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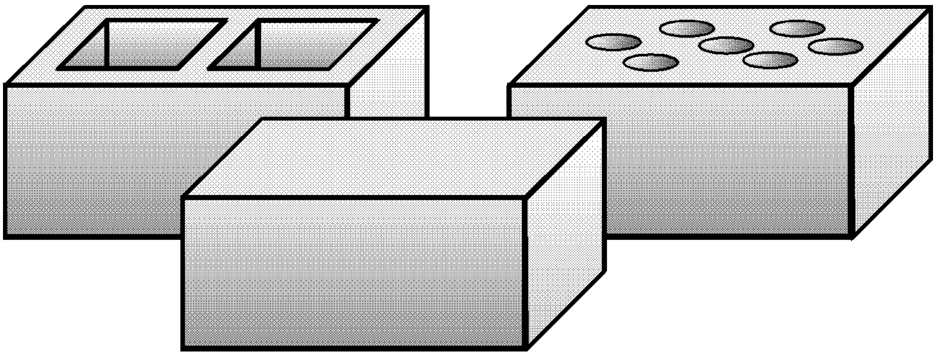
Stabilised Soil Research Progress Report SSRPR8



Minimising the cement requirement of stabilised soil block walling

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March 2001

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Titles of Stabilised Soil Research Progress Reports Produced to date:

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A dedication to someone special

Sometimes at the beginning of a publication one finds a dedication to a certain person or member of the family who has been an influence in the author's life either in general or specifically in generating the work in question. There is one person in my life that immediately springs to mind who is worthy of such a dedication. Furthermore, my experience with this person is not unique as millions of others have found him to be a great inspiration, comfort, guide and friend. "What's his name?" you may be asking yourself and, "Why haven't I heard of this incredibly influential person". The sad thing is that you probably have, but you have never accepted him as such or welcomed him into your heart and life. Well, now you have an opportunity to do just that. Please read on.

The man's name is Jesus and although he was born nearly 2000 years ago his testimony still remains and his power to save is just as great. "Save from what?" you may ask, sin and the consequences thereof, or more specifically, your sins and the consequences you face when you die. As humans we demand justice to be done, and justice will be done, but on a perfect scale and to a perfect standard. That leaves us all falling short and without hope when we come face to face with a holy God. But, God in his great love towards us send his only begotten Son into the world that the world through him might be saved. Jesus Christ died for you so that you would not have to be punished for what you have done wrong. You can be spared eternal punishment in hell and enjoy love and peace in the presence of God forever. Today the choice is yours. Reject God's free gift of love at your peril, accept it and who knows you too may have the joy of writing a dedication such as this someday. Please ponder the verses below and make your choice carefully, it will be the most important decision you ever make.

David E. Montgomery

"*For by grace are ye saved through faith; and that not of yourselves: it is the gift of God: not of works, lest any man should boast.*" Ephesians 2:8,9.

"*For God so loved the world, that he gave his only begotten Son, that whosoever believeth in him should not perish, but have everlasting life.*" John 3:16.

"*For whosoever shall call upon the name of the Lord shall be saved.*" Romans 10:13

"*He that believeth on him is not condemned: be he that believeth not is condemned already, because he hath not believed in the name of the only begotten Son of God.*" John 3:18.

"*Jesus saith unto him, I am the way, the truth, and the life: no man commeth unto the Father, but by me.*" John 14:6.

Abstract

The monetary cost of low-cost walling in developing countries is greatly dependent on the expensive additives that are used to manufacture the building units and the cost of transportation of raw materials or finished products to the site of construction. Another cost associated with the production of anything is an energy cost and that can give an approximate overall measure of environmental impact. Within this paper several different types of existing walling materials are investigated for their overall cement and energy consumption. The purpose is to see how favourably they compare with high-density compressed and stabilised soil blocks using these suitable comparative measures. Assessment of suitability of local and on-site production will also be indicated for each of the materials in this study.

The study indicates that only three of the materials examined utilise less than 15kg/m² of cement, two of those are unsuitable for local production and the third uses about three times the energy in production. High-density compressed and stabilised soil blocks use slightly more than 15kg/m² of cement but have a low energy requirement for production. The other sections of this paper deal with the possible methods of further reducing the cement requirement of high-density compressed and stabilised soil blocks to a value below 15kg/m².

Several different cement-reducing methods are outlined within this paper. These include: placing voids in the block, incorporation of a cement rich-skin (either within the block itself or applied as a render), interlocking blocks requiring very little or no mortar and taller blocks that reduce the number of block courses needed for mortaring. In isolation each method does not reduce the cement demand below 15kg/m². However, it is possible to apply several of these methods together that safely brings the cement requirements to well below the target of 15kg/m² with a low energy cost.

Nomenclature

Brick: An object (usually of fired clay) used in construction, usually of retangular shape, whose largest dimension does not exceed 300mm.

Block: A larger type of brick not necessarily made of fired clay, but stabilised in some way, sometimes with central cores removed to reduce the weight.

Cement: Ordinary Portland Cement (OPC).

Clay: The finest of the particles found in soil, usually of less than 0.002mm in size and possesses significant cohesive properties.

Concrete: The finished form of a mixture of cement, sand, aggregate and water.

Dynamic Compaction: A process that densifies soil by applying a series of impact blows to it.

Fines: General category of silts and clays.

Green Strength: The strength present in a freshly formed block prior to curing.

Sand: A mixture of rock particles ranging from 0.06mm to 2 mm in diameter.

Silt: Moderately fine particles of rock from 0.002mm to 0.06mm in size.

Soil: Material found on the surface of the earth not bigger than 20mm in size, not including rocks and boulders and predominantly non-organic. If soil is to be used for building material it must not contain any organic material and it can be a natural selection of particles or a mixture of different soils to attain a more suitable particle distribution.

Stabilised soil: Soil which has been stabilised (treated to improve structural characteristics) by using one or more of the following stabilisation techniques: mechanical, chemical and physical.

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1. Introduction

Cement (opc) is the normal material used to stabilise soil in compressed block walling. It gives them a 'wet strength' they would otherwise lack. Other stabilisers are possible, but few meet the requirement of being readily and economically available in the target area for low-cost house walling, namely developing countries. However work at Warwick on micro-silica (both in its classical form and as a product of low temperature rice-husk processing) has led us to investigate its advantages as an opc additive in block-making. Interestingly, at clay contents below 15% Kaolin equivalent, lime has not proved to be a useful substitute for opc in soil block manufacture.

