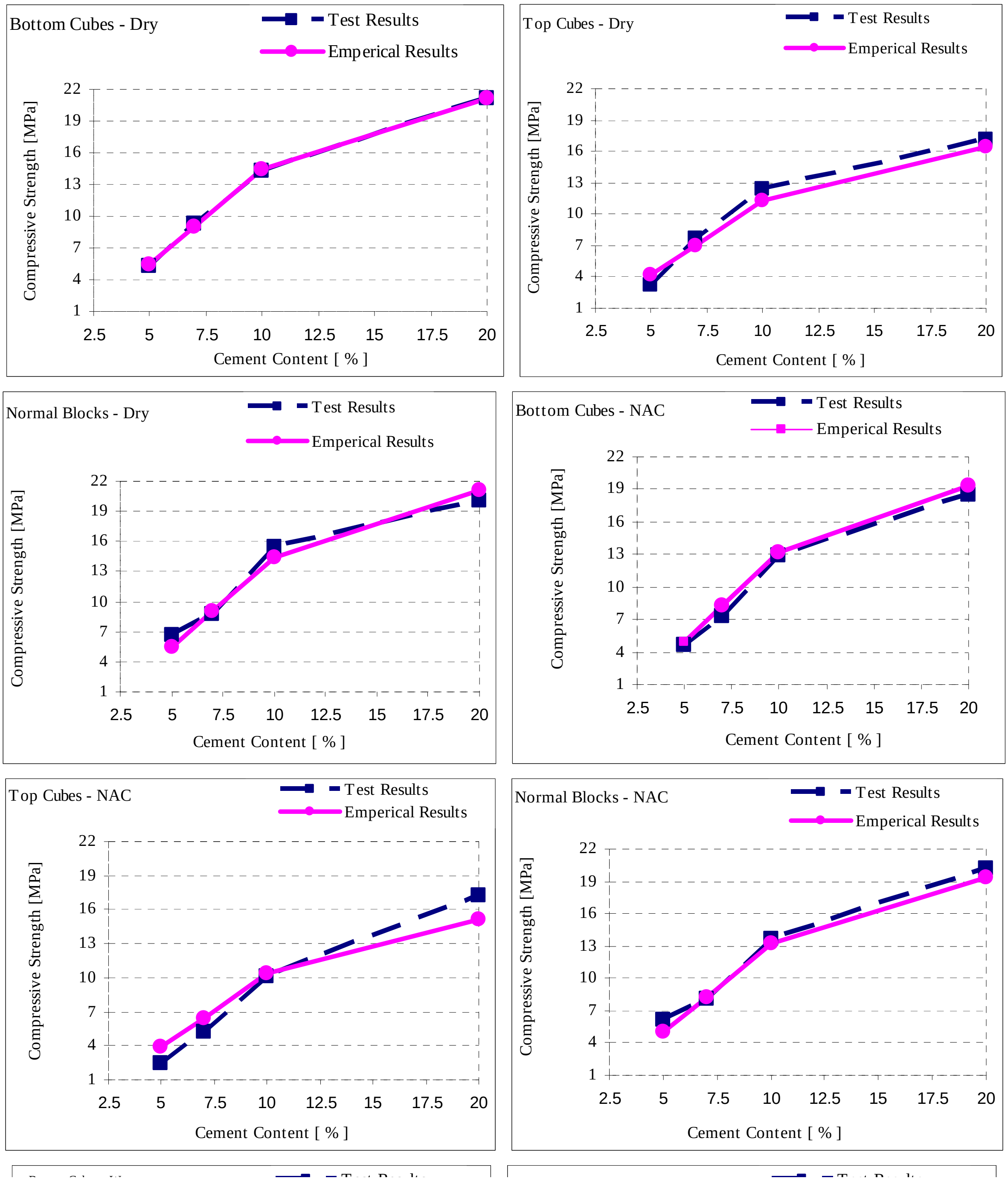

Figure - 3.17: Test versus empirical results

3.10 Recommended Strength for Standard Hydraform Block Units

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 and the designers to base their designs on standardized block strengths. 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 - 3.2 suggests the nominal compressive strength for Hydraform block units based on wet specimens (bottom cubes or full scale or corner block units). The proposal is based on an attempt to obtain a feasible standard nominal compressive strength which also does not differ so much to that of conventional block units. The upper and lower limit of nominal compressive strength of block units are guided by limits of cement content within the blocks already in practice on Hydraform block yards. The proposal summarised in table - 3.2 is based on the use of standard materials for the block production. Tests are required to ensure compliance and appropriate reduction factor introduced where minimum strengths are not achieved.

Table - 3.2: Hydraform block unit compressive strength[1]

Cement Content [%]	Nominal Compressive Strength of Block Units [MPa]
5	3.0
7	5.0
10	8.0
15	10.0
20	12.0

To obtain the nominal compressive strength of block units, an average of ten specimens should be tested in wet conditions described on this work. Wet specimens have revealed to be the weakest specimens, therefore the safe case scenario to predict the nominal compressive strength of block units. With the Nominal Compressive Strength systematized in a standard form, the masonry compressive strength can also be easily defined and used for design.

[1] Applicable for standard soils (see table - 2.1). Different soils will give different values.

CHAPTER - 4

DRY-STACK MASONRY COMPRESSIVE STRENGTH

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 South Africa, the laboratory determination of characteristic compressive strength of masonry is specified in SANS 10164-I. In the absence of laboratory tests, standardized values of characteristic compressive strength provided in Tables 3a and 3b of SANS 10164-I may be used. For dry-stack masonry there is no laboratory testing method or standard values of characteristic compressive strength. In this chapter, the author used available recent laboratory testing data on Hydraform dry-stack masonry panels, analysed it and made additional prism tests to explain the failure modes. Recommendations were made towards a standard determination of characteristic compressive strength of Hydraform dry-stack masonry.

4.2 Conventional Masonry Panels Testing Procedure and Requirements

The SANS 10164-I states that the determination of characteristic compressive strength of conventional masonry is done through testing masonry panels having the following geometry:

(4-1)

$$L \leq \frac{3}{4}h \qquad (4\text{-}2)$$

$$A \geq 0{,}2 \ \ m^2 \qquad (4\text{-}3)$$

Where,

t Panel thickness;

h Panel height

L Panel length

A Cross section area

When it is desired to test panels that do not comply with the above requirements, the code states that, it may be necessary to make allowances for deviations from the requirements when the results are assessed.

Where $h > 20t$, slenderness effects may give significant lower test results than those expected from a wall in the recommended height/thickness ratio range. This effect can approximately be accounted for by measuring the maximum lateral wall deflection δ_u at ultimate load and the application of a correction factor $\frac{t}{t-\delta_u}$ to the test value $\frac{F_m}{A}$, subject to a maximum increase of 15 %.

