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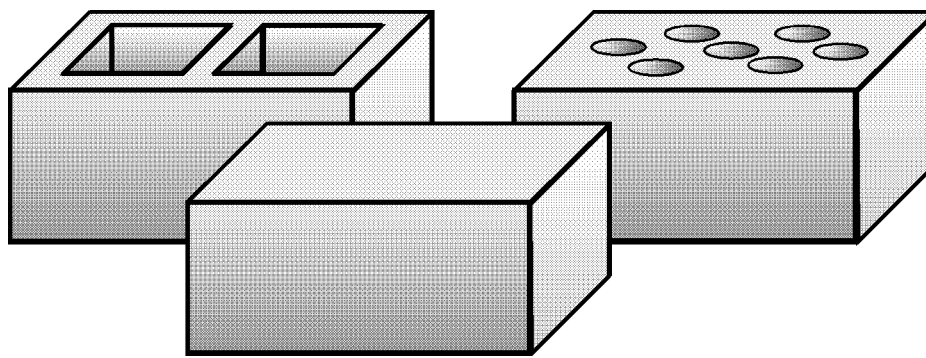Email dtu@eng.warwick.ac.uk

# Stabilised Soil Research Progress Report SSRPR2

# How does cement stabilisation work?

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### October 1998

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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.

"*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

After a brief study of some relevant texts documenting the production, characteristics and use of Portland cement a better understanding of its cementitous qualities has been gained. The bonding of cement is caused by the hydration of the cement particles which grow into crystals that can interlock with one another giving a high compressive strength.

In order to achieve a successful bond the cement particles need to coat most of the material particles so that upon hydration a crystalline structure is created throughout the mixture of particles. Particle intimacy is important to ensure a good number of cementitic bonds between adjoining particles and this can be helped by mixing the cement into a mixture of particles with a good size distribution. The water in the mixture needs to be monitored to guarantee sufficient hydration of the cement and also to ensure adequate workability of the mix. Too much water will leave voids in the mixture after the water has evaporated off and will reduce the final set strength of the material.

The limitations to cement besides the careful control of materials and moisture are that cement requires time to fully cure and that it is susceptible to chemical attack. Never-the-less it is a highly suitable method of stabilisation and can easily be applied to stabilise a moderate variety of different soils for use in making building materials.

## Nomenclature

**Aggregate:** Pieces of crushed stone, gravel, etc. used in making concrete.

**Brick:** An object usually of fired clay used in construction, usually of rectangular 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), a finely ground clinker which sets hard after mixing with water.

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

**Clinker:** A slag formed when clay and lime a burnt in a furnace together.

**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.

**Gravel:** A mixture of rock particles ranging from 2mm to 60 mm in diameter.

**Green:** Describing the state of material containing cement and water before it reaches the critical time, after which further plastic deformation hinders the final set strength.

**Gypsum:** A hydrated form of calcium sulphate.

**Mortar:** A mixture of sand, cement and water.

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

**Sandcrete (Cured Mortar):** The finished form of a mixture of cement, sand and water.

**Sharp Sand:** Describes the angular nature of sand particles that are very good for making concrete or mortar.

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

**Slaked Lime (Lime):** Quicklime (calcium oxide obtained by burning limestone), that has been mixed with water creating calcium hydroxide which has further setting qualities.

**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.

**Soil-cement:** Similar to mortar, but prepared from soil with a wider 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.

# Table of Contents

# 1. Introduction

Cement is to be the primary means of chemically stabilising the soil samples during this research project. Consequently a good understanding of how cement works and how it forms cemetitious bonds with other particles would be most desirable. This report will briefly outline what cement is made of, and how it is produced, but it will spend more time detailing the bonding and curing processes in concrete. During the report it will also establish the various requirements that cement has in being able to perform properly as a stabilising medium. Finally, these theories will be applied to the stabilising of soil.

As a stabilising material cement is well researched, well understood and its properties clearly defined. Portland cement is readily available in most urban areas, and usually available in semi-urban areas, as it is one of the major components for any building construction. Earlier studies have shown that cement is a suitable stabiliser for use with soil in the production of soil-cement blocks, (International Labour Office, 1987), (p. 38). As this is established and recognised technology it provides a suitable basis for further research into the production of better soil-cement materials. Further studies hope to minimise the quantity of cement required to form soil-cement structures.

For the purposes of this report and further study it is assumed that ordinary Portland cement (OPC) is readily available in bags on location. A significant cost may have been incurred in getting the cement to where it is needed, but this report is not intended to analyse the cost effectiveness of cement over other brick stabilising methods. Instead it is to concentrate on modifying and improving the existing cement stabilising of soil, with perhaps a breakthrough in the entire block production routine.

## 2. Some facts about cement.

This section will concentrate on establishing the properties and composition of cement. This knowledge will provide a simple foundation for understanding the way that cement works. It will not describe in too much detail the characteristics or production of cement, as this has already been previously established to a sufficient level, (Akroyd, 1962), (p. 46-54), (United Nations, 1972).

### 2.1 Chemical composition and production

Cement can simply be described as being a mixture of lime and clay which is heated to about 1,500°C, and the resulting clinker has gypsum added and the sum is then ground to very fine powder. An extract from (Akroyd, 1962), (p. 50) contains sufficient detail of the chemical composition of cement itself, featured below.

|  | Percent (%) | Average(%) |
|---|---|---|
| Lime (CaO) | 59 -67 | 64 |
| Silica ($SiO_2$) | 17 -25 | 21 |
| Alumina ($Al_2O_3$) | 3 - 9 | 7 |
| Iron oxide ($Fe_2O_3$) | 0.5-6 | 3 |
| Magnesia (MgO) | 0.1-4 | 2 |
| Sulphur trioxide ($SO_3$) | 1 - 3 | 2 |
| Sodium potash | 0.5-1.3 | 1 |

Below is a diagram showing both the Wet and Dry cement manufacturing processes as extracted from (Akroyd, 1962), (p. 48). There has been a move from the former to the latter in recent years, as the dry process requires less energy per unit of cement output.

**Wet process**                                    **Dry_process**

Soft chalk          Clay            Limestone   Clay or shale

Roller crusher                      Primary crusher          Roller crusher

Water                               Granulator               Screens

Washmill            Oversize returned to granulator

Oversize returned                   Screen                   Dry blending silos

Fine screens                        Re-blending

Slurry

Slurry tank                         Alternative feed to pelletiser

Feed to kiln       Feed to kiln

Feed dried                          Pelletiser

Kiln  Warmed                        Moving grate kiln

Coal   Dried   Pulverised  Injector
       Screened                     Clinkered

Warm air
Air warmed    Clinker cooled        To ball mill

Cold air

Clinker storage    Clinker direct to grinding mill

Gypsum added       Ball mill

Bulk storage silos                  Bagging plant

                    Supply in bags
Bulk supply

## 2.2 Relative cost to other materials

The price per kilogram of cement will vary greatly depending on the distribution network and the proximity to the cement processing plant. Cement can usually be considered to be one of the more expensive materials necessary for building construction. In the field of low tech, low cost soil brick housing, it is crucial that the total cost of the cement as a proportion of the entire structure is kept as low as possible. One would ultimately like to minimise the cement content and maximise the strength and life of the structure. Through a variety of procedures the amount of cement necessary can be reduced and these may be investigated in more depth separately later on in the research. For the moment, the author is taking previous

research to suggest that a nominal 5% cement is sufficient for good stabilising of soil blocks.

## 2.3 Distribution problem

In the vast majority of cases OPC will not be made on site, consequently it will have to be delivered. Once cement has been manufactured, it is generally available in two forms. It can be purchased in a bulk form from a silo, or it can come in bags of 50 kg each. (A new bag size of 25kg is becoming popular in some countries.) Cement that is purchased from a silo is mixed and delivered using cement trucks. These will usually ensure that the cement arrives in good condition, ready for immediate use. However, if cement is purchased in bags, there is no guarantee what state the cement will arrive in. Cement is usually distributed in a multi-layer paper bag that only gives it a small degree of protection. If bagged cement has come a long distance and has been exposed to the elements for any period of time it is highly likely that the cement will have absorbed some moisture and will have started to set. This partial setting of the bag of cement does not render the entire bag useless but it does hinder the use of what is still OK. The good cement has to be sifted out and the remaining lumps can be broken up to make a lower quality cement.

# 3. Making concrete

In this section the main focus will be on the existing procedures for making concrete. There are established techniques for achieving different grades of concrete, each of which performs a specific task. The analysis of these different grades and how exactly they are all generated is not of great relevance here, but understanding the underlying principles of concrete manufacture will be helpful in later applying similar methods to stabilising soil. Some specialised grades of concrete requiring cements other than OPC, but for the ensuing discussion assumes that OPC has been selected.

## 3.1 Material selection and requirements

Cement can be mixed with virtually any size and shape of sand or aggregate, depending on the purpose of the concrete that is to be made. Particles are usually graded according to physical size ranging from clay particles (< 0.002 mm) up to boulders (> 200 mm). Particles smaller than 0.02 mm are considered to consist of silts and clays, too much of which will hinder the cementitous process. Particles larger than 60 mm are only usually used in large continuous structures such as dams etc. Cement is mixed in with these other particles and when water is added that starts a chemical reaction within the cement particles that grow to form an interlocking matrix. To aid the particle intimacy, a mixture of aggregate grades are mixed together giving a spectrum of different particle sizes that reduces the size of air voids in the material. This further enhances the final concrete block strength.

The concrete composition depends on the job that is being done. Each concrete mix should be designed for the purpose for which it is intended, (for example a concrete mix for a floor cast will be very different to a mortar mix for brick laying.). This requires a selection of grades of sands and aggregates to be mixed with specified quantities of cement and water. Additional ingredients can give the concrete special properties if necessary and these need to be determined and added in the correct quantity. These may affect one or more of the following; workability, strength, density, thermal characteristics, elastic modulus, durability and speed of setting.