Cement is expensive in some countries (e.g. over $0.2 per kg in Uganda) and the ratio of (50kg) cement cost to daily wage exceeds 5 in most developing countries. It is currently uneconomic to use much cement – say more than 15 kg cement per m^2 of walling. Additives like micro-silica, while they are only used to substitute a small part of the opc, are considerably more expensive per kg and therefore even more restricted in their concentrations.

If we take as a norm a wall thickness of 140 mm, and assume mortaring consumes 30% of the available cement, then we are restricted to about 4% opc by weight within the blocks, or less than 4% if a costly additive is included. Even with very high moulding pressures (10 MPa), or high impact energies, it is difficult to produce really durable blocks with so little stabiliser.

There are however some paths we might follow that would allow us to use denser stabilisation without exceeding this cost target (of 15kg opc per m^2). One is to produce hollow or indented blocks that use less material per unit area of walling. Saving 50% of the material would allow a doubling of the cement:soil ratio. A second path is to employ non-homogenous material, increasing the concentration of stabiliser in the block faces (where deterioration is focussed) and reducing it in the block interior. A third path is to reserve much of the cement for a render, placed over hardlystabilised blocks. A fourth is to employ dimensionally tight interlocking blocks requiring little mortar to lay.

The purpose of this Research Progress Report is to discuss the advantages, disadvantages and practical implications of following each of these paths.

2. Summary of existing materials for building

In this document we cannot provide an exhaustive list of building materials, just some of the more popular methods of providing walling at tolerable cost. Hollow and aerated concrete blocks, clamp and kiln fired brick and compressed and stabilised soil blocks (hereafter CSSB) are the main materials for consideration. Some of these materials require a thicker level of mortar to compensate for the irregularities of the blocks. Furthermore certain materials need further protection from the elements if they are to last for tolerable periods and this is usually done by applying a render to the external face of the building. Sometimes this is only done for visual reasons, but for the purposes of this investigation we will assume that aesthetics are not the primary concern and certainly not worth extra expense.

Possibly one of the most striking differences between different types of building materials is their width. Some concrete hollow blocks are 250mm (10”) wide whist the clay fired brick is usually only 103mm (4”) wide. A wider block is more stable and can be used to build taller walls with a high slenderness ratio, (width/height). A single skin 103mm wall is not considered to be stable enough except for in-fill walling between columns and beams or for relatively small structures. In our analysis of single skin brick construction we have included a buttress pillar of two bricks at 1-metre centres, which increases the brick and material requirement by 25%. It is more common to make a single skin brick wall of closer to 150mm (6”) thick and this practice can be extended to two storey construction.

2.1 Hollow concrete blocks

These are expensive due to their need for graded sand and large amounts of cement (12-17% by weight). If manufactured properly they can have a very high strength and have excellent durability. Cost reduction is achieved by removing material from the block core thus making it lighter as well. Machinery for production requires a vibrating table to settle the cement mix into the mould. Sometimes a heavy hinged lid slammed a couple of times or low pressures are applied to compress the material.

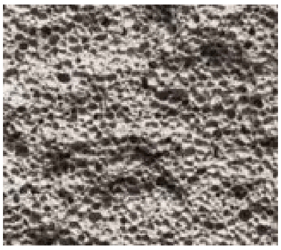
High-pressure compaction of these blocks is highly uncommon and is well out of the scope of low-cost building materials.

Good dimensional accuracy means that these blocks can be laid on a 10mm mortar joint. However, due to the voids in the block much mortar falls down these holes and is wasted. (In calculating the required mortar we have assumed that the mortar actually used is closer to the total surface area of the entire top surface of the block rather than just the edges where a joint is made with the neighbouring block.) These blocks are sometimes rendered for aesthetic reasons, which we will omit from any calculations for the time being.

2.2 Aerated concrete blocks

Aerated concrete is a much lighter form of concrete that omits the use of coarse aggregate and includes a high percentage of air voids in the material. A cement rich mixture has a foaming agent applied to it before the material is pumped or can be cast into suitable moulds (Neville, 1995). This material has been developed into a high performance building material and is currently marketed as aerated concrete blocks (Thermalite, 2001). The large proportion of air within the block reduces the density to around 500kg/m^3.

Although these blocks are not considered suitable for heavy-load bearing conditions, (over 7MPa), they are highly favourable to low-rise structures such as typical homes. Other features such as high wall area per block, low thermal conductivity, easily shaped by hand tools and low moisture penetration make this a highly attractive material. The production costs are reasonable as the main ingredient is coal ash from power stations, (which itself is a pozzolanic material that helps the cementitic process), but the complexity of the process makes it relatively unsuitable for small-scale manufacture. Moreover coal-burning power stations are not present in all countries



A – Aircrete B – Thermalite block C – Thin mortar joints

The above photographs show the structure of aircrete (A), it's ease of handling (B) and the high dimensional accuracy required for thin mortar joints (C). The textured surface of the blocks help to bond the to the block mortar, (if desired as it is not necessary on external walling).

2.3 Kiln fired brick

Over the centuries the process of burning clay to make brick has become more and more automated, sophisticated and complex, but not necessarily more cost effective, particularly in developing countries. (Parry, 1979) very eloquently and persuasively describes two methods of brick production in terms of cost and shows quite clearly that where labour costs are low, kiln-fired brick production would be unsuitable. Kiln-fired brick production requires a high capital investment and a significant amount of infrastructure to support production. A greater degree of material selection must be employed, staff needs to be highly skilled, spares and servicing is highly specialised and energy requirements are considerable. Production output is very high, typically 10,000 - 30,000 bricks per day and needs to be continuous if to achieve high efficiency and to achieve the greatest return on investment.

The characteristics of such kiln-fired bricks are highly desirable as the material has a high wet-compressive strength and does not deteriorate rapidly over time even in the harshest of climates (Hanson, 2001). The material is pleasing to the eye and is sought after as an attractive material for home building.

2.4 Clamp fired brick

Can be inexpensive in monetary terms because the raw materials are dug from the ground and the energy required firing the brick could come from collected firewood.

Clay fired blocks need good sources of clay for production and like graded sand must be obtained from a suitable source nearby. Forming the blocks requires a wooden or metal mould and after forming they are laid out to dry. After drying they are stacked into a clamp where fires are burnt inside (Parry, 1979). These fires raise the temperature of the blocks to the point where the particles bond together (Stulz & Mukerji, 1993). Thorough burning is necessary to fire all the blocks properly and this takes several days to achieve. The finished blocks can be quite badly misshapen and this requires a thick layer of mortar between the blocks, sometimes as thick as 20mm. Furthermore, if the blocks are poorly fired then in order to achieve adequate durability they may need to be rendered as well. Fired blocks are considered attractive and so they are not generally rendered unless necessary.