The panels must be covered with polyethylene sheets for a period of three days after construction, and then uncovered until tested at the edge of 28 days. The covering process plays an important role for a curing process on early days of the specimen. From the above proceedings, it may be noted that at the testing date, both units and mortar are not in wet conditions but rather normal (at a room humidity conditions). It follows that the characteristic compressive strength of masonry is referred to a normal humidity conditions. Contrarily, the nominal compressive strength of block units is referred to wet condition, socked in water for many hours before tested.

The characteristic compressive strength for conventional masonry is calculated using the expression (4-4).

$$f_k = \frac{F_m}{A} * \frac{\Psi_u \Psi_m}{1,2} \qquad (4\text{-}4)$$

Where,

f_k Masonry characteristic compressive strength;

F_m Mean of the maximum load carried by the two test panels;

A Cross-sectional area of each panel

Ψ_m Reduction factor for strength of mortar given in Table 4-1.

Ψ_u Unit reduction factor (not exceeding 1) given by:

a) When the structural units are not subject to regular quality control;

$$\Psi_u = \frac{p_o}{p_u} \leq 1;$$

Where:

p_o Specified compressive strength, from the manufacturer, below which the value for samples taken from consignments supplied for the building are not expected to fall;

p_u Unit mean compressive strength obtained on laboratory;

b) When the structural units are subject to a category A quality control;

$$\Psi_u = \frac{p_1}{p_u} \leq 1;$$

Where:

Acceptance limit for compressive strength;

Unit mean compressive strength obtained on laboratory;

Table - 4.1: Reduction factor, Ψm, for mortar strength (Source: SANS - 10164-I)

1	2
Ratio = (strength of mortar used for test panels / Specified minimum site compressive strength)	Reduction factor Ψm
1,0 to 1,5	1,00
2,0	0,93
2,5	0,88
3,0	0,84
3,5	0,81
4,0	0,78

4.3 Hydraform Dry-stack Panels Testing

4.3.1 Preparation of specimens

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 - 4.1). A conventional wall panel (with all block units laid on mortar) was also tested for comparison. Tests were carried out on the age of fourteen days.

Each wall panel was 3,0 m long, 2,5 m height and 220 mm thick (see Figure - 4.1) and was constructed on a Macklow-Smith machine platen that was mounted on a hydraulic Ram. The code requirements for conventional wall dimension were observed for the wall height limit and cross sectional area limit except the length limit which was greater than that recommended in the code. In Hydraform dry-stack masonry, the bearing cross-section net area is about 45 % of the gross section area. In order to meet the minimum bearing area of 0,20 m^2 specified by the code, the length limits should be increased. The code also allows tests of different geometry provided that the results are adjusted to take into account the deviation on standard geometry (SANS 10164-I, 2005). It was assumed that exceeding the wall length would have no, or have little effect on distorting the compressive strength results since the limits for slenderness ratio are within the code limits.

To meet the minimum bearing area of 0,20 m^2 in the Hydraform dry-stack panels, the length limits of $L \leq \frac{3}{4}h$ for conventional masonry, should be revised and a new limit of $L \leq \frac{3{,}5}{4}h$ would be fine. The reason is that the bearing net cross-section area is about 45 % of the gross cross-section area. It was found important not to change the limit of minimum bearing area $A \geq 0{,}20\ m^2$ required by the code for conventional masonry. The practicability of new proposed limits for Hydraform block units needs support on further research.

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. The beam was stiffened with plates at the loading position and at intervals of 400 mm. Dial gauges were placed in positions indicated in Figure - 4.1 to monitor deflections. Axial compression load was applied at a rate of 2 kN/min. At each interval the lateral displacement and the corresponding load were recorded.

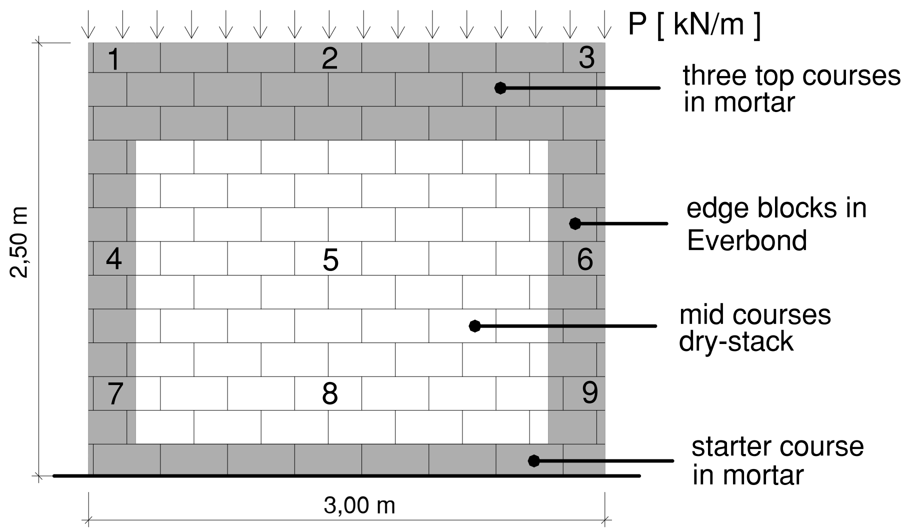

Figure - 4.1: Wall panel construction details and strain gauge positions

4.4 Failure Mode for Masonry Wall Compressive Test

The wall panel compression tests indicate that the onset of failure was characterised by formation of a vertical crack (less than 3 mm) parallel to the axis of loading along the mid section of the wall (see Figure - 4.2). This crack running down suggests the possibility of stress concentration around the mid-section.

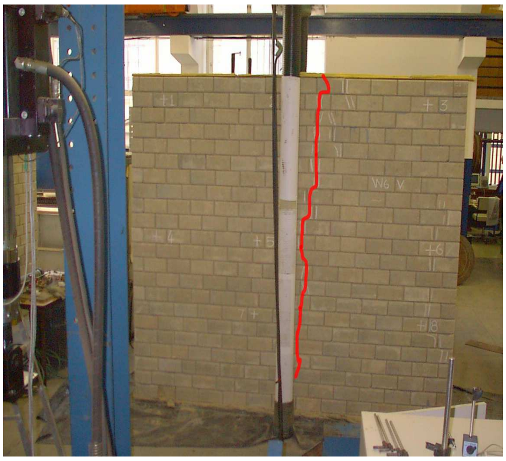

Figure - 4.2: Wall plane view - failure line (source: Ngowi - 2005)

At ultimate state, cracks also appeared on the faces and edges of the specimen as shown on Figure - 4.3. The line of crack running vertically along the edge of the interlocking groove is similar to that experienced by the block unit when loaded at centre. This failure mode suggests that the block units have failed by shear before they can develop the full compressive capacity. In the masonry wall compressive capacity, it can be said that the premature shear failure is accounted for and is one of the reasons for less masonry to unit aspect ratio.

Figure - 4.3: Cross section view of top cracks (source: Ngowi - 2005)

Failure in low-strength unit walls was characterised by a local crushing of the top courses as shown in Figure - 4.4. The weakest sample (5 MPa) failed in this manner, by the crushing of the top 10 courses.

