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DURABILITY OF COMPRESSED STABILISED EARTH BLOCKS

BY IYAMBO IPINGE **JULY 2012**

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by

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A research report submitted to the Faculty of Engineering, University of the Witwatersrand, in partial fulfilment of the requirements of the Master of Science in Civil Engineering.

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DECLARATION

I declare that this research report is my own, unaided work. It is being submitted in partial fulfilment of a Master of Science in Civil Engineering, Faculty of Engineering and the Built Environment. It has not been submitted before for any other degree or examination in any other University.

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Iyambo Lisias Ipinge

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ABSTRACT

The world is facing the dilemma of housing its ever increasing population whilst preserving the state of the environment for future generations. From an anthropocentric to an ecocentric world outlook, the focus in building design and construction has shifted from the maximum utilisation of all available resources without due consideration for the environment, to the use of construction technologies that lessen demands on natural resources. For this reason, the use of alternative technologies such as the drystack compressed stabilised earth block (CSEB) in building construction is burgeoning.

This study uses the Hydraform CSEB as a general representation of the drystack CSEB technology. Owing to the Hydraform blocks irregular shape, a specific test method for the characteristic unconfined compressive strength of the Hydraform block had to be developed. Hydraform blocks produced with varying soil properties and stabilised with various cement contents are evaluated by means of the developed test method. Saturated and unsaturated block strengths are evaluated where it has been found that in certain cases as much as half of the dry strength of blocks is lost when blocks become saturated.

Consequence of using such blocks in saturated conditions could potentially be disastrous, if stresses exerted by the wall on the block exceed the blocks allowable stress limit. Thus, three chemicals, namely Masterseal 550, Masterseal 501 and Acronal S400 are used to waterproof blocks and in turn increase the saturated strength and durability properties of Hydraform blocks.

Compressive strength and other CSEB durability measures such as resistance to abrasion, resistance to water uptake and water sorptivity testing are used to compare blocks produced without chemicals to blocks produced with chemicals additives.

Through the mentioned durability measures it is found that Masterseal 501 increases the dry and saturated strength properties above that of any other chemical additives. To the contrary, it is found that Masterseal 550 and Acronal S400 completely protect Hydraform blocks against the ingress of water, whereas Masterseal 501 allows water absorption into the blocks. In addition, it has been found that increase of cement concentrations in blocks in the most effective measure in resisting abrasion or wind and rain driven erosion.

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1 INTRODUCTION

1.1 General

It is well known that the growth in the world's population is physically taxing the world of its renewable and non-renewable resources with associated environmental impacts. The UN-Habitat [39] reports that 5 million houses are needed annually to curb the current global housing backlog by 2050. The world is thus facing the dilemma of housing its ever growing population whilst preserving the environment for the needs of the future generation. Conventional construction methods use conventional construction materials (concrete, aluminium, steel and timber) which have high energy inputs for the production of these materials and environmental impacts generated in the construction process, including raw material use, waste generation, energy consumption and its associated air emissions.

In line with sustainable development and the urgent need to provide shelter for the world's growing population, there is a need for alternative environmental benign technologies in construction that lessen demands on renewable resources. One such technology is the dry stack interlocking compressed stabilised earth block (CSEB) which is used alternative to traditional brick and mortar construction.

In conventional concrete masonry little to no clay is allowed in brick/block manufacture [1], making Aeolian, river or crushed rock sands the preferred sands for manufacturing conventional masonry units. Whereas in CSEB production as much as 25% clay is allowed [1], allowing a wider range of local available soil to be used in the manufacture of CSEB. In addition to the above, the dry stack method used in CSEB improves on some setbacks in conventional masonry construction such as low construction speed, extra costs of mortar and difficulty in controlling workmanship in joints. Other advantages of using the CSEB over conventional concrete include [22]:

- Maximum utilisation of local available material
- Onsite block production reducing transportation costs
- Simple construction methods requiring minimal skilled labour reducing construction time and costs
- Earth material offering thermal and acoustic insulation
- As little as 5% cement content is used in CSEB in comparison to conventional concrete where as much as 15% cement content can be used

It has further been estimated [1] that the use of soil-cement as an alternative to conventional concrete masonry could save up to 40% in construction costs.

In spite of the mentioned advantages, studies have found that moisture weakens CSEB's reducing the strength of blocks [1, 8, 10, 20, 29]. Furthermore, Pave [29] and Walker [42] report that due to the higher clay and silt content coupled by the lower cement content found in the CSEB when compared to ordinary concrete masonry units, as much as half the dry strength of CSEB's can be lost when CSEB's become saturated. The loss in strength of blocks in saturated conditions could result in the allowable stress limits of blocks being exceeded, ultimately leading to the collapse of the wall in question.

Ongoing research at the University of the Witwatersrand with Hydraform (Pty) Ltd is geared at the development and improvement of one such dry stack CSEB alternative technology, namely, the Hydraform drystack CSEB. Tests undertaken at the University of the Witwatersrand include methods of compressive strength load application on irregular shaped blocks [29], block characteristic strength testing [29], full scale wall panel testing for strength properties[26], lateral load testing on wall panels [40] and seismic load testing of a full scale house[17]. The positive outcome of testing to current masonry design standards has led to the Hydraform block and construction technique being approved for non-load bearing single storey construction in South Africa (Agreement Certification) [22]. However little to no consideration has been given to the inherent properties of blocks and the resulting durability of blocks in their given design environment. This report will thus look into the durability of the CSEB, using the Hydraform block as a general representation of the soil-cement drystack technology where it is hoped inferences to similar technologies can be made from this study.

1.2 Problem Statement and Objectives of the Study

The general problems experienced by the CSEB are as follows:

- Inadequate understanding of soil properties (lack of reliable soil parameters) and the lack of appropriate building standards inhibit the use of CSEB technologies in many countries

- In water prone areas, i.e. flood prone areas, areas with high humidity or areas with high ground water table the strength and durability characteristics of CSEB is not fully understood. Limited understanding of block behaviour in water prone areas could possibly negate the use of CSEB as an alternative technology

Using the Hydraform block making machine to make sample test blocks, this study will objectively look into:

- Tentatively suggesting material limits to be used in CSEB's, suitable block test methods and requisite block strengths

- Using chemicals other than Ordinary Portland Cement (OPC) binders to increase the strength and durability properties of soil-cement blocks

1.3 Scope of Work

The study will use a Hydraform mechanical block making machine to make CSEB. Soil texture will be assessed by mixing three different blend soils, namely a river sand (without clay), a clay soil and pit sand (small percentage of clay present). Cement content changes will also be studied to observe the effects of increases in cement content on the strength and durability properties of blocks.

Three different methods of unconfined compressive strength load application will be studied in order to assess the best measure of compressive strength testing.

Three waterproofing chemicals, namely Masterseal 501, Masterseal 550 and Acronal S400 are used to enhance the durability of blocks. Two will be added to soil-cement mixes and one will be applied as a coating to blocks.The measures that will be used to assess durability of blocks are the characteristic unconfined compressive strength of blocks, resistance to erosion by wire brushing and water ingress properties by water uptake and water sorptivity testing. The durability measures will be used to compare blocks made with chemicals to those made without chemicals

1.4 Layout of the Work

Chapters 1 – 3 introduce the work and touch on some literature regarding CSEB test procedures in practise. Chapter 4 details how blocks are produced for this study, in addition it details the type of chemicals used in this study.

Chapters 5 – 9 describe the tests carried out in this study and furthermore present results each individual test carried out. Test results for each respective test are also discussed. Chapters 10, 11 and 12 present conclusion and further areas on interest.

2 HYDRAFORM CSEB CONSTRUCTION PROCESS

The form of block used in the study is the Hydraform block, therefore the production process detailed will be the Hydraform block production process. Other CSEB have similar if not identical production procedures. The Hydraform dry-stack interlocking CSEB was developed by Hydraform Africa Ltd in 1988, where Hydraform blocks are produced by stabilising local available soils with small amounts of ordinary cement and mixed with small amounts of water. The mix is the compressed by a mechanically operated Hydraform block making machine under a compressive pressure of up to 10 N/mm^2. Various forms mechanical electrical and diesel power generated Hydraform block making machines are available. Figure 1, underlying shows a mobile diesel powered block making machine.

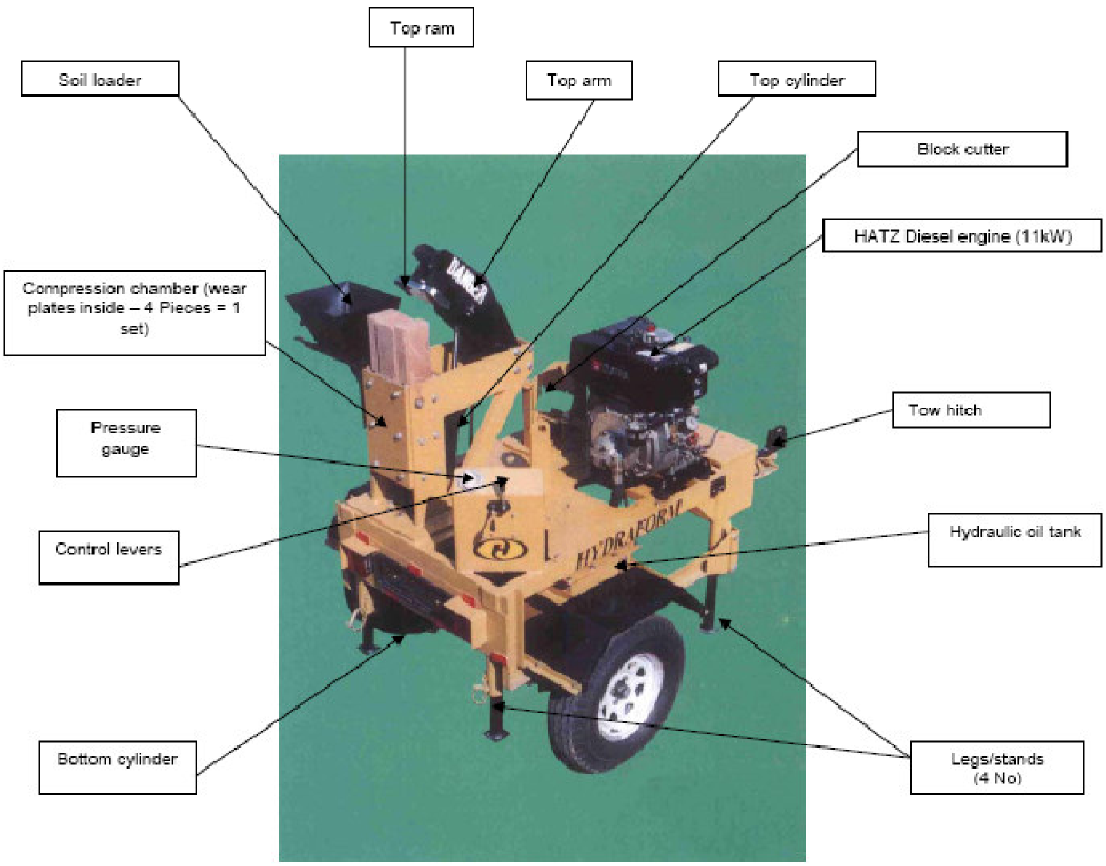


Figure 1: Mobile Hydraform block making machine [22]

Soil Selection

The soil for block production is typically sourced from the site where block production takes place. The soil sourced for block production must be free from topsoil, soil with organic material usually found up to 1m below ground surface. The is dug up and then sieved through a 6 – 8mm aperture size sieve before being mixed with small amounts of water and cement, either manually or by pan-mixer. It must be noted that mixing by drum-roll mixer is not recommended due to the balling effect of mix [22]. If expensive laboratory testing techniques are not available, as in most rural settings, soil may be selected by the following:

Visual Test - Soil below the topsoil layer is obtained. Very sandy soils or very clayey soils are not suitable for block production. Very clayey soils are usually visible by the presence of a large number of cracks in the soil. Very sandy soils are usually visible by by the lack of plasticity in the given soil.

The Jar Test - A jar is filled with a third soil and two thirds water. The jar is then shaken vigorously for 5 minutes and left to settle for 24 hours. The soil will settle in gradations, sand, clay and silt. Ideally clay should be between 15 and 35%.

Shrinkage Test - A rectangular shrinkage box is filled with wetted soil and left to dry in the sun for five days. Shrinkage is measured with a ruler. ideally shrinkage should be between 20 – 40mm.

Drop Test - This test is required to check the moisture in the mix for block production. The soil-cement-water mixture is squeezed in one hand, the resulting ball is dropped from waist level, if the ball shatters into many pieces it is too wet, if ball breaks into five to six lumps then right content, if ball does not break then the mix is too dry.

Figure 2: Sieving of soil for block production

When soil laboratory analysis techniques are available, soil can be analysed using conventional methods to determine soil gradation and Attenberg Limits. Hydraform recommends the soil limits as presented in table 1.

Table 1: Recommended limits for properties of soil suitable for soil-cement mixes

Soil Range	% passing 0.075 sieve		Maximum Plasticity Index	Estimated Cured Compressive strength
	Min	Max	%	(MPA)
A	10	35	15	4
B	10	25	10	7

A minimum of 10% clay and silt content is recommended for cohesion during block handling. Hydraform [22] suggests that more than 35% clay content comprises block strengths and that blocks and that high silt and clay content must be blended with more sandy soils.

Block Production

Not withstanding the limits in Table 1, the following strengths are achievable: 5% Cement (by volume) produces a 4 MPa block and 8% Cement gives a 7 MPa block [22]. Figure 3 shows typical block dimensions when optimum soil, cement and water are used.

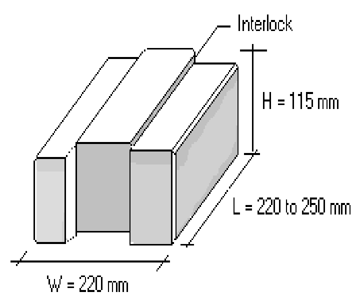


Figure 3: Standard Hydraform block dimensions

Blocks are cured under plastic sheeting for up 14 days before they can gain adequate strength for use. Hydraform further suggests that in hot, dry climates blocks be watered with watering canister twice daily. Enough water is to be used to facilitate the hydration of cement, but not too much water is to be used such that the block slumps whilst being handled. The optimal water content is initially gauged by the drop test and then finally by the length of block produced. Hydraform [22] recommends that blocks be between 225 mm and 235 mm of length. A tape rule can be used to measure blocks produced. If blocks are longer than 235 mm, there is too little water in the mix, whereas blocks produced shorter than 225 usually have vertical cracks along the length of the block indicating that the mix is too wet. Consistent block lengths are maintained keeping water in the soil-cement mix consistent. High clay contents in addition to compromising the strength cause horizontal and vertical cracks in blocks within 7 days of block curing.

Figure 4: Block mixture too wet, horizontal cracks formed, block sticks to rammer

Figure 4 illustrates a block cast with excess water and then extruded from the Hydraform machine. A shiny glean watery surface is visible over the extruded area of block accompanied by latitudinal cracks.

Construction Process

Hydraform blocks are laid in stretcher bond, with the typical building technique illustrated in Figure 6 on the page to follow. The base course is laid in mortar up to one course above the 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 as shown in Figure 5(a). Figure 5(b) shows a completed house built with Hydraform blocks.

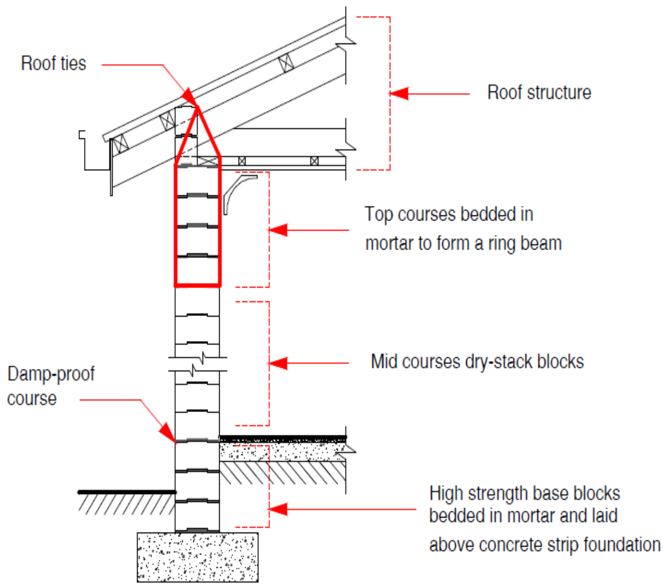


Figure 5(a): Section through a single storey Hydraform House **Figure 5(b): Typical Hydraform house completed**

Higher strength blocks are required below damp proof coursing, as illustrated in figure 5(a). Soil-cement blocks loose strength when they become damp, thus blocks of higher than ordinary strength blocks are required where there is possibility of blocks being dampened. Figure 6 shows the stretcher bond formation of the midcourse dry-stacked blocks.

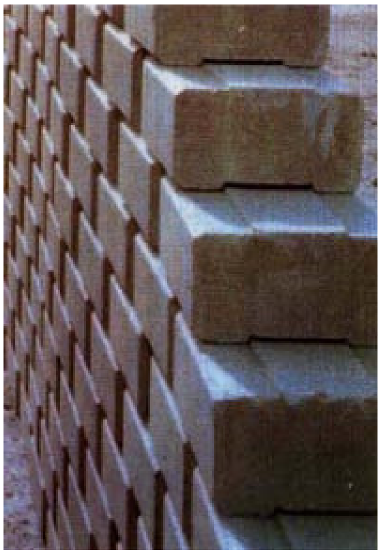


Figure 6: Dry Stacking at Mid Course Level [26]

3 DURABILITY IN THE CSEB CONTEXT

Every manmade structure, irrespective of the construction material used (steel, aluminium, stone or concrete) used to build it, deteriorates with time. The only aspect which one can determine and control is the rate at which the different materials deteriorate. The above underpins the study of the durability of construction materials and the use of the various construction materials in differing environments. If we look at the CSEB in particular, the three factors that influence the durability of CSEB are shown in Figure 7 below.

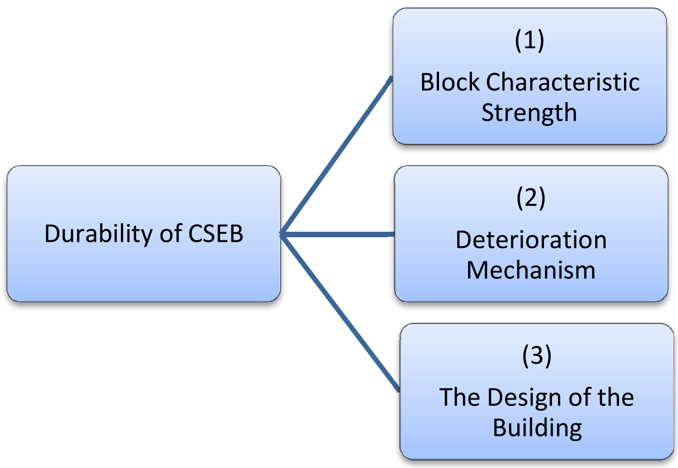


Figure 7: Factors influencing the durability of CSEBs

The three factors are further detailed below:

1. *The characteristic strength* of individual blocks determines the load carrying ability of walls built with CSEBs. If the strength of blocks is below the stresses exerted on the blocks by the wall, the wall in question will collapse. To fully understand the strength property of soil-cement, one must look into the elements that make block strength, elements such as type of soil used to make the block, the type and amount of binder used, the block production and the curing process. Soil characteristics, block production and curing effects have been discussed in Chapter 2. Discussion on the use of different type of strengthening binders is beyond the scope of this study.

2. Three predominant *deterioration mechanisms* affect CSEBs. Firstly the strength of CSEBs can be weakened if water is allowed to permeate into or through blocks. Secondly, if blocks are used as face blocks, erosion of blocks caused by impacting raindrops can severely hamper the aesthetic outlook of the building. Thirdly the affects of chemically aggressive environment on CSEBs is unknown and has potentially disastrous consequences. The first two deterioration mechanisms are outlined in next section,

however the affects of chemically aggressive environments is outside the scope of this study.