This is a particularly poor example of clamp-fired bricks and thick poorly used mortar. The result is unattractive and wasteful of cement.

However, due to the high cement content of the wall and the fired brick used it will probably achieve adequate durability.

The poor dimensional accuracy of the bricks can be clearly seen in this photograph.

2.5 Compressed and Stabilised Soil Blocks

These blocks use the same parent material as unstabilised mud but offer the significant advantage of wet compressive strength. One of the methods of stabilisation is to compact a soil sample to reduce the voids in the finished block. Compaction is achieved by applying some mechanical effort to the soil, which in turn drives out some of the air voids. Increasing the density of the material gives it a higher compressive strength and also reduces the potential for ingress of moisture into the block (Houben & Guillaud, 1989), (Norton, 1997). CSSB are further stabilised with the addition of a chemical stabiliser that helps to bind the particles together. Cement or lime are expensive additives but are generally available and although the practice of adding them to soil is reasonably popular the results can be disappointing unless it is done carefully.

Here is a good example of a wall made of stabilised soil blocks.

The blocks are approx. 0.4 × 0.2 × 0.125m and may have some voids through the centre. No render has been applied to the wall and no significant roof eaves have been used.

A solid cement rich foundation had been used to build the blocks onto. This is a high quality construction and would have been quite costly but not as much as hollow cement blocks.

CSSB can be compacted using low or high-pressures or dynamically compressed using falling weights. The greater the level of compaction the greater the compressive strength of the block and the more effective any added stabiliser becomes, (Gooding, 1993). CSSB compacted to higher densities are also usually more dimensionally consistent and therefore can be laid using a thinner mortar layer of around 10 – 15mm. Some CSSB need to be rendered in order to enhance the protection from the elements, but this can be avoided with higher levels of compaction and or higher quantities of stabiliser. Making a hollow CSSB can be done by straight-through perforations or deep and shallow frogs (Houben & Guillaud, 1989). Each of these reduces the material present and therefore reduces the stabiliser quantity necessary for each block. Removal of material from the core must be done carefully as it decreases the maximum supportive load of the blocks.

3. Criteria for comparing walling materials and assessment of current materials

There are a number of criteria we could use for comparing walling materials. For our present purposes we would like to hold ‘performance’ constant so that we can meaningfully compare some of the costs of production. Whilst different building materials have can have very different characteristics, we can suggest a minimum standard that all the materials must comply with. We have therefore chosen the following performance specification:

- bulk wet crushing strength = 1.5 MPa
- exterior surface wet crushing strength = 3.0 MPa

Blocks with this performance should be wholly adequate for low-rise housing construction up to a roof-ridge height of 8 meters (for which the bottom-course pressure < 0.15 MPa). It has been suggested that blocks that have a wet compressive strength of over 3.0 MPa can be used in tropical environments without the need for external render. We will therefore consider that a block with a similar surface strength will exhibit adequate durability for most circumstances.

Market cost is the most familiar criterion for materials comparison, but is not easy to use in situations where part of the building process is performed within the subsistence economy. A fairly universally applicable measure of resource-use in walling is ‘primary energy consumed per square meter’. This is the sum of primary energy required in the extraction and manufacture of the materials, in their transportation to site and in their final erection on site. However as the last item is comparatively small and also very difficult to estimate, we have chosen to neglect it. Transport energy obviously depends upon distance and we have chosen, for various reasons, to estimate distance as 25% of the mean spacing between points of production in one country (namely Uganda), i.e. 100km for cement and less for other materials.

For those types of walling for which cement (opc) is the main bonding agent, or is the only purchased material, cement content provides another comparative measure. The energy required to produce the cement will also be included in the energy calculations. The cement literature suggests that the energy requirements for material extraction, processing, firing and grinding for cement production is approximately 6MJ/kg.

For low-cost housing in developing countries, there is an additional criterion for comparing materials. It is their ease of access (geographical or socio-economic) to potential users. Thus a material that can sensibly be manufactured ‘locally’ – say on a scale of under 10,000 m^2 walling per year – is more likely to be available in an area of poor transport, and more likely to receive production investment, than a material requiring a trans-national scale of capital.

An even more severe constraint arises where the production of housing does not fall wholly within the monetary economy, i.e. where the tradition has been for householders to construct their own housing out of ‘free’ local materials. Actually few traditional materials meet the *wet* strength criteria listed above. However there remains a strong householder interest in making *some* use of local or on-site materials or of employing artisanal members of their own community in materials production.

3.1 Assessment results

We have therefore chosen to assess the most commonly used walling materials according to the four measures:

- Primary energy consumption in MJ per m^2 walling
- Cement usage in kg per m^2 walling
- Ranking for suitability for small-scale (‘local’) production
- Ranking for suitability for on-site production using mainly on-site materials

To limit the number of materials we have chosen those most prevalent in humid areas of East Africa and South Asia (excluding stone and timber walling) and added one high-tech material namely foamed PFA blocks. These are compared with two well-established variants of stabilised-soil blocks, namely low-density low-cement CSSB and high-density very-low-cement CSSB.

The table and associated notes below is a summary of a spreadsheet used to make the calculations.

Material	Dimensions (l x b x h)	Note	Energy	Cement	Suitability for production	
					'Locally'	On-site
	mm		MJ/m^2	kg/m^2	Ranking (1 = best)	
High-density CSSB	290 x 140 x 90	1	290	18.7	2	1
Low-density CSSB	290 x 140 x 90	2	420	34.1	1	1
Brick (kiln-fired)	215 x 105 x 65	3	430	8.1	2	3
Brick (clamp-fired)	215 x 105 x 65	4	1340	11.4	1	2
'Cement' block (hollow) N	300 x 150 x 200	5	430	27.0	1	2
'Cement' block (hollow) F	300 x 150 x 200	6	590	27.0	1	2
Foamed PFA-cement block	440 x 140 x 215	7	230	12.4	2	3

Notes

1. High-density (2000kg/m^3) solid blocks manufactured on-site from local soil/cement mix (5% cement), laid with 10 mm of soil/cement mortar (20% cement) and no render, (Cement transported 100km).
2. Low-density (1700kg/m^3) solid blocks manufactured on-site from local soil/cement mix (10% cement), laid with 15 mm of soil/cement mortar (20% cement) and 15mm render, (Cement transported 100km).
3. Kiln fired brick (3000MJ/1000 bricks) laid with 10 mm of sand/cement mortar (20% cement) and no render, double brick buttress column at 1m centres, (Cement transported 100km).
4. Clamp fired brick (16000MJ/1000 bricks) laid with 15 mm of soil/cement mortar (20% cement) and no render, wall has double brick buttress column at 1m centres, (Cement transported 100km).
5. Hollow (50% voids) cement blocks made from 10% cement mixed with gravel and sand from nearby source, with a 10mm mortar joint, (sand/cement, 4:1 ratio). Cement transported 100km.
6. Hollow (50% voids) cement blocks made from 15% cement mixed with gravel and sand transported from 50km away, with a 10mm mortar joint, (sand/cement, 4:1 ratio). Cement transported 100km.
7. High-tech aeration process using coal ash mixed with cement (15%) to make a very light (480kg/m^3) material. Laid with a 3mm mortar joint using cement rich paste (50% cement). Blocks transported 50km.