The two characteristics of sands and aggregates that affect their performance when mixed with cement are the particle's shape and surface texture. The shape affects the workability of the cement during mixing and placement and the surface texture affects the bond between the particles and the cement. Very large angular particles decrease the workability of the mix, whilst smaller more rounded particles do the opposite. Angular shaped particles are generally formed by crushing larger particles down to size. More rounded particles can exist naturally as their shape has been formed due to slow abrasive action between particles in the environment. Angular particles usually have a lower workability but achieve a higher strength since angularity is usually accompanied by surface roughness. Crushing or selection of angular aggregates is only necessary when a very high compressive strength (over 50MPa) is necessary, (Teychenne et al., 1988), (p. 7). For the purposes of this project a compressive strength of that order will not be necessary.

### 3.2 Mixing quantities and preparation

The approximate quantities of cement, sand and gravel are often found quoted in a ratio of their respective volumes, e.g.: 1:2:4; one part cement, two parts sand and four parts gravel. There are standards for mixing cement so that a required compressive strength can be reached in a given time provided that the type of aggregate and the free-water to cement ratio is known, (Teychenne et al., 1988), (p. 10).

The free-water content is calculated from the slump or Vebe time test. In simple terms the higher the free-water content the greater the amount of slump will occur over a given period. Ideally the amount of water used in the mix should also be monitored to be sufficient to hydrate all the cement and not more than is necessary to fill all the voids present in the material as further moisture drives the particles further apart. Unfortunately this yields a highly unworkable mixture and more water has to be added to form the mixture into the desired shape. Excess free-water increases the workability of the mix but will be detrimental to the final strength of the concrete. The minimum water/cement volume ratio is between 0.22 and 0.25 (Akroyd, 1962), (p. 13) for adequate cement hydration, but this is generally increased to the order of between 0.5 and 0.8 for normal mixes, (Lea, 1970), (p. 392).

The aggregates that are to be used in the concrete mix usually need to be washed before mixing with the sand and cement. The washing process removes fine particles on the surface of the aggregate allowing the cement to achieve a better bond. In the case of purchased aggregate this is usually done for you, but if excavation is part of the process then washing should be included in the preparation of the aggregate particles before mixing with cement.

### 3.3  The effect of compaction

It has been shown that if the particles in a cement mixture are in some way brought closer together, the greater particle intimacy results in a higher final strength. Achieving this closer particle intimacy can be done in a number of ways. We have already noted that excess water in the cement mix will drive particles further apart and will cause a loss in strength. So keeping the free-water content to a minimum is a good way of ensuring closeness between particles.

Another method is to use a vibrator, that effectively shakes the cement mixture and helps to drive any air pockets to the surface. This is usually done in concrete casts as the vibrator can be inserted into the mix and the vibrating action will permeate throughout the mix. The size and number of vibrators will depend on the size of the cast. Obviously this technique cannot be used with very small casts (where it is normal to externally vibrate the whole mould instead) and there are some other drawbacks to the method. A higher free-water content is necessary for gravity-cast concrete in order to permit the cement mix to flow into all parts of the mould. Properly mixed concrete will have the different grades of aggregate well dispersed throughout the mixture. Using a vibrator in a cast with a high free-water content can cause the larger particles of the mix to sink to the bottom, resulting in a non-uniform distribution of particles.

As yet the author has not found little information (other than previous work at Warwick) on the compacting of a green mix using a moving mass, such as a hammer or weight. This process has been hinted at in (Akroyd, 1962), (p. 196), but no details

were given, as the compaction process has been replaced by internal and external vibrators to reduce the labour costs of manual compaction. It is precisely this manual compaction that is of interest to this project as the stabilised soil samples are to be compacted and hence the cement also is compacted. What we can learn from the references Akroyd and Gooding, is that compacted concrete has stronger characteristics than un-compacted concrete.

# 4. Curing process

By way of a simple illustration of the adhesive qualities of cement we can look at a much simpler example of Papier Mâché. Papier Mâché consists of a flour suspension in water into which paper strips can be immersed and then laid over a former to create a hard shell when it dries. Neither flour nor water have adhesive properties on their own, but when mixed and allowed to dry with a close particle particle intimacy a remarkably strong structure can be created. The flour particles become embedded into the pieces of paper, because the paper absorbs some of the water as well, and once the water is displaced by evaporation, strong bonds between the pieces of paper remain.

The analogy between Papier Mâché and cement breaks down when you add water to the structure again. Cement will retain much of its strength (e.g. 50%) whilst Papier Mâché will break down again and become weak. With Papier Mâché the bonds stay strong so long as moisture is absent, the cohesion is caused by inter-particle intimacy and that breaks down when water is added, as the particles are driven apart by the presence of water coating the surface of the particles. Cement on the other hand undergoes a chemical reaction that remains strong even after moisture is re-applied. Exactly what happens as cement bonds with adjoining particles is what this chapter will endeavour to describe.

## 4.1 Inter-particle bonds, Why are they formed?

Originally they were two popular theories about how OPC worked. The older of the two was a crystalline theory of Le Chatelier which dates back to 1882. This theory stated that the hardening is due to the locking together of an inter-growth of crystals hence giving the crystalline theory. The alternative theory came later in 1893 proposed by Michaelis which was the gel theory. He suggested a non-reversible gel is formed in saturated solution which surrounds the cemented particles. As the gel coagulates the cement sets. These two theories were then integrated into a combined gel/crystalline theory that describe the different stages of curing, (Lea, 1970), (p. 253-260).

Once cement, sand, aggregate and water are mixed thoroughly the mixture gains a certain cohesion with itself. This cohesion greatly depends on the amount of free-water present as an excess of water will lead to a more runny consistency. Assuming the correct amount of water is applied to ensure complete hydration of the cement, each cement particle will be coated in water and this turns into a gel-like film. These gel-coated particles of cement are themselves coated all over the sand and aggregate particles throughout the mixing process. At this stage the cement is still workable and has not begun to set. The reaction between the water and the cement begins a crystallisation process and small single crystals begin to form.

After the "critical time" has passed, these single crystals grow into one another and a huge crystalline network begins to form. The critical time is loosely defined as the time after which further working of the cement is detrimental to the final set strength. Adjoining crystals do not chemically join, but are attracted to one another by Van de Waal forces. The small single crystals begin to inter-link to form a network of interlocking crystals throughout the mixture. If the mixture has been properly graded to include a good range of particles sizes, and these have been thoroughly mixed together with the cement, the crystalline structure will be surrounding each of the particles interlocking them one to another.

There may still be moisture present in the mixture after the crystalline network has been formed and this will slowly be evaporated to the atmosphere as the water particles are drawn to the surface by capillary action. During this drying out phase the concrete will experience a small amount of shrinkage depending on the excess of free-water present. Part of the attraction of employing blocks rather than mass concrete walling is that shrinkage takes place where, due to lack of hard constraints, cracking is unlikely to ensue. This drying out process can take some time to finish completely, but for general purposes it can be assumed that the concrete has virtually reached its' final strength after 28 days. The final result is a chemically bonded solid mass with a very high compressive strength.

The difference between the strength available in tension and compression is suggested to be that in tension the particles are held together with relatively weak Van der Waal
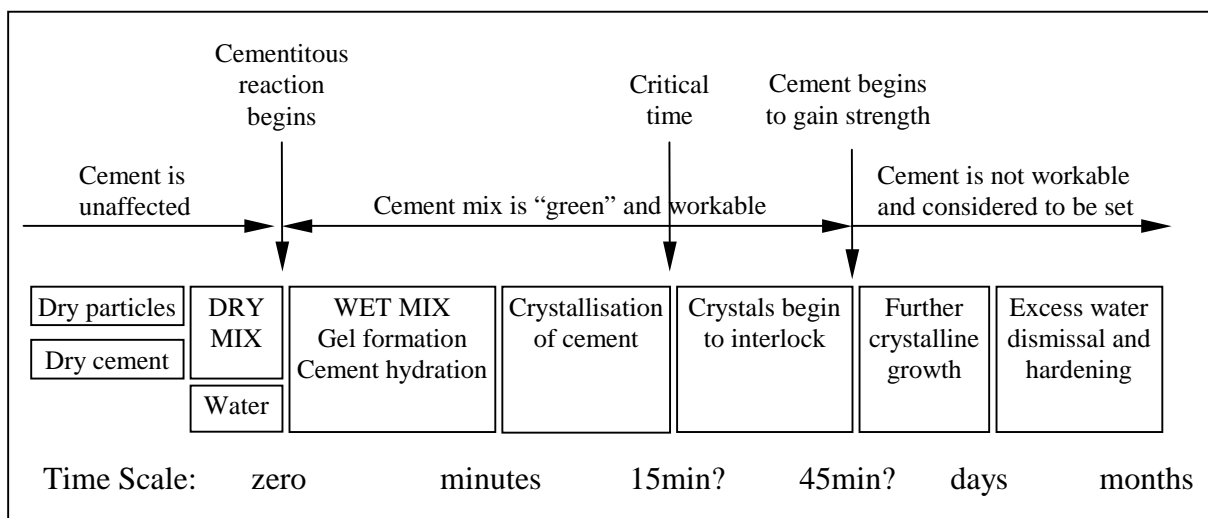
forces. However, in order to separate the particles in compression the forces are acting against the much stronger hydrogen bonds in the crystals that are heavily interlocked with one another. It has been suggested that the crystals do not actually bond with one another, but instead nest together giving the concrete a more mechanical bond than a chemical one. Compression intensifies this bond whereas tension opens up cracks that in turn generate stress concentrations at their ends. The final tensile strength of concrete is typically only 10% of the compressive strength and consequently if loaded in this fashion it must be reinforced with steel. For the purpose of building walls the load is almost always compressive and so this reinforcing with steel is not going to be considered further as it will be outside of the scope of this project.