Figure - 4.4: Failure mode of panel made of low strength units (source: Ngowi - 2005)

4.5 Prism Test

To explain the wall failure modes, the author carried out additional tests on prisms. Failure modes similar to those seen on block unit as well as on wall panel testing were again seen on prism testing. When the prism is loaded at shoulders, it reveals a failure mode characterised by vertical cracks similar of those seen on block units loaded at shoulder (see Figure - 4.5).

Figure - 4.5: Prism failure mode when loaded at shoulders

When the prism is loaded at centre, the failure plane is along the vertical joint of the interlocking groove as shown in Figure - 4.6. Exception is seen on the top block which, due to effect of load concentration exhibits a flexural failure. This prism failure mode is similar to that of block units loaded at centre. To understand the reason for shear failure mode, let us consider the top block loaded at centre. When the top block collapses by shear or flexure, it constitutes a centre loading to the next block unit which also fails by shear, hence loading the third block at centre, and so on. Starting by centre loading on the top course block unit, the following block units will be loaded at centre (see Figure - 4.6). Starting by shoulder loading on the top course block unit, the following block units will be loaded at shoulders as shown in Figure - 4.5.

Figure - 4.6: Prism failure mode when loaded at centre

Both shoulder loading of block unit and a prism, lead to higher failure loads. The centre loading leads to lower failure loads. The wall panel had shown a shear failure mode therefore, it had failed at lower load value. In order to increase the masonry strength capacity, a centre loading should be avoided and only a shoulder loading allowed. It can be attained by revising the block geometry of the last block course or/and by introducing accessories to allow shoulder loading. The tested panels were loaded at centre, hence the shear failure mode (see Figure - 4.3 and 4.4).

4.6 Test Results

Table - 4.2 shows test results conducted in the masonry dry-stack masonry panel tests. Four dry-stack wall panels were tested. The block units' mean compressive strengths were 5, 9, 12 and 23 MPa, based on shoulder or bottom cube testing.

Table - 4.2: Dry-stack masonry compressive test results

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

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.

4.7 Relationship Between Conventional and Dry-stack Compressive Strength

In order to compare strength of conventional and dry-stack masonry, a wall panel was constructed using Hydraform block units of 12 MPa compressive strength and mortar class II of 5,6 MPa cube strength. The panel had same geometry as the dry-stack panels. The panel was cured and tested at the edge of 28 days. Table - 4.3 compares the strength of dry-stack panel versus conventional panel of similar unit strength (12 MPa).

Table - 4.3: Dry-stack vs. conventional masonry strength

Block Unit compressive strength [MPa]	Ultimate compressive load [kN]	Bearing Area [m2]	Masonry compressive strength [MPa]	Masonry / Unit strength ratio
12 (dry-stack)	938	0.30	3.13	0.26
12 (conventional)	1553	0.66	2.35	0.20

Test results indicate that due to its lower net bearing area "block shoulders", dry-stack masonry panel failed at lower ultimate point load compared to conventional masonry. However, in terms of uniformly distributing load, dry-stack masonry has higher resistance capacity therefore the higher (masonry / unit strength) aspect ratio.

Previous research work carried out by Monk (1967), Morsy (1968) and Hendry (1981), was used as basis for determining brickwork design strength in conventional masonry. Tests were done on block units, prisms and masonry panels bonded on mortar and without joint material (dry-stack). Researchers were unanimous in reporting that dry-stack specimens with flat faces were two times stronger than specimens bonded with mortar (Ngowi, 2005).

The reason for a masonry wall having less strength than that of its block units is a complex matter. In conventional masonry, the major reason is attributed to the presence of a soft material (mortar) used to join the block units (Vermeltfoort, 2005). The wall resistance differs according to mortar class, curing conditions, layer thickness and mortar/block relative strength. Wall slenderness effects and the load eccentricity also contribute to a reduction on the wall resistance strength.

Dry-stack wall strength reduction compared to that of its block units can also be linked to the interface joints which, in this case, lead to wall large displacements and instability. The wall slenderness effects and the load eccentricity contribute to the wall strength reduction. Depending on the interlocking mechanism, each dry-stack system may have additional and unique reasons for reduction in wall strength. For example in the investigated dry-stack system, the shear failure mode above discussed lead to a wall lower resistance compared to that of its block units.

4.8 Empirical Expressions for Masonry Strength

Test results were used for a regression analysis to establish a strength relationship between the units and the masonry wall. The mean compressive strength of dry-stack wall panel f_m as a function of the discussed unit strength f_{cu} is given by the expression (4-5).

$$f_m = 0{,}15 f_{cu} + 1 \qquad (4\text{-}5)$$

Expressing the unit compressive strength as a function of cement content by substituting the expression (3-1) and (3-2) into expression (4-5), the mean masonry wall compressive strength f_m follows:

$$f_m = 0{,}15[kt\phi(c-2)] + 1 \quad for \;\; c \leq 10 \qquad (4\text{-}6)$$

$$f_m = 0{,}15\left[kt\left(\frac{1.25c}{\phi} + 4\phi\right)\right] + 1 \quad for \;\; c > 10 \qquad (4\text{-}7)$$

Parameters on the above expression have so far been explained.

Comparison between test and the proposed empirical results are represented in Figure - 4.7. Agreement between the above two approaches is achieved.

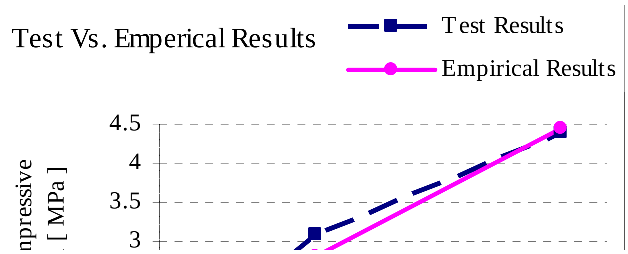

Figure - 4.7: Test vs. empirical results

4.9 Characteristic Compressive Strength for Dry-stack Masonry

In the principle of limit states design, the masonry resistance is described by its characteristic compressive strength. The characteristic compressive strength for conventional masonry is obtained by applying proper reduction factors to the mean compressive strength. The already discussed expression (4-4) rewritten here $f_k = \frac{F_m}{A} * \frac{\Psi_u \Psi_m}{1,2}$, is used to transform the mean to characteristic compressive strength of convectional masonry.

In order to use the same approach to determine the characteristic compressive strength of dry-stack masonry, the reduction coefficient Ψ_m accounting for mortar quality control should be removed since the dry-stack system does not use mortar or uses minimum amount of mortar. The reduction coefficient Ψ_u accounting for block units' quality control should remain on the same basis. The reduction coefficient 1,2 used to transform the mean compressive strength into characteristic compressive strength should also remain the same.