3. Building design is an important factor when the CSEB technology is considered. Buildings with long roof overhangs will protect blocks from rain driven erosion. Moreover a cement plaster can equally protect buildings for rain erosion. In situations where protective covering is provided over blocks attention need not be paid to deterioration of buildings due the rain driven erosion.

Consequently, when studying the durability of CSEBs used in building construction, one must study the interaction between the design of the building, the prevailing environmental conditions and associated deterioration processes. For the purpose of this study the durability a CSEB will be defined as the ability of a block to meet both strength and appearance parameters over the service life of the block, under given design conditions, without undue loss to both parameters.

The sections to follow will present literature on the mentioned deterioration processes, describing water transportation mechanisms affecting the strength of CSEB and rain driven erosion. Standard test methods that evaluate the given deterioration processes will also be described before mentioning broader studies that have touched on the deterioration mechanisms and CSEB technology in general.

3.1 Deterioration Mechanisms in CSEB

3.1.1 Strength of CSEB

Studies on the compressive strength of CSEB's [1, 8, 9, 14, 20 - 21, 24, 29] report that the strength of blocks is improved by increased compactive effort and increases in cement content, whereas strength of CSEB's is reduced by increased moisture and clay contents.

Quality control of CSEB's using the compressive strength parameter has often followed procedures developed for burnt clay and concrete block units. Morel [24] however points out that the strength of CSEB's may be, at many times lower than ordinary burnt clay or concrete blocks because the strength of CSEB's is sometimes influenced by the blocks hygroscopic moisture content at the time of testing. Much academic debate has surrounded the conditioning of blocks at time of testing [24]. Most masonry standards (Eurocode, BS, SANS, ASTM) adopted method of unconfined compressive strength is indicated by equation 1.

Compressive Strength = Max Load at Failure/Average Net Area of Compression ………(1)

Normative documents published in Zimbabwe, Australia, France and the USA, reviewed by Delgado and Guerrero [15] indicate CSEB standards, compressive strength standards range between 1.3 and 2.1 MPa for use in non-load bearing walls. However Deboucha and Hashim's [14] study find that in practise typical compressive stresses in up to 1 storey construction range from 1 – 4MPa.

ASTM C62 [3], BS EN 771 1-3 [11, 12] and SANS 1215/SANS 227 [33] are some of the national standards prescribing minimum compressive strength of solid clay and concrete masonry units, where the minimums are given by 8.6, 5 and 3.5 MPa respectively. Mention is however not made of the condition of bricks before testing, i.e. are to be tested when dry or when saturated. Invariably national standards require somewhat higher strengths to account for all design possibilities.

3.1.2 Physical attack by water, relating to strength of CSEB

CSEB's are commonly used for up to one storey construction. In structural masonry design, blocks used to construction buildings up to one storey are referred to as non-load bearing implying minimal stresses are found in these type walls. Guillard et al [19] point out that the stability of dry-stack masonry is dependent on:

- The quality of the block itself
- The bonding pattern between blocks,
- The quality of design of the building system (ensuring good protection against natural elements by providing protection such as longer roof overhangs)
- The quality of execution of works

Focusing on the quality of block in use, the quality of CSEB is in turn dependent on, amongst others, the properties of the soil used, the type and amount of stabiliser used, the block production process and humidity of the block at point of testing [19]. Figure 8 illustrates how weakening effect of water on CSEB which might leading to effected blocks being weaker than stresses developed in the wall, ultimately causing structural failure and the wall to topple. Such failure can be averted by ensuring adequate saturated strength design of blocks and or adequate protective measure to ensure no passage of moisture through the block. Figure 8 shows the weakened block failing through crushing. The block crushes due to it being weakened by ingress of moisture, creating stresses in the block below the stresses found in the wall.

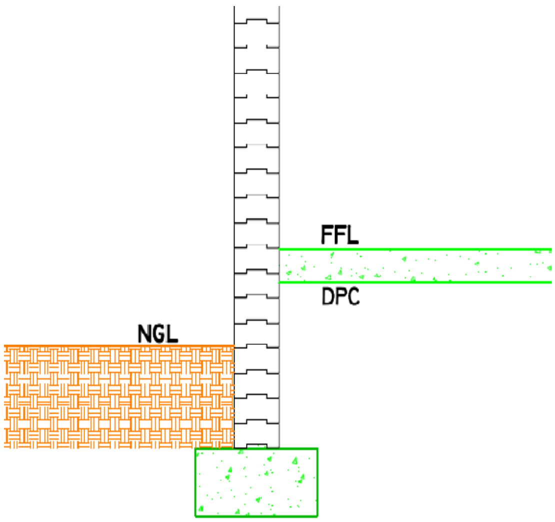


Figure 8: Long term effect of humidity on external wall constructed using CSEB

Literature highlights the following two mechanisms by which water can travel through mass concrete and or soil cement [31].

Permeation – The flow of water by means of pressure head acting on the block. In this mechanism, water travels from a higher pressure to a lower pressure through interconnected voids or through the weakened mass of soil cement itself.

Absorption – Also known as capillary action, soil particles themselves have an affinity for water, the water is drawn into the pores of unsaturated material through capillary forces.

Problems relating to CSEB use in areas prone to inundation or intermittent wetting are as displayed in Figures 9, 10 and 11.

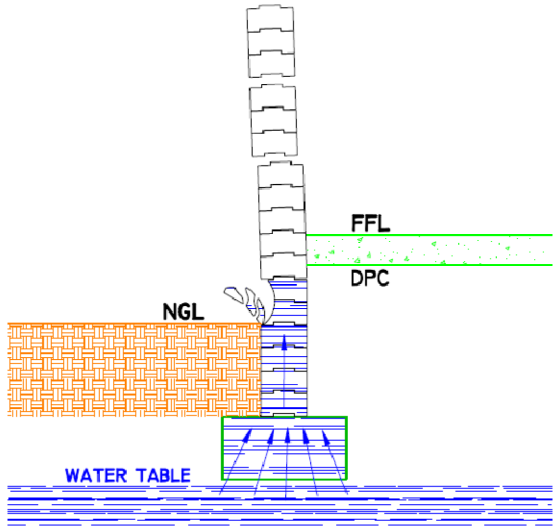


Figure 9: Sketch showing absorption caused by capillary action

Figure 9 shows a water table at the base of the footing, water rises up into the block from the base of the footing due to capillary action. The water subsequently weakens the blocks leading to the failure situation illustrated in Figure 9. Capillary action can be caused by the seasonal fluctuation in watertable or water retention by plants growing close to the wall.

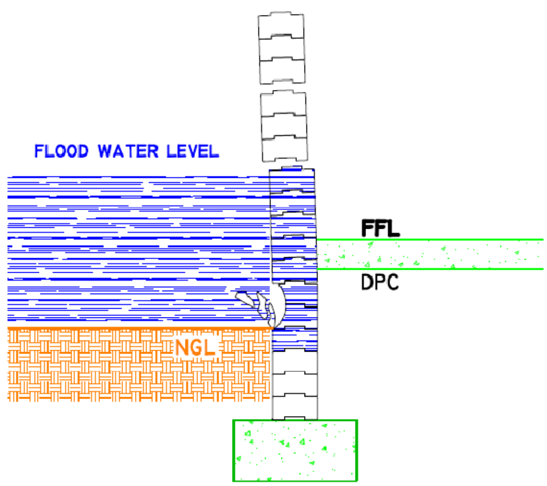


Figure 10: Sketch showing permeation caused by inundation

Figure 10 shows a water table above ground level. This is caused by flooding leading to inundation of the area around the wall. Permeation of water through the block ultimately leads to strength loss of effected blocks which could subsequently cause structural failure.

<u>Testing undertaken to assess deterioration by water</u>

Water uptake test is undertaken in order to determine how much water fills the voids of masonry units when submerged underwater. This limit is a useful property in determining burnt clay masonry units' susceptibility to degradation from freeze thaw action or how much water will be taken from blocks placed on mortar when blocks are laid without mortar. Prescribed limits fall below 10% [1]. Equation 2 presents the formula used to calculate water uptake.

$$W = (M - N)/M \times 100 \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Where:

W = the mass of water absorbed during the time interval, expressed as a percentage of inital mass of the block, i.e. the rate of absorption

N = the initial mass of the block in grams

M = the mass of the block at specified time interval

The water absorption test has merit in being simple and can give results that compared with other samples on relative performance, but the results can however not be related to any absolute property, i.e. porosity or permeability [31].

The water penetration test is a national (ASTM E 514M, SANS 10400 Part K) standardised test used to assess the ability of a masonry wall to resist water penetration and leakage. A spray pipe is positioned and spray jet of 50 kPa is directed at the wall for 24 hours on one side of the wall whilst observations of dampness are made on adjacent side of the wall. Testing standards require that the adjacent side of the wall not be dampened with water after 24 hours of spraying. Hydraform undertook testing according to SANS 10400 by treating two walls with different waterproofers. It was found that wet patches appear on both walls 600 mm from ground in both cases.

3.1.3 Physical Attack by Erosion

Figure 11 shows flow of droplets of water causing erosion of a CSEB wall. The source of water with kinetic causing erosion of CSEB walls is endless. For example possibilities like badly designed gutters, pitched rainfall or from passer-by cars splashing puddles of water on the wall. Any one of the above mentioned actions might cause the wall to erode and a subsequent loss of aesthetic appeal on effected area.

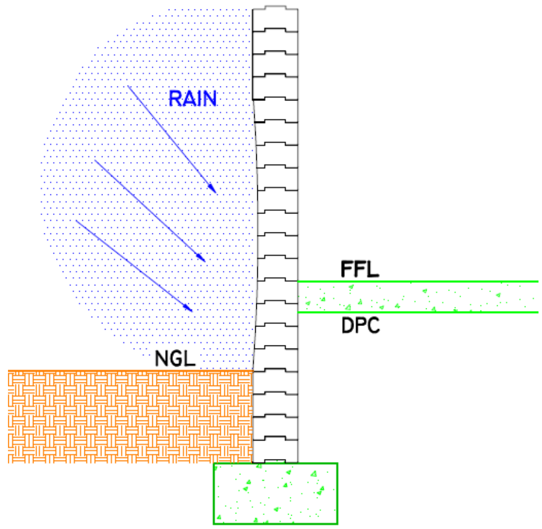


Figure 11: Sketch showing erosion of wall from flow of water leading to loss of aesthetic appeal

Testing undertaken to assess deterioration by erosion

The rain erosion test standardised by BS 4315 also known as the Bulletin 5 Spray Test dates back to the 1960's [28], this test mimics the effects of wind driven rain erosion on an individual block by spraying water on the block with up to 450 kN/m^2 pressure for an hour. Erosion of the block is measured by percentage loss in weight of the block. The spray pressure (intensity of rain), particle size and distance of nozzle from the block can be adjusted in order to calculate terminal velocities and in turn correlate simulated velocities to natural occurring rain drop velocities. Ola and Mbata [28] recommend a percentage mass loss from erosion of less than 3%.

Wet dry durability testing is a form of abrasion testing first used in road pavements applications; it gives indication of the soil-cement durability to the natural element of erosion. Heathcote [21] established that the principal mechanism causing removal of material from the surface of earth walls results from the release of kinetic energy associated with raindrops impacting on the surface. The resulting erosion is dependent on the roughness of the wall, the intensity of the rainfall, angle of the rainfall and the extent of protection from the overhangs. Heathcote [21] used the wet/dry durability test to measure the mentioned erosion. Heathcote further suggest for Permanent buildings in urban areas where rainfall is less than 500mm, a 5% loss and where rainfall is more than 500mm a 10% loss.

3.2 CSEB Studies in Literature

Blight [10] – Durability of and Material Characteristics of Soil Cement Blocks

Blight looked at the durability of Hydraform soil cement blocks by varying the cement content (0, 4, 6 and 8 percent) of a block and undertaking strength, drying shrinkage, wet/dry durability, sorptivity and spray jet testing. Two soil samples were chosen to manufacture test blocks, firstly decomposed granite and secondly quaternary sand. Blight used a combination of 85% Portland cement blended to 15% fly ash. Soils used were not classified according to any soil grading standards.

Blight reports that the addition of 4 percent OPC15FA (85% Ordinary Portland Cement 15% Fly Ash blend) will give an average block strength of 3MPa at 28 day strength for 'most' soils. It must however be noted that Blight tested the dry strengths of blocks only. Blight also does not indicate the compactive pressures used to compress blocks.

Moreover, the addition of 4% OPC15FA reduces rain induced erosion of bricks, where this amount is also sufficient to prevent abrasion damage. The porosity of soil cement blocks is reduced by increasing the concentration of OPC15FA used in mix design. Blights study concludes that a 4%OPC15FA blend produces durable blocks suitable for one storey load bearing masonry construction.

Walker [42] – Strength, Durability and Shrinkage Characteristics of Cement Stabilised Bricks

Walker studied the influence of soil characteristics and cement content on the physical properties of stabilised bricks. Walker mixed two soil types together, one a clay soil with 50% clay content and a river soil with 1% clay content to get a combination of soil properties. A manually operated machined was used to press blocks, under compaction pressures of 4MPa. The blocks were then cured under polythene sheeting.

Both saturated and dry unconfined compressive strength testing was undertaken. Shrinkage was assessed using a 200mm demec gauge. Determination of the resistance to water erosion was undertaken by means of the wire brush test specified in wet/dry durability test.

Dry compressive strength ranged between 5.54 MPa and 3MPa whilst saturated compressive 0.95 and 3.2 MPa. Compressive strengths varied largely depending on the clay content. Walker concluded that clays have a uniaxial dry compressive strength which is lost with saturation.

Drying shrinkage of the blocks is primarily governed by plasticity index of the parent soil. Once the plasticity index exceeded 20, there is a steady increase in drying shrinkage with increasing clay content.

Resistance to abrasion from the wire brush is improved with increasing cement content and reduced by clay content. Cement acts to bond soil particles together whereas clay minerals disrupt cement bonding. At 10% cement content, at maximum clay content, 11% mass is lost whilst at minimum clay content 1% mass is lost.

Water absorption increases with increasing clay content as a greater portion of water is absorbed by the clay minerals. Thus porosity increases as clay content increases. Moisture attracting characteristics of increasing clay content. Water absorption ranges between 13.4 at highest clay content and 8.2% at lowest clay content.

Pave [29] – Strength Evaluation of Dry-Stack Masonry

Pave looked at the structural behaviour of Hydraform CSEB by investigating the unit compressive strength, masonry wall compressive strength and flexural resistance of dry stack masonry/reinforced concrete beams. More to the point of durability, Pave looked at three type compressive strength tests, the shoulder test, the centre test and the cube test for block strength evaluation. These tests were carried out during dry, wet and normal humidity conditions. It must be noted that the soil properties used by Pave in the assessment of strength are not presented.

From test results Pave found that wet strength is approximately 60% of normal strength and that the shoulder test was an adequate measure of block strength. Pave also recommended that a minimum strength of 5MPa for testing be maintained. Pave further recommends the following nominal block strengths, based on shoulder testing

Table 2: Recommended nominal block strengths for Hydraform blocks [29]

Cement Content [%]	Compressive Strength [MPa]
5	3.0
7	5.0
10	8.0
15	10.0
20	12.0
25	14.0

Obonyo et al [27]: Durability of Compressed Earth Blocks: Assessing Erosion Resistance Using the Modified Spray Testing

Obonyo et al looked at spray testing of compressed bricks from Tanzania in order to counter deterioration due to wind driven erosion. The impacts of using cement, lime, fiber and a commercial stabilising fluid were assessed. Compressed blocks were benchmarked against a standard factory produced bricks. Factory produced bricks hardly eroded whereas the depth of erosion of soil-cement blocks maximum depth of erosion was 40mm. Inclusion of natural fibre in bricks sharply increase the rate of erosion.

Drying Shrinkage in CSEB

As humid soil-cement dries, water is expelled from the pores of the soil, accompanied by a reduction in volume of sample. Drying shrinkage is this reduction in size of sample due to the water being expelled from the pores of the soil-cement [30]. CSEB's are allowed to dry before being used in walling, thus the drying shrinkage of blocks occurs before blocks are used in construction.

If CSEB are used in conventional masonry construction, drying shrinkage is usually not an important design parameter. This is due to the mortar between joints giving leeway to reduce block dimensions (shrinkage of blocks). Shrinkage of CSEBs used in conventional construction will thus not cause the collapse of the walls built with blocks.

However in drystack CSEB construction, dimensional exactness is of critical important. In order for blocks to interlock in the drystack manner, they have to be of exact specific dimensions. Drying shrinkage of blocks with different shrinkage characteristics could result in overlaying drystack blocks with improper fit to underlying drystack blocks ultimately leading to the instability of the wall. Thus dimensional tolerances for dry-stacked CSEB need be more stringent than ordinary units. SANS 227 [33] South African Standard Specification for Burnt Clay Masonry Units denotes the drying shrinkage test procedure, however no specified shrinkage limits were found in reviewed literature.

Summary of Test Results from Literature

Table 3: Summary of durability results obtained from various sources

Country (Author, date)	Compactive Effort (MPa)	Clay Content (%)	PI (%)	Cement Content (%)	Wet Strength (MPa)	Dry Strength (MPa)	Absorption by Water Uptake Test (%)	Abrasion by Wet/Dry Durability Test (%)
South Africa (Blight, 1994)	10	12	-	0	-	0.9	-	-
				4	-	4.17	4.2	14.6
				6	-	4.2	2.75	11.7
				8	-	7.93	2.72	10.6
Zimbabwe (Walker, 1997)	4	9	10	5	1.6	3.67	14.6	4.9
			10	10	3.2	7.11	13.1	0.7
		40	35	5	0.3	0.3	27.3	75.7
			35	10	0.95	2.13	25.9	25.7
Algeria (Guettala et al, 2005)	15	18	14	5	9	15.4	8.27	1.4
				8	12.7	18.4	7.35	1.25
South Africa (Pave, 2009)	10	-	-	5	3.1	6.1	-	-
		-	-	7	4.8	8.2	-	-
		-	-	10	9	13.6	-	-

Table 3 presents different studies of various aspects that affect the durability of CSEBs. Commonly found CSEB durability measures are also presented. Generally what can be observed from the above results is that the strength of CSEBs is dependent on the compactive effort imparted by the block press, the clay and cement contents of the soil-cement-water mix used to make blocks. Increases in cement contents are accompanied by increases in wet and dry strength, whereas increases in clay content reduce wet and dry strengths.

What would be a helpful observation is whether the wet strength increases or decreases with amount of compactive effort imparted to the soil; however such studies are yet to be undertaken thus. One must note that the results presented by the different authors cannot be conclusively compared owing to the fact that varying block parameters (soil characteristics, compactive effort, and cement content) are used in each individual study presented. The resulting durability measures used to assess the quality of blocks depend on the block production parameters.

The methods of compressive strength testing are also unknown, where incorrect testing procedures affect the outcome of results. In general what the above results show is that with increasing wet strength, generally resistance to abrasion and resistance to water uptake increase. This shows the connection between strength and durability of blocks, in that the increase in strength of CSEB's leads to increased durability of blocks.

4 BLOCK PRODUCTION

This chapter details the different types of soils used to produce blocks in this study and the blocks production process. The chemicals used to enhance durability properties of blocks are described.

4.1 Soil Properties

Combinations of three different soils were used in this study to make Hydraform blocks. The three soils are mixed at different quantities to achieve soil properties (clay content, plasticity index) in order to compare properties and report on the strength of blocks. The properties of the natural soils (Soils A to H) are presented in the Table 4, where Soil A is a river sand, Soil C is a pit sand and Soil H is a red clay brick soil, all sourced from the greater Johannesburg area, South Africa.