The diagram below aims to help visualise the bonding process between the cement particles and the sand particles which are in turn bonded to the larger lumps of aggregate. This diagram is not to scale nor is any of the chemical changes that occur noted in diagrammatic form. It merely illustrates the particle arrangement and the presence of moisture coating the cement particles that in turn disappear leaving the strong cementitic bonds behind.
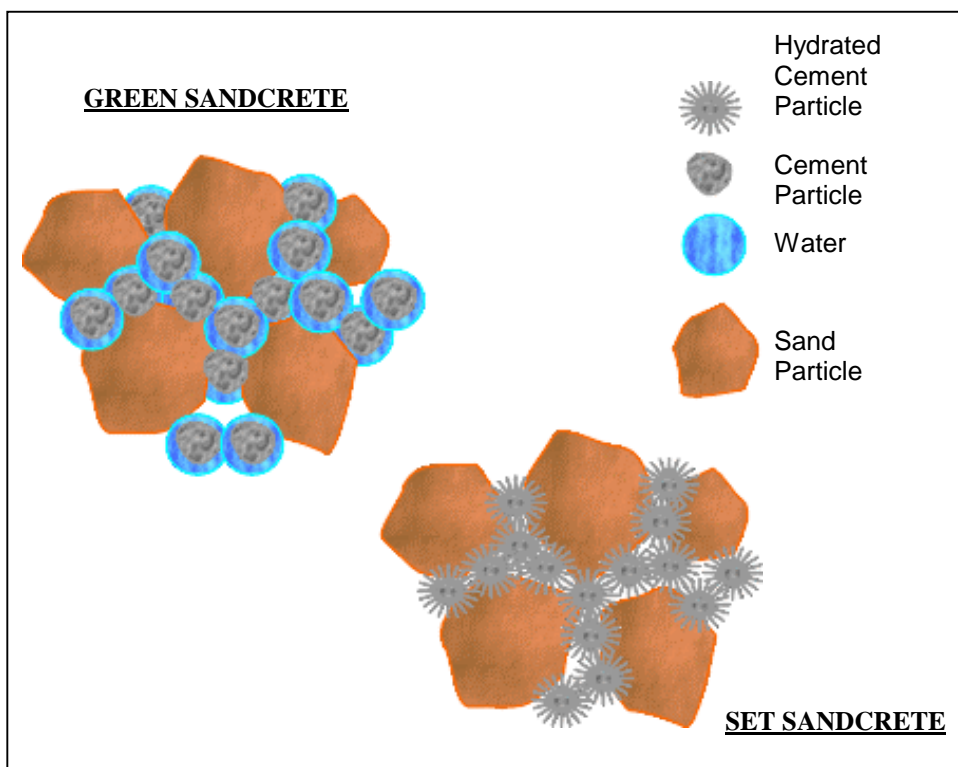
## 4.2 Wet strength and curing times or cycles

As mentioned above the cement mixture can still be worked up until the critical time is reached without causing a loss in the final set strength. After this point the crystallisation process begins to give the mixture a more rigid nature. The mixture has not fully set at this point, but it does have some internal cohesion as bonds are being formed. The strength of the mixture early on in the curing process is called the "wet strength" or the "green strength". Certain levels of green strength will permit the mixture to be handled in a solid form, but it will still be very fragile. Below is a time-line diagram to illustrate the setting of cement.

|  | Cementitous reaction begins | | Critical time | Cement begins to gain strength | |
|---|---|---|---|---|---|
| Cement is unaffected | | Cement mix is "green" and workable | | Cement is not workable and considered to be set | |
| Dry particles / Dry cement | DRY MIX / Water | WET MIX Gel formation Cement hydration | Crystallisation of cement | Crystals begin to interlock | Further crystalline growth | Excess water dismissal and hardening |

| Time Scale: | zero | minutes | 15min? | 45min? | days | months |

In the example of making blocks from concrete the mixture is placed into a mould and after a set period of time the formed block can be removed and put to one side so that the mould can be reused. The length of time that the block must be left in the mould will depend on the wet strength that is required for ejection from the mould and subsequent handling. The time to reach this point will vary depending on the speed of the cement curing and beginning the crystallisation process. This will depend on the amount of cement present, the final block density and the free-water content.

In order to maximise the green strength of the mixture one needs to ensure that the free-water content is as small as possible and to leave the mixture untouched for as long as possible to permit the cementitous action to bond the particles together. The exact length of time that is necessary to achieve this may be discovered by trial and error, but as mixture quantities and handling techniques may vary "as long as

possible" may be a good initial estimate. Setting can take place in as little as 45 minutes, but useful hardening will take much longer, (Stulz & Mukerji, 1993), (p. 63). The green strength of mixed samples can be tested to give a more accurate answer, using both destructive, i.e. compressive tests, or non-destructive, i.e. scratch tests, to determine the approximate green strength of the formed mixture.

It may be possible to put the mixture through a series of curing cycles to achieve a greater overall strength over a longer period of time. The initial curing time may only be sufficient to manipulate the formed mixture and place it in its final position, in a wall for example. Further cycles of wetting and drying could then encourage any unhydrated cement particles to become hydrated and cure within the finished product. This is of particular interest where the cement content, and therefore the water content, is very low. This low water content may be able to hydrate all the cement, if given time to do so, but evaporation takes over and takes away the moisture before the cement has had a chance to hydrate properly.

The amount of hydration that is necessary to achieve the desired strength is another point in question. Tests done by Grun (Lea, 1970), (p. 268) have been done that illustrate that even after a cement sample has fully cured, it can be broken up again and rehydrated and encouraged to cure again. This evidence strongly suggests that all the cement is not hydrated in the first setting period. Therefore, in order to achieve a desired strength, in the long term, complete hydration could theoretically occur over a period of time ranging from weeks to even years depending on the circumstances.

As concrete is porous when set it would still be able to receive moisture into the surface and permit further hydration of the unhydrated cement particles. What increase in strength this would give is not clear as the porosity itself is a weakening factor due to the voids present between particles. These voids provide no structural strength and the re-hydration will only help the overall strength if has the potential of filling some of these voids with cementitic crystals. Although this is perfectly plausible, how effective it is in practice is unclear.

### 4.3 Moisture dismissal and shrinkage

The moisture content of a cement mixture is of great importance, primarily because too little water will cause insufficient cement hydration, and too much water will reduce the final set strength. Keeping the right moisture content during the mixing and forming stage would therefore be quite important to monitor and control, if possible. This is especially true in hot climates where the moisture content will drop rapidly if left in the environment unmonitored and uncontrolled.

In order to ensure that the cement goes through a complete hydration process, and maximising final strength, the water content needs to be minimised, whilst also preventing the existing moisture from escaping. In practice this has been done in two ways. Once the initial cement has set the formed mixture can be submersed in water during the hardening process. This guarantees that there is sufficient water present for the cement to hydrate, but since the immersion occurs after initial setting, the extra water present will not affect particle intimacy and jeopardise the final strength of the formed mixture. The other, simpler, method is to keep the formed mixture in an environment with a 100% humidity. This prevents water within the block from escaping to the surface too quickly as the surface evaporation will be almost non-existent in an environment with a 100% humidity. In practice this too can be difficult and so a compromise of sprinkling water over the formed mixture repeatedly during the hardening process helps to minimise internal moisture from evaporating too quickly.

We have already discussed the movement of water through the mixture during the curing process by mechanisms of evaporation and capillary action. What now needs looking at is the effect that this moisture movement has on the finished article. By inspection the limiting factors for shrinkage are the amount of excess water present and consequently the voids that it leaves behind, and the overall density of the mixture prior to curing.

To minimise shrinkage one must minimise the potential space between particles in the mixture. Clearly the sand and aggregate particles themselves do not shrink, and similarly the cement and formed cementitic crystals are not prone to shrinkage. This

leaves the physical gaps between adjoining particles and the gaps left by excess water when it has evaporated off, being the primary cause for potential shrinkage.

The problems associated with shrinkage are mainly to do with uneven shrinkage and different relative amounts of shrinkage. If every mixture shrunk in exactly the same way and by the same amount each time, then it could be accounted for and there would be no problem. In practice the shrinkage is often uneven, due to insufficient mixing or uneven drying. The desired form into which the cement mix was placed will not be the same as what is finally achieved after the hardening process is finished, and this may not completely finish for many months.

The amount of potential shrinkage is not insignificant either. Gessner discovered that using a pure OPC-water mixture a volumetric change of over 6% could be noted in the 28 day curing time, (Lea, 1970), (p. 269). The cement samples that were used had quite a high water content using three parts cement to one part water. Previous suggestions were that the ratio should be closer to four to one or four and a half to one instead of the three to one that Gessner used. This could partially account for the high shrinkage, and a better cement to water ratio may yield much better shrinkage results, never-the-less, it does illustrate the significance of potential shrinkage that may occur during curing. As we will see later, this potential shrinkage is a considerable nuisance when trying to build structures with many slightly different formed cement mixtures.

## 4.4 Strength testing

The strength of a concrete structure is limited by one of two factors. Simply speaking, either the bond between the cement and the aggregate fails (cement matrix failure), or the aggregate itself fails and shears along existing fault lines within the material. Usually the former occurs because the aggregate has a higher crushing strength than cement, (Akroyd, 1962), (p. 85). A stronger bond between the cement and aggregate can be achieved if the aggregate is angular and clean, which has already been recommended earlier in this report.

The final set strength of a concrete mix is directly proportional to the water/cement ratio, provided that the workable concrete is compacted so that it contain less than 1% by volume of air voids. This relationship can be expressed as $S = A/B^x$, where S is the compressive strength, x is the water/cement ratio, and A and B are constants determined by the materials used and the conditions of the test. The table below, based on (Lea, 1970), (p. 392), shows how the water/cement ratio affects the strength of the concrete after different periods of curing.

The influence of water content on the strength of a 1:2:4 concrete based on Lea, Table 59.