In absence of test results, values presented on Table - 4.4 may be used conservatively as the characteristic compressive strength for dry-stack masonry. The values were obtained from the above discussed dry-stack panel testing. Expression (4-4) was used to transform the mean compressive test into characteristic compressive strength. The worst case scenarios for the reduction factors were applied. The reduction factor for unit quality control was taken as $\Psi_u = \frac{p_o}{p_u} \approx 0,80$. The reduction factor for mortar quality control was considered the worst scenario of quality control with 30% of masonry mortared, $\Psi_m = 1 - \Delta\delta = 1 - (1 - 0.78) * 0.25 \approx 0.95$.

Table - 4.4: Hydraform dry-stack masonry mean and characteristic compressive strength

Cement contente [%]	Unit compressive strength [MPa]	Masonry mean compressive strength [MPa]	Reduction factor Ψu	Reduction factor Ψmd	Masonry characteristic compressive strength [MPa]
5	3.0	1.7	0.8	0.95	1.1
7	5.0	2.0	0.8	0.95	1.3
10	8.0	2.5	0.8	0.95	1.6
15	10.0	2.8	0.8	0.95	1.8
20	12.0	3.1	0.8	0.95	2.0
25	14.0	3.4	0.8	0.95	2.2
30	16.0	3.8	0.8	0.95	2.4

Table - 4.5 below summarizes Hydraform dry-stack masonry characteristic compressive strength as function of block unit compressive strength.

Table - 4.5: 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. The next chapter deals with testing and theoretical evaluation of dry-stack masonry/reinforced concrete composite beams under flexural loading.

CHAPTER - 5

FLEXURAL STRENGTH OF DRY-STACK MASONRY/REINFORCED CONCRETE COMPOSITE BEAMS

5. FLEXURAL STRENGTH OF DRY-STACK MASONRY / REINFORCED CONCRETE COMPOSITE BEAMS

5.1 General

Masonry walls, beams and columns are used to resist vertical and horizontal flexural loads. To improve the flexural resistant mechanism, reinforced concrete is incorporated into plain masonry elements to form composite elements. Among common applications of reinforced masonry beams is the banding technique application used to resist horizontal loading due to earthquakes. The banding process consists of constructing masonry beams where the masonry is confined inside reinforced concrete bands.

The behaviour and the design philosophy of conventional reinforced and prestressed masonry (composite elements) are presented in many codes of practice and are similar to those of reinforced and prestressed concrete (Crofts, 2000). The design of conventional reinforced masonry in South Africa is based on the SANS 10164 - Part 2 code of practice. So far, no formal design procedure has been presented in codes of practice for the innovative dry-stack reinforced masonry. The present work constitutes an early attempt to understand the behaviour of Hydraform dry-stack reinforced beams under flexural loading. The methodology followed consists of checking the applicability of the design philosophy used to access the flexural strength of conventional reinforced masonry to the dry-stack reinforced masonry.

5.2 Flexural Resistance of Hydraform Dry-stack Masonry/Reinforced Concrete Composite Beams

The rectangular stress block shown in Figure - 5.1, is widely used to predict the flexural capacity of rectangular reinforced concrete elements. At ultimate limit state, the concrete is assumed to be fully stressed therefore the strain is taken to be $\varepsilon_c = 0{,}0035$. For tensile reinforcement, three situations may occur. When the strain is less than the yield strain, $\varepsilon_{s1} < \varepsilon_y = 0{,}002$ the reinforcement is not fully stressed and the sections is said to be over reinforced. If the strain is equal to the yield value, $\varepsilon_{s1} = \varepsilon_y = 0{,}002$ the reinforcement is fully stressed and the section is said to be balanced. This is an ideal situation which is difficult to achieve met in practice. When the strain is greater that the yield value, $\varepsilon_{s1} > \varepsilon_y = 0{,}002$ the reinforcement is fully stressed, hence the section is said to be under reinforced.

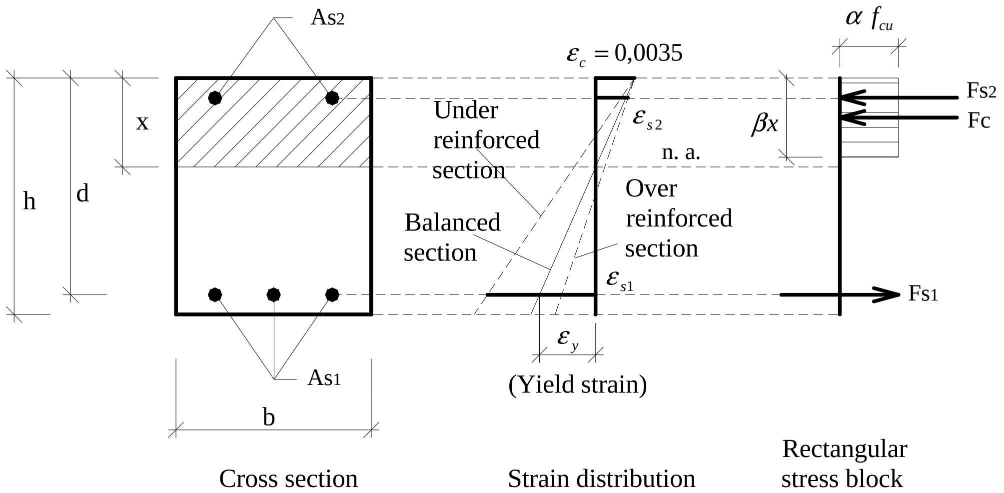

Figure - 5.1: Flexural analysis of reinforced concrete sections

For high sections, it may be necessary to design tensile reinforcement at the mid section height. In this case, the diagram showed in Figure - 5.1, is adjusted to take into account another layer of reinforcement say, and the corresponding force . This principle applies for as many reinforcement layers as existing on the section. When several layers of reinforcement are considered, it is likely to find some reinforcement layers fully stressed while others are not. Examples of such different design situations can be seen in appendix B.

It was said earlier on that the assumptions used in the flexural analysis of reinforced concrete sections are similar to those used in the flexural analysis of conventional reinforced masonry (see Figure - 5.2). Few changes, such as, replacement of compressive strength of concrete by masonry compressive strength may be noticed and are presented below.