Of the materials listed above only three of them use less than the desired 15kg of cement per m^2 of walling, two of which are unsuitable for local production and the third has an extravagant energy requirement. High-density CSSB is the only material that uses a modest amount of cement, a low energy requirement and is suitable for local and on-site production. The following chapters will discuss other methods that may further reduce the cement requirement of High-density CSSB to less than the desired 15kg per m^2 of walling.

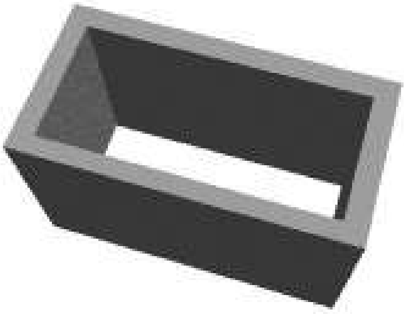
4. Perforated and indented blocks

When considering to place indentations or to perforate a block it is a good idea to determine the reasons behind existing block shapes to see what can be learnt from them. There are a huge variety of block shapes and sizes available and we shall not investigate them all. For the purposes of this study we will limit the possible shape of the blocks to those that specifically remove material from the block core to reduce material. These will include perforated blocks, deep and shallow frog indentations.

The design of a block can vary a great deal depending on the application. The standard clay fired brick includes a shallow frog that aids the process of keying the brick into the underlying mortar. This purpose of the frog is not really to reduce the overall material of the brick, but this is a beneficial result of the technique. In a similar fashion hollow concrete blocks are hollow typically for two reasons. Firstly due to their size a solid block would be much too heavy for easy manual movement and placement in a wall. Secondly the hollowness of the blocks permits the inclusion of reinforcement for more massive structures to gain sufficient strength even in areas with seismic activity.

In order to remove significant amounts of material from the centre regions of a block there must be sufficient block width to accommodate the voids left behind. Also the minimum material thickness needs to be carefully chosen so that the material does not become too weak to support the necessary loads. The drawback to including any perforations or voids in a block is that it increases the mould complexity and reduces the ease of block manufacture, particularly block ejection.

Below are a series of images depicting different types of concrete blocks with different shapes.



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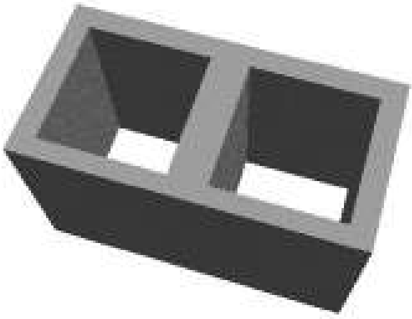

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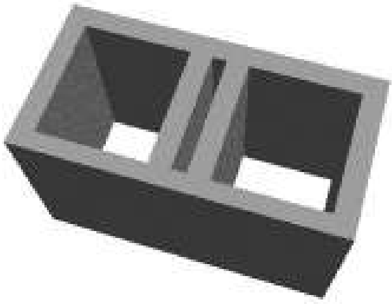

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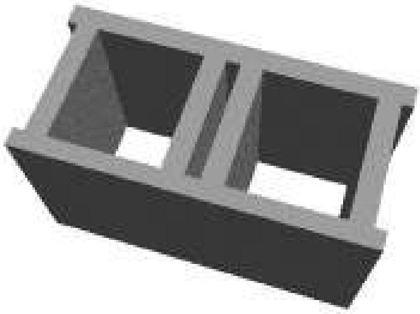


D

<u>NOTES</u>

Block A has the least material but mortar joints on the top and bottom surfaces are limited to the front and back face.

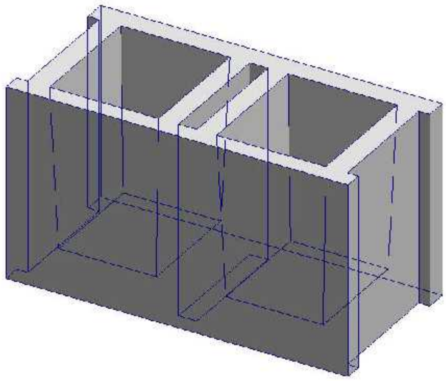
Block B overcomes this problem by putting a central web so that block tessellation can occur and good mortar contact is achieved.

Block C incorporates a double web so that the block can be more easily split into halves for wall ends etc.

Block D adds a few further flanges on the ends of the block to reduce the mortar contact area and also to help with more accurate tessellation of the blocks.

With all of the above blocks there is a significant problem with mortar falling into the holes when it is laid. A better block would have a flat surface onto which a thin layer of mortar could be placed. This idea follows the deep frog concept where a significant internal void is achieved but without going though the entire block.

An even better example of block is like the one shown below, where the internal voids don't go all the way through. The thin lines indicate the outline of the material, more clearly showing the internal voids.



If mortar is being used to join the blocks together then a deep frog arrangement is better than the hollow section as less mortar is wasted. Chapter five of this document deals with the proposal of interlocking blocks that have no need of mortar between the courses.