TABLE 59

| Water/cement | Compressive strength (MPa) | | | |
|---|---|---|---|---|
| ratio | 3 days | 7 days | 28 days | 90 days |
| 0.5 | 16.55 | 24.82 | 35.85 | 48.27 |
| 0.6 | 11.72 | 18.62 | 28.96 | 37.92 |
| 0.7 | 7.58 | 13.79 | 21.37 | 29.65 |
| 0.8 | 4.83 | 10.34 | 17.24 | 24.13 |

Or viewed graphically:



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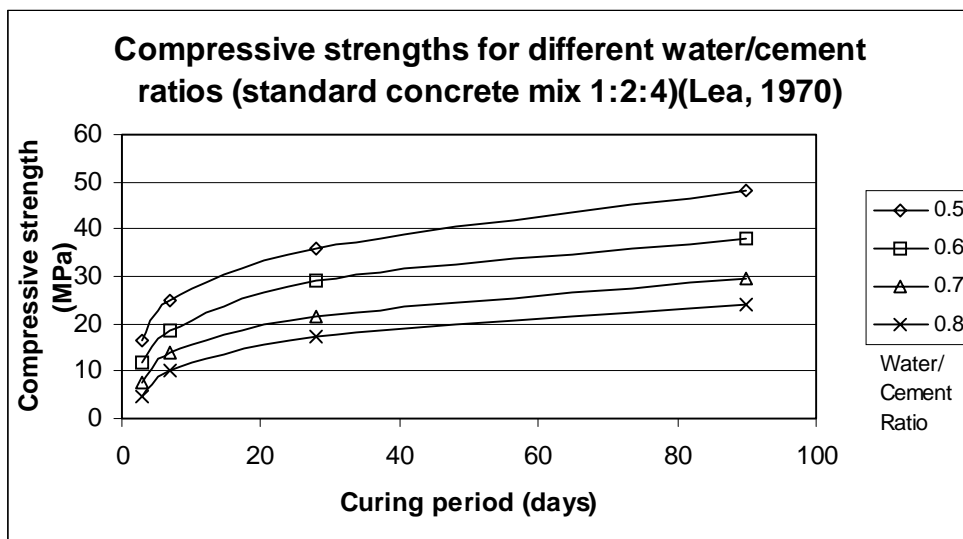
## 4.5  Longevity, environmental attack

Well-made concrete using quality ingredients is usually considered to be a building material of a very high standard. Such concrete has a very high resistance to environmental attack of any kind, apart from major natural disasters of course. Consequently as a building material it can in theory last for a very long period of time. There are of course certain chemicals that will cause slow deterioration of finished concrete, but most of these can be ignored as their occurrence would be so improbable in wall construction that they are not worth considering. (Akroyd, 1962), (p. 247-250), gives a list of such chemicals; Carbon dioxide, Chloride, Chlorine, Chromium salts, Detergents, Fatty oils, Formaldehyde, Fruit juices and sugars, Gypsum, Hydrogen sulphide, Inorganic acids, Lactic acid, Lead, Oils, Organic acids, Salt for de-icing and Water.

Two of the above chemicals stand out as being strange in a list of things harmful to concrete; gypsum and water. Gypsum is an additive used in making cement, but it is also a sulphate and all sulphates attack concrete, so it must be included in the list. Water itself is not harmful to cement, but water often carries with it harmful salts and sulphates and these are what cause the problem. In extremes of temperature change, where frost and freezing occur water can pose a problem if the porosity of the concrete is high. If water is permitted to penetrate the surface of the concrete and this is subsequently frozen it will expand can cause damage to the concrete. This damage may occur superficially as spalling or it may cause deep internal cracking that is much more severe. These cases are worth considering generally, but for the purposes of this project such extremes are not going to be considered.

# 5. Application of cement to stabilise soil

By now we have a better understanding of the way that cement bonds with itself and other particles in making concrete. We also know some of the important guidelines that need to be followed when making successful mixes of concrete. Furthermore, many of these guidelines can be followed when applying the same principles to mixing cement with soil as this chapter will set about to illustrate.

## 5.1 Basic requirements of soil

According to the ideal specifications given by the United Nations, in "Soil-cement: Its use in Building, (1964)", as quoted by (Gooding, 1993), (p. 263), the best soil composition for soil-cement is as follows; 75% sand, 25% silt and clay, of which more than 10% is clay. This composition will yield a sandcrete product if mixed with cement and will exhibit good structural characteristics. Unfortunately, soil with these exact characteristics will not be found easily near every potential building site and so one of two things must be done. Either the soil is tested and the required parts added to make the ideal soil, or a compromise is made and a slightly higher percentage of cement is used to ensure a satisfactory outcome whatever the type of soil is used.

Unfortunately, there is an underlying problem with randomly mixing cement with any type of soil, and it is to do with the clay fraction of the soil. Clay consists of the finest particles in the soil and can, in same way that cement does, coat the other particles when mixed with water and cause a significant cohesion after the mixture is dried. Indeed this is how the majority of earth bricks are made today. Clayey soil is mixed with water, formed in moulds, ejected and left to dry in the sun. The clay in the soil has to be protected from getting wet again, as moisture will drive the clay particles apart and cause considerable material breakdown. To do this, these formed bricks can be fired, or be placed into a structure and protected from the elements with some form of paint or render, an effective damp-course and an effective roof.

Clay and cement will work against one another if the quantities are not carefully monitored. Too much clay will result in the cement not coating all the particles sufficiently and subsequent wetting will cause expansion of the formed mixture breaking apart the cement crystals and causing breakdown. [Remember,] Cement is not strong in tension and the expansion of the clay particles cause internal expansion working against the weaker of the cementitous bonds. Also because clay is so very small (0.002 - 0mm) it is difficult for the cement to successfully coat the clay particles. Therefore, let us assume that a high composition of clay in a soil that is to be stabilised with a very small quantity of cement, makes it unacceptable.

According to (Norton, 1997), (p. 16), a suitable particle size distribution for building with earth is:

| | |
|---|---|
| Sand/fine gravel | 40 - 75% |
| Silt | 10 - 30% |
| Clay | 15 - 30% |

The values may of course need to be more closely defined for soil-cement, and it may be the case that the clay fraction is the critical quantity. Clays can be removed from soils by washlines. However washlines may be impractical in the field because of the large amounts of water necessary and another source of soil may have to be found. Sieving the soil can also separate out the larger grains but this is also time consuming and labour intensive. Soil sieving may only be practical for removing large particles such as coarse gravel, (over 20 mm in size).

Particles within the soil will generally be rounded due to the natural environment that the soil is being excavated from. Secondary crushing techniques are assumed not to be used in developing countries because of the high cost of the complex and heavy duty machinery required to crush large aggregate into smaller angular particles. The extraction and breaking up of soil clumps will be enough of a labour intensive exercise, without having to further crush rocks up into smaller angular pieces. For the purposes of soil-cement building materials any particles over 20 mm are considered too large and should be discarded. Thus we will normally be working with soils having rounded particles in the size range clay to fine gravel.

### 5.2  Particle, particle interaction/intimacy

The main source of soil will be to dig it out of the ground. It will therefore be removed in dense clumps which will have to be broken up and have the cement thoroughly mixed into it. This process of breaking up the clumps will lower the overall density of the soil and reduce the particle intimacy. This will need to be reversed after the cement is mixed into the soil to ensure maximum strength and minimum porosity.

We have described already the necessity of keeping the particles closer together in the previous chapter, and also the consistency of particle intimacy throughout the mix. Keeping particles close together reduces the air voids present in a soil mixture and will generate two distinct benefits. Firstly the closer particle interaction will help to ensure good bonds between the cement and the particles, and secondly the porosity of the mixture will decrease leading to reduced levels of water penetration.

It is intended that the soil samples will be compacted by impact and this requires a degree of workability within the soil and compatible with a high speed of production. Good workability is desirable as the particles will need to "flow" past each other to achieve a uniform density through the compacted sample. Workability is determined by particle shape and the moisture content, the former depends on the soil and the latter we want to keep as low as possible.

The time between mixing in the cement and water and the final finishing impact could be the most crucial factor in compacting the mixture. One hardly wants to be breaking the  cementitious bonds through the impacting process and therefore the compacting of the mixture should take place before the mixture passes the critical time. In order to achieve this, the time taken for the mixture to reach the critical time in different circumstances will need to be determined. More practically, this will probably lead to a small batch production of the cement mix so that it can be quickly compacted into finished stabilised blocks.

### 5.3 The curing process re-applied

The curing of the cement within the soil needs to take place in the same way that it would in a well mixed batch of concrete. Before adding moisture and allowing the curing process to begin, there should be a good particle size distribution and all the particles in the mixture should be closely packed with one another and the cement. The theory behind the bonding of the hydrated cement crystals is exactly the same with soil as it is with concrete additives. Upon the addition of water the crystals form and grow to interlock with one another leading to a high compressive strength. Full strength will not be reached for many weeks and to help the cement hydrate fully the finished mixture should be kept in a 100% humidity environment for the curing period.

### 5.4 Moisture attack

Most soils contain a fraction of clay as a part of their overall composition. Clay is the finest of the soil particles and can actually bond other particles together if sufficient clay and moisture is present. Clay has a very large volumetric expansion when water is added. If the moisture in unstabilised soil increases, swelling occurs. Conversely, drying causes shrinkage and therefore danger of cracking. This process leads to the breakdown of the soil and internal strength is lost making the material useless for building construction.

The balance of clay with respect to the other fractions is quite important. On one hand clay helps bond particles together, yet if another stabilising medium is not applied the clay can be instrumental in driving the particles apart should the material get wet. The common practice of firing clay bricks converts a loose particulate material into a solid ceramic. These fired bricks are no longer affected by moisture and although a modest level of porosity is still present, sustained contact with water is not detrimental to the integrity of the brick. Firing of the brick uses a great deal of energy, which either means using large quantities of firewood for small scale manufacture, or consuming fossil fuels in large-scale dedicated tunnel furnaces. The manufacture of cement also uses a large amount of energy, but that can be done away from the building site and the finished product can be delivered to where the structure needs to be erected.

## 6. Conclusions and recommendations for further work

Cement as a stabilising medium can be very effective if used properly. Appropriate particle size distribution, thorough mixing and maintenance of optimum moisture levels will yield a successful mix with maximum final set strength. A compromise in any of the above will result in a reduction in strength of the finished product. However final set strength is not the only requirement of a cement, adequate workability and adequate (if low) strength prior to curing are two others. These other requirements often conflict with the maximisation of final strength – for example by calling for a higher clay content.