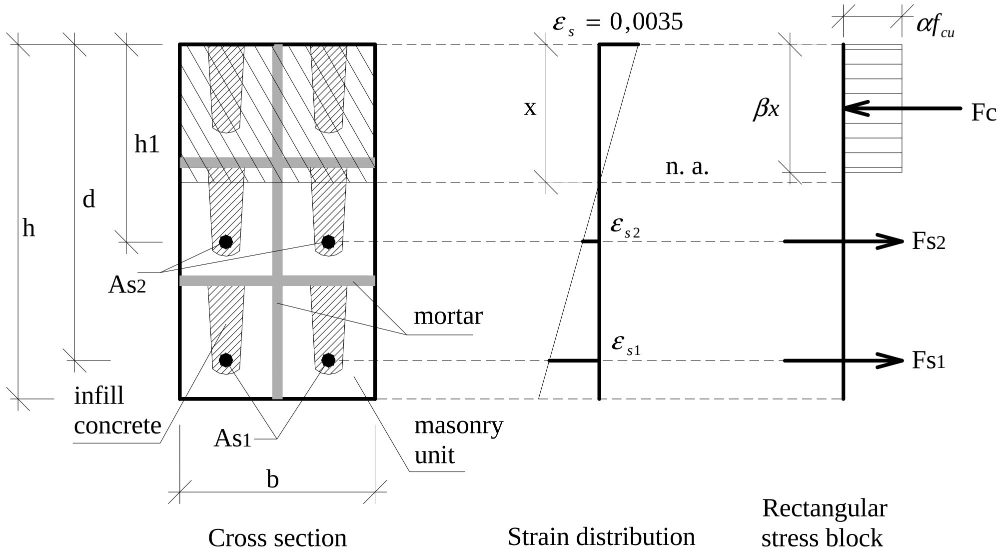

Figure - 5.2: Flexural analysis of reinforced masonry sections

The force of masonry in the compression zone, above the neural axis (n. a.) is given by:

$$F_c = \alpha\ \beta\ x\ b\ f_{cu} \qquad (5\text{-}1)$$

Where,

α is a coefficient which accounts for the deviations in the masonry strength. The SABS 0164 code of practice considers $\alpha = 0{,}67$;

β is a coefficient adopted to correct x from the really parabolic stress-strain diagram to the approximate rectangular diagram. The SABS 0100 code of practice considers ;

is the depth of the compression zone of the section, the position of the neutral axis;

is the cross section width;

is taken to be the compressive strength of the reinforced masonry. The code allows the designer, where necessary, to adjust to take into account the influence of the infill concrete. It will depend mainly on the relative volume of the infill concrete compared to the masonry volume and the relative compressive strength of infill concrete compared to the masonry compressive strength. At ultimate limit state, the reinforced masonry section is assumed to experience a strain of $\varepsilon_c = 0{,}0035$.

The force on each reinforcement layer is given by one of the two expressions:

a) For a fully stressed reinforcement

$$F_{si} = A_{si} f_y / \gamma_{ms} \qquad (5\text{-}2)$$

Where,

A_{si} Cross section area of reinforcement of a layer i;

f_y Reinforcement steel characteristic yield strength;

γ_{ms} Safety coefficient for reinforcement, the SABS 920 code of practice considers $\gamma_{ms} = 1{,}15$.

b) For a not fully stressed reinforcement

$$F_{si} = A_{si}\sigma_{si} = A_{si} E \varepsilon_{si} \qquad (5\text{-}3)$$

Where,

E Reinforcement modulus of elasticity, in the SABS 920, $E = 200 GPa$

$\varepsilon = \varepsilon_{si}(x)$ Reinforcement strain on layer i and is a function of the neutral axis position x.

ε_y Yield strain for reinforcement, the SABS 920 code of practice considers $\varepsilon_y = 0{,}002$.

5.3 Shear Action and Resistance

The acting shear stress at any cross section is given by the following equation:

(5-4)

Where,

v^{acting} Acting shear stress at a given cross section;

V Acting shear force due to applied loads;

b Width of the section;

d Effective depth of a section;

This equation approximates the shear stress as if it were uniformly distributed whole cross the section as far as the tensile reinforcement (see Figure - 5.3).

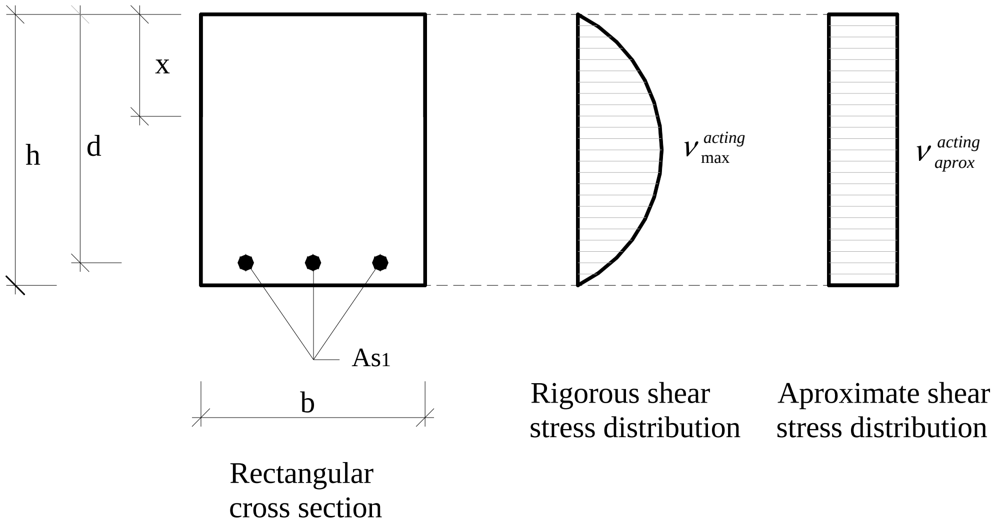

Figure - 5.3: Shear stress distribution on a rectangular section

The shear resistance mechanism for dry-stack reinforced masonry is yet unknown. The shear resistance mechanism for conventional reinforced masonry is similar to that of reinforced concrete. The shear resistance of the section includes contribution from the non cracked part of the section, dowel action of tensile reinforcement, any interlock along the tensile cracks and shear reinforcement in form of links. For conventional reinforced masonry there is no a recognized method of allowing for interlock which, in case of reinforced concrete, is due to aggregates (Roberts, Tovey & Fried, 2001).

The shear resistance mechanism of plain dry-stack masonry and dry-stack reinforced masonry still to be researched. In this work, verifications were made to ensure that the beams have failed by flexural effect rather than shear. It was showed that shear resistance of reinforced concrete zones were, itself enough to secure the shear resistance of the beams. The shear resistance of reinforced concrete section is given by the following expression which describes the resistance due to plain concrete v_c and the transversal shear reinforcement links v_{sv}.

$$v^{resis\tan e} = v_c + v_{sv} = \frac{0,75}{\gamma_m}\left(\frac{f_{cu}}{25}\right)^{\frac{1}{3}}\left(\frac{100A_s}{bd}\right)^{\frac{1}{3}}\left(\frac{400}{d}\right)^{\frac{1}{4}} + \frac{0,87 f_{yv}}{b}\frac{A_{sv}}{s_v} \qquad (5\text{-}5)$$

Where,

$v^{reis\tan ce}$	Shear resistance stress at a given cross section;
v_c	Shear resistance attributed to plain concrete;
v_{sv}	Shear resistance attributed to shear reinforcement links;
γ_m	Partial safety factor for material; SABS 0100 code of practice uses $\gamma_m = 1,4$;
f_{cu}	Characteristic strength of concrete;
A_s	Area of tensile reinforcement;
b	Section width;
d	Effective depth of a section;
A_{sv}	Cross section area of resisting legs of a link;
s_{sv}	Spacing of the links;
f_{yv}	Characteristic strength of reinforcement links.