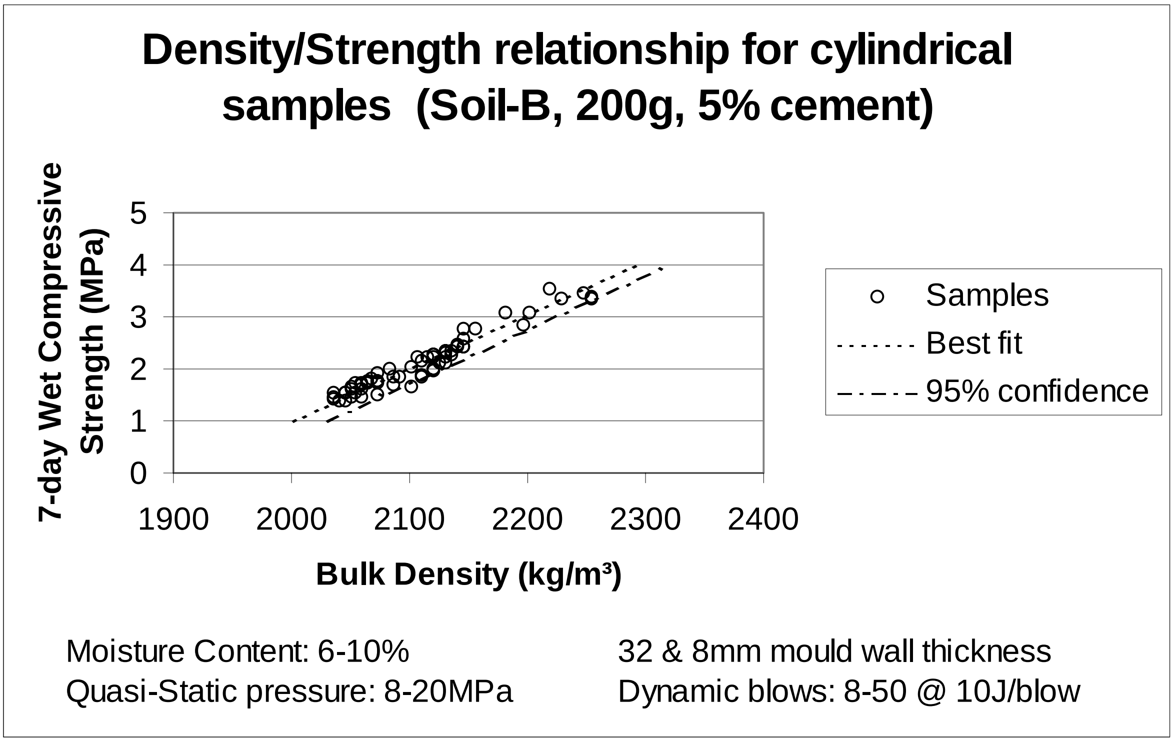
4.1 Results of material removal

In the production of low-cost building materials cost reduction is paramount, and if the cost can be reduced without jeopardising the strength of the material beyond acceptable limits then this would be a significant advantage. One obvious way of achieving this cost reduction is to reduce the amount of raw materials that are necessary to make the block, or more specifically to reduce the expensive raw materials that are necessary to make the block, i.e. opc. If the material mass of each block could be reduced by 50% then that would constitute a saving of opc of 50% in the block itself. If the material strength remained the same then the maximum load that could be applied to the block would also be approximately 50% less.

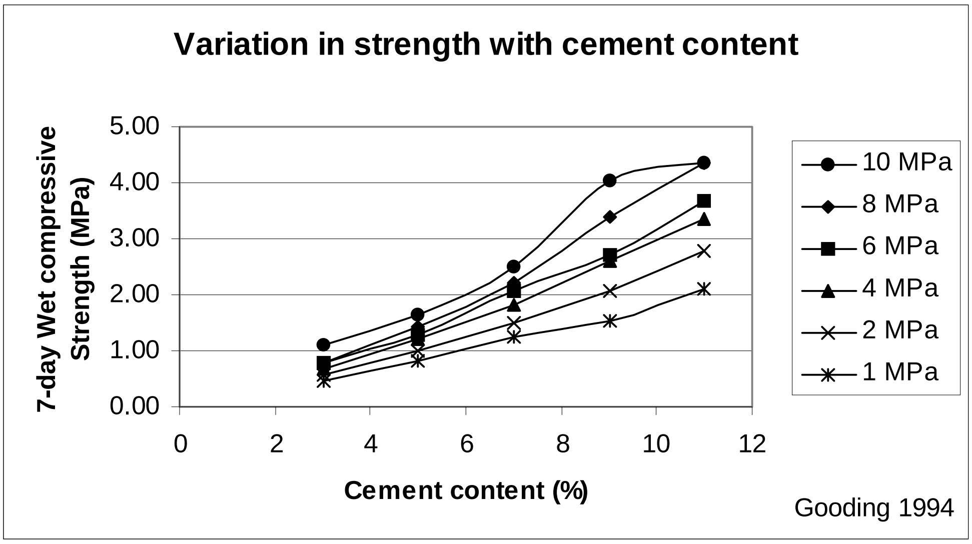
Now that we have seen a number of different types of hollow and indented blocks, we now need to assess the effectiveness and notice any implications that the addition of indentations will have. Indentations will quite clearly remove material from the core of the block and therefore reduce the amount of material required to produce each block. This removal of material also reduces the maximum load of the block itself and this should be taken into account when designing the structure.

Strengths of materials are usually given in compressive strength terms in MPa or equivalent N/mm². Thus block strength is directly proportional to the surface area on the compression face. In the case of a hollow block removing 50% material reduces the compressive surface area by 50%. This means that the same material will only be able to support 50% of the load. Fortunately the reduction of material from the cores reduces the mass of the block so that the mass of walling is also reduced and therefore a similar height wall can still be accommodated. In order for the block to support the same load it will need to have an increased compressive strength.

Significant indentations can only really be accommodated if the material strength is high enough and this may require the addition of more stabilisation, (compaction and/or opc). The strength of the material is dependent on the amount of compaction and the amount of opc present in the material. This relationship is not a linear one either for the compaction or for the cement. For a certain range of densities it has been found that an increase in density by 10% yields a 100% increase in compressive strength. Furthermore the doubling of the cement content has the effect of more than doubling the achieved strength of the material.



The above graph shows research results from the author's work that indicates the relationship between density and strength. It clearly shows that a small increase in bulk density can yield a significant increase in strength for the same cement content. Both the dynamic and quasi-static methods of compaction were used to make these samples the latter being much more difficult to increase the compactive effort if it is necessary.



This graph shows the change in compressive strength with extra pressure and extra cement. For the low pressure samples (1 and 2 MPa) as the cement content doubles the strength also doubles. For the higher pressure samples the fractional increase in strength for the same increase in cement is greater. This clearly indicates that the effectiveness of the cement present increases as the level of compaction is also increased.

With the combination of increasing the cement content and increasing the level of compaction it would be possible to remove significant amounts of material from the centre regions of a block without jeopardising the strength and gaining an overall reduction in costly opc.