A suitable soil can be considered to be one that has no organic material, has a clay content between 10% and 20% and has a fair range of well distributed particle sizes up to a maximum of  20mm in diameter. The moisture of the soil-cement mixture needs to be carefully controlled. There needs to be sufficient moisture for the cement to fully hydrate but no excess of water which would reduce the final density, increase porosity and reduce final strength.

The dry soil is to be mixed with the cement and the required water added. The mixture then needs to be formed and left in a 100% humidity environment within 30 to 45 minutes of mixing the cement and soil with the water. This is to ensure that the cement has sufficient water to hydrate and also that the mixture is not manipulated again after the critical time.

Curing of the mixture takes several weeks, but the green strength of the material must be sufficient to remove the formed material, handle it and perhaps even directly place it into a structure. Multi-stage curing may be possible, but the re-application of moisture may cause surface cracking and the extent of this needs to be further investigated.

Topics for further investigation

- A more detailed account of the interaction between cement and clay and why too much clay in the mixture is detrimental to the effectiveness of the cement.

- A brief study of the effect of multi-stage curing or wetting cycles on cement stabilised soil. Is an environment of 100% humidity totally necessary? or can a series of wetting cycles be just as adequate?

- How critical is the moisture content for dynamic compaction? Can a drier mix of soil can be compacted by this method better than quasi-staticly compressed soil-cement?

- If a much drier soil is used for compacting, can wetting after compacting encourage further cement particles to hydrate and hence increase the overall strength?

These questions and more will hopefully be answered later on in the project after further investigation into the available literature and perhaps after some experimental analysis of some of the interesting characteristics of soil-cement.
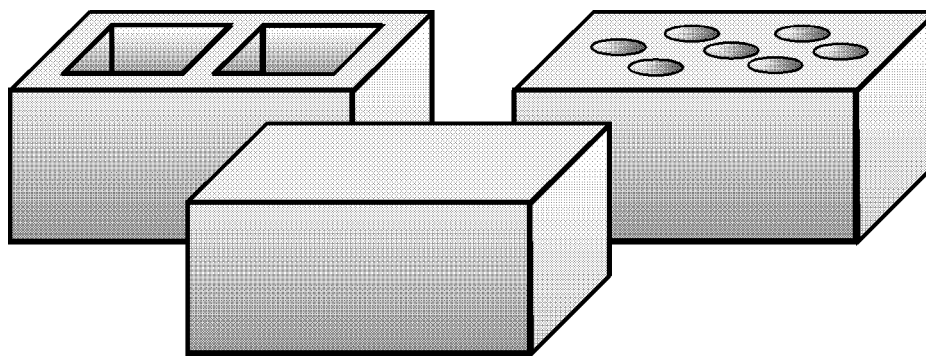
## 7. Summary

The subject of how cement stabilises soil has not been exhaustively investigated and documented during this report. However, what has been achieved is a broad understanding of the simple processes and requirements of the technique of using cement to stabilise soil. By investigating the literature available on how concrete is made, we are able to make general statements on how to stabilise soil effectively using cement as a stabiliser.

The investigation has revealed that many different factors are responsible for ensuring a good bond between the cement and the particles mixed within it. These requirements not only affect the components of the mixture used, how it is prepared, delivered into its final state, but also subsequent curing times and environmental conditions of the finished product.

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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.

# Table of Contents

# 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 hardly-

stabilised 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/m³.

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. $0.4 \times 0.2 \times 0.125$m 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/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. Low-density (1700kg/m³) 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/m³) 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.

A

B

C

D
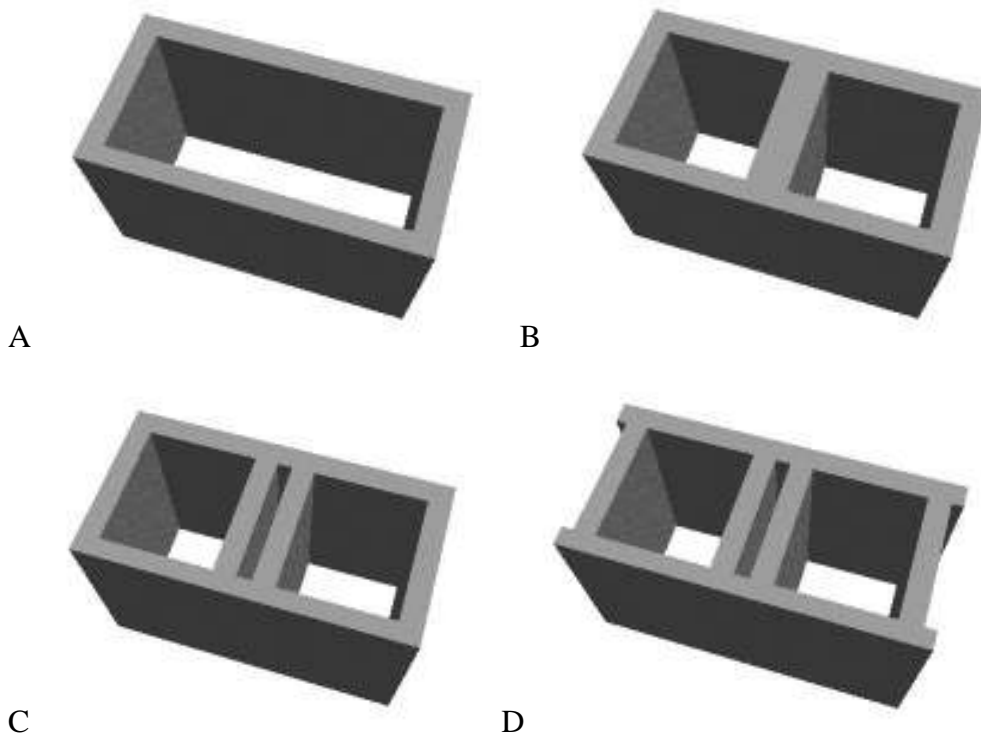
NOTES

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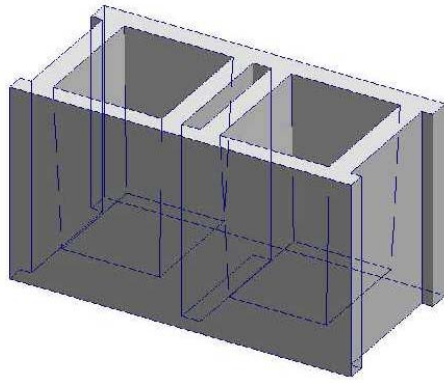
If mortar is being used to join the blocks together then a deep frog arrangement is better than the hollow section as less mortar is wasted. Chapter five of this document deals with the proposal of interlocking blocks that have no need of mortar between the courses.
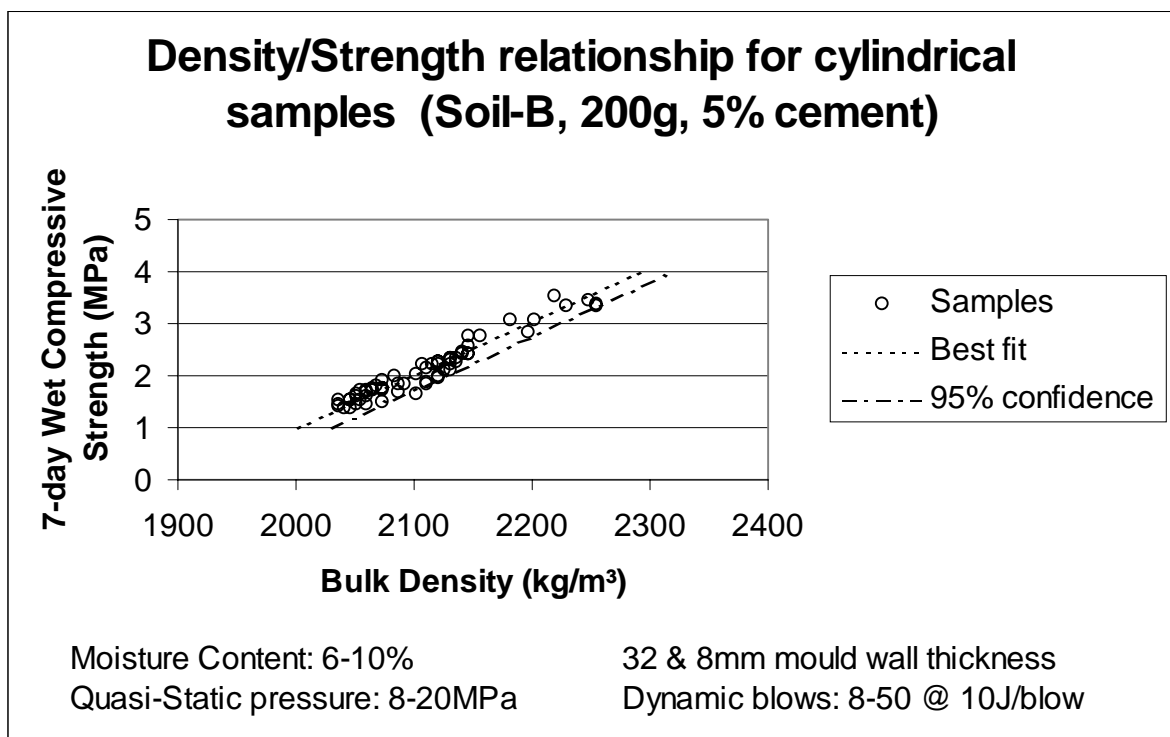
## 4.1 Results of material removal

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.



**Density/Strength relationship for cylindrical samples  (Soil-B, 200g, 5% cement)**

Moisture Content: 6-10%          32 & 8mm mould wall thickness
Quasi-Static pressure: 8-20MPa    Dynamic blows: 8-50 @ 10J/blow

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.