Table 4: Soil Properties used for block production

(%)	Soil A	SOIL B 50% Soil A + 50% Soil C	Soil C	Soil D 90% Soil C + 10% Soil H	Soil E 85% Soil C + 15% Soil H	Soil F 80% Soil C + 20% Soil H	Soil G 50% Soil C + 50% Soil H	Soil H
Gravel (2 - 6mm)	23.52	15.77	1.12	8.79	7.01	7.37	6.58	5.59
Sand (0.06 - 2mm)	73.00	75.58	83.48	75.71	76.65	69.88	53.98	44.54
Silt (0.002 - 0.06mm)	2.70	5.77	7.78	7.02	6.75	9.05	14.36	12.85
Clay (< 0.002mm)	0.78	2.88	7.62	8.48	9.54	13.71	25.08	37.02
Specific Gravity (Gs)	2.68	2.67	2.67	2.67	2.67	2.65	2.63	2.42
Liquid Limit (LL %)	Non-plastic		23.25	26.75	26.85	27.25	36.25	46.00
Plastic Limit (PL%)			22.59	22.64	22.59	22.94	28.11	33.08
Plasticity Index (PI%)			0.66	4.11	4.26	4.31	8.14	12.92
Linear Shrinkage			2.00	3.17	6.25	5.64	6.51	8.73

A combination of the sieve and hydrometer method was used to obtain particle size distributions. The MIT soil classification system is used to classify the soil in terms of percentage gravel, sand, silt and clay. ASTM D442 [5] and ASTM D438 [6] are used to determine the particle size distributions and Attenberg Limits respectively. From Table 4 it is clear to see that an increase in clay content is accompanied by increases in plasticity indices and linear shrinkage. Figure 11 shows the cumulative grading of Soil A, Soil C and Soil H. In Figure 12, the area between Soil A and Soil H represents the envelope in which Soils' B – G are bound.

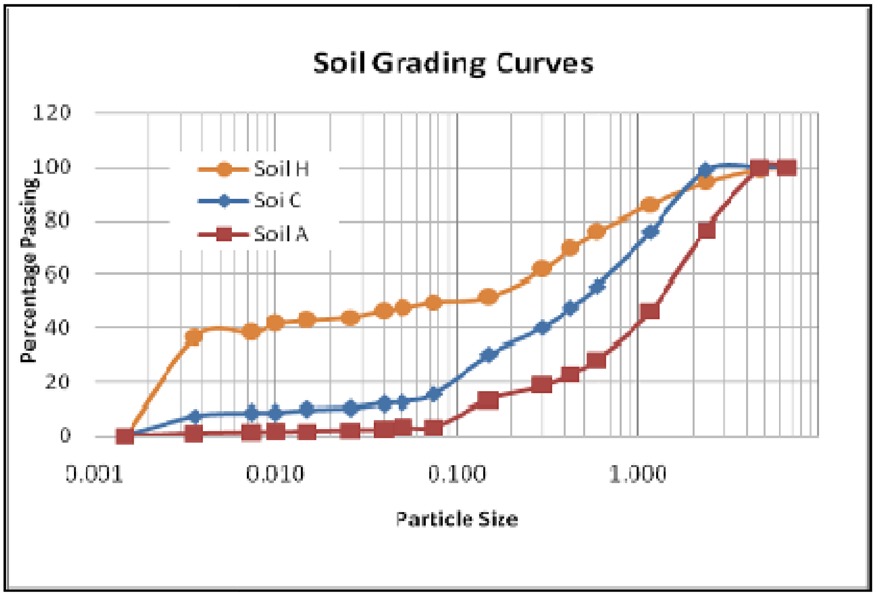


Figure 12: Soil grading curves for Soil A, Soil C and Soil H

4.2 Block Production Process

A pan mixer was used to mix the required quantities of combined soil thoroughly before cement and or the chemical additives are added. The contents are mixed in the pan mixer for up to 1 minute. Mixing continues with additives for a further minute after which the required water content is slowly added to the mix by watering canister. The watering process should take no longer than 1 minute whilst ensuring the contents is mixed thoroughly.

For same mix with recurrent block strengths, it is imperative to ensure that all contents are mixed consistently. The blades of ordinary concrete pan mixers operate at a faster angular velocity than required for soil-cement mixes, if possible the angular velocity of the blades need to be reduced in order to not create too many 'balls'[22]. Unlike concrete, due to the cohesive nature of soil-cement and its semi-dry state, rounded soil-cement balls form when water is added rapidly to a dry mix.

The 'balling' of soil-cement can also occur as a result of high angular velocity of turning blades. The larger the balls that form, the less consistent the mix is. The balling effect of soil-cement can be seen in Figure 13.

Figure 13: Example of soil-cement 'balling' effect when mixed with a pan mixer

Blocks are cured for 3, 7, 28 days before the various tests can be conducted on the blocks. The various tests conducted on the blocks require blocks to be tested at room temperature, oven dried and saturated conditions.

Each chemical has different application method and differing set/hardening periods, so specific curing methods will be presented in the relevant block production processes to follow. As for the generic block case, blocks were cast, where blocks requiring normal temperature curing were placed under plastic sheet between a temperature range of 21^0C and 23^0C for up to 28 days.

Blocks that are to be tested at a saturated state were cured under plastic sheeting for one day, before being placed in a water bath between a temperature range of 16^0C and 18^0C for the remainder of the required curing period. Blocks that are tested at oven dried state are cured for an initial curing period under plastic sheeting. They are removed one day before testing and are oven dried between temperature range of 70^0C and 72^0C for 24 hours before testing.

It must be noted that only ordinary CEM1 32.5 Portland cement was used as the cement binder in this study.

Figure 14: Blocks placed in the drying oven for dry over a 24 hour period

4.2.1 Blocks produced without chemicals additives

Reviewed literature suggests that the strength and durability of a CSEB is directly related to the proportion of clay and cement in the block. The full range of available soils was used to make blocks in order to assess the validity of literature. It is hoped more insight into properties effecting block strength and inturn the durability can be gained. It is also essential that soil properties used for the control block, the block used as a benchmark to asses the effectiveness of the chemical additives, represent a sandy soil >65% sand content and <10% clay content as recommended in literature [15].

Blocks were firstly produced by keeping the cement content constant and increasing the clay content (i.e. Soils A-H were all used to produce blocks). A 8% cement content is used to produce blocks to assess the effect of the changes in clay content on block strength. Secondly blocks were produced by varying the cement content whilst keeping the clay content constant. Soil D, with properties shown in table 4, an average sandy soil was used to produce blocks with varying cement content (3, 5, 8, 12, 16 and 20%).

Two strength type control blocks (Control blocks A and B) were further produced with the hope that, firstly results of blocks produced with chemicals can be benchmarked again the first block with minimum cement content. Control block A is produced with 8% cement and Soil D. The secondly reason is to increase chemical dosages in blocks in hope of achieving similar properties to the second control block which has uneconomically high cement content and of higher quality than the first control block. Control block B is produced with 20% cement and Soil D.

4.2.2 Blocks produced with chemicals

Admixtures are materials other than cement, water, aggregates and cement extenders which are added to the cement mix before or after mixing [1] in order to enhance the quality of concrete or soil-cement. Coatings on the other hand are chemicals that are applied as a protective coating to area of interest. They may be either in solid or liquid form. The history of admixtures is sparse, with no literature available on the use of admixtures in soil-cement applications. Only literature available is on application of waterproofing admixtures in applications that use concrete, thus application of waterproofing admixtures in this case can be considered first of a kind.

Two types of waterproofing admixtures are available, one that imparts water-repelling or damp-proofing properties *(hydrophobers)* Water-repellents or hydrophobers reduce the passage of water through concrete by capillary action. Principally these materials impart a water repellent property to the concrete surface as well as lining the pores with the repellent material. It has been suggested [31] that the action of water repelling is achieved by imparting an electrostatic charge on capillary walls. Materials from selected petroleum products are common water repellents. Secondly, there is an admixture that reduces permeation by blocking pores *(permeability reducers).* Permeability reducers are usually very fine materials that have some form of pozzolanic reactivity densifying the cement gel matrix by the replacement of coarse calcium hydroxide crystals by finer gel-like hydrated calcium silicate products, thereby reducing the permeability of the material.

Permeability reducers may reduce permeation and absorption, whilst water repellents may not reduce permeation under positive head of water. In each group they may be reactive or non-reactive, in other words when the admixture comes into contact with the wet cement a chemical interaction occurs resulting in a new product being formed which imparts the waterproofing property [31].

Two different admixtures and one chemical coating were supplied by BASF Chemical Company South Africa. Information on whether the given admixtures are water repellents or hydrophobers is not given, thus permeation and absorption by capillary action testing will conducted in order to ascertain the waterproofing mechanism. The properties and application methods of each admixture are presented below:

Acronal S400

Acronal S400 is a polymer based admixture. Areas of application include waterproofing basecoats for concrete products, protective coatings, anti-corrosion protective coatings and as an additive for hydraulic binder systems. Acronal S400 can be applied both as a coating and as an additive to the binder system, however it is not specified if it retains its waterproofing qualities as an additive to the binder system.

Acronal S400 is supplied as a concentrated solution and needs further dilution with water before it can be applied. **For the coating application**, blocks are produced with same design-mix (water-cement-soil) mix as control block A. The coatings are applied after 1 day of curing under plastic sheeting. BASF recommends that product be applied first as a primer at 1 part chemical to 8 parts water. The water and admixture together are mixed in a clean bowls and then applied with soft bristle brush. The primer is allowed to dry for at least 24 hours before the base coat is applied. The base coat dosage was coated at varying concentrations; at 1 part water to (8, 6, 4, 2 and 1) part water and applied as mentioned before. As for blocks tested in dry and oven dry states, there is no difference to the procedure detailed section 4.2.

Whereas blocks that are tested at saturated conditioning are allowed to dry for a further 24 hours subsequent to the base coat application. After the drying period, the blocks are immersed in water for the remainder of the curing period. Blocks coated with Acronal S400 are tested at dry, saturated and oven dry states at 3, 7 and 28 days.

Figure 15: Acronal S400 supplied in a 100/ drum

Acronal S400 added to the hydraulic binder system reduces the soil-cement mixes water content by amount of additive. So as the amount of water is calculated for normal mix as for Control block A, the water required is lessened by amount of admixture used. The reduced water is mixed thoroughly with the admixture in a clean bowl and then a watering canister is used to add the water-admixture mix to the soil-cement mix.

Additive concentrations are taken as a percentage weight of total cement formulation (5, 10, 15 and 20 % cement content). Blocks were produced with Acronal S400 as an admixture are tested for 3, 7and up to 28 days at dry, oven dry and saturated conditioning. Blocks at the saturated condition were immersed in water after 1 day room temperature curing up until date of testing.

Figure 16: Solution of Acronal S400 about to be applied to blocks as a coating

Masterseal 501

Masterseal 501 is supplied in powdered form in 25kg bags as an additive to the soil-cement mix. By definition, Masterseal 501 is a corrosion free concrete waterproofing admixture used for treatment of concrete products against water intrusion, leakage, cracking, chemical attack and corrosion of steel reinforcement. It reacts with the hydration products of cement to form crystals within the pores and capillaries of concrete structures, thereby effectively blocking the passage of water. It is claimed that complete waterproofing is usually achieved within 7 days of final set.

This form of admixture is batched and added to the soil just as cement is added before water is added into the mix. The addition of this admixture is said to increase strength of standard concrete over the control mix and reduce shrinkage and permeability properties of concrete. Control block A's mix was used as the design soil cement mix for block production. The admixture was added to the soil-cement mix in 5 dosages as percentage weight of total cement formulation (5, 10, 15, 20 and 50%). Blocks produced with Masterseal 501 are tested for 3, 7, 28 days at dry, oven-dry and saturated conditions. Blocks at saturated conditioning are immersed in a water bath after 1 day normal atmospheric curing until date of testing.

Masterseal 550

Masterseal 550 is a waterproofing coating supplied as a double pack, it is applied as a coating only. A 20kg cement fined grained powder and a liquid component. Masterseal 550 is composed of specially selected cements, silica sand and reactive fillers supplied in powdered form together with a liquid component of blended acrylic copolymers and wetting agents. It is furthermore claimed that Masterseal 550 is extremely effective barrier to atmospheric carbonation causing gasses in concrete structures. The chemical also prevents ingress of water vapour to the structure that is being protected.

Figure 17: Masterseal 550 in bag and bottled form, contents also mixed in mixing bowl

Surface preparation is of paramount importance as no contaminants that impair adhesion are required. The contents of the liquid are mixed to the solid content at 2 volumes powder to 1 volume liquid. Mixed content is applied with a stiff bristle brush. It is recommended that each coat being applied be at least 1mm thick. Only one coating of Masterseal was applied to blocks.

Control block A mix was used as the soil-cement-water design mix for blocks coated with Masterseal 550. Masterseal 550 is only applied to the blocks as a coating, where only one coat is applied as recommended. Blocks were initially cast as control blocks and then coated with Masterseal 550 after a day of curing under normal atmospheric conditions. In addition, blocks produced and coated with Chemical C are allowed to for 24 hours before being immersed in water. Blocks produced with Masterseal 550 are tested in dry, oven dry and saturated states at 3, 7, 28 days and up to three months.

5 UNCONFINED COMPRESSIVE STRENGTH TESTING

5.1 Test Procedure

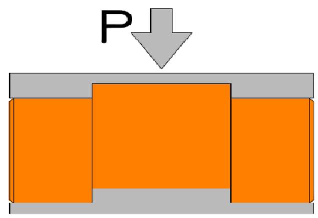
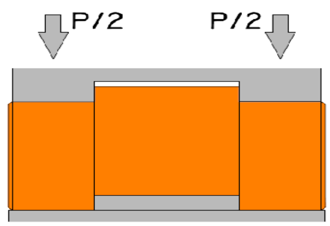
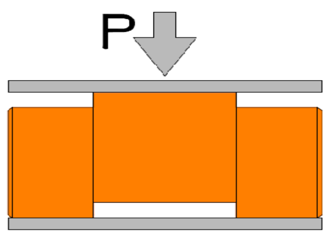
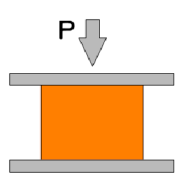
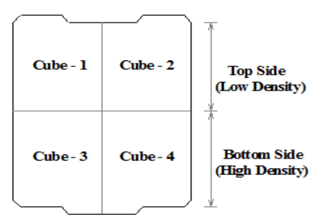
Studies show that the unconfined compressive strength of masonry units is usually directly related to other durability properties such as resistance to abrasion and water absorption [24]. Thus the unit of measuring the quality of a masonry unit is usually specified as the characteristic unconfined compressive strength. For the above reason National Codes (ASTM, BS, SANS) specify grades or classes of masonry units synonymous with the compressive strength and quality of units. Different grades of masonry units have different applications, for example a grade 1 masonry unit can be used for non-load bearing masonry walls only. A grade 2 unit would can be used for non-load bearing including load bearing masonry walls and a grade 3 unit can be used for both the above where units are susceptible to the action of freeze-thaw.

Although masonry standards specify classes for conventional regular shaped masonry, the general problem with interlocking CSEB's is that the blocks are usually irregular in shape, with each specific type block having its unique particular shape. In addition each unique shaped block employs a unique method of interlocking, be it with or without mortar, where international masonry standards describe and standardise construction methods for regular mortar bonded masonry units. This makes it difficult to standardise each unique blocks construction technique, making it all the more harder to develop a unified code of practise for irregular shaped interlocking blocks.

Looking at the characteristic strength of individual masonry units only and not the blocks' construction techniques', ASTM [4] and BS [12] codes of practise recommend that irregular shaped masonry units either be capped with mortar to even out irregular surfaces or that irregular surfaces be evenly saw cut. This is done to facilitate testing between flat parallel compressive strength testing platens.

However, neither of the two methods described above were used to test the unconfined compressive strength of the blocks used in this study. The methods described are simply too tedious. Four simpler methods of compressive strength assessment were adopted for ease of testing methods, namely; the block was loaded across the gross area, the block was loaded across the shoulder of the block, the block was loaded across the tongue and four 100 x 100 mm cubes were cut from the blocks and tested. Pave [29] tested similar block tests where results obtained in Pave's study will be compared to results from this study. Control block A mix is used to produced blocks and an average of six blocks are tested for each method of load application. Table 5 shows adopted methods, the loading arrangement and the methods' respective failure patterns.

Table 5: Methods of load application for irregular shaped Hydraform block and resulting failure patterns

Method of Load Application		Load Regime	Failure Pattern/ Cube Loading Arrangement
1	**Load application across the gross area of the block**		
2	**Load application across the shoulders of the block**		
3	**Load application across the Tongue of the block**		
4	**Testing of Cubes**		
		↑ Colour Scheme: Brown - Hydraform Block Grey - Platen	

Method 1 entails loading the block across the full width and breadth of the block. Special steel platens were manufactured to be placed within the grooves of the blocks. This type of loading method is set to simulate behaviour of blocks in practise, where blocks are laid in an interlocking tongue and groove manner and all voids are filled with mortar. Similar method of load application has been recommended by Deepak [16]. Failure is recorded at first sign of block crushing. Crack that development on tested blocks are approximately parallel to the direction of applied load.

Method 2 simulates the behaviour of blocks laid in practise with no mortar between blocks. When blocks are laid in practise in this manner it is found that there is a small interface between groove and tongue of block above and below, respectively. If blocks are loaded by means of this given loading arrangement the shoulders fail with the remainder of the block remaining in tact.

Method 3 simulates the behaviour of loading a block centrally between two platens, with voids remaining between the top platen and tongue, the bottom platen and underside groove area. It is expected that the block fail in shear because of loading method restrains bottom two sides of block whilst top platen pushes tongue area only.

Method 4: Standard concrete testing procedure requires cubes of 100 x 100 mm to be cast and tested in order to estimate the strength of concrete. Four cubes were cube from each block, two blocks from the top half and two from the bottom half of the block. The part extruded first from the machine is known as the top side whilst the part nearest the bottom rammer is known as the bottom. The cubes are then tested in a dry state under a uniformly applied load.

5.2 Results

Methods of Load Application

Table 6: 28 Day strength of blocks compressed with different methods of load application

	Pave [29]		Current Study		
Load Application	Strength MPa	% of Shoulder Load	Failure Load (kN)	Strength MPa	% of Shoulder Load
Along the Tongue			23.32	1.01	24.6
Top Cube	3.2	47.8	22.7	2.27	55.4
Bottom Cube	5.3	79.1	29.6	2.96	72.2
Along the Shoulders	6.7	-	114	4.1	-
Along the Gross width of block	-	-	197.9	3.91	95.4

Table 6 shows the 28 day dry compressive strength of blocks (a block mix with 8% cement content added to Soil D) tested with the four different load arrangements. Pave [29] undertook similar tests on Hydraform blocks produced with 7% cement content. It is however not clear what type of soil Pave used to produce blocks or how much compactive force is used to compress blocks. Pave's results are thus presented for comparison sake only, further analysis and discussion is undertaken.

The individual entries in the column percentage shoulder load in table 6 shows a given rows method of load application result represented as a percentage of method of load application along the shoulders of the block. The present results show that load applied along the tongue of the block fails at 26% of shoulder loading. The top cube fails at 55% of shoulder loading and the bottom cube fails at 72% of shoulder loading. When the block is laid loaded across the full width of the block, it fails at 95% of shoulder loading.

The difference in results obtained when the block is loaded across the tongue and when the block is loaded across its gross width can be attributed to the block failing prematurely through shear when loaded along the tongue. Generally, the density of blocks produced using a single action compression ramming motion block production press (such as the Hydraform blockmaking machine) is not constant, the density decreases with distance away from the compressing ram due to the effects of friction along the sides of the mould [24]. The hydraulic rammer in the Hydraform machine compresses the block vertically upwards from bottom upwards, with a top rammer confining the block in place. This gives rise to the difference in strength between top, bottom cubes and load application across the shoulders of the block.

Using the percentage of shoulder load as the basis for comparison, there seems to be no relation between Paves work and the present studies. It would be premature to conclude that the present work undertaken is incorrect or that Pave's work is correct, as correlations might be established between the compactive effort imparted on the blocks and the resulting strength of the block.

The usefulness of work done on methods of load application can assist in obtaining quick and easy field test methods. If one can reach a conclusion on the accuracy of factors as a percentage of shoulder loading (method accurately emulating conditions in practise), then a quick and easy field test using for example the method of load application along the tongue of the block can be used as a proxy tests for compressive strength analysis of Hydraform blocks.