5.4 Experimental Testing

5.4.1 Test Specimens

Series of simply supported dry-stack reinforced masonry beams were prepared in laboratory and tested. The beams are composite structures of concrete, dry-stack masonry and reinforcement bars. Beams were constructed on wood pallets to facilitate transport to the test rig (see Figure - 5.4). A thin layer of about 20 mm of soil was placed on top of the pallet to reduce to minimum the friction between the beam and the wood pallet during testing. Reinforced concrete was cast on ordinary manner direct to the block surface and a wooden formwork. A curing period of 28 days was observed. Polythene sheeting was used to cover concrete to prevent moisture expel.

Figure - 5.4: Dry-stack reinforced beams

Masonry was dry-stack and relied on interlocking features as shown in Figure - 5.5. Reinforcement bars were placed between courses of dry stack blocks. The reinforcement was bonded by class 3 mortar. A 6 mm high yield tensile reinforcement bars were used.

Figure - 5.5: Dry-stack feature and reinforcement detail

To access the beam infill concrete strength, cube concrete samples were taken and tested at 28th day. Compressive strength of block units were also evaluated by ordinary compressive test discussed in chapter two. All beams were 2 m long with 1,8 m span measured from the centre of the supports. Figure - 5.6 shows beam's cross section geometry.

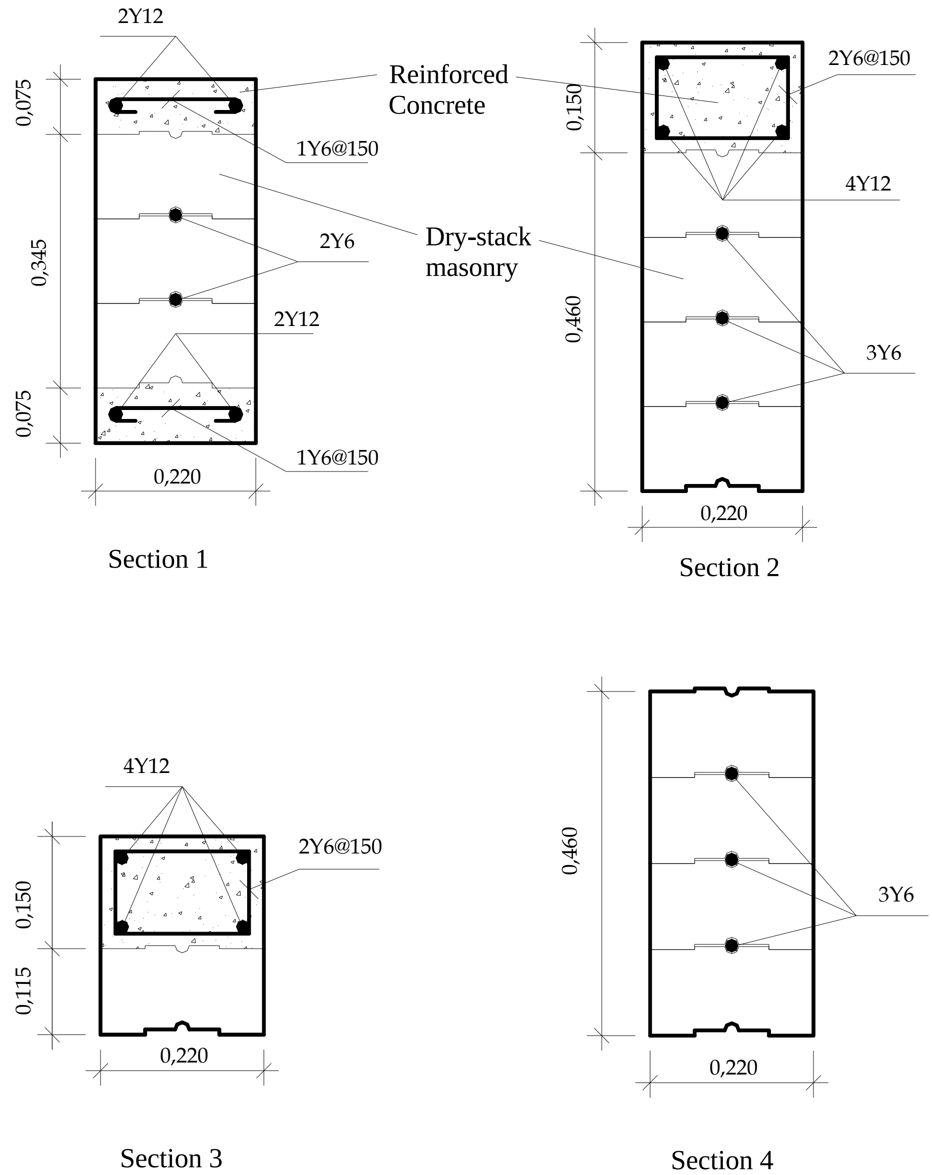

Figure - 5.6: Dry-stack reinforced beams specimens' cross sections

5.5 Test Rig Arrangement

A metal test rig was designed and fixed on laboratory floor. The rig formed a simply support for the beam as shown in Figure - 5.7. A manual hydraulic jack was used to supply the required force to the actuator. A load cell was used to record the load and transmit it to the computer data receiver system.