**Variation in strength with cement content**

Gooding 1994
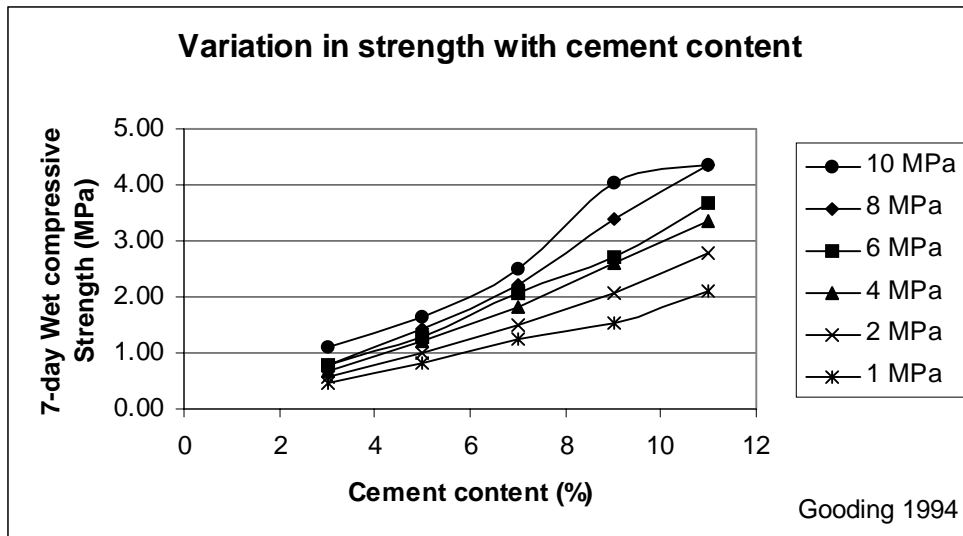
This graph shows the change in compressive strength with extra pressure and extra cement. For the low pressure samples (1 and 2 MPa) as the cement content doubles the strength also doubles. For the higher pressure samples the fractional increase in strength for the same increase in cement is greater. 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 $0.29 \times 0.14 \times 0.09$m 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 $\rho b^2$. 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 $\rho$

| 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 m² 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 m² 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 m² 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 |

Notes

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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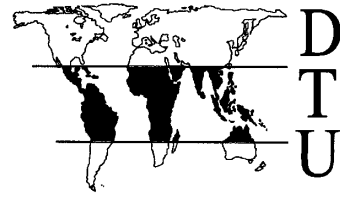
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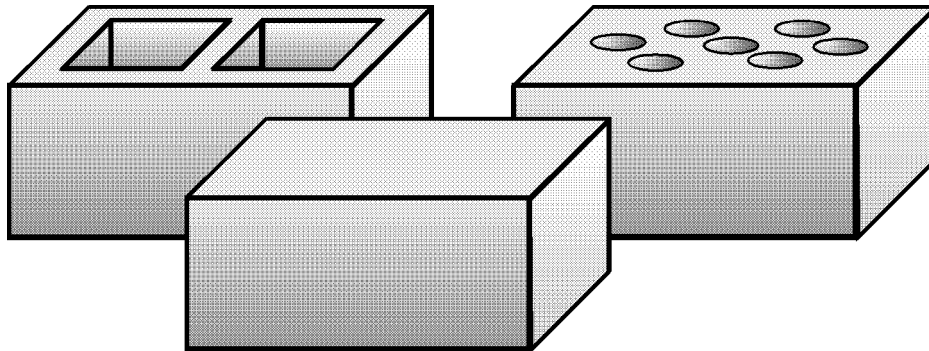
# Initial critique of existing papers on dynamic compaction of stabilised soil samples

## Author: Mr D E Montgomery
## April 1999

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Titles of Stabilised Soil Research Progress Reports Produced to date:

[Put printed list of current reports in place of this page.]

## *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.

"*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

Implusion (dynamic) compaction of soil building blocks has been shown to promise certain advantages over block pressing, however previous researchers have already expressed their dismay at the general lack of information in the field of dynamic compaction of soil blocks. This paper reviews what such information is redily available. The information that is available on dynamic compaction mainly comes from the civil engineering industry from ground compaction methods. Whilst these are suitable for gaining a basic understanding of soil compaction, they are not entirely applicable to compaction of blocks confined in a mould. Modelling of the compaction process has been attempted within this field and some mathematical models are described in this report.

Dynamic compaction of soil blocks without the use of cement has been investigated to establish optimum compaction efficiencies when the energy transfer is kept constant. This has shown that between 8-32 blows gives the greatest compaction for the same total energy transfer. The research did not investigate the effect of adding cement to the compaction process, nor did it identify the moisture content to optimise dry block strength. Research done in the civil engineering industry has briefly investigated the effect of moisture on unconstrained compaction as well as the efficiency of different methods of energy transfer. These results are significant but cannot easily be applied to the research done on block compaction.

Several major gaps in the understanding of soil compaction still exist, and these need to be tackled one by one. It is of fundamental importance that thorough testing of dynamically compacted cement stabilised block be carried out in the near future. Optimisation of energy transfer can yield small increases in density, which results in much greater gains in strength. More time spent researching the optimum method of energy transfer would be a valuable exercise especially with the addition of cement which has an effect on the compaction process.

# Nomenclature

**Bre-pack machine:** A high quality 10MPa manual block-making machine as developed in the U.K. for block manufacture in developing countries.

**Brick:** An object (usually of fired clay) used in construction, usually of rectangular 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:** Describing the state of material containing cement and water before it reaches the critical time, after which further plastic deformation hinders the final set strength.

**Permeability:** Describing a material that permits a liquid or gaseous substance to travel through the material.

**Porosity:** A measure of the void volume as a percentage of the total material volume.

**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.

# Table of Contents

# 1. Introduction

There is a small quantity of existing information on dynamic compaction of stabilised soil blocks, but this is limited to a few simple surveys and thesis reports. Much of the work for this project will reference these previous works as they too discovered a lack of information in this field. Other studied have provided information of direct relevance to other fields, but which can only be applied to the field of interest with a small degree of confidence.

Soil compaction is an important area of study within the civil engineering and geotechnics and this is similar to the working being carried out here. Some sources give a bit of detail on a form of dynamic compaction that is used to compact soil prior to construction, or to aid stabilisation of slopes etc. These are of interest especially if any quantitative description of the compaction process is given that would be useful in application to compaction of blocks.

Ground compaction always concentrates on a small area of ground where compaction is desired and the machinery used has to move around the area to ensure thorough compaction of the desired surface. This type of compaction could be considered analogous to the tamping down of soil in a block mould or the compaction of soil between shutters for rammed earth walling. However, simultaneous compaction of the entire block surface is not in the same category as there are no potential slip planes for soil movement under the direct compaction force. Unlike ground stabilisation the compaction force is uniform over the whole surface of the block making the two processes fundamentally different to each other. This makes the information in this field interesting, but not entirely useful. Consequently much of the research into dynamic compaction of soil blocks will be received from previous research done by Dr. Gooding and his thesis.
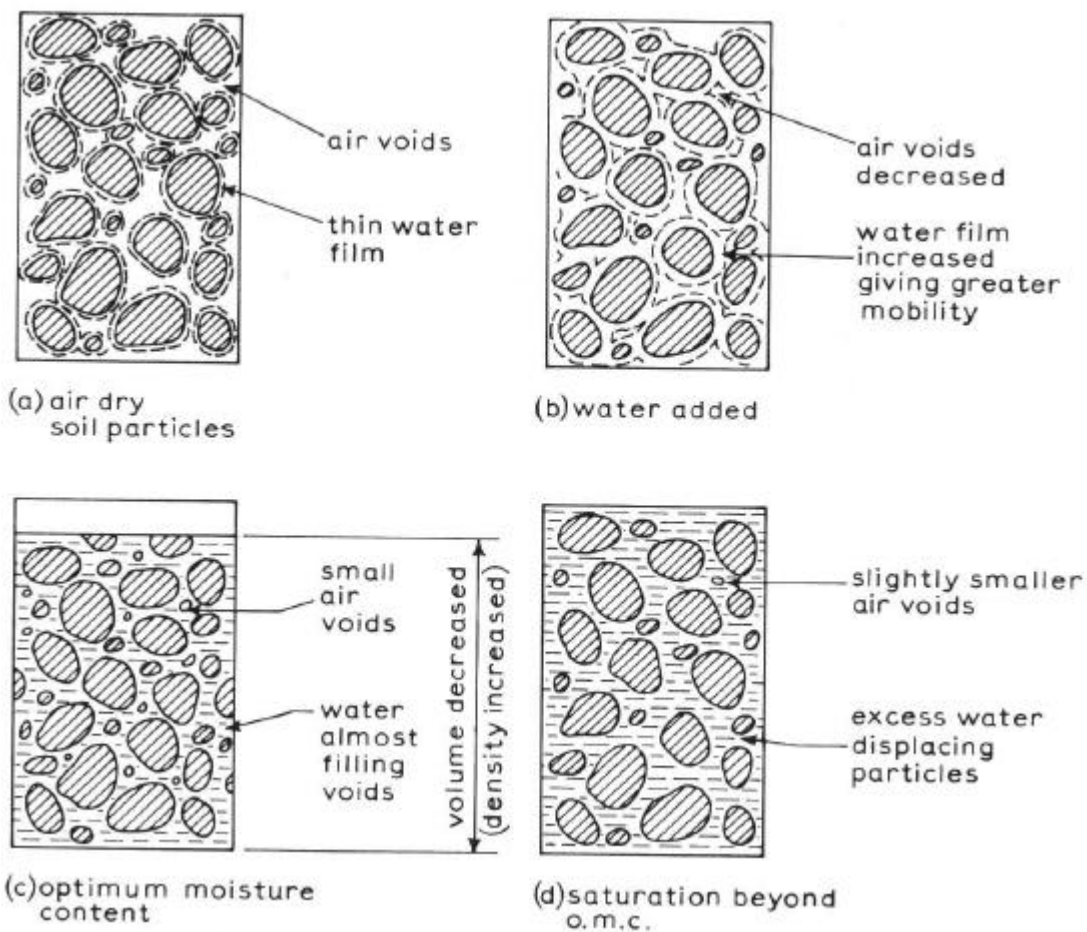
# 2. Principles of soil compaction

Soil generally consists of a mix of solid, liquid and gas. These are more commonly referred to as the soil particles, water and air. The combination of the volume occupied by the water and the air is called the void volume. Compaction of a soil sample is done to decrease the air voids present in the soil and hence increase the dry density of the sample. Dynamic compaction achieves this by permitting a moving mass to strike the surface of the soil sample and deliver energy into the sample that causes densification. The level of densification that can be achieved relates to a number of different parameters, the most important of which are the moisture content and the compacting energy transferred. Other factors that affect the densification are the number of blows applied to the soil and the momentum of each blow delivered by the falling mass.