4.2 Analysis of material removal

According the graph above a sample with 10% cement and compressed to 4MPa has a wet compressive strength of 3MPa. A standard block 0.29 × 0.14 × 0.09m and an approximate bulk density of 2060kg/m³ would have a cement mass of around 0.7kg present in it. If the level of compaction was increased to 10MPa the cement content drops to 8% to achieve the same 3MPa compressive strength. The same block has now reached a bulk density of 2160kg/m³ and would have a cement mass of around 0.58kg present in it. A more than two-fold increase in pressure results in only an 18% drop in cement content. This has already been shown to be a false economy in quasi-static compaction because this extra moulding pressure seriously increases the machinery rental and labour costs of production.

Now if half of the material present in the block is removed then the cement mass would naturally drop to 0.28kg per block which is less than half of the original value. This removal could be achieved by the inclusion of voids in the material. The higher density of the material would yield sufficient strength for forming and handling and whilst the absolute load that the block could sustain would be less, the compressive strength would still be within the required limits. This option would not be possible with blocks of lower densities, as they would not be strong enough to have such large voids placed in them and still keep strong enough for forming and handling.

4.3 Note on strength of rival walling materials

If house walls 'fail', it is usually by surface erosion, by overturning of by internal material changes like swelling. To prevent erosion we require adequate surface properties such as hardness or wet-compressive strength that are unaffected by whether or not the building blocks are hollow. To prevent overturning we look first to architectural measures such as providing adequate foundations, connecting perpendicular walls or constraining the outwards thrusts from roofs. However the block properties also affect a wall's ability to resist horizontal forces applied to its top. Increasing both block mean density ($=\rho$) and wall thickness (=Block width b) are beneficial. Although there are various overturning failure modes, almost all have a force threshold determined by ρb^2. For example the formation of a hinge at the wall bottom (assuming the mortar has no tensile strength) occurs when $F=\rho g b^2/2$ where F is the outward force per unit length of a wall.

The table below compares different materials by this criteria. Employing hollow blocks instead of solid ones lowers F because it lowers the mean block density ρ

Material	**Wall Thickness (b)**	**Mean Density (ρ)**	**Failure Force (F)**
	m	kg/m³	N/m
Single skin brick	0.105	1350	74
Double skin brick	0.220	1350	327
Solid cement block	0.150	2200	248
Hollow (50%) cement block	0.150	1100	124
Foamed cement block	0.140	480	47
Low-density solid CSSB	0.140	1700	167
High-density solid CSSB	0.140	2000	196
High-density hollow (30%) CSSB	0.140	1400	137

5. Cement-rich skin

As mentioned in Chapter 3, there are several different methods that are under investigation for cement and energy reduction in the production of low-cost building materials. This chapter will briefly assess the method of putting the greatest stabilisation in the region of the block were it is needed most. This can be accomplished by either incorporating a cement-rich layer in the external face of every block, or by adding a cement render to the surface of a block which has a very low cement content.

5.1 Non-homogeneous blocks

As an alternative to reducing the cement content of the block to perilously low quantities, it may be possible to concentrate the cement in the area where it is needed most, i.e. the exterior surface. This cement rich layer would effectively be acting as a built in layer of render protecting the more fragile material behind it from the elements. For example instead of having 5% cement throughout the block one could put 10% cement in the first 20mm and have the rest of the block stabilised with only 3% cement. Providing that the cement rich layer did not suffer from de-lamination from the rest of the block, (which is doubtful if the block contains cement and the courses of blocks are joined with a cement based mortar), then this could reduce the cement demand for each block.

The production of such blocks with this cement rich layer greatly increases the complexity of the block production and construction processes. A very clear means of identification would be necessary to indicate which face of the block was cement rich, and furthermore the staff erecting the structure would need to be trained to lay the blocks in the correct manner. Homogenous blocks would also be necessary for the corners and any exposed edges, that adds another type of building material to the construction. The calculations carried out on this type of construction shows that the saving in cement is not terribly significant, (approximately 13%).

5.2 Rendered soil block construction

There are a number of reasons why a wall might be rendered. Leaving aside the aesthetic reasons, rendering is usually done to protect the walling from the elements or other forms of attack. Unstabilised walling has to be protected in humid areas and this can be achieved through the application of render. Cement-based renders do not work with an unstabilised soil wall as the coating is much too stiff to accommodate the movement of the soil wall as it absorbs and rejects moisture from the atmosphere. Lime-based renders are more suitable for this purpose. However, with more stable forms of walling, cement render is acceptable providing a good bond can be achieved to the surface of the block.

It may be possible to achieve a sufficiently high degree of surface hardness to negate the need of a render altogether as discussed earlier. This is indeed the most favourable option as the cement render is an expensive component of the walling construction if it has to be applied. In the application of render there are only really three different variables that are of interest if cost reduction is the main objective. They are the render thickness, the cement content of the render and the surface area that needs to be rendered.

The size and shape of the blocks under the render don't have a direct effect on the quantity of render needed to cover the wall, (providing the external surface is flat). This is a pity, as larger blocks need less mortar per m^2 than smaller blocks. The same gains however are not achieved when it comes to rendering. If we assume that the thickness of the render has already been minimised and also the cement/lime content has also been minimised then the only variable left to work with is the surface area that the render covers.

A practise that has been used in developing countries is to restrict the rendering to the areas of the walling most prone to attack. This generally constitutes render application to the corners of the building and the first 300 to 600mm of walling above ground level. The vast majority of the walling is then left in barefaced brick.

This photograph shows an earth walled house with a limited amount of rendering at the lower level.

A small amount of render has also been applied to the corners of the building.

Notice too the significant roof eaves that have been constructed to protect the walls from precipitation.

If the cement was concentrated in the render on the external surface of the wall and a very small amount was used to stabilise the blocks behind the render, then this might provide a saving in cement use. If we assume that the entire wall needs to be rendered to achieve adequate durability then we can calculate the cement requirements for this type of construction. Unfortunately the calculations do not suggest that this is a favourable method of reducing the cement quantity need per square metre. Applying a 15mm render (20% cement) to a 3% cement stabilised block actually increases the cement used per m^2 by 3%. If portions of the wall could be protected by some other means and the area of rendering reduced, then this method might yield greater saving in cement use.

6. Mortar reduction methods

In the previous chapters we have seen some suggestions for minimising the cement content in the blocks and in the render, but we haven't yet discussed the mortar that joins the blocks together. The mortar used in wall construction can account for a significant part of the cement cost and if this can be minimised then this would be an added saving. Fortunately the mortar required is dependent on the size and shape of the blocks used to construct the wall and even in some circumstances the mortar may be omitted entirely like with interlocking blocks.