What can however be deduced is that the load application across the gross width and the method of load application along the shoulders of the block give similar strength results. Blocks laid in practise would be typically loaded akin to the two methods mentioned above, thus any of the two methods can be used as the methods of load application in laboratory testing. The method of load application across the gross width of the block will henceforth be used as the method of compressive strength evaluation of the Hydraform block for the remainder of this study.

Strengths properties of blocks produced without chemicals at varying clay and cement contents

Table 7 summarises strength results of block produced without chemicals cured for up to 28 days. An attempt is made to make blocks with all available soils (soils A – H) with properties represented in Table 4 (page 20). It was however found that only soils B-G are suitable for making blocks. Soil A proved to be non-cohesive resulting in blocks crumbling at demoulding stage. In contrast, Soil H proved to be too cohesive such that it became increasingly difficult to remove blocks during demoulding. In certain cases pieces of blocks broke off and remained fixed to the bottom rammer when Soil H was used. Moreover, it was noticed that blocks produced with above 15% clay content are harder to remove from moulds whereas blocks produced with below 5% clay content are hard to handle whilst being transporting to curing area. Optimum clay content for handling purposes was thus found to be between 5 – 10% clay content for the particular range of soils used.

Table 7: Summary of Hydraform block strength results produced with different soils and cement contents

Time (Days)	Cement Content (%)	Soil Type	Clay Content (%)	Strength (MPa)		Saturated/Dry Ratio
				Saturated	Dry	
28	8	Soil B	3.0	5.17	6.78	0.76
		Soil C	7.5	3.02	4.09	0.74
		Soil D	8.5	2.62	3.91	0.67
		Soil E	9.5	2.35	3.53	0.67
		Soil F	15.0	1.00	2.09	0.48
		Soil G	25.0	0.85	2.02	0.42
28	3	Soil D	8.5	1.02	1.29	0.79
	5			1.98	2.84	0.70
	8			2.62	3.91	0.67
	12			3.43	4.46	0.77
	16			6.08	7.41	0.82
	20			10.35	11.36	0.91
3	8	Soil D	8.5	1.97	2.16	0.91
7				2.35	3.14	0.75
28				2.62	3.91	0.67

The saturated dry ratio presented in Table 7 is the ratio of the saturated cured strength versus the dry cured strength of blocks. It will be used to indicate how much strength is lost when buildings are built using the CSEB technology in an environment where blocks are susceptible to become saturated instead of dry environments. What can further be seen from Table 7 is that the saturated/dry ratio decreases with increasing clay content. This is due to the fact that small grained clay particles have a larger surface area than the bigger sand granules used in ordinary concrete. Consequently, compounded by the semi-dry state of soil-cement, the reduced cement content and the large surface area of clay particles in soil-cement, it is unlikely that all the clay particles in the soil-cement matrix are bonded together with the cement paste [42]. Thus the 'uncemented' clay particles are free to expand in the presence of water, loosening the already weak existing cement paste-soil matrix, effectively reducing the strength of the block.

Also visible in Table 7 is the increase in saturated/dry ratio with increasing cement content. This can be attributed to more cement paste being formed. The cement paste covers more clay particles creating stronger inter-particle bonds. The stronger inter-particle bonds reduce the expansion of uncemented clay particles, accounting for the higher saturated/dry strength ratios. Petrography studies can reveal what occurs at a microscopic level between clay/silt-soil-aggregate-cement paste interactions.

Changes in clay content versus strength of blocks is presented graphically in Figure 18. A minimum SANS [33] allowable strength of 3.5MPa will be used to evaluate the characteristic compressive strength of blocks made with different soils (represented by their clay content percentages).

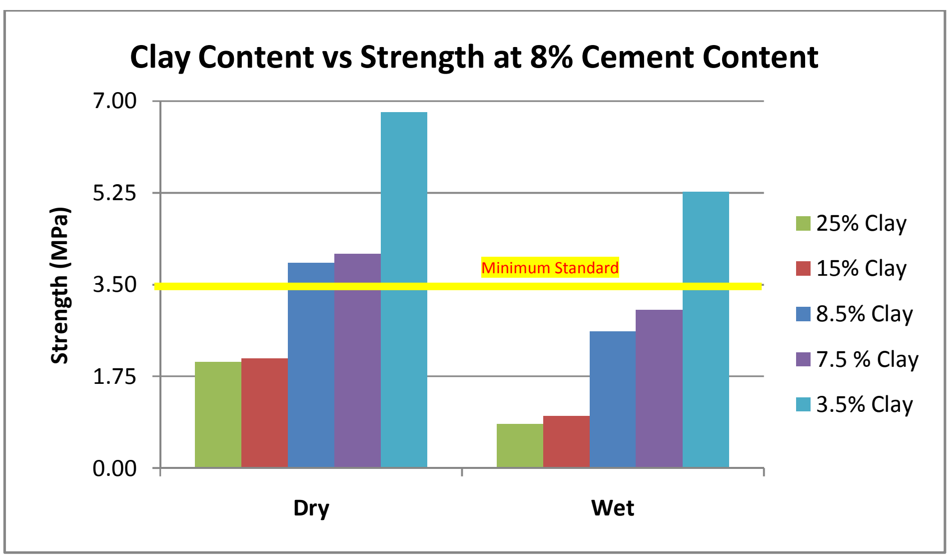


Figure 18: 28 Day strength of blocks produced with different clay contents

Using the requirement that the minimum strength of 3.5MPa be achieved in any condition, Figure 18 is analysed. From the figure it can be seen that for case where blocks are used in dry conditions, blocks produced with soils having a clay content greater than 8.5% do not meet the minimum strength requirement. As for blocks used in saturated conditions, only blocks produced with soils having a clay content of below 3.5% meet the minimum strength requirement. Thus blocks stabilised at 8% percent cement content may only be used in situation where they are required to absorb water when they are produced with a soil having a clay content lower than 3.5%.

In addition to the testing of variations in clay content, blocks were tested at various cement contents, whilst keeping the clay content constant. This was done to determine the cement content that achieves the required wet strength.

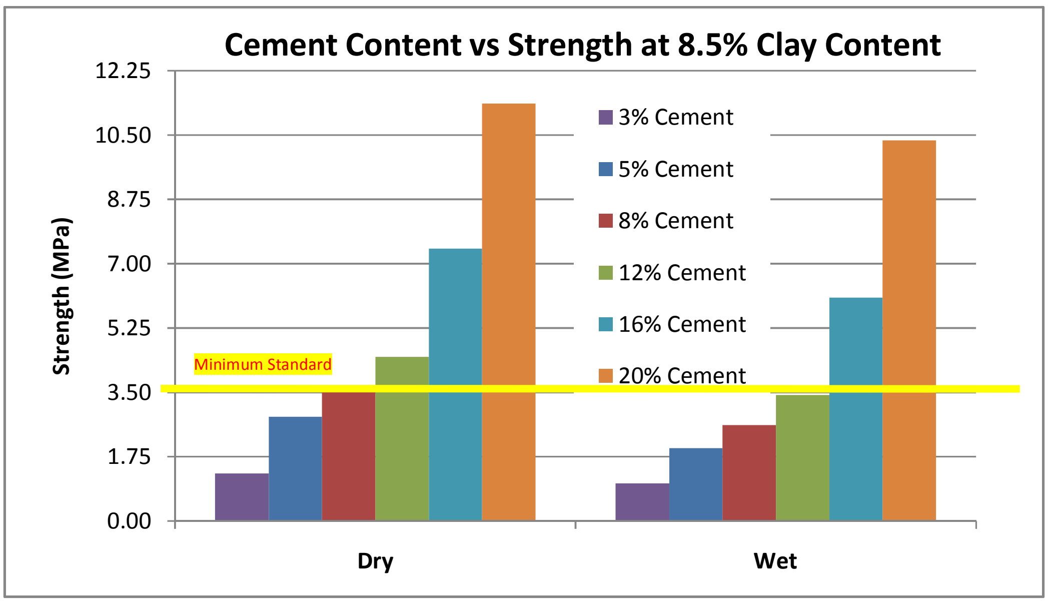


Figure 19: 28 Day strength at different cement contents

Figure 19 shows the 28 day strength of blocks produced with Soil D at various cement contents. Using the allowable minimum standard, for the case where blocks are used in a dry environment, a minimum of 8% cement content is required. As for the case where blocks are used in a saturated environment a minimum of 12% cement content is required. It is on the other hand important to appreciate that at reduced clay contents the strength results would been higher. What is unknown is the minimum cement content in conjunction with the minimum clay content that gives the highest saturated strength. To make a factual conclusion of the required cement content at minimum clay content, one would have to study clay and cement content changes until an optimum point is reached.

Studies relating the strength of block to the number of days of curing were also undertaken. This was only done for blocks produced with Soil D and 8% cement content. If curing time is an aspect being considered for block production, optimisation studies including clay content (representing different soils), cement content, curing time and resulting block strength can be considered. Studies could also include different curing methods, such as chamber curing as apposed to curing under plastic sheeting.

Hydraform recommends that blocks are to be cured for up to 14 days under plastic sheeting [28], but from Figure 20 it is evident that blocks produced with a 8.5% clay and 8% cement content can only be used in construction after 17 days of curing. If a safety factor of 1.2 is applied to the number of days, it will be safe to say blocks can only be used after 20 days of curing under plastic sheeting.

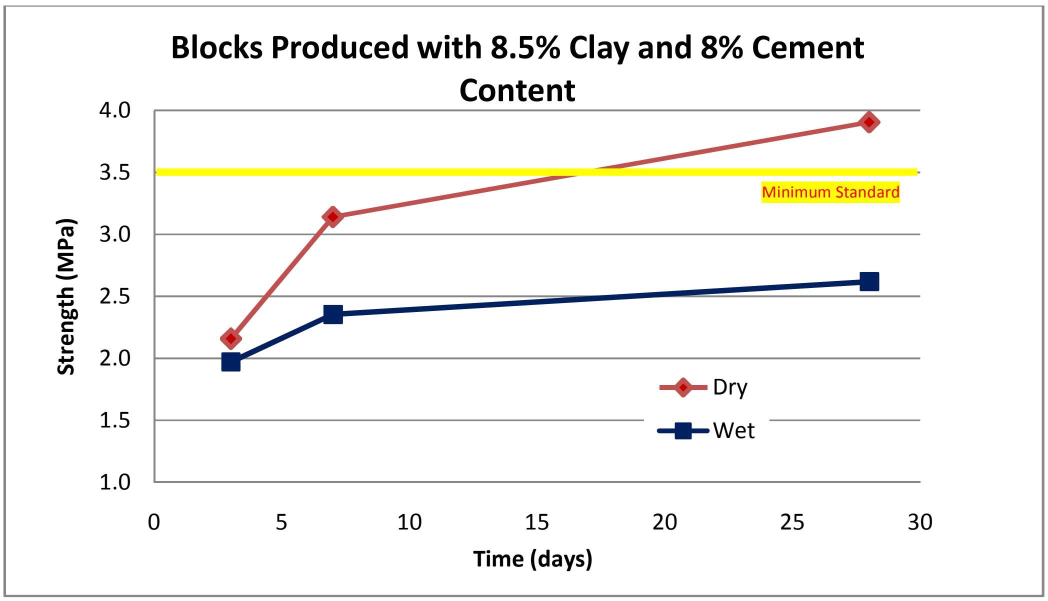


Figure 20: Illustration of strength development of blocks produced with 8.5 clay and 8% cement content

Blocks produced with chemicals additives

The saturated/dry strength ratio is of much concern in soil cement. Chemicals are introduced to try and increase this ratio, and inturn increase resistance to other durability measures. Two control blocks, control block A and B, are produced in order to benchmark and contrast results obtained against results obtained by blocks produced with chemical additives. Control block A is produced with Soil D and 8% cement content where the same soil-cement mix (Soil D and 8% cement content) is used to produce blocks with chemicals. Control block B is produced with Soil D and 20% cement in hope that blocks produced with chemicals can achieve similar properties.

Table 8 highlights the 28 day strength results obtained for the changes in concentration of the three different chemicals. Control block A, with 8% cement content has a saturated strength of 2.62MPa and air dried strength of 3.91 MPa. Control block B, with 20% cement content has a saturated strength of 10.35MPa and air dried strength of 11.36 MPa respectively.

Table 8: 28 Day Strength of blocks cast with different chemicals at varying concentrations

	Concentration (% of Total cement content)	Strength (MPa)			Saturated/Dry Ratio
		Saturated	Air Dried	Oven Dry	
Control Block B	**0**	10.35	11.36	14.09	0.91
Control Block A	**0**	2.62	3.91	5.87	0.67
Acronal S400 - Added to Block	**5**	3.85	4.45	7.78	0.87
	10	3.97	5.86	-	0.68
	15	4.19	6.19	-	0.68
	20	4.47	6.32	-	0.71
	50	4.47	7.70	-	0.58
Masterseal 501 - Added to the Block	**0**	2.62	3.91	5.87	0.67
	5	4.02	6.29	8.75	0.64
	10	5.68	8.57	-	0.66
	15	6.01	10.04	-	0.60
	20	6.63	10.82	-	0.61
	50	6.24	9.56	-	0.65
Coatings	**Acronal S400**	4.22	4.13	5.07	1.02
	Masterseal 550	6.05	6.66	8.98	0.91

If we look at the results for the control blocks in the above table, one can deduce that the strength increases with increases in cement content and strength decreases with increases in humidity. In addition the saturated/dry strength increases with increasing cement content.

The aim of Control block B is to have chemicals achieve similar block qualities as those obtained by Control block B. From Table 8, it is clear that coated blocks achieve similar saturated/dry ratios to Control Block B. This as an initial measure of quality of waterproofing shows that waterproofing coatings work well with the blocks. As for the strength property, only Masterseal 501 comes close to strengths obtained by Control Block B. In positive light, it can be noted that all chemicals lead to strength development above Control Block A, either through coating or by imparting strength to blocks.

Figures 21 and 22 show the strength gain and subsequent loss by increases in chemical concentrations. The dosage of chemicals that meet the minimum required strength of 3.5 MPa can be read off the graphs. From Figures 20 and 21 it is clear to see that that the Masterseal dosage that meets minimum strength requirement lies between 2 – 3 percent cement content, while the dosage for the addition of Acronal S400 is 5%.

Masterseal 550 is applied as a coating. It is only applied one recommended coat (one part liquid to two parts liquid) as specified by the supplier.

For Acronal S400 applied as a coat, the primer is applied at one concentration with only the base coat varying. It was found that required saturated strength is only achieved at a base coating of 1 part Acronal to 4 parts water, where lower concentrations give inadequate strength.

Compressive strength testing on oven dried blocks is only undertaken on blocks produced with chemical additive/coating contents that achieve the chosen saturated strength of 3.5MPa.

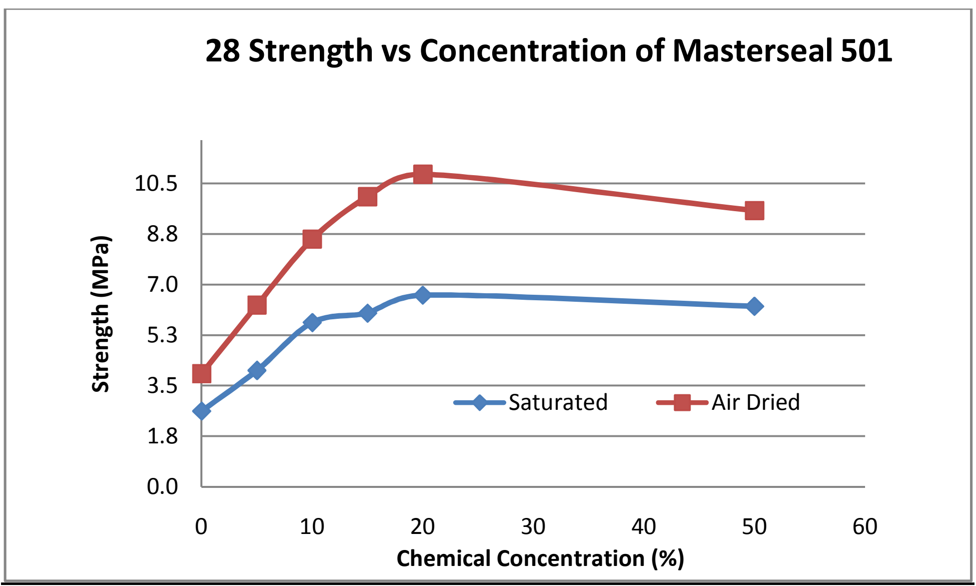


Figure 21: Blocks cast with Masterseal 501, 28 day compressive strength at different chemical concentrations

In order to work with rounded average numbers, it was decided that 5% concentration of Acronal S400 and 5 % concentration of Masterseal 501 would be used as the concentrations that meet the required strength, rather than their exact concentrations as read off graphs Figures 29 and 30. These concentrations will henceforth be used as the concentrations that achieve the allowable 3.5 MPa saturated strength.

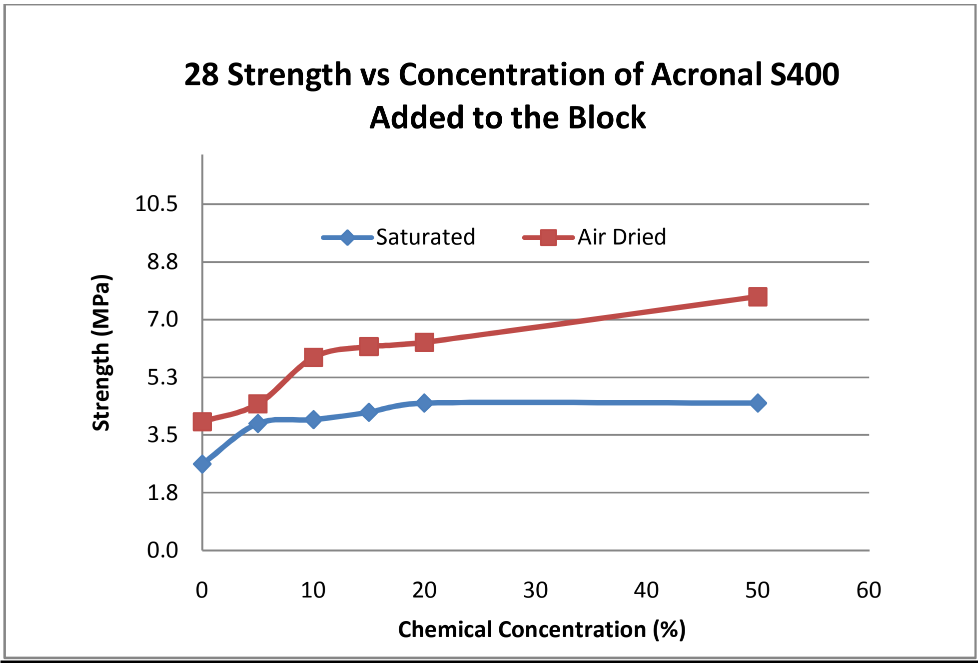


Figure 22: Blocks cast with Acronal S400, 28 day compressive strength at different chemical concentrations

Saturated compressive strength development over 28 day period for blocks made with different chemicals (at chosen chemical concentrations) was undertaken in order to gauge within what timeframe blocks could be laid an achieve the allowable strength of 3.5MPa. Table 9 and Figure 23 show the saturated strength development of blocks.

Table 9: Compressive strength development of blocks at required chemical concentrations

		Testing Condition	Curing Period (Days)			
			3	7	28	90
Control Block A (8% Cement Content)		Wet	1.97	2.35	2.62	-
		Dry	2.16	3.14	3.91	-
Control Block B (20% Cement Content)		Wet	3.56	5.9	10.35	-
		Dry	4.44	6.47	11.36	-
Acronal S400	Added to the Block	Wet	1.82	2.19	3.85	-
		Dry	2.44	3.09	4.45	-
	Applied as a Coating	Wet	1.82	2.91	4.22	-
		Dry	1.89	3.04	4.13	-
Masterseal 501		Wet	1.85	2.45	4.02	-
		Dry	2.38	3.22	6.29	-
Masterseal 550		Wet	1.97	2.99	6.05	-
		Dry	2.12	3.16	6.66	-

From Table 9 it can be seen that Acronal S400 applied as a coating and Masterseal 501 achieve comparable saturated strengths, although lower than Masterseal 550 or control block B. Despite this they behave more favourably than Acronal S400 added to the block. The time period required for blocks to be laid, when saturated strength reaches 3.5 MPa can be read of the Figure 15.