## 2.1 Air void reduction

An air dry mass of soil will have a certain amount of spaces between the soil particles and these spaces are referred to as "air voids". This is sometimes expressed as a percentage of the total volume (air + soil) occupied by the air. Indirectly it can be represented by the "dry density" of the soil, as the weight of air in a soil is negligible compared with the weight of the soil particles. If a soil sample is compacted at it's density-optimum moisture content, by definition it will be at its greatest dry density for that compacting pressure. After such compaction, the volume occupied by the moisture will be virtually equal to the percentage of air voids present in the sample after subsequent drying out. Incidentally the density-optimum moisture content is not the same as the strength-optimum content. We must not use volumetric definition of OMC as it changes (rises) during the compaction process. We use a mass definition. Alternatively we use volume but define when it is measured, e.g. immediately after compaction.

The density-optimum moisture content (OMC) depends on the compacting energy delivered into the sample. The greater the compacting energy the lower the OMC and hence the greater the final dry density. The diagram below taken from Head, 1980, pg. 270, illustrates the particle arrangement of a soil sample at different moisture contents as well as the OMC.

(a) air dry soil particles

air voids

thin water film

(b) water added

air voids decreased

water film increased giving greater mobility

(c) optimum moisture content

small air voids

water almost filling voids

volume decreased (density increased)

(d) saturation beyond o.m.c.

slightly smaller air voids

excess water displacing particles

## 2.2  Compacting methods

Several methods for dynamically compacting a soil sample exist as tests for soil compactability. These involve a mass that is raised to a consistent height above the surface of a soil sample constrained within the walls of a mould. Some impactor designs cover the entire area of the soil sample whilst others are dropped over the surface in a standard pattern. The latter technique could be analogous to tamping the soil down into a block mould, whilst the former is like the dynamic compaction tests as done by Gooding. Both tests are of interest but the former will be more helpful when trying to extend Gooding's research.

### 2.2.1  Soil compaction tests

The complete description of all the possible compaction tests is not necessary for the purposes of this report. A brief outline of each test is given and their possible relevance to the dynamic compaction research will be suggested. The tests described below are taken from Head, 1980, pg. 281-306.

*BS Ordinary Test (or the Proctor test)*

This test uses a 2.5 kg metal rammer with a 50mm diameter face that falls into a cylindrical mould of 105mm diameter. The drop height is kept at a constant 300mm to ensure consistent energy transfer between blows. The blows follow a pattern over the face of the sample to ensure repeatability and consistent compaction of the entire sample. Each sample made up of three layers of soil that has passed through a 20mm sieve and each layer is given 27 blows of the rammer. After compaction the sample is trimmed off to a set height that gives a constant volume of 1000cm³. This is then weighed and the density can be calculated.

*BS Heavy Test*

This test is virtually identical to the BS Ordinary Test, with the only difference being the mass of the rammer and the drop height. For this test a 4.5 kg rammer is used and it is dropped from a constant height of 450mm above the level of the soil. Compaction is also carried out in five layers instead of three. All other dimensions and quantities remain the same.

*Compaction by Vibration*

This test uses an electric vibrating hammer operating at a frequency of between 25-45 Hz and a power consumption of 600-700 W. The soil is compacted in a cylindrical mould with an internal diameter of 152mm and a height of 127mm (CBR mould). The vibration from the hammer is transferred into the soil through a steel rod with a circular foot 145mm in diameter, (i.e. that nearly fills the mould). The soil is compacted in three layers by the hammer action and a steady force of 300-400N is applied to the vibrating hammer to prevent it from bouncing up and down on the surface of the soil. The final compacted height is measured using a steel ruler. The mass of the soil and mould is then weighed and weight of

the empty mould subtracted from it. From these measurements of height and net weight the density can be calculated.

*Dietert Compaction*

Of all the compacting methods this one is most similar to the tests done by Gooding. It is a hand-operated device that uses a large cam to lift a mass of about 8kg through a constant height above the surface of the soil. The cam permits the mass to be dropped repeatedly onto a foot that rests on the surface of the soil sample transferring the energy into the soil and causing compaction. This apparatus uses a standard 50mm mould and the foot is fractionally smaller (48mm) to ensure free movement on impact. Density is calculated from measuring the height of the soil in the mould and the mass of the soil that is originally placed into the mould; the number of blows applied is recorded.
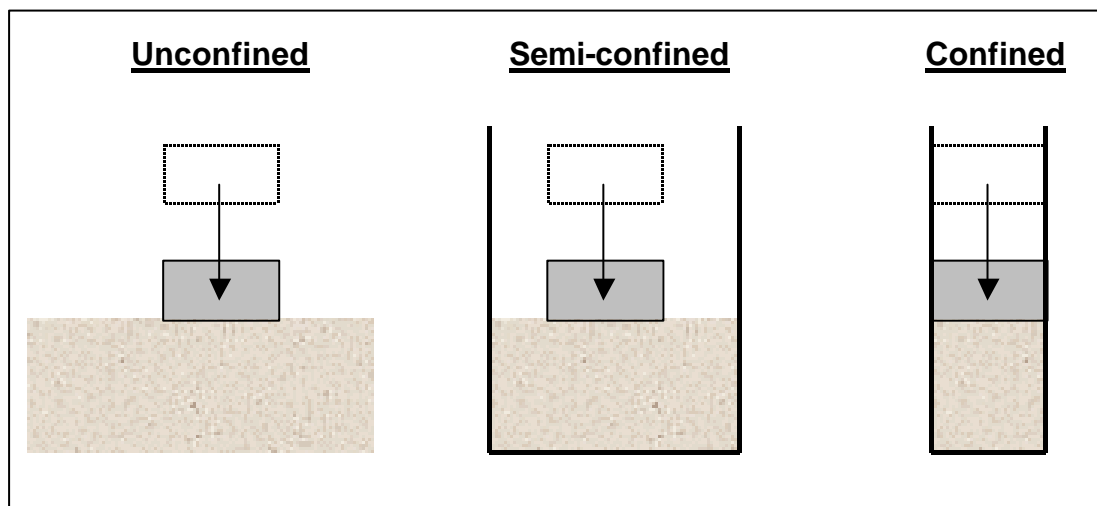
*Harvard miniature compaction*

In the situation where material for analysis is scarce and the soil particles are finely grained this test may be used. It uses a hand-held spring-loaded tamper and a special mould. The spring ensures that a consistent force is applied to the surface of the soil during each successive 'tamp'. This force equates to 178N and is applied through a tamper rod of 12.7mm in diameter over the surface of the soil. The mould is 33.3mm in diameter and 71.5mm high. This volume yields the useful feature that the mass of soil, in grams, is equal to its density in pounds per cubic foot.

### 2.2.2 Compaction test analysis

Both the BS Ordinary test and the BS Heavy compaction test show similarities to the compaction process that is of interest because they involve a mass dropping onto the surface of the soil in a mould. To compact the soil sample evenly the rammer must be dropped in a pattern over the surface of the soil. Although the soil is restrained within the sides of the stiff-sided mould it is only semi-confined to a volume. In other words, compaction applied to one area doesn't cause compaction in another and slip planes within the soil can exist. Conversely, confined compaction is similar to the Dietert compaction where the compaction

occurs over the entire surface of the soil in the mould, thereby confining the volume and restricting any slip planes in the soil. Both of these compaction methods are very different to the unconfined ground compaction as used in civil engineering.

Now we can separate out any compaction test into three classes groups: confined, semi-confined and unconfined compaction. Of the three, confined compaction is of most interest as it replicates the dynamic compacting process that will be employed for block manufacture during this project. Semi-confined and unconfined compaction may be useful to investigate, but will be limited in their application to this project. Below is a sketch to illustrate the three classes of compaction.



Unconfined compaction is limited to ground compaction as used in civil engineering and no compaction tests have been described above for this case. Semi-confined compaction tests are BS Ordinary and Heavy tests as well as the Harvard miniature compaction test. Confined tests are the Dietert and the Vibrating Hammer compaction tests, although the latter uses a different means of transferring the compaction energy.

It is not advisable to compare compaction methods that use vibration with impact compaction. Vibration expels air from the mixture and does not usually crush soil samples in any way. Instead vibration redistributes particles (largest ones sink) and it does not leave compressed air pockets.

# 3. Previous dynamic compaction research

It has been suggested already that the information on dynamic compaction of stabilised soil blocks is very scarce. Up till now the author is only aware of two pieces of work that cover this topic, and only one of which he has been able to access. There are however, other publications that deal with the subject of soil compaction, both from a theoretical and practical viewpoint.

## 3.1 Mathematical modelling

In the unconfined state, a soil sample that receives an impact will compress in the localised area and send shock waves through the surrounding soil. It can be modelled as a highly damped spring with characteristics that depend on the Young's Modulus, Dilation Velocity, Poisson's Ratio, and Elastic Limit of the soil. Scott R. A. and Pearce R. W. give an equation that links these characteristics to the rate of deceleration of a moving mass in order to model the stress and movement at the impact surface.

Scott and Pearce 1976 modelled an unconfined mass of soil that has been hit by a falling weight. They investigate the effect of unsaturated and saturated soils monitoring the elastic properties, surface deflection and stress concentrations. They also suggest a model for a one-dimensional situation that may be analogous to dynamic compaction within a constrained mould. Below is an extract from their paper as found on pg. 23-26 of *GROUND TREATMENT BY DEEP COMPACTION*.