Mortar is necessary to carry out two basic functions, one is alignment and the other is cohesion. Due to the surface irregularities of blocks a certain amount of mortar is needed to ensure that the two faces of adjoining blocks sit well together and spread the load over the entire surface of the blocks. This layer of mortar also permits a degree of alignment so that the wall can be built to conform to a vertical face. The mortar between the blocks also creates a physical joint that will help to keep all the separate block units in the wall bonded together.

6.1 Variables affecting mortar quantity

Apart from making the mortar thinner one can reduce the mortar requirements by changing the size and shape of the block. These adjustments change the mortar requirements for each block, but also change the requirements per m^2 of walling. If the block size is increased then the mortar necessary per block increases, but the overall mortar requirement for the walling goes down. In order to determine the most important variables in wall production a spreadsheet was drawn up. It calculated the changes in cement demand for small changes in every variable that could be altered in block design and wall covering.

The table below shows all of these variables and the sensitivity that a change of that variable of ±10% gives to the overall cement requirement per square meter of walling.

	Cement (kg/m²)			
Variable	+10%	0%	-10%	Sensitivity
Block Length	34.5	34.5	34.6	0.02
Block Breadth *	37.6	34.5	31.4	-0.98
Block Height	34.3	34.5	34.7	0.06
Block Density *	36.9	34.5	32.1	-0.76
Cement content of block *	36.9	34.5	32.1	-0.76
Cement content of mortar	35.2	34.5	33.9	-0.19
Mortar Thickness	34.8	34.5	34.2	-0.08
Render Thickness	34.9	34.5	34.2	-0.11
Voids fraction of block *	32.1	34.5	36.9	0.76
Combination of four * variables	46.5	34.5	25.5	-0.89

The four main variables are ‘block breadth’, ‘block density’, ‘cement content of material’ and ‘voids fraction’. Reducing the block breadth is not an option and we want to achieve the highest density possible to give the greatest strength.

Below is a table showing the four block variables that exhibit the greatest sensitivity to changes of 10% with the effect that each one has on the different areas of cement use, namely in the material, the mortar and the render.

	Cement mass required (kg)					Cement
Variable	Material	Mortar	Render	Total	Sensitivity	kg per m²
Standard block configuration	0.731	0.197	0.108	1.035	N/A	34.5
10% decrease in breadth	0.658	0.177	0.108	0.943	-0.98	31.4
10% decrease in material density	0.658	0.197	0.108	0.962	-0.76	32.1
10% decrease in cement in Mat.	0.658	0.197	0.108	0.962	-0.76	32.1
10% decrease in material (voids)	0.658	0.197	0.108	0.962	-0.76	32.1
Combination of all variants	0.479	0.177	0.108	0.764	-0.89	25.5

By concentrating on the variables that have a significant effect on the cement in the material and the mortar use we can suggest a combined scenario that may give a tolerable cement usage. A suggestion is shown in the table below.

	Cement mass required (kg)	Cement

Variable	Material	Mortar	Render	Total	kg/m²	Reduction (%)
Standard block configuration	0.731	0.197	0.108	1.035	34.5	N/A
25% increase in height	0.974	0.212	0.140	1.326	34.0	1
Removal of render	0.731	0.197	0.000	0.927	30.9	10
50% decrease in cement in Mat.	0.365	0.197	0.108	0.670	22.3	35
25% decrease in material (voids)	0.548	0.197	0.108	0.853	28.4	18
Combination of all variants	0.365	0.212	0.000	0.577	19.2	44

Instead of getting the cement per m² down to as low as 15 kg/m² the minimum suggested here is only 19.2kg.

Note:

Standard block to be considered as the following:

External dimensions (L × B × H) = 0.29 × 0.14 × 0.09m

Material = 2000kg/m³ (dry) with 10% cement, (NB different to Table in Ch 3)

Mortar = 1800kg/m³ (dry) with 20% cement and 0.01m thick

Render = 1800kg/m³ (dry) with 20% cement and 0.01m thick

Internal void volume = 0

This value for the cement demand per m² of walling is still too high. It is estimated that the Thermalite blocks described in Ch 2 use approximately 12.4kg of cement per m². If the mortar could be removed entirely from the example above then the total cement demand would reduce to 12.2kg per m², below our target cement consumption per square metre.

6.2 Mortarless blocks

Interlocking blocks have been available in a number of different styles for quite some time now. The designs differ but the basic principles are the same. Some form of indentation and protrusion on facing blocks form a mechanical link between the two building units. The difficulty with producing mortarless blocks is that you no longer have any freedom of adjustment during the laying process. Any alignment errors present in the lowest block course will be present in every subsequent layer on top. Not only does the bottom layer have to be set very accurately, but also every block must have a very high dimensional accuracy. An error of only 1mm in the height of a block between the internal and external face of a 150mm wide block will generate a vertical alignment error of 13mm at the top of a 2m wall. A 2mm error leads to 26mm, etc. Alignment errors approaching 25% of the block width would be of great concern as the wall stability is significantly reduced.

The other role that mortar plays is one of ensuring that the load is spread over the entire face of the block. Mortar removes any stress concentrations that would otherwise be there if the blocks were laid on top of one another. Even blocks with very high dimensional accuracy will still suffer from this. However, the process of production of stabilised soil blocks may offer a solution to both the problems of alignment and stress concentrations found in mortarless construction.

6.3 Block alignment while 'green'

When a cement-stabilised block is formed it has what is referred to as a "green strength". It is this strength that needs to be there for the block to be handled immediately after production. This strength enables the formed block to be moved from the production machine to a place of curing where blocks may even be stacked one on top of another to conserve curing floor area. Full strength of the material is not achieved for some time and the strength of the blocks at the time of production is a small fraction of the final compressive strength.

This low initial strength could be an advantage in mortarless construction. If the blocks are formed and placed directly into the wall then this may solve the two problems with mortarless construction. (The process of building walls from freshly made mud bricks is currently in use in the U.S. but these walls are not stabilised and an external render is applied to protect the bricks.) The construction of the wall in its green state enables a degree of flexibility with the material itself. As the material has a small amount of "give" to it, the different courses could be laid and as the blocks settle and begin to harden they will be taking the shape of their neighbours and therefore greatly reduce the chance of stress concentrations.