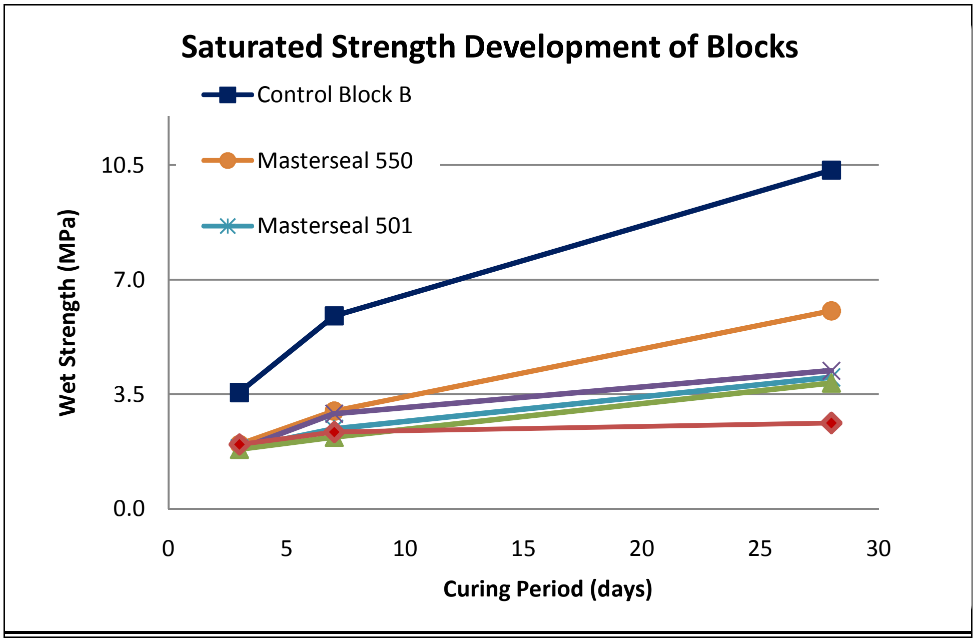


Figure 23: Saturated strength development of blocks with and without chemicals

Blocks made with mix Control block B can be laid 3 days after being cast. Blocks made with Acronal S400 added to the block can be laid (with safety factor of 1.2 included) after 30 days of curing. Blocks made with Acronal S400 applied as a coating can be laid after 24 days of curing. Blocks made with Masterseal 501 can be laid after 20 days of curing whilst blocks coated with Masterseal 550 can be laid after 15 days of curing.

A very important note is that the above results only represent addition of chemical concentrations that achieve 3.5MPa strength. If other standards are used that ascribe higher strengths to blocks, higher concentrations of additives Masterseal 501 and Acronal S400 would need to be added to blocks to achieve required strengths. For the coatings not much can be done to increase strengths, lest more cement in the mix be used.

The effects of humidity on strengths of each type control block and chemical can also be graphically represented by inferences made from Tables 8 and 9. Figure 24 illustrates the 28 day strength of blocks made with different chemicals at different humidity conditions. As from Figure 24, it can be seen that strength decreases with increasing humidity. Thus it can not be concluded with absolute certainty whether 28 days of curing is sufficient for curing of blocks to get accurate representative dry strength of blocks without the influence of moisture in the blocks. If blocks cure for longer periods then more moisture will be removed from the block by the natural drying process.

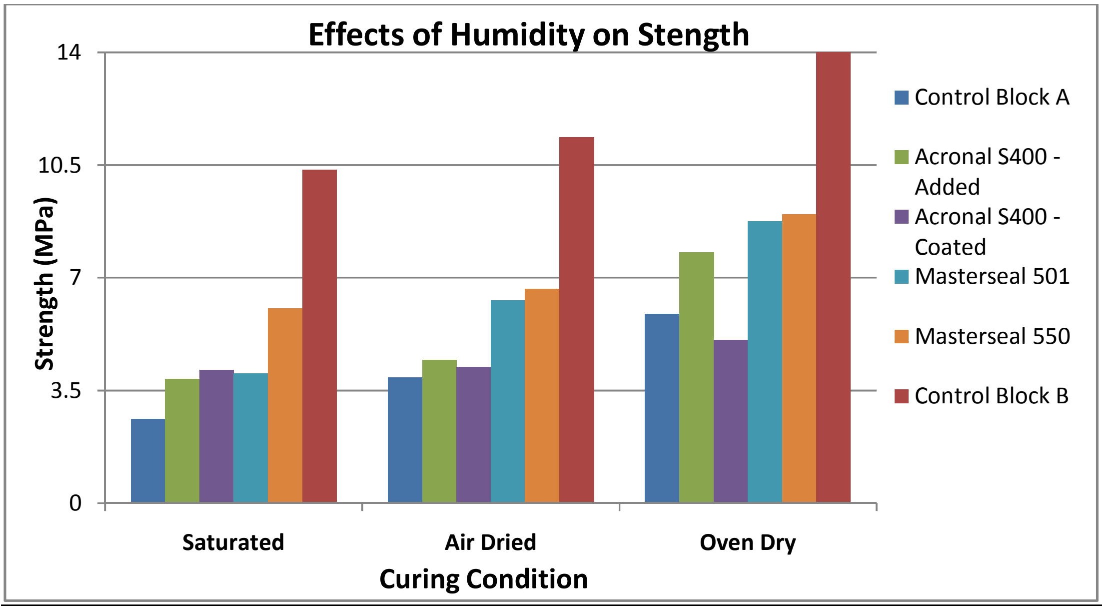


Figure 24: 28 Day strength of blocks made with different chemicals at different humidity conditions

6 DRYING SHRINKAGE TESTING

This test looks at the shrinkage characteristics of blocks while blocks dry out, from a moisture content of block at casting to moisture content when blocks are dry, available for use in construction. Although drying shrinkage in the dry stack construction method is not considered a serious cause for concern, owing to the fact that blocks dry out before stacking, drying shrinkage is looked at in this study by comparing the shrinkage of blocks produced with chemicals to control blocks. This is done in order to gauge if chemical additives cause blocks to shrink more than the control blocks. It might be that shrinkage of chemical additives effect dimensional tolerances of blocks. The method employed follows drying shrinkage methodology in SANS 1215 (2008).

6.1 Test Procedure

Blocks are manufactured with and without chemicals in accordance to chapter 4.4 and allowed to cure for 28 days under plastic sheeting. Rectangular blocks with dimensions of 200 x 60 x 60 mm are cut out of standard Hydraform blocks with a diamond edge saw cutter. Metallic targets are placed in the centre of the two latitudinal faces as reference points to take measurements from. Measurements are taken with a vernier calliper, recorded to an accuracy of 0.01 mm.

The rectangular blocks are submerged in a water bath at temperatures between 16^o C and 18^o C for 96 hours after which measurement A is taken. The rectangular blocks are then placed in a drying oven at temperatures between 69^o C and 71^o C for a further 48 hours before measurement B is taken. The drying shrinkage is calculated by equation 3 below:

Drying shrinkage = (A-B)/B x 100…………………………………………(3)

Where

A = original oven dried length

B = final saturated length

Figure 25: Shrinkage measurement using vernier calliper

Figure 25 shows length measurements being taken on a typical drying shrinkage block, saw cut from standard Hydraform block. Three drying shrinkage blocks are used to calculate an average shrinkage value for 1 control/admixture type.

6.2 Test Results

In the context of the Hydraform CSEB, the drying shrinkage will be used to assess if the dimensional tolerances of the block change with increasing cement content or with addition of chemical to the block. Drying shrinkage results are presented in Table 10. SANS 1215[33] gives the minimum dimensional tolerance of a brick or block to be between 3 and 4mm.

Table 10: Drying shrinkage, represented by change in length over original length

Block Type	(%) Drying Shrinkage	Gap Block Tolerance (mm)
Control A	0.32	0.75
Control B	0	0
Acronal S400 Added	0.83	1.95
Acronal S400 Applied	-	-
Masterseal 501	-	-
Masterseal 550	0.27	0.63

The gap block tolerance shows the shrinkage expressed as a reduction in the length of the block. The length of the block is taken as the length of the longest Hydraform block which is 235mm. The results show that shrinkage is within tolerance, no decrease in length is greater than 4mm.

If blocks were outside the tolerance, this could possibly affect the interlocking mechanism between overlaying and underlaying blocks. The possibly exists where blocks made with and with and without chemicals are laid in subsequent courses of the wall, if for instance the overlaying blocks have a high drying shrinkage, they will not interlock with underlying blocks with a low drying shrinkage, with the extreme possibility of causing dimensional instability.

7 WATER UPTAKE TESTING

This test described in this section follows the same procedure as one mentioned in SANS 227, South African National Standard for Burnt Clay Masonry Units. Initially produced blocks are cured up to 28 days under plastic sheeting. Water uptake is then tested by submerging blocks in a water bath for up to a 72 hour period.

7.1 Test Procedure

28 Day cured blocks are oven dried at between 69^{o}C and 71^{o}C until constant block masses are obtained. Three blocks are used to obtain average sample results. After oven drying blocks are submerged in a water bath for 72 hours. Blocks are then removed from the water and cleaned with a sponge or dry towel surface over before being weighed. Blocks must be weighed within 20 seconds of removing blocks from the bath, to make sure blocks do not become unsaturated. Equation 4 is used to calculate the percentage mass gained by water uptake.

Water Uptake (%) = (W-M)/W x 100…………………………………………… (4)

Where

W = weight of block after submerging in water bath for up to 72 hours

M = original oven dried mass

7.2 Test Results

Results for the water uptake test are presented in Table 11 and graphically in Figure 26. The column showing percentage reduction compared to Control block A shows the reduction in percentage water uptake as compared to Control block A. This can be used to compare other blocks relative to Control block A. What can be seen from Table 11 is that the coatings (Acronal S400 applied as a coat and Masterseal 550) achieve significant reductions in water uptake when compared to Control block A.

If percentage water uptake is used as a measure of quality of waterproofing, the coating achieve better quality waterproofing than Control block B, meaning that the coatings provide better protection than the increase in the portion of cement in blocks to uneconomically high levels.

Table 11: Water uptake (%) of different blocks

Block Type	(%) Water Uptake	(%) Reduction compared to Control block A
Control A	8.03	-
Control B	5.68	2.35
Acronal Added	7.80	0.23
Acronal Applied	2.81	5.22
Masterseal 501	6.86	1.17
Masterseal 550	3.00	5.03

As for Acronal S400 added to the block, no significant reduction in water uptake properties is recorded when compared to Control block A. Masterseal 501 also shows little reduction in water uptake in comparison to Control block A.

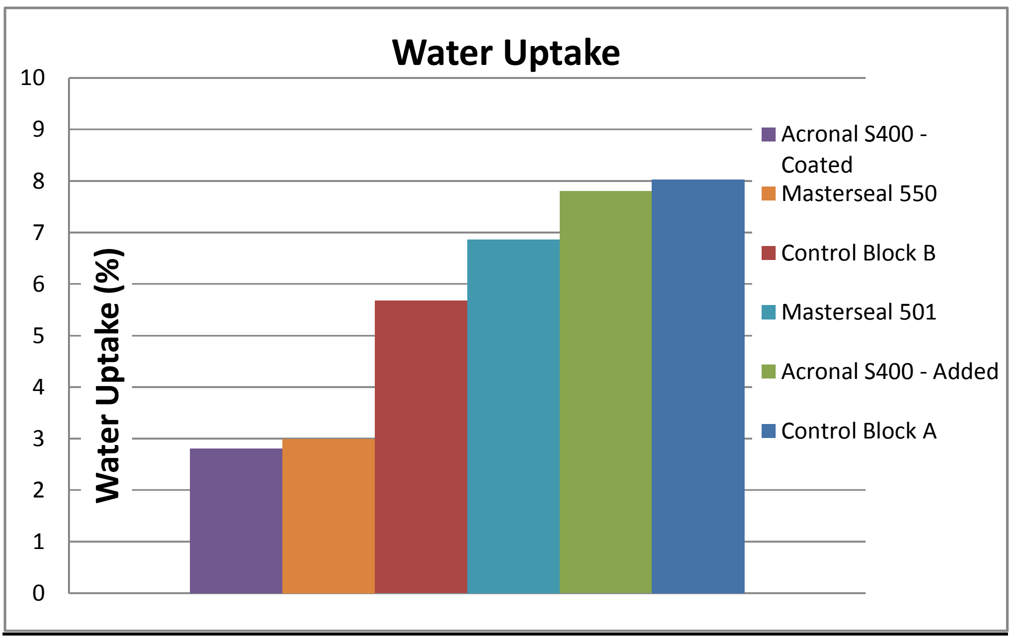


Figure 26: Graphical presentation of water uptake results

8 THE WATER SORPTIVITY TEST

The water sorptivity test is a uni-directional absorption test. It involves coring a 68 mm diameter, ±30 mm width sample then placing it in a tray with solution of water and $Ca(OH)_2$ in order to measure the water uptake of the cylinder by capillary rise. Blocks were produced and cured for 28 days before blocks are cored. The vertical sides of the cored specimens are taped with plastic tape to ensure that the water solution will only be absorbed from the face of the core that is placed in the water. Three blocks were cored to give average results for one sample. The mass of water absorbed is recorded in $mm/h^{1/2}$. The test procedure highlighted here follows test procedure adopted by Alexander et al (1999).

8.1 Test Procedure

Cored cylinders are oven dried at ±50^{o} C for a 24 hour period. After the drying period cylinders are allowed to cool in a room at 60% relative humidity for 1 hour before testing commences. The initial oven-dried mass is then recorded. During the cooling period a vernier calliper is used to measure the average thickness of all samples, used to measure thickness at 4 equally spaced positions of one sample.

A plastic or metallic tray is used for the test, 10 layers of absorbent paper is placed into the tray and solution of $Ca(OH)_2$ (added 5 grams / litre water) and water is added to the tray such that the free surface of the water is just visible above the surface of the paper.

Time is recorded with a stop watch as the samples are placed into the tray in successively. It is advised that a maximum of six samples be tested at one time. When the first minute has lapsed, the first core placed on the tray is removed wiped with absorbent paper on the face that was submerged in the water and weighed. The process is repeated until all samples have been weighed. The weighing procedure is further repeated at intervals of 2, 4, 8, 16, 32 and 64 minutes, this being after the first sample was placed in the water solution. Figure 26 shows samples being immersed into the tray of water and $Ca(OH)_2$ solution.

Figure 27: Cylinders in Water/$Ca(OH)_2$ solution

At the end of the weighing period, samples are placed in a de-airing vacuum chamber for 2hours, the chamber is then filled with water until samples become saturated and the sample plus water is further de-aired for an hour. Saturated final weights of cored cylinders are finally obtained after the 3 hour de-airing process.

Calculations

The mass of water absorbed at each period in time is given by equation 5:

$$M_{wt} = M_{st} - M_{so} \quad \text{………………………………………………………….}(5)$$

M_{wt} – Mass of water absorbed at any given time period

M_{st} – Mass of sample at time t

M_{so} – Mass of sample at t = 0.

A linear regression analysis is conducted in order to determine the value of F as plotted in equation 6. M_{wt} values are plotted against square root time in hours to obtain F values.

$$M_{wt} = F \times t^{1/2} \quad \text{…………………………………………………………. (6)}$$

The water sorptivity is thus obtained by equation 7.

$$S = (F \times d)/ (M_{sv} \times M_{so}) \text{……………………………………………. (7)}$$

S – Sorptivity in $mm/hr^{1/2}$

d – Average thickness of sample in mm

M_{sv} – Vacuum saturated mass of sample

M_{so} – The mass of sample at t = 0

8.2 Test Results

Water sorptivity results are presented in Table 12 and graphically represented in Figure 28. Increasing sorptivity results shows less resistance against permeation through capillary action. Results for water sorptivity follow same pattern as those for water uptake. Control block A being the highest and the coatings (Masterseal 501 and Acronal S400 applied) having far superior protection against capillary action than Control block B. However Masterseal 550 seems to be distinctly better than Acronal S400 as a coat in protection against capillary action.

Table 12: Water permeation through capillary action

Block Type	Water Sorptivity (mm/hr ½)
Control Block A	19.00
Control Block B	8.12
Acronal S400 – Added	15.28
Acronal S400 – Coated	2.72
Masterseal 501	18.31
Masterseal 550	0.52

Masterseal 501 shows no resistance against capillary action, even less resistance than Acronal S400 added to the block. This renders Masterseal 501 ineffective against capillary rise. Masterseal 501 is said to block pores, but if water permeates by capillary action, then there is a possiblity water then permeates through the mass soil-cement itself. Again it can be seen that the coatings show better performance than Control B against capillary action.

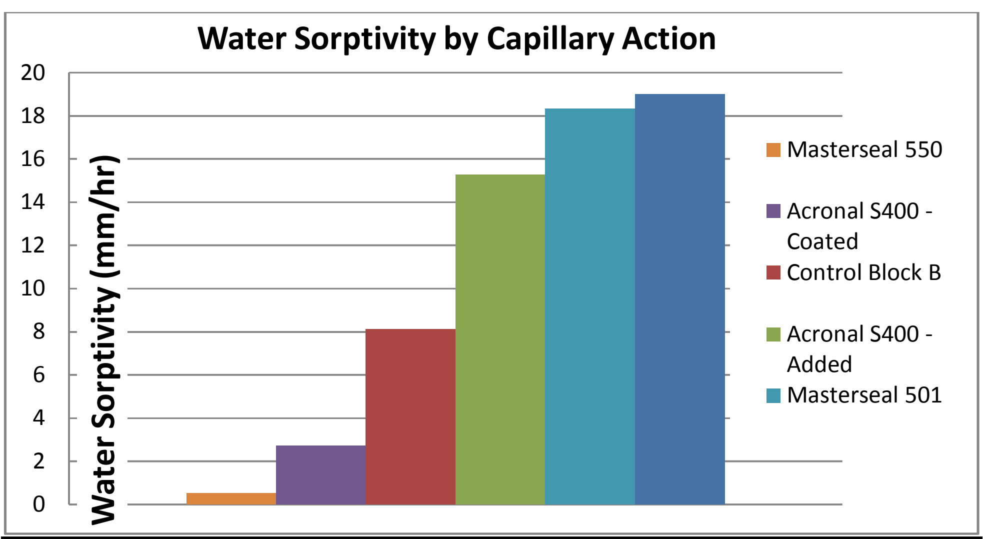


Figure 28: Graphical presentation of sorptivity results

9 ABRASION BY WET/DRY DURABILITY TEST

The wet/dry durability test is a form of abrasion testing that mimics the abrasive effects of the elements of water and wind driven erosion on a wall structure. This tests ability to mimic even the most severe rainstorms has come to question, with no correlation between experimental field data, somewhat test data being gross overestimation of reality [20]. In this case, this test will however only be used to compare abrasion resistance of control blocks to blocks produced with different chemical additives. Blocks are produced and cured under plastic sheeting for up to 28 days before testing.

9.1 Test Procedure

A stiff wire brush made of 50 of 1,6mm flat 26 gauge wire bristles assembled in 50 groups of 10 and mounted to form 5 longitudinal and 10 transverse rows is used to brush the blocks cyclically after intermittent drying and wetting periods. Three blocks are used to average one block type.

Blocks are initially oven dried at ±70^{o}C (for 19 hours) or until a constant dry mass is achieved. The initial oven dried mass is recorded before any brushing commences. Brushing of blocks is to take place with an applied force of 13.5N. The blocks are to be brushed two firm strokes with the wire brush over all surfaces. Blocks are then submerged in a water bath at ±17^{o}C for a period of 5 hours. The oven drying, brushing and submerging representing a 24 hour period is one cycle of the test. 12 Cycles of wetting, drying and brushing are undertaken before the blocks are oven dried at ±70^{o}C for final mass reading to be taken. Final mass reading is accurate when constant block masses are achieved. Figure 29 below illustrates the wet dry durability testing procedure, accompanied by figure 30 showing typical brush and block.