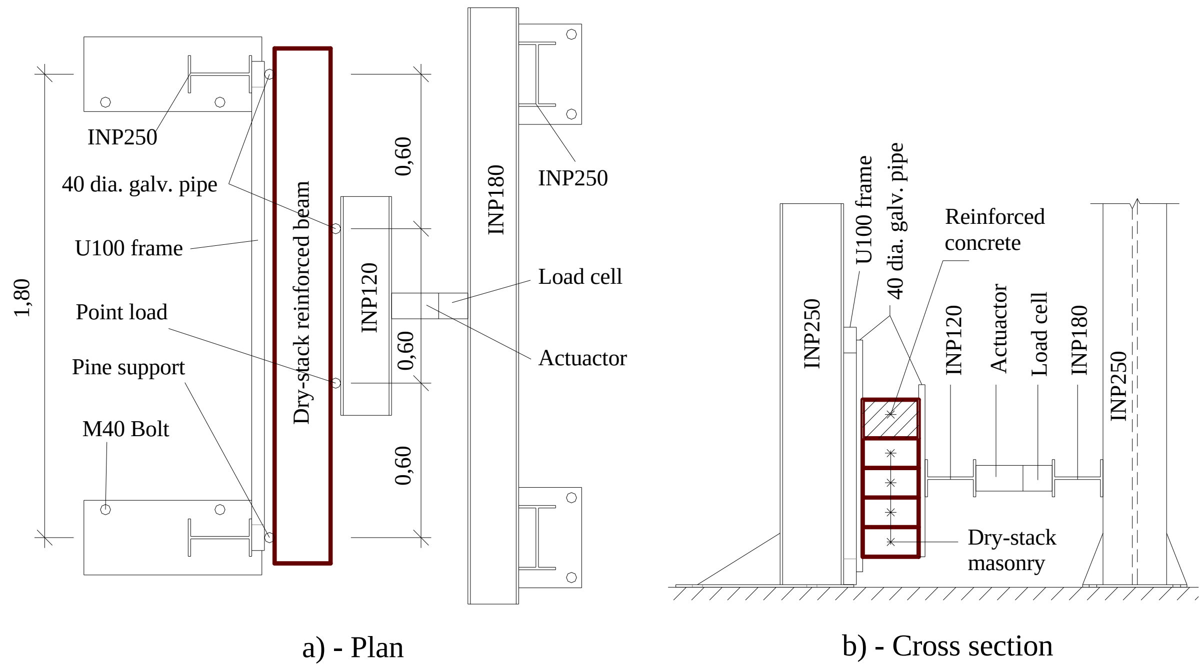

Figure - 5.7: Testing rig detail

Figure - 5.8 shows a photo and a sketch of the simply supported beam loaded by two static point loads. Two dial-gages were used to record maximum displacements on the concrete and dray-stack block layers. An ordinary workshop crane was used to position and remove the beams from the test rig.

Figure - 5.8: Photo and sketch of the simply supported beam and load detail

5.6 Failure Mode for Dry-stack Masonry/Reinforced Concrete Composite Beams

Dry-stack reinforced beam testing indicates a failure mechanism characterized by vertical and inclined cracks similar to those seen on reinforced concrete beam under similar testing. This can be seen as proving that the resistance mechanism of reinforced masonry is similar to that of reinforced concrete. Cracks run from concrete down into dry-stack blocks showing good bonding on the interface between the two materials and its togetherness on load resistance (see Figure - 5.9). By inspection on flexural cracks patterns, it can be seen that the depth of neutral axis is very small. Theoretical calculations later shown have revealed small values of neutral axis depth.

Figure - 5.9: Vertical flexural cracks

Inclined cracks running from points of load application to support reactions appeared on beams as shown in Figure - 5.10. Many ordinary literatures on reinforced concrete refer to the inclined cracks as shear cracks. For dry-stack reinforced beams, is difficulty to determine whether the inclined cracks are flexural or shear cracks. The doubt is that from theoretical calculations, the acting shear stresses are far lower compared to the shear resisting stresses. Analytical calculation shown in appendix - B, reveals that the shear resistance is guaranteed by reinforced concrete portion. Detailed research on shear resistance mechanism of dry-stack system is recommended.

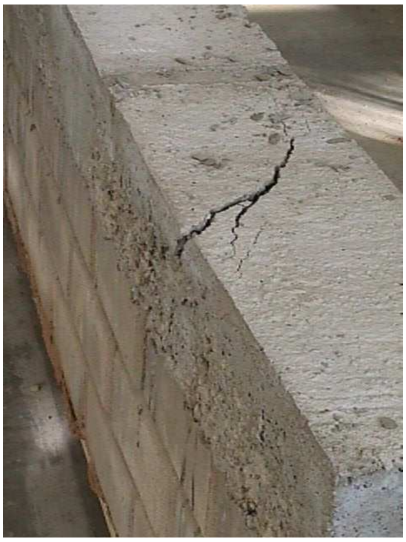

Figure - 5.10: Inclined crack

For non symmetric higher sections, the concrete portion of the beam displaces less than the masonry portion, as shown in Figure - 5.11. This fact leads to a lateral instability and loss of element resistance.

Figure - 5.11: Lateral instability on non symmetric high section

There is no lateral instability in symmetric sections. Masonry is confined between two concrete portions and the beam element becomes much stronger (see Figure - 5.12).

Figure - 5.12: No lateral instability on symmetric section

The absence of concrete infill on a cross section type 4, partial dry-stack masonry, allows the dry-stack units to displace and rotate highly relatively to each other. The beam behaves as a mechanism with progressive deflections (see Figure - 5.13). The beam resistance is very low and the design methodology of reinforced masonry cannot be applied to predict the resistance of plain or partial dry-stack beams.

Figure - 5.13: Excessive deflections of partial dry-stack masonry section type 4

5.7 Test Results and Discussion

Test results of dry-stack reinforced beams testing are summarised in Table - 5.1. Four different cross section types were considered as shown in Figure - 5.6. Failure load and maximum deflections were recorded on concrete and on a dry-stack block layers and arithmetic mean value was taken as the test resistance or displacement of each section type.

Table - 5.1: Dry-stack masonry/reinforced concrete composite beam test results

Section type	Beam number	Maximum load [kN]	Mean load [kN]	Maximum deflection on block [mm]	Maximum deflection on concrete [mm]	Mean deflection on block [mm]	Mean deflection on concrete [mm]
1	1	70	**69.67**	68	68	**56.33**	**58.67**
	2	76		57	60		
	3	63		44	48		
2	4	60	**64.67**	70	41	**62.00**	**40.67**
	5	60		43	31		
	6	74		73	50		
3	7	50	**50.00**		41	**41.00**	**41.00**
4	8	10	**8.27**	136		**79.33**	
	9	6		49			
	10	8.8		53			

Test results are represented against theoretical results in Figure - 5.14. Detailed theoretical calculations are presented in the Appendix - B. In general, theoretical values agree with test results. For section type 1, the difference between theoretical and test results is 3,5 % being the test results slightly higher. The symmetrical distribution of concrete and reinforcement on section type 1 has lead to a better behaviour on resisting loads. For section type 2, a difference of 12,2 % between test and theoretical results were recorded. The reinforced concrete portion is not symmetrical distributed throughout the cross section leading to lateral instability of a beam during testing. The lateral instability might lead to the slight loss on beam strength, hence offering less resistance than the theoretical prediction. Findings from section type 2 beams are applicable to section type 3. However due to less block courses (short specimens) the effect of lateral instability is less and a difference of 8,46 % between test and theoretical results were recorded.