The other issue that has been raised is the one of alignment. If dimensional accuracy of ±0.5mm can be achieved then the maximum 'out of plumb' for a single storey wall would be a tolerable 13mm. However, this is a very high level of accuracy and probably not possible with CSSB production techniques. Blocks that are laid in their green state will accommodate a degree of manipulation and this may be all that is necessary to ensure that the blocks are being built in alignment with the vertical. Very slight adjustments could be made to the finished blocks during the construction process that would be impossible to do once the block has fully cured.

Even if removal of the mortar entirely is not a feasible option, the reduction of its thickness will generate great savings in cement. The thermalite blocks described in Ch 2 use a very thin mortar joint of around 3mm. The mortar is more of slurry consistency than a paste and is almost poured into position. Such a system could easily be incorporated into wall erection if the dimensional accuracy was as high as described able. Even a tolerable ±1.0mm error in the block height would still be able to use this very-thin mortar technique.

6.4 In wall curing

The process of building a wall of green uncured material generates a fresh problem of achieving a high strength successfully to an exposed material. Once the blocks are placed into the wall there is almost maximum exposure to the air and therefore to the blocks drying out. If cement is the stabiliser of choice then this drying out process must be hindered and even stopped if possible. While the blocks are on the ground or in tidy piles it is much easier to cover them and keep them moist than if they are already made into a wall.

Curing the blocks in the wall may be achievable if something could be draped over the wall that protects the block from the wind and the drying of the sun. If plastic sheets are used then this would be acceptable although would incur a greater cost even if the sheets are reused a number of times. Keeping the blocks under plastic sheets in the direct sun would have the effect of raising the temperature of the blocks and the cement within the block would achieve a higher strength faster then through normal temperature curing. This early higher strength caused by the higher temperatures would result in a slightly lower overall strength in the block once curing is finished.

The effect of temperature on pure cement is well documented and the following information just summarises some of these that may be of use in curing the blocks in the wall. The table below clearly shows that if a small reduction in final compressive strength can be accommodated then curing the material at a higher temperature can increase early strength. This may be a rather desirable side effect to construction in the humid tropics and one that should be exploited if possible.

Extracted from graph found in (Neville, 1995)

Time	Strength in MPa at curing temperature (°C)				
	20	35	50	65	80
6 hours	30	55	100	135	140
1 day	140	165	165	165	165
7 days	220	210	200	190	180
28 days	250	235	230	210	195

If three times the strength could be achieved in the material after 6 hours if it was being cured at 50°C then construction could proceed at a faster rate as well. The only problem is that we do not know if these results still apply to a material that has such a small amount of cement as would be used in CSSB production.

6.5 Tall thin blocks

The ratio of a block's height to width is its' slenderness ratio (height/width), (Norton, 1997), (Keable, 1996). Typically this slenderness ratio is not more than 1 but with some more advanced materials at can be as high as 2. If the height of the block is large then this will reduce the number of blocks necessary to fill the same area of walling. Another measure that we can have to assess the shape of a building block is the number of blocks required per square meter of walling. In order to maximise the use of the material therefore we want to have a high slenderness ratio and a large surface area of the external face of the block.

As mentioned in the pervious section the larger the external surface area of a block is the smaller the number of blocks needed per square metre and consequently less mortar is required. Increasing the height of the block therefore doesn’t so much as reduce the cement requirement per block as reduce the mortar requirement to lay the same area of walling.

In section 6.1 a suggested block arrangement was drawn up to try and reduce the overall amount of cement. One of the variables that were changed was the block height. This increased the amount of cement required in the material, mortar and render per block, but actually decreased the overall cement requirement per square metre. Although the decrease was quite small, if that is then applied to blocks with less cement in the material, laid with thinner mortar and without any render then significant savings can be made.

7. Conclusions and recommendations

The high-density compressed and stabilised soil block seems to be a reasonable contender in low-cost building materials. It requires less energy than all of the available competitors and slightly less cement than most of them. Variants on the CSSB can reduce the cement still further making it even more acceptable to a wider range financial capacity. Furthermore the ability for the CSSB to utilise local materials and be manufactured either on-site or very locally makes the material more suitable to cottage industries and self-build schemes.

The table below summarises the different possible variants that can be accomplished with the CSSB and how each one performs with reference to the unmodified CSSB. By combining several of these variants into a single block the material can theoretically achieve a tolerable cement requirement, (less than 15kg/m²), without excessive energy consumption. The tall, hollow, interlocking block as described below even uses less cement then the clamp fired bricks outlined in Ch 3. As this is one of the more common and more wasteful methods of making satisfactory building materials, this confirms that this variant of CSSB is a real contender.

Material	**Dimensions (*l* x *b* x *h*)**	**Note**	**Energy**	**Cement**	**Suitability for production**	
					'Locally'	**On-site**
High-density CSSB	Mm		MJ/m^2	kg/m^2	Ranking (1 = best)	
Normal	290 x 140 x 90	1	290	18.7	2	1
Hollow	290 x 140 x 90	2	220	15.1	2	1
Cement-rich skin	290 x 140 x 90	3	270	16.3	1	2
Interlocking	297 x 140 x 97	4	270	15.4	2	1
Tall	290 x 140 x 90	5	280	17.6	2	1
Rendered	290 x 140 x 140	6	300	19.3	2	1
Tall, Hollow, Interlocking	297 x 140 x 147	7	190	11.0	2	1

<u>Notes</u>

1. High-density (2000kg/m³) solid blocks manufactured on-site from local soil/cement mix (5% cement), laid with 10 mm of soil/cement mortar (20% cement) and no render, (Cement transported 100km).
2. As 1. but with 30% material remove from the block core.
3. As 1. but with 10% cement in first 20mm of exterior block surface and 3% in the body of the block.
4. As 1. but with thin mortar of 3mm required.
5. As 1. but with increased block height to 140mm to reduce mortar per square metre.
6. As 1. but with 15mm render on a block with only 3% cement in the body of the block.
7. As 1. but with a combination of tall, hollow and interlocking arrangements.

Many different variants of the CSSB have already been successfully made. However, the author is not aware of any specific manufacturer that can produce the tall, hollow, interlocking CSSB variant that seems so frugal in its cement use. It is hoped that the application of compaction by impact can yield such a material without the addition of expensive machinery, but has yet to be confirmed.

Tests need to be conducted to see if such a variant of CSSB can indeed be made successfully. Following that it would need to be tested to determine whether or not it exhibits the necessary level of durability for use in the humid tropics. If these proved successful, then a pilot scheme would need to be implemented to disseminate the information and necessary technology to a suitable area where low-cost housing is needed.

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