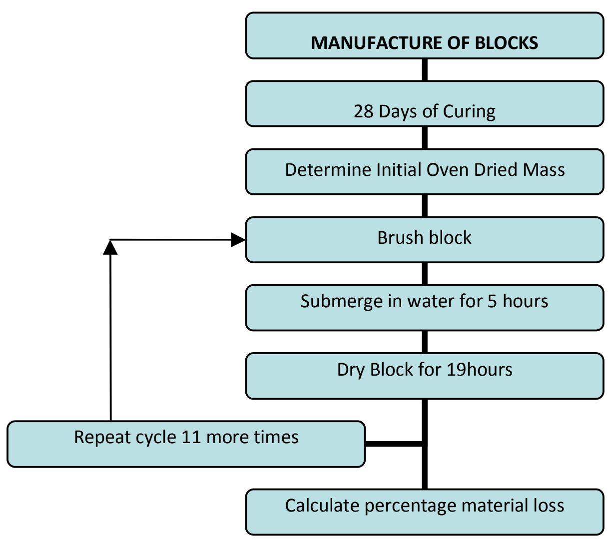


Figure 29: Wet/dry durability testing procedure

The percentage mass loss is then calculated after 12 cycles of wet dying and brushing by the equation 4:

Soil Cement Loss (%) = (W-M)/W x 100……………………………………………. (4)

Where

W = original oven dried mass

M = final oven dried mass

Figure 30: Oven dried block and wire bristle brush

9.2 Test Results

Table 13 and Figure 31 represent the abrasion testing results. All results are within the envelopes of Control blocks A and B, with Control A being minimum and Control B being maximum. Acronal S400 added to the binder system and Masterseal 501 offer little to no protection against abrasion, whilst the coatings (Acronal S400 applied as a coat and Masterseal 550) offer some measure of resistance against abrasion.

It is disappointing one cannot quantify the abrasion measured by this test in any meaningful way other than for comparison sake. Much work is need in correlating abrasion testing laboratory results to actual field data. If in the design stage, abrasion/erosion is identified as one of the key design parameters, it would still more advantageous in terms of resistance to abrasion to increase cement content in blocks over using the tested chemicals.

Table 13: Abrasion testing, represented by block material loss

Block No	% Material Loss
Control Block A	15.70
Control Block B	2.40
Acronal S400 - Added	14.80
Acronal S400 - Coated	4.60
Masterseal 501	13.50
Masterseal 550	5.30

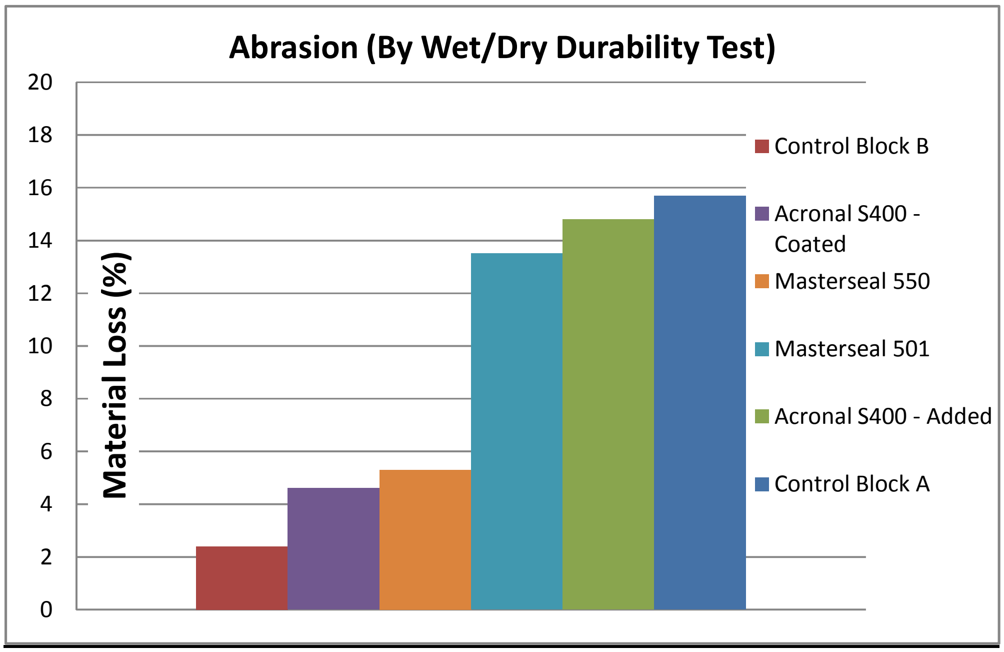


Figure 31: Graphical presentation of material loss by wet/dry durability testing

10 CONCLUSIONS

10.1 General Conclusions

The primary durability assessment measure used in this study is the unconfined compressive strength. A target saturated unconfined compressive strength of 3.5MPa is set to evaluate whether CSEB's are of sufficient quality to be used in single storey construction.

This same target strength of 3.5MPa is used to recommend the amount of dosage of the various chemicals (Acronal S400, Masterseal 501 and Masterseal 550) required to make the resulting blocks durable. Furthermore, three secondary durability assessment measures are used to assess the durability of the CSEB, namely: resistance to abrasion, water uptake potential and drying shrinkage. The secondary durability assessment measures are conducted on blocks produced with the various chemicals at their recommended dosages. It is clearly notable that the target compressive strength factor controls the outcome of this research.

The target strength of 3.5MPa is a minimum South African masonry standard which is chosen mainly because this study is written from a South African perspective. If this study was written from another perspective, say from an American point of view where the ASTM code of practise is considered, a higher target strength would be required. Thus higher chemical dosages would be deemed necessary to meet the minimum saturated strength criterion.

Increased dosage of the various chemicals would lead to increased saturated strengths. Additionally higher chemical dosages' might lead to the betterment of other durability parameters (e.g. abrasion resistance and resistance to water uptake). Altogether, different specific conclusion might have been drawn if a broader study including increased dosages' of the various chemicals.

Thus, this research is not at an end by itself when it comes to the effect of chemicals on durability properties of blocks. A study needs to be carried out where parameters; chemical concentrations, cement and clay concentrations are varied at block production to reflect and understand the true ability of chemicals.

10.2 Unconfined compressive strength

Methods of load application

Laboratory testing shows that when blocks are loaded across the shoulder or the gross width of the block, the methods produce the same results. These two methods of unconfined compressive strength evaluation both represent situations in Hydraform block construction practise. Any one of the methods can be used in the laboratory to test for the unconfined compressive strength of Hydraform blocks.

For in the field conditions, this study suggests the method of load application along the tongue of the block be used as a quick and easy way of testing the unconfined compressive strength of the Hydraform block. However further investigation that correlates the method of load application along the tongue of the block to the method of load application along the shoulders of the block is required. Work in this regard could lead to the development of a shear test failure method (application of load along the tongue of the block) as quick and easy methods used to test Hydraform blocks in the field.

Varying clay and cement contents

Generally when we look at blocks produced without chemicals, it can be seen that increases in the content of clay at constant cement content weakens the strength of blocks. Increasing moisture content in blocks at constant clay and cement contents also act to weaken blocks. Water generally reduces the strength of CSEB's with the rate of decrease in strength increasing with increases in clay content.

Furthermore, it can be concluded that for the particular range of soils (soils A – H) used in this study, using the required compressive strength (3.5 MPa) as a measure:

- At 8% cement content, blocks produced with a soil that has a clay grading limit of 10% meet required dry strength
- At 8% cement content, blocks produced with a soil having a clay grading limit of 3.5% meet the required saturated strength
- Blocks produced with a soil having a clay grading limit of 8.5% can only be used in construction, where blocks are to become saturated, when blocks have approximately above 12% cement content
- Blocks produced with 8% cement content with a soil having a clay grading limit of 8.5% will have to be cured for up to 20 days before they can be used for building works

These results only represent a sample of the broad spectrum of possibilities of the given soils. Optimisation studies need to be undertaken with the three dominant variables, namely number of days curing required, clay and cement contents to obtain broad spectrum of results. It is also important to appreciate that different national standards recommend different compressive strengths and that better understanding of block behaviour will lead to more informed strength characteristics decisions in any design environment.

10.3 Drying shrinkage

The added chemicals do not give rise to negative changes in block dimensions. What can also be noted is that increases in cement content lead to decreases in changes in dimensions, i.e. shrinkage is reduced by increasing the cement content in blocks.

10.4 The Control Blocks

The results from Control blocks A and B show that an increase in cement content is accompanied by increases; in strength, in reduction to water uptake by capillary action, to reduction in permeation of water through blocks and to reduction in losses through abrasion/erosion. In most cases Control block B having uneconomically high cement content shows to be more durable (assessed using durability measures) than blocks produced with chemical.

10.5 Acronal S400 Added to the Blocks

When Acronal S400 is added to the block it shows increased strength properties over the control block with the least cement content, Control block A. Strength is gained with increased chemical concentration. In spite of the gain in strength, the chemical does not obtain similar strength to that of the control block with uneconomically high cement content, Control block B. The saturated strength gain with addition in concentration of Acronal S400 added to the block is not as rapid as strength gain with increases in concentration of Masterseal 550 added to the block.

As for water uptake, sorptivity and abrasion results, blocks with Acronal S400 added to them show little to no increase in these properties over the properties of Control block A.

10.6 Acronal S400 Coated over the Blocks

When blocks are coated with Acronal S400, they exhibit increased saturated strength when compared to Control block A. However, the coating does not impart strength to the block. If the saturated/dry ratio is used as the basis of on which the chemicals waterproofing qualities are assessed, then complete waterproofing is achieved when Acronal S400 is applied as a coat.

Acronal S400 applied as a coat significantly reduces water uptake and resistance to abrasion potential when compared to Control block A. It fairs similar to the other coating (Masterseal 550) in terms of waterproofing and resistance to abrasion.

10.7 Masterseal 501

Masterseal 501 has the advantage that it is added to the dry soil –cement mix. No labourious work over and on top of adding it to the mix is required. Increases in dry and saturated strength with additions in concentrations of Masterseal 501 are higher than that of any other chemical additive/coating.

In spite of increases in the strength property, blocks produced with Masterseal 501 do not show signs of significant reduction in abrasion losses, water uptake by permeation or water uptake by capillary action if compared to Control block A. From water uptake and water sorptivity results it is clear that water travels through blocks produced with Masterseal 501.

10.8 Masterseal 550

Masterseal 550 shows increases in dry and saturated strength properties over that of Control block A, thus imparting, although not much, some strength properties to the block. This is due to the rigidity of the seal when applied, adding strength to the block. The saturated/dry ratio is comparable to Control block B giving an initial indication that similar, if not better waterproofing qualities are achieved.

Masterseal 550's water sorptivity and water uptake present comparable results to that of Acronal S400 applied as a coating. The same results show superiority over Control block B, showing that better waterproofing qualities are achieved by the use of Masterseal 550 over that of the increase in cement content in blocks. As for abrasion resistance, results are comparable to that of Acronal S400 applied as a coating, and show superiority over results obtained by Masterseal 501 and Acronal S400 added to the block.

11 FACTORS INFLUENCING THE CHOICE OF CHEMICAL

Chapter one mentions that the Hydraform block and construction method was invented to meet both sustainability and economy criteria, but the lack of durability of blocks negate the use of blocks in all design conditions and hence as an alternative to conventional concrete/clay fired brick and mortar construction. Drawn conclusions detail that all chemicals enhance block properties making blocks more durable. However the final choice of chemical will not only depend on the design environment, but both sustainability and economy criteria too. This chapter will therefore present criteria for the selection of chemicals including durability, sustainability and economy.

11.1 Cost

From the foregoing chapters it has been gathered that increases in amounts of cement increase the durability properties of the blocks more than increases in any of the chemical additives. Cost is a major factor when taking the ability to achieve a certain standard of durability into consideration. Durability is assessed using parameters of strength, water uptake and erosion. Typical price parameters include; cost of soil, cost of cement with variable concentration, cost of chemical with variable concentration, operating costs, cost of maintenance, cost of machinery and allocation of profits. Prices can be reduced to an amount per block if all costs are known.

The company supplying the chemicals is still in the development of products stage and prices for chemicals are yet to be fixed.

11.2 Decision aid

Ultimately as highlighted in the chapter 3, the stability of walls built with CSEB is not only dependent on the quality of the block, but all the design parameters of the building. Building can be designed to avert some problems facing CSEB and an in certain instances make the use of certain chemicals redundant.

For example, long roof overhangs protecting the wall against rain driven erosion, presenting no need to coat the wall against effects of erosion. Some factors that affect the choice of the chemical to be used are highlighted hereunder:

- What are the problems being faced, permeation, capillary action or erosion

- Is there a need to retain initial appearance
- Does the end product smell make significant impact in choice of chemical
- Does the chemical of choice provide more environmental benefits over the use of another chemical, i.e. reduction of GHG's, less energy used during production; over and on top of the use of more cement
- Is time of the essence, application of coatings per block or alternatively use of admixture that is less time consuming and is added as a substance into the block
- The end user in block production, does he have the expertise required to use chemicals

A simple table that can possibly aid decision is draw up incorporating test measures and above factors. Table 18 undertakes to answer the following questions; does the chemical used significantly increase the given properties over and on top of the control mix and or increase properties in comparison to the use of cement to increase the said properties?

Table 14: Aid to making decision as to which chemical is preferred

	Chemical A Added (Acronal S400)	Chemical A Applied (Acronal S400)	Chemical B (Masterseal 501)	Chemical C (Masterseal 550)
Saturated Strength	X	↗	↗	↗
Water Uptake	X	↗	X	↗
Water Sorptivity	X	↗	X	↗
Abrasion	X	↗	X	
Initial Appearance	-	-	↗	X
Smell	-	-	-	X
Applicability to end user	↗	X	↗	↗
Time Required	-	X	-	X
Cost	U	U	U	U
Environmental Impact	U	U	U	U

↗ = Yes; X = No; - = Remains Constant; U = Unknown

The final decision will depend of which of the above criteria are most important to the design being considered. Hereunder three examples are made for reference sake:

Example 1 is a building with long roof overhangs in order to protect building against the elements. It is foreseeable that the watertable is to rise above foundation level. If damp proof coursing is available, chemical B would adequately provide for the saturated strength requirement.

Example 2 is a school building with inadequate roof cover to protect building against the elements. It is foreseeable that the watertable is to rise above foundation level. Initial appearance of blocks is favoured. Chemical A as apposed to Chemical C can be used to coat the outer walls for protection against the elements. The choice of Chemical A is made because Chemical C comes with an unpleasant smell accompanied by losses in appeal. Chemical A can further be used to coat blocks at damp proofing level, without the use of expensive damp-proofing material. Below damp-proof course Chemical B can be used to ensure adequate strength.

Example 3 is a boundary wall and initial appearance of blocks is not a concern. The decision whether to coat the wall either with chemical A or chemical C will depend on the if time required to undertake works is of concern, also if prudent design principles are followed, it will also depend on environmental impact each chemical causes.

12 FURTHER AREAS OF INTEREST

This study has left many unanswered questions raised in the conclusion, thus the study is not at an end in itself and more research on the durability aspects of CSEB need to be done. Some further investigation topics to the unanswered questions are presented below:

- Compressive strength testing up to 90 days or more, this needs to be done to know the optimum time required for when the strength of blocks is not negated by the effects of humidity in the block. This will be done by comparing dry strengths to oven dry strengths. The optimum curing time will be gauged by the decrease in ratio of dry/oven dry strength over time.

- Optimisation studies including the three variables of block production; clay content, cement content and compaction in order to determine definite limits of the variables and achievable durability properties

- Optimisation studies on blocks produced with chemicals with variables including clay content, cement content and chemical concentrations. The study will obtain the combined effects of variables on durability of blocks.

- Study of compressive strength load application methods with variables of cement content and compactive effort in order to obtain conclusive factors for quick and easy field testing as a percentage of laboratory strength tests. This will achieve standardisation of field test method.

- Work towards correlating field results to durability testing measures undertaken in the laboratory. For example correlating worst storm erosion events and wet/dry durability tests in the laboratory, thus creating the possibility of indexing results.

- Work towards the all important effects of blocks in aggressive environments. Do blocks retain durability (strength and appearance) in chemically aggressive environments?

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APPENDIX A
DETAILED RESULTS

SOIL PROPERTIES

Table A1: Soil Grading Analysis

Particle Size	Percent Passing							
	Soil A	SOIL B 50% Soil A + 50% Soil C	Soil C	Soil D 90% Soil C + 10% Soil H	Soil E 85% Soil C + 15% Soil H	Soil F 80% Soil C + 20% Soil H	Soil G 50% Soil C + 50% Soil H	Soil H
6.700	100.00	100.00	100	100	100.00	100	100	100
4.750	99.89	100.00	99.97	99.73	99.69	99.71	98.59	99.03
2.360	76.48	84.23	98.88	91.21	92.99	92.63	93.42	94.41
1.180	46.49	59.57	76.12	72.09	75.83	76.46	82.71	85.73
0.600	28.50	42.42	55.73	54.51	60.73	60.85	72.55	75.89
0.425	23.09	36.42	47.55	47.45	54.50	53.58	67.62	69.56
0.300	18.71	30.95	40.17	40.26	48.30	46.48	62.62	61.74
0.150	13.36	23.77	30.25	30.57	38.89	36.43	56.37	51.60
0.075	3.47	8.65	15.40	15.51	16.33	22.75	39.44	49.86
0.05	3.24	7.30	12.62	13.88	15.60	20.67	37.23	47.53
0.04	2.33	6.40	12.06	13.34	14.13	19.97	36.13	46.36
0.026	2.10	5.95	10.40	12.26	13.39	18.58	35.02	44.03
0.015	1.65	5.04	9.84	10.64	13.12	16.49	31.71	42.86
0.01	1.42	4.14	8.73	10.10	11.65	15.80	29.50	41.69
0.0074	1.19	3.69	8.73	9.56	10.18	15.10	28.39	38.19
0.0036	0.78	2.88	7.62	8.48	9.59	13.71	25.08	36.80
0.0015	0.00	0.00	0.00	0.00	0	0.00	0.00	0.00

Table A2: Soil properties

	Soil A	SOIL B 50% Soil A + 50% Soil C	Soil C	Soil D 90% Soil C + 10% Soil H	Soil E 85% Soil C + 15% Soil H	Soil F 80% Soil C + 20% Soil H	Soil G 50% Soil C + 50% Soil H	Soil H
Specific Gravity (Gs)	2.68	2.67	2.67	2.67	2.67	2.65	2.63	2.42
Liquid Limit (LL %)	Non-plastic		23.25	26.75	26.85	27.25	36.25	46.00
Plastic Limit (PL%)			22.59	22.64	22.59	22.94	28.11	33.08
Plasticity Index (PI%)			0.66	4.11	4.26	4.31	8.14	12.92
Linear Shrinkage			2.00	3.17	6.25	5.64	6.51	8.73

UNCONFINED COMPRESSIVE STRENGTH

Method of load application

Table A3: Strength results for load applied across the centre and shoulders of the block

Load applied across the centre of the block

Curing Method/Period	Length (mm)	Bed Face Area (mm2)	Load (kN)	Strength (MPa)	Ave Strength (MPa)
Dry/28Day	229	0.0229	24.6	1.07	1.01
Dry/28Day	228	0.0228	21.6	0.95	
Dry/28Day	231	0.0231	20.9	0.90	
Dry/28Day	234	0.0234	28.5	1.22	
Dry/28Day	229	0.0229	21.6	0.94	
Dry/28Day	231	0.0231	22.7	0.98	

Load applied across the shoulders of the block

Curing Method/Period	Length (mm)	Bed Face Area (mm2)	Load (kN)	Strength (MPa)	Ave Strength (MPa)
Dry/28Day	234	0.02808	112.4	4.00	4.10
Dry/28Day	233	0.02796	106.3	3.80	
Dry/28Day	230	0.0276	114.1	4.13	
Dry/28Day	231	0.02772	99.5	3.59	
Dry/28Day	229	0.02748	102.4	3.73	
Dry/28Day	231	0.0231	124.1	5.37	