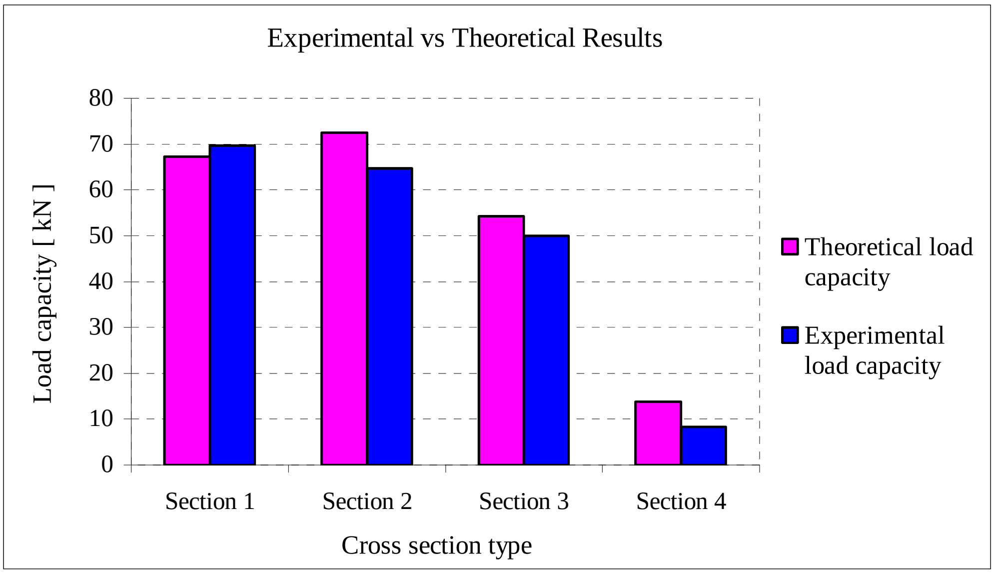

Figure - 5.14 - Experimental versus theoretical results

Figure - 5.15 represents displacements on tested specimens. For section type 1, displacements on concrete portion (58,67 mm) are close to those on blocks portion (56,33 mm). Excessive displacement of dry-stack blocks were prevented by the two edge reinforced concrete beams which confined and restrained the blocks as shown in Figure - 5.12. In a higher section, section type 2, displacements on concrete portion (40,67 mm) are less than on block portion (62,00 mm). The unrestrained block had large movement as shown in Figure - 5. 11.

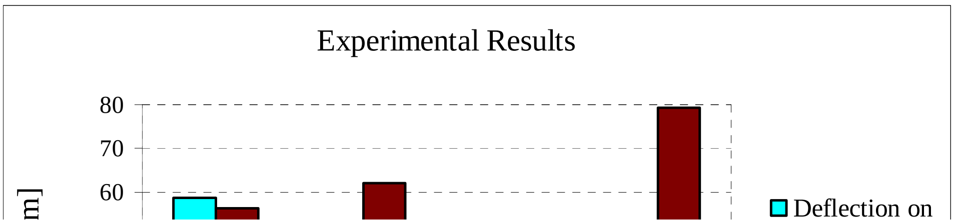

Figure - 5.15: Beam maximum displacements

For section type 3, short section, displacements on concrete portion were similar to those on block portion (41,00 mm). Excessive displacements were seen on section type 4 (79,33 mm), for which nor concrete were provided. The units displaced and rotated largely with no a practical limit. The element behaved as a mechanism as shown in Figure - 5.13.

In all situations, the displacements are more that the limit set on the code for conventional reinforced masonry which is $\frac{span}{250} = \frac{1800\ mm}{250} = 7{,}20\ mm$. In fact, many reports in dry-stack construction concern about its excessive displacements (Ngowi, 2005). This fact is restraining dry-stack construction to low raise and non bearing structures. Challenge still in researching methods of restraining the excessive displacements.

CHAPTER - 6

CONCLUSIONS AND RECOMMENDATIONS

6. CONCLUSIONS AND RECOMMENDATIONS

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. In conventional masonry, testing methods are well known and documented in several codes of practice. 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.

The uniqueness of Hydraform dry-stack system associated with the limited information regarding to dry-stack masonry has made it difficult to select appropriate decisions during this research work. Unusual findings during testing were seen and had to be approached in a different manner. One of the most difficult decision was to base the unit compressive strength on the shoulder or bottom cube test instead of top cube. The reason comes from the practical usage of Hydraform masonry where only block units are used. The system offers corner blocks to adjust the wall edges. It was then seen that there is no way of using top cubes within the masonry wall. Nevertheless, this aspect is still open for future research since this work constitutes an early attempt to standardize Hydraform dry-stack system.

Cube compressive test results have shown that, due to a production process, Hydraform dry-stack block unit is more compacted on bottom side than on top. Compressive strength of cubes from top side of the block is approximately 78 % of the bottom cube. However, the shoulder test of both full scale and the corner unit revealed same strength as the bottom strong cube. In a real Hydraform dry-stack construction, only full scale and corner blocks are used.

Basing the design on top cube strength may, unnecessarily lead to an uneconomical construction. It is reiterated not to cut block units to adjust wall edges, but rather to use corner blocks. Cutting blocks may be used guaranteed that only the strong bottom block half is used. Full responsibility is given to the contractor to observe the system recommendations.

Test results have shown that compressive strength of bottom cube is almost the same as those of the full and corner blocks loaded at shoulders. It is concluded that the shoulder testing can be used to access the compressive strength of Hydraform block units.

When loaded at centre, the block unit fails at lower load by shear. A block unit loaded at centre fails at about 60% of its shoulder or cube compressive strength. From the above, it was concluded that a centre loading does not give the compressive capacity of a block unit, therefore cannot be used as a method of accessing compressive strength.

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 safety, it is reasonable to recommend wet specimens to be used as a standard method for evaluation of block compressive strength. Certainly for masonry that will be subject to wet conditions such as below ground level, the strength must be reduced to account for wetness.

It can be concluded that sufficient conditions to establish standard compressive testing methods are created.

From wall panels testing, it was found that, as in conventional masonry the wall panel strength of dry-stack systems under vertical load is directly proportional to the strength of the masonry units. The test results were used to establish expressions that relate the strength of block units to that of the masonry wall. This will be useful in design.

The shear failure mechanism along the interlocking edge groove of the block reduces the compressive load capacity of the dry-stack masonry. Shear failure occurs when the top block unit is loaded at centre. Centre loading should be avoided as much as possible. Centre loading can be avoided by revising the geometry of the top course block layer ore by introduction of accessories that will help to avoid centre loading.

Shear failure and discontinuities between block units, reduces the wall versus masonry aspect ratio in dry-stack masonry compared to conventional masonry. Shear failure pattern bases the design of Hydraform dry-stack masonry wall.

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

Investigation from dry-stack masonry/reinforced concrete composite beams had established that the flexural design philosophy of dry-stack reinforced masonry is similar to that of reinforced concrete. Shear resistant mechanism is yet to be investigated.

The infill concrete and the reinforcement bars improve the resistance capacity of dry stack masonry. When the infill concrete is cast at the beam edges, it confines the dry-stack masonry reducing its excessive deflections and allowing the resistance capacity of dry-stack masonry to be rationally used.

The symmetrical distribution of infill concrete and reinforcement has positive effect on the beam resistance capacity, while the non symmetrical distribution of infill concrete allows the dry-stack block layers to displace further causing lateral instability which reduces the beam capacity in bending;

The design philosophy of reinforced masonry cannot be applied to predict the resistance of plain or partial dry-stack beams. Test results differed from theoretical results and a relative deviation of 67 % was found.

Deflections limit set on the code for conventional masonry are exceeded on dry-stack system. The plain dry-stack beam behaves as a mechanism with excessive displacements and rotations. This fact had limited the use of dry-stack systems to low rise and non bearing structures. Methods of restraining deflections in dry-stack system need further researched.

Fore better understanding of the structural behaviour of Hydraform system, a computational modelling is recommended. Additional properties must be obtained in laboratory, the modulus of elasticity, Poisson’s coefficient, shear resistance, coefficient of friction, and more.

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