Table A4: Strength results for blocks cut into cubes and tested

Cube Position, Top Cube

Curing Method/Period	Length (mm)	Bed Face Area (mm2)	Load (kN)	Strength (MPa)	Ave Strength (MPa)
Dry/28Day	100	0.01	23.5	2.35	2.27
Dry/28Day	100	0.01	25.4	2.54	
Dry/28Day	100	0.01	21.2	2.12	
Dry/28Day	100	0.01	21.6	2.16	
Dry/28Day	100	0.01	22.4	2.24	
Dry/28Day	100	0.01	21.8	2.18	

Cube Position, Bottom Cube

Curing Method/Period	Length (mm)	Bed Face Area (mm2)	Load (kN)	Strength (MPa)	Ave Strength (MPa)
Dry/28Day	100	0.01	32.5	3.25	2.96
Dry/28Day	100	0.01	29.4	2.94	
Dry/28Day	100	0.01	29.6	2.96	
Dry/28Day	100	0.01	31.6	3.16	
Dry/28Day	100	0.01	27.4	2.74	
Dry/28Day	100	0.01	27.1	2.71	

Blocks produced without chemicals

Table A5: Strength results for blocks produced with 8.5% clay content at varying cement contents (1)

Curing Method/Period	Length	Bed Face Area	Load	Strength	Ave Strength
	(mm)	(mm2)	(kN)	(MPa)	(MPa)
3% Cement / 8.5% Clay					
Dry/28Day	235	0.0517	71.2	1.38	1.29
Dry/28Day	229	0.05038	65.3	1.30	
Dry/28Day	231	0.05082	60.2	1.18	
Wet/28Day	232	0.05104	58.90	1.15	1.02
Wet/28Day	228	0.05016	44.3	0.88	
Wet/28Day	229	0.05038	51.2	1.02	
5% Cement / 8.5% Clay					
Dry/28Day	225	0.0495	155.1	3.13	2.84
Dry/28Day	230	0.0506	139.7	2.76	
Dry/28Day	225	0.0495	130.0	2.63	
Wet/28Day	230	0.0506	86.7	1.71	1.98
Wet/28Day	230	0.0506	103.6	2.05	
Wet/28Day	225	0.0495	107.7	2.18	
8% Cement / 8.5% Clay					
Dry/28Day	226	0.0452	175.9	3.89	3.91
Dry/28Day	228	0.0456	171.3	3.76	
Dry/28Day	229	0.0458	186.4	4.07	
Wet/28Day	228	0.0456	125.7	2.76	2.62
Wet/28Day	230	0.046	120.5	2.62	
Wet/28Day	228	0.0456	113.2	2.48	

Table A6: Strength results for blocks produced with 8.5% clay content at varying cement contents (2)

Curing Method/Period	Length	Bed Face Area	Load	Strength	Ave Strength
	(mm)	(mm2)	(kN)	(MPa)	(MPa)
12% Cement / 8.5% Clay					
Dry/28Day	235	0.047	189.7	4.04	4.46
Dry/28Day	226	0.0452	224.5	4.97	
Dry/28Day	235	0.047	205.7	4.38	
Wet/28Day	236	0.0472	143.2	3.03	3.43
Wet/28Day	229	0.0458	161.3	3.52	
Wet/28Day	211	0.0422	157.4	3.73	
16% Cement / 8.5% Clay					
Dry/28Day	235	0.0517	387.9	7.50	7.43
Dry/28Day	229	0.05038	366.5	7.27	
Dry/28Day	231	0.05082	382.1	7.52	
Wet/28Day	232	0.05104	358.7	7.03	6.59
Wet/28Day	228	0.05016	309	6.16	
Wet/28Day	229	0.05038	330.9	6.57	
20% Cement / 8.5% Clay					
Dry/28Day	230	0.046	507.9	11.04	11.36
Dry/28Day	240	0.048	530.2	11.05	
Dry/28Day	241	0.0482	578.1	11.99	
Wet/28Day	234	0.0468	470.2	10.05	10.35
Wet/28Day	230	0.046	485.6	10.56	
Wet/28Day	235	0.047	490.7	10.44	

Table A7: Strength results for blocks produced with 8% cement content at varying clay contents (1)

Curing Method/Period	Length	Bed Face Area	Load	Strength	Ave Strength
	(mm)	(mm^2)	(kN)	(MPa)	(MPa)
8% Cement / 3.5% Clay					
Dry/28Day	239	0.0478	358.3	7.50	6.78
Dry/28Day	228	0.0456	306.5	6.72	
Dry/28Day	230	0.046	281.5	6.12	
Wet/28Day	245	0.049	245.6	5.01	5.17
Wet/28Day	235	0.047	267.8	5.70	
Wet/28Day	233	0.0466	223.8	4.80	
8% Cement / 7.5% Clay					
Dry/28Day	225	0.0495	209	4.22	4.09
Dry/28Day	230	0.0506	198	3.91	
Dry/28Day	225	0.0495	204	4.12	
Wet/28Day	230	0.0506	141.4	2.79	3.02
Wet/28Day	230	0.0506	165.3	3.27	
Wet/28Day	225	0.0495	147.8	2.99	
8% Cement / 8.5% Clay					
Dry/28Day	226	0.0452	175.9	3.89	3.91
Dry/28Day	228	0.0456	171.3	3.76	
Dry/28Day	229	0.0458	186.4	4.07	
Wet/28Day	228	0.0456	125.7	2.76	2.62
Wet/28Day	230	0.046	120.5	2.62	
Wet/28Day	228	0.0456	113.2	2.48	

Table A8: Strength results for blocks produced with 8% cement content at varying clay contents (2)

Block No	Length	Bed Face Area	Load	Strength	Ave Strength
	(mm)	(mm^2)	(kN)	(MPa)	(MPa)
8% Cement / 9.5% Clay					
Dry/28Day	235	0.047	148.3	3.16	3.53
Dry/28Day	226	0.0452	165.7	3.67	
Dry/28Day	235	0.047	176.8	3.76	
Wet/28Day	236	0.0472	116.3	2.46	2.35
Wet/28Day	229	0.0458	103.9	2.27	
Wet/28Day	211	0.0422	97.6	2.31	
8% Cement / 15% Clay					
Dry/28Day	235	0.0517	107.8	2.09	2.09
Dry/28Day	229	0.05038	115.2	2.29	
Dry/28Day	231	0.05082	96.5	1.90	
Wet/28Day	232	0.05104	49.5	0.97	1.01
Wet/28Day	228	0.05016	45.6	0.91	
Wet/28Day	229	0.05038	57.9	1.15	
8% Cement / 25% Clay					
Dry/28Day	235	0.0517	99.2	1.92	2.02
Dry/28Day	229	0.05038	103.4	2.05	
Dry/28Day	231	0.05082	105.8	2.08	
Wet/28Day	232	0.05104	39.2	0.77	0.85
Wet/28Day	228	0.05016	42.3	0.84	
Wet/28Day	229	0.05038	47.8	0.95	

Table A9: Strength results for blocks produced with 8% Cement/3% Clay

8% Cement / 3% Clay					
Block No	**Length**	**Bed Face Area**	**Load**	**Strength**	**Ave Strength**
	(mm)	**(mm2)**	**(kN)**	**(MPa)**	**(MPa)**
Dry/3Day	235	0.0517	117.2	2.27	2.30
Dry/3Day	230	0.0506	106.8	2.11	
Dry/3Day	232	0.05104	128.6	2.52	
Wet/3Day	232	0.05104	87.9	1.72	2.13
Wet/3Day	235	0.0517	121.2	2.34	
Wet/3Day	234	0.05148	119.8	2.33	
Dry/7Day	230	0.0506	178.3	3.52	3.33
Dry/7Day	233	0.05126	168.5	3.29	
Dry/7Day	232	0.05104	161.6	3.17	
Wet/7Day	232	0.05104	157.4	3.08	3.08
Wet/7Day	234	0.05148	166	3.22	
Wet/7Day	231	0.05082	149.2	2.94	
Dry/28Day	239	0.0478	358.3	7.50	6.78
Dry/28Day	228	0.0456	306.5	6.72	
Dry/28Day	230	0.046	281.5	6.12	
Wet/28Day	245	0.049	245.6	5.01	5.17
Wet/28Day	235	0.047	267.8	5.70	
Wet/28Day	233	0.0466	223.8	4.80	
Oven dry/28Day	-	-	-	-	-
Oven dry/28Day	-	-	-	-	
Oven dry/28Day	-	-	-	-	
Dry/3month	-	-	-	-	-
Dry/3month	-	-	-	-	
Dry/3month	-	-	-	-	
Wet/3month	-	-	-	-	-
Wet/3month	-	-	-	-	
Wet/3month	-	-	-	-	

Table A10: Strength results for blocks produced with 8% Cement/8.5% Clay

8% Cement / 8.5% Clay					
Curing Method/Period	**Length**	**Bed Face Area**	**Load**	**Strength**	**Ave Strength**
	(mm)	**(mm2)**	**(kN)**	**(MPa)**	**(MPa)**
Dry/3Day	231	0.05082	97.0	1.91	
Dry/3Day	230	0.0506	100.7	1.99	2.16
Dry/3Day	234	0.05148	132.4	2.57	
Wet/3Day	227	0.04994	85.7	1.72	
Wet/3Day	226	0.04972	103.6	2.08	1.97
Wet/3Day	227	0.04994	105.7	2.12	
Dry/7Day	227	0.04994	159.7	3.20	
Dry/7Day	229	0.05038	163.2	3.24	3.14
Dry/7Day	231	0.05082	151.9	2.99	
Wet/7Day	231	0.05082	103.0	2.03	
Wet/7Day	229	0.05038	131.6	2.61	2.35
Wet/7Day	227	0.04994	121.1	2.42	
Dry/28Day	226	0.0452	175.9	3.89	
Dry/28Day	228	0.0456	171.3	3.76	3.91
Dry/28Day	229	0.0458	186.4	4.07	
Wet/28Day	228	0.0456	125.7	2.76	
Wet/28Day	230	0.046	120.5	2.62	2.62
Wet/28Day	228	0.0456	113.2	2.48	
Oven dry/28Day	232	0.0464	266.6	5.75	
Oven dry/28Day	233	0.0466	249.9	5.36	5.87
Oven dry/28Day	231	0.0462	300.0	6.49	
Dry/3month	229	0.0458	403.9	8.82	
Dry/3month	234	0.0468	395.4	8.45	8.52
Dry/3month	231	0.0462	383.8	8.31	
Wet/3month	231	0.0462	252.1	5.46	
Wet/3month	229	0.0458	238.4	5.21	5.27
Wet/3month	234	0.0468	241.4	5.16	

Table A11: Strength results for blocks produced with 20% Cement/8.5% Clay

20% Cement / 8.5% Clay					
Curing Method/Period	**Length**	**Bed Face Area**	**Load**	**Strength**	**Ave Strength**
	(mm)	**(mm^2)**	**(kN)**	**(MPa)**	**(MPa)**
Dry/3Day	230	0.0506	275.7	5.45	4.44
Dry/3Day	230	0.0506	283.8	5.61	
Dry/3Day	180	0.0396	89.9	2.27	
Wet/3Day	231	0.05082	146	2.87	3.56
Wet/3Day	225	0.0495	115.2	2.33	
Wet/3Day	229	0.05038	276	5.48	
Dry/7Day	232	0.05104	358.7	7.03	6.47
Dry/7Day	235	0.0517	309	5.98	
Dry/7Day	235	0.0517	330.9	6.40	
Wet/7Day	234	0.05148	269.9	5.24	5.90
Wet/7Day	230	0.0506	318.8	6.30	
Wet/7Day	227	0.04994	307	6.15	
Dry/28Day	230	0.046	507.9	11.04	11.36
Dry/28Day	240	0.048	530.2	11.05	
Dry/28Day	241	0.0482	578.1	11.99	
Wet/28Day	234	0.0468	470.2	10.05	10.35
Wet/28Day	230	0.046	485.6	10.56	
Wet/28Day	235	0.047	490.7	10.44	
Oven dry/28Day	239	0.0478	679.2	14.21	14.09
Oven dry/28Day	235	0.047	627.6	13.35	
Oven dry/28Day	233	0.0466	685.4	14.71	
Dry/3month	230	0.046	1054	22.91	23.50
Dry/3month	235	0.047	1144	24.34	
Dry/3month	235	0.047	1092	23.23	
Wet/3month	235	0.047	795	16.91	17.96
Wet/3month	233	0.0466	897	19.25	
Wet/3month	235	0.047	832	17.70	

Blocks with Chemicals

Chemical A – Acronal S400 Added to Block

Table A12: Strength results for blocks produced with 8% Cement/8.5% Clay and Acronal S400 added to the block(1)

Curing Method/ Period	Length	Bed Face Area	Load	Strength	Ave Strength
	(mm)	(mm2)	(kN)	(MPa)	(MPa)
8% Cement / 8.5% Clay/ 5% Acronal S400					
Dry/28Day	228	0.0456	209.3	4.59	4.45
Dry/28Day	225	0.045	192.8	4.28	
Dry/28Day	230	0.046	205.2	4.46	
Wet/28Day	225	0.045	176.8	3.93	3.85
Wet/28Day	229	0.0458	167.8	3.66	
Wet/28Day	230	0.046	182.4	3.97	
8% Cement / 8.5% Clay/ 10% Acronal S400					
Dry/28Day	229	0.05	259.5	5.67	5.86
Dry/28Day	230	0.05	265.5	5.77	
Dry/28Day	225	0.05	276.1	6.14	
Wet/28Day	229	0.05	185.6	4.05	3.97
Wet/28Day	225	0.05	179.6	3.99	
Wet/28Day	232	0.05	179.8	3.88	
8% Cement / 8.5% Clay/ 15% Acronal S400					
Dry/28Day	231	0.0462	285.7	6.18	6.19
Dry/28Day	230	0.046	285.5	6.21	
Dry/28Day	229	0.0458	283.6	6.19	
Wet/28Day	225	0.045	188.4	4.19	4.19
Wet/28Day	225	0.045	195.2	4.34	
Wet/28Day	230	0.046	185.5	4.03	
8% Cement / 8.5% Clay/ 20% Acronal S400					
Dry/28Day	230	0.046	291.4	6.33	6.32
Dry/28Day	227	0.0454	281.2	6.19	
Dry/28Day	225	0.045	289.7	6.44	
Wet/28Day	227	0.0454	206.3	4.54	4.47
Wet/28Day	225	0.045	204.9	4.55	
Wet/28Day	225	0.045	194.3	4.32	

8% Cement / 8.5% Clay/ 50% Acronal S400

Dry/28Day	235	0.047	359	7.64	7.70
Dry/28Day	232	0.0464	355.5	7.66	
Dry/28Day	233	0.0466	363.1	7.79	
Wet/28Day	235	0.047	202.7	4.31	4.45
Wet/28Day	235	0.047	206.4	4.39	
Wet/28Day	232	0.0464	215.3	4.64	

Table A13: Strength results for blocks produced with 8% Cement/8.5% Clay and Acronal S400 added to the block (2)

5% Admix 1 / 8% Cement / 8.5% Clay					
Block No	**Length**	**Bed Face Area**	**Load**	**Strength**	**AVE**
	(mm)	**(mm2)**	**(kN)**	**(MPa)**	
Dry/3Day	205	0.0451	108.3	2.40	2.44
Dry/3Day	205	0.0451	111.4	2.47	
Dry/3Day	210	0.0462	113	2.45	
Wet/3Day	223	0.04906	97.6	1.99	1.82
Wet/3Day	201	0.04422	82.1	1.86	
Wet/3Day	222	0.04884	79.5	1.63	
Dry/7Day	225	0.0495	142.8	2.88	3.06
Dry/7Day	200	0.044	143.2	3.25	
Dry/7Day	209	0.04598	140	3.04	
Wet/7Day	222	0.04884	113.7	2.33	2.19
Wet/7Day	217	0.04774	102.4	2.14	
Wet/7Day	225	0.0495	104.2	2.11	
Dry/28Day	228	0.0456	209.3	4.59	4.45
Dry/28Day	225	0.045	192.8	4.28	
Dry/28Day	230	0.046	205.2	4.46	
Wet/28Day	225	0.045	176.8	3.93	3.85
Wet/28Day	229	0.0458	167.8	3.66	
Wet/28Day	230	0.046	182.4	3.97	

Table A14: Strength results for blocks produced with 8% Cement/8.5% Clay and Acronal S400 coated over the block

Acronal S400 Applied as a Coating @ 1:4 (Chemical : Water)					
Curing Method/ Period	**Length**	**Bed Face Area**	**Load**	**Strength**	**AVE**
	(mm)	**(mm2)**	**(kN)**	**(MPa)**	
Dry/3Day	229	0.05038	104.9	2.08	1.89
Dry/3Day	231	0.05082	92.4	1.82	
Dry/3Day	231	0.05082	90	1.77	
Wet/3Day	230	0.0506	99.5	1.97	1.82
Wet/3Day	231	0.05082	90.3	1.78	
Wet/3Day	233	0.05126	87.3	1.70	
Dry/7Day	229	0.05038	155.8	3.09	3.04
Dry/7Day	230	0.0506	145.6	2.88	
Dry/7Day	230	0.0506	159.1	3.14	
Wet/7Day	232	0.05104	135.4	2.65	2.91
Wet/7Day	227	0.04994	153.7	3.08	
Wet/7Day	230	0.0506	151.3	2.99	
Dry/28Day	228	0.0456	202.4	4.44	4.13
Dry/28Day	229	0.0458	175.2	3.83	
Dry/28Day	227	0.0454	187.3	4.13	
Wet/28Day	229	0.0458	186.1	4.06	4.22
Wet/28Day	232	0.0464	204.6	4.41	
Wet/28Day	230	0.046	192.5	4.18	
Oven dry/28Day	229	0.0458	237.6	5.19	5.07
Oven dry/28Day	232	0.0464	242.7	5.23	
Oven dry/28Day	230	0.046	220.5	4.79	

Chemical B – Masterseal 501

Table A15: Strength results for blocks produced with 8% Cement/8.5% Clay and Masterseal 501 (1)

Curing Method/ Period	Length	Bed Face Area	Load	Strength	Ave Strength
	(mm)	(mm2)	(kN)	(MPa)	(MPa)
8% Cement / 8.5% Clay/ 5% Masterseal 501					
Dry/28Day	235	0.047	292.7	6.23	6.29
Dry/28Day	231	0.0462	283.4	6.13	
Dry/28Day	232	0.0464	302.2	6.51	
Wet/28Day	231	0.0462	184.9	4.00	4.02
Wet/28Day	232	0.0464	195.4	4.21	
Wet/28Day	230	0.046	176.5	3.84	
8% Cement / 8.5% Clay/ 10% Masterseal 501					
Dry/28Day	231	0.0462	410.2	8.88	8.57
Dry/28Day	231	0.0462	375.1	8.12	
Dry/28Day	231	0.0462	402	8.70	
Wet/28Day	230	0.046	269.3	5.85	5.68
Wet/28Day	230	0.046	255.1	5.55	
Wet/28Day	230	0.046	259.6	5.64	
8% Cement / 8.5% Clay/ 15% Masterseal 501					
Dry/28Day	230	0.046	472.5	10.27	10.04
Dry/28Day	231	0.0462	452.3	9.79	
Dry/28Day	230	0.046	462.6	10.06	
Wet/28Day	227	0.0454	270.9	5.97	6.01
Wet/28Day	229	0.0458	259.2	5.66	
Wet/28Day	228	0.0456	291.8	6.40	

Table A16: Strength results for blocks produced with 8% Cement/8.5% Clay and Masterseal 501 (2)

Curing Method/ Period	Length (mm)	Bed Face Area (mm2)	Load (kN)	Strength (MPa)	Ave Strength (MPa)
8% Cement / 8.5% Clay/ 20% Masterseal 501					
Dry/28Day	230	0.046	497.4	10.81	10.82
Dry/28Day	230	0.046	516.3	11.22	
Dry/28Day	230	0.046	480	10.43	
Wet/28Day	229	0.0458	300.3	6.56	6.63
Wet/28Day	230	0.046	321.5	6.99	
Wet/28Day	234	0.0468	297.4	6.35	
8% Cement / 8.5% Clay/ 50% Masterseal 501					
Dry/28Day	235	0.047	386.3	8.22	9.56
Dry/28Day	234	0.0468	510	10.90	
Dry/28Day	230	0.046	439.7	9.56	
Wet/28Day	235	0.047	261.30	5.56	6.24
Wet/28Day	235	0.047	270.70	5.76	
Wet/28Day	234	0.0468	346.60	7.41	

Table A17: Strength results for blocks produced with 8% Cement/8.5% Clay and Masterseal 501 (3)

8% Cement / 8.5% Clay/ 5% Masterseal 501					
Curing Method/Period	**Length**	**Bed Face Area**	**Load**	**Strength**	**AVE**
	(mm)	**(mm2)**	**(kN)**	**(MPa)**	
Dry/3Day	229	0.05038	129.4	2.57	2.38
Dry/3Day	231	0.05082	110.9	2.18	
Dry/3Day	230	0.0506	121.3	2.40	
Wet/3Day	235	0.0517	90.2	1.74	1.85
Wet/3Day	235	0.0517	99.8	1.93	
Wet/3Day	235	0.0517	97.7	1.89	
Dry/7Day	231	0.05082	157.8	3.11	3.22
Dry/7Day	233	0.05126	161.1	3.14	
Dry/7Day	230	0.0506	172.1	3.40	
Wet/7Day	232	0.05104	115.7	2.27	2.45
Wet/7Day	232	0.05104	124.2	2.43	
Wet/7Day	231	0.05082	134	2.64	
Dry/28Day	235	0.047	292.7	6.23	6.29
Dry/28Day	231	0.0462	283.4	6.13	
Dry/28Day	232	0.0464	302.2	6.51	
Wet/28Day	231	0.0462	184.9	4.00	4.02
Wet/28Day	232	0.0464	195.4	4.21	
Wet/28Day	230	0.046	176.5	3.84	

Chemical C – Masterseal 550

Table A18: Strength results for blocks produced with 8% Cement/8.5% Clay and Masterseal 550

8% Cement / 8.5% Clay/ Masterseal 550

Curing Period/Method	Length	Bed Face Area	Load	Strength	AVE
	(mm)	(mm2)	(kN)	(MPa)	
Dry/3Day	229	0.05038	107.1	2.13	
Dry/3Day	231	0.05082	98.7	1.94	2.12
Dry/3Day	231	0.05082	115.8	2.28	
Wet/3Day	230	0.0506	99.5	1.97	
Wet/3Day	231	0.05082	95.4	1.88	1.97
Wet/3Day	233	0.05126	105.2	2.05	
Dry/7Day	229	0.05038	150.9	3.00	
Dry/7Day	230	0.0506	166.4	3.29	3.16
Dry/7Day	230	0.0506	161.2	3.19	
Wet/7Day	232	0.05104	147.2	2.88	
Wet/7Day	227	0.04994	154.5	3.09	2.99
Wet/7Day	230	0.0506	151.3	2.99	
Dry/28Day	228	0.0456	304.5	6.68	
Dry/28Day	229	0.0458	290.7	6.35	6.66
Dry/28Day	227	0.0454	315.8	6.96	
Wet/28Day	229	0.0458	287.3	6.27	
Wet/28Day	232	0.0464	256.3	5.52	6.05
Wet/28Day	230	0.046	292.6	6.36	
Oven dry/28Day	229	0.0458	415.1	9.06	
Oven dry/28Day	232	0.0464	425.7	9.17	8.98
Oven dry/28Day	228	0.0456	396.2	8.69	

WATER UPTAKE

Table A19: Water Uptake (%)

Block Type	Specimen No	Mass (g)			Uptake (%)			
		Dry	24h	72h	24h		72h	
Control Block A	1	11.626	12.211	12.565	5.03	5.07	8.08	8.03
	2	12.377	13.017	13.353	5.17		7.89	
	3	11.411	11.984	12.337	5.02		8.11	
Control Block B	1	12.158	12.6	12.909	3.64	3.41	6.18	5.68
	2	12.402	12.82	12.993	3.37		4.77	
	3	12.259	12.656	13.005	3.24		6.09	
Acronal Added	1	10.471	11.279	11.307	7.72	7.55	7.98	7.80
	2	10.603	11.383	11.41	7.36		7.61	
	3	10.6	11.404	11.426	7.58		7.79	
Acronal Coated	1	11.367	11.627	11.627	2.29	2.81	2.29	2.81
	2	11.314	11.625	11.625	2.75		2.75	
	3	11.235	11.615	11.615	3.38		3.38	
Masterseal 501	1	11.458	12.009	12.235	4.81	4.93	6.78	6.86
	2	11.444	12.037	12.229	5.18		6.86	
	3	11.514	12.065	12.313	4.79		6.94	
Masterseal 550	1	11.491	11.805	11.823	2.73	2.88	2.89	3.00
	2	11.646	11.992	11.996	2.97		3.01	
	3	11.535	11.872	11.892	2.92		3.09	

WATER SORPTIVITY

Table A20: Control block A water sorptivity (mm/hr$^{1/2}$)

Control Block A				
		Specimen 1	**Specimen 2**	**Specimen 3**
T (min)	**$T^{1/2}$ (h)**	**M_{wt} (g)**	**M_{wt} (g)**	**M_{wt} (g)**
0	**0**	156.62	179.09	186.15
1	**0.129**	161.13	183.43	189.94
2	**0.183**	162.83	184.74	191.44
4	**0.258**	165.15	186.46	193.23
8	**0.365**	168.26	189.00	195.75
16	**0.516**	171.47	192.51	199.22
32	**0.73**	174.39	196.58	203.70
64	**1.033**	174.29	198.98	206.58
M_{sv}(g)=		180.59	204.70	213.08
F=		17.51	19.38	20.11
d (mm)=		23.30	26.20	27.00
S (mm/h $^{1/2}$) =		17.02	19.83	20.16
$S_{average}$			19.00	

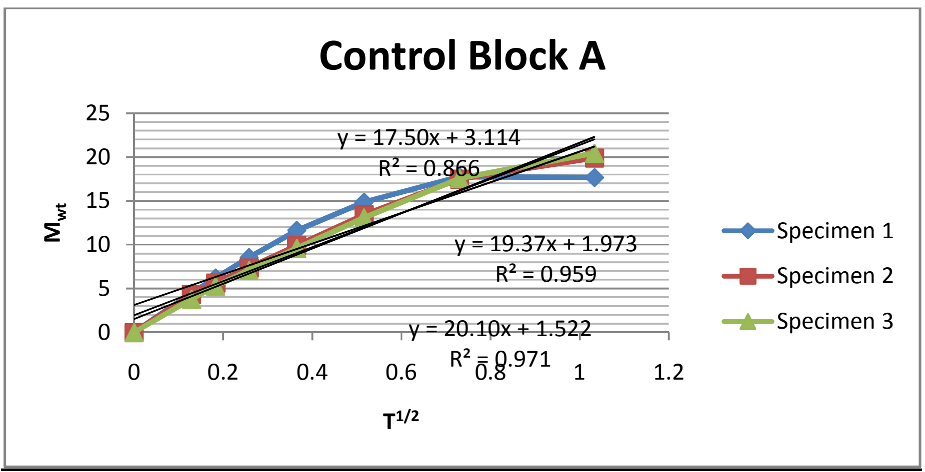

Figure A1: Graph showing control block A water sorptivity regression

Table A21: Control block B water sorptivity (mm/hr$^{1/2}$)

Control Block B				
		Specimen 1	Specimen 2	Specimen 3
T (min)	**$T^{1/2}$ (h)**	**M_{wt} (g)**	**M_{wt} (g)**	**M_{wt} (g)**
0	**0**	205.02	212.14	180.75
1	**0.129**	206.56	213.74	182.67
2	**0.183**	207.13	214.39	183.30
4	**0.258**	207.51	214.84	183.77
8	**0.365**	208.28	215.56	184.66
16	**0.516**	209.49	216.67	185.89
32	**0.73**	210.89	218.13	187.63
64	**1.033**	212.89	219.94	189.76
M_{sv}(g)=		234.11	239.80	204.72
F=		7.33	7.23	8.33
d (mm)=		29.80	30.10	25.80
S (mm/h $^{1/2}$) =		7.51	7.87	8.97
$S_{average}$		8.12		

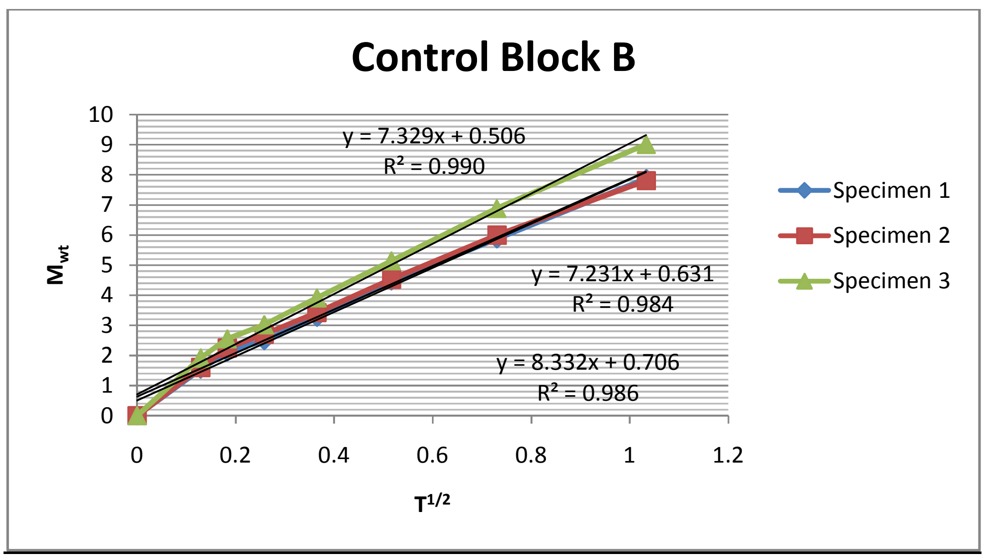

Figure A2: Graph showing control block B water sorptivity regression

Table A22: Acronal S400 applied as a coat water sorptivity (mm/hr$^{1/2}$)

Acronal S400 Coated				
		Specimen 1	Specimen 2	Specimen 3
T (min)	$T^{1/2}$ (h)	M_{wt} (g)	M_{wt} (g)	M_{wt} (g)
0	0	239.66	248.99	229.88
1	0.129	239.81	249.19	230.13
2	0.183	239.91	249.36	230.16
4	0.258	240.07	249.46	230.22
8	0.365	240.14	249.68	230.4
16	0.516	240.58	250.09	230.69
32	0.73	241.1	250.82	231.14
64	1.033	242.03	252.03	232
M_{sv}(g)=		271.82	282.84	260.47
F=		2.31	2.93	2.00
d (mm)=		39.40	36.40	33.60
S (mm/h $^{1/2}$) =		2.82	3.15	2.19
$S_{average}$		2.72		

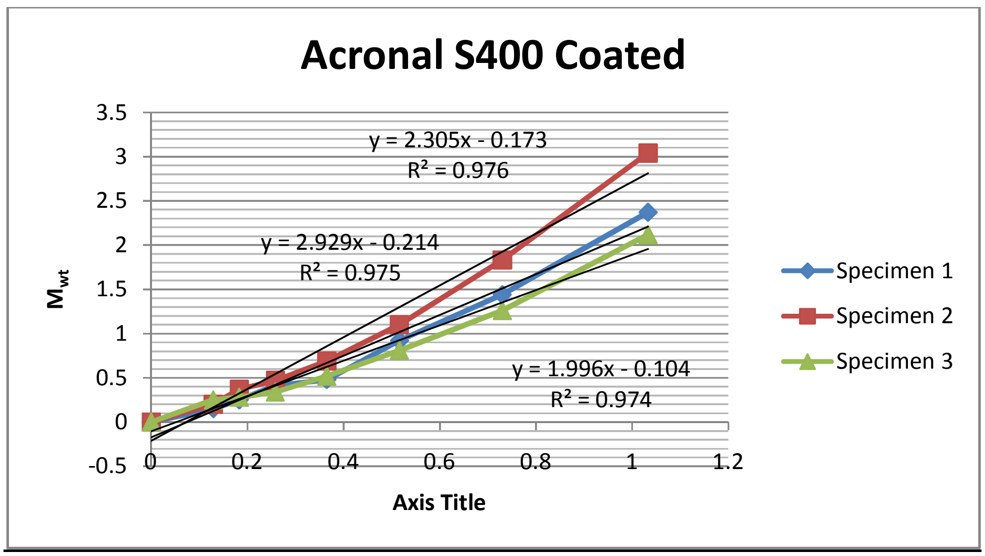

Figure A3: Graph showing Acronal S400 applied as a coat water sorptivity regression

Table A23: Masterseal 501 sorptivity ($mm/hr^{1/2}$)

Masterseal 501				
		Specimen 1	Specimen 2	Specimen 3
T (min)	$T^{1/2}$ (h)	M_{wt} (g)	M_{wt} (g)	M_{wt} (g)
0	0	275.3	254.87	282.04
1	0.129	277	258.12	285.42
2	0.183	280.79	259.75	286.94
4	0.258	281.84	260.34	287.61
8	0.365	283.01	261.57	288.87
16	0.516	285.66	263.99	291.45
32	0.73	289.51	267.56	295.27
64	1.033	294.82	272.43	300.58
M_{sv}(g)=		313.47	289.83	320.71
F=		18.90	16.42	17.36
d (mm)=		39.60	36.60	40.40
S ($mm/h^{1/2}$) =		19.61	17.19	18.14
$S_{average}$		18.31		

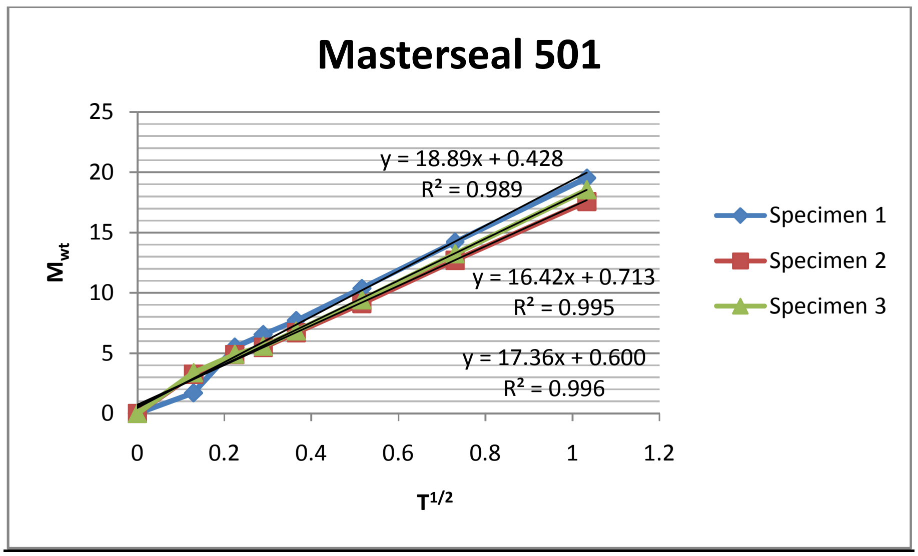

Figure A4: Graph showing Masterseal 501 water sorptivity regression

Table A24: Masterseal 550 sorptivity (mm/hr$^{1/2}$)

Masterseal 550				
		Specimen 1	Specimen 2	Specimen 3
T (min)	$T^{1/2}$ (h)	M_{wt} (g)	M_{wt} (g)	M_{wt} (g)
0	0	300.33	273.01	297.01
1	0.129	300.53	273.2	297.17
2	0.183	300.56	273.43	297.34
4	0.258	300.66	273.47	297.41
8	0.365	300.79	273.49	297.46
16	0.516	300.91	273.55	297.47
32	0.73	300.92	273.66	297.49
64	1.033	300.88	273.53	297.49
M_{sv}(g)=		343.71	311.50	330.48
F=		0.54	0.47	0.41
d (mm)=		45.00	40.90	41.60
S (mm/h $^{1/2}$) =		0.56	0.50	0.50
$S_{average}$		0.52		

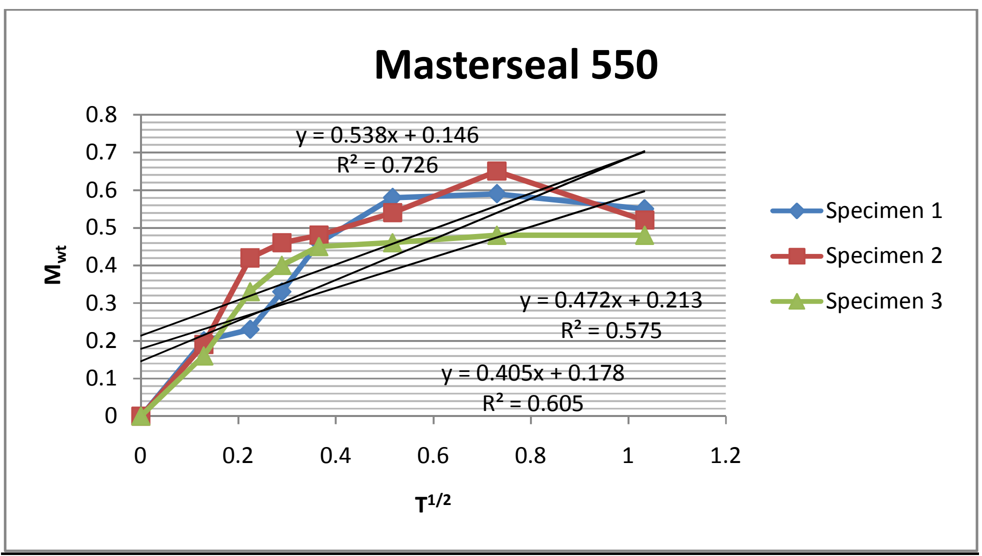

Figure A5: Graph showing Masterseal 550 water sorptivity regression

DRYING SHRINKAGE

Table A25: Drying shrinkage (% of original length)

Block Type	Specimen No	Wet Length	Dry Length	Drying Shrinkage	
Control A	1	155.65	154.65	0.647	0.32
	2	155.9	155.75	0.096	
	3	156.1	155.75	0.225	
Control B	1	156.1	156.1	0.000	0.00
	2	160.4	160.4	0.000	
	3	155.75	155.75	0.000	
Acronal S400 Added	1	152.6	151.34	0.833	0.83
	2	153.05	151.75	0.857	
	3	155.4	154.15	0.811	
Masterseal 550	1	154.15	153.8	0.228	0.27
	2	149.15	148.65	0.336	
	3	151.1	150.75	0.232	

WET/DRY DURABILITY (ABRASION TESTING)

Table A26: Abrasion testing (% mass loss)

Block Type	Block No	CYCLE		Mass Loss	
		Initial	Final	Individual	Average
Control A	1	11.922	10.342	15.277509	15.68
	2	11.615	10.12	14.772727	
	3	11.919	10.187	17.002061	
Control B	1	11.483	11.184	2.6734621	2.40
	2	11.525	11.301	1.9821255	
	3	11.581	11.295	2.5320938	
Acronal S400 Added	1	11.993	10.45	14.76555	14.79
	2	11.623	10.12	14.851779	
	3	11.962	10.424	14.754413	
Acronal S400 Coated	1	12.059	11.487	4.9795421	4.60
	2	12.06	11.535	4.5513654	
	3	12.198	11.698	4.2742349	
Masterseal 550	1	12.051	10.614	13.538722	13.61
	2	11.671	10.27	13.641675	
	3	12.026	10.582	13.645814	
Masterseal 501	1	11.978	11.376	5.2918425	5.32
	2	12.029	11.389	5.6194574	
	3	12.084	11.502	5.0599896	