> "Loose unsaturated soils subject to steady localised surface loading deform typically as shown by the curve A of Fig. 2. The deformation is of a generally elastic nature at low stress levels and at these stresses the soils can propagate seismic waves. With increasing stress the slope of the deformation curve falls more or less sharply due to the relative ease with which voids can be collapsed at the higher stress levels.
> If such a soil is subjected to impact by a fast falling weight, the soil rigidity may play a much less important role than the soil inertia in controlling the deceleration of the weight and in absorbing the energy of the impact. An idealised representation of a compactable soil in respect of these inertial and energy consuming effects in the elasto-plastic soil is represented by the curve B of Fig. 2. The stress level of the plateau has been chosen to lie in the region of the reduced slope.
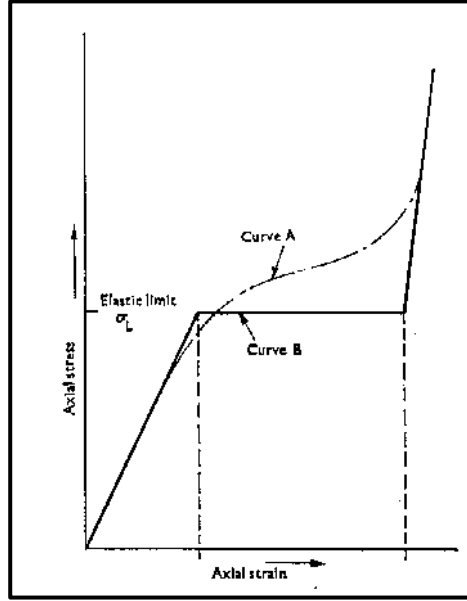
Fig. 2. Axial deformation of confined compactable soil

A three-dimensional treatment of the reaction of the soil underlying the contact is impracticable as the strains are generally so large that the shear restraints due to flanking regions of soil are not easy to quantify.

However, when the impact momentum is high the weight will punch through the upper soil layers and carry down a growing zone of compacted material of a generally cylindrical shape. For present purposes of illustration we shall discount the inevitable lateral spread of the compacted zone and use a one-dimensional description based on the approach mapped out for example by Salvadori (1960).

Immediately upon impact the stress level rises because of stress wave reaction due to the elastic nature of the first small movements of the soil at the contact surface. When the stress level has reached the level $\sigma_L$ of the plateau, the soil particles at the surface have acquired a velocity $v$ associated with a radiating stress wave which travels downwards into the medium with the seismic dilation velocity $c$ appropriate to initial elasticity. The wave is accompanied by a pressure front in which the axial stress is given by a form of equation (1) that is,

$$\boldsymbol{S}_L = \boldsymbol{r}cv$$

The radiation of the stress wave is followed almost immediately by a further acceleration of the surface particles such as to bring the surface to the same instantaneous velocity $V$ as the weight.

If $z$ is the instantaneous position of the front of the steadily lengthening compacted material (Fig. 3) the retarding stress applied at the bottom surface of the weight is

$$-m\frac{d}{dt}(\dot{u}-v) = \boldsymbol{r}_c\frac{d}{dt}\left[(z-u)\frac{d}{dt}(u-vt)\right]+\boldsymbol{s}_L \qquad (8)$$

where $m$ is written for the ratio $M/\boldsymbol{p}a^2$ and $\rho_c$ is the compacted density. The distances $z$ and $u$ can be shown to be related by the expression $z=k(u-vt)+vt$ where $k=\boldsymbol{r}c/(\boldsymbol{r}c-\boldsymbol{r})$. This relation can be used to eliminate $z$ in equation (8), with the result that

$$-m\frac{d}{dt}(\dot{u}-v) + k_r\frac{d}{dt}\left[(u-vt)\frac{d}{dt}(u-vt)\right]+\boldsymbol{s}_L = 0 \qquad (9)$$
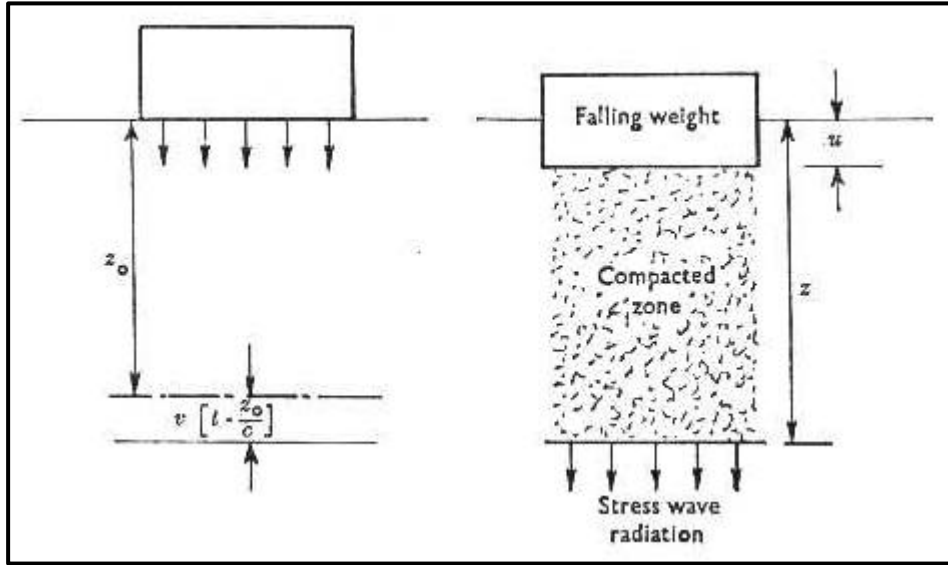
Fig. 3. One-dimensional compaction

The displacement $u$ of the surface is obtained by solving equation (9) hence

$$u = vt + m(F-1)/k_r \qquad (10)$$

where

$$F = \left(1 + \frac{2k_r}{m}t - \frac{s_L}{m^2}t^2\right)^{1/2}$$

The surface stress in the soil is then given by

$$s = \frac{s_L + k_r(V-v)^2}{F^3} \qquad (11)$$

Surface motion ceases after a time given by $t = m(V-v)/s_L$ and at this time the final depth $h$ of the compacted zone is given by evaluating $(z-u)$ and therefore by

$$h = \frac{m}{r_c}\left\{\left[1 + \frac{k_r(V-v)^2}{s_L}\right]^{1/2} - 1\right\} \qquad (12)$$

It should be observed that while the stress just ahead of the compaction zone is at the elastic limit stress $\sigma_L$ the stress at the surface may be considerably higher, especially at the early stages of compaction."

The author does not confess to understand all of the above nor what approximations have been made to develop such a model. Further reference to other source texts will be attempted to try and establish an appropriate model for a fully constrained soil. This model would then need to be checked with actual readings taken from the dynamic compaction process to verify its consistency. Both of these have yet to be done, but they are included in the scope of this project.

Another theoretical analysis of the impact method was found in Parsons pg 199 as follows:

*"Theoretical analysis of the factors influencing the performance of dropping-weight compactors*
12.27 To give an indication of the important factors to be considered in the design of impact compactors in general, and dropping-weight compactors in particular, Lewis (1957) produced a simplified theoretical analysis of the impact pressures produced on the surface of soil by a rammer. The experimental dropping-weight compactor shown in Plates 12.3 and 12.4 was used to verify the theoretical analysis.

12.28 From the well known equations of motion:-

$$V^2 = 2fx \qquad (1)$$
$$\text{And } pA = Mf \qquad (2)$$

where    V = velocity of rammer on impact
f = deceleration of rammer on striking soil
x = deformation of soil during impact
p = pressure generated on surface of soil by the impact
A = area of rammer base
M = mass of rammer

Hence:-  $$p = \left( \frac{Mk_s V^2}{2A} \right) \qquad (3)$$

where $k_s = \dfrac{p}{x}$

=dynamic modulus of deformation of the soil

In the case of a rammer falling freely from a height h:-

$$p = \sqrt{\frac{Mhgk_s}{A}} \qquad (4)$$

If the acceleration of the falling weight is less than g as a result of frictional losses:-

$$p = \sqrt{\frac{Mhg'k_s}{A}} \qquad (5)$$

where g' = actual acceleration of the falling rammer.
$$p = \sqrt{E_s k_s} \qquad (6)$$

where $E_s$ = specific energy

12.29        These relations indicate that the impact pressure is a function of the energy per unit area of the rammer base (specific energy) and the deformation properties of the soil under dynamic conditions of loading. The latter factor is also likely to be a function to some extent of the area and shape of the rammer base, but

little information was available on that aspect at the time that the analysis was made. If it is assumed that the dynamic modulus of deformation behaves similarly to the static modulus of deformation in that the modulus is often found to be inversely proportional to the square root of the loaded area, then:-

$$k_s = \frac{C}{\sqrt{A}} \qquad\qquad (7)$$

where C is a constant

The expression for the impact pressure developed can then be written:-

$$p = \sqrt{\frac{MV^2C}{A2\sqrt{A}}} \qquad\qquad (8)$$

where C = constant for the particular soil conditions.

Thus, if the rammer area is changed, the compaction energy provided by each blow per unit area of rammer base (specific energy) $\left(\frac{1}{2}M\frac{V^2}{A}\right)$ would have to be kept proportional to the square root of the area of the rammer base $\left(\sqrt{A}\right)$ for a constant pressure to be developed."

The author can apply these formulae to his results from the dynamic compaction of full-sized blocks that was done in 1997. The table below shows the increase in energy that was delivered by the impactor as the soil block was compacted. It also indicates the total transfer of energy into the block after a certain number of blows.

| Impactor stroke (m) | 0.1364 | 0.1571 | 0.1661 | 0.1748 | 0.1814 | 0.1866 | 0.1913 |
|---|---|---|---|---|---|---|---|
| Energy(J) / blow | | 55.5 | 58.7 | 61.7 | 64.0 | 65.9 | 67.5 |
| Energy increase | | 7.3 | 3.2 | 3.1 | 2.3 | 1.9 | 1.6 |
| Energy transferred after blows (J) | 0 blows | 1 blows | 2 blows | 4 blows | 8 blows | 16 blows | 32 blows |
| | 0 | 55.5 | 104 | 221 | 468 | 980 | 2035 |

Between the initial resting place of the impactor and the resting place after one blow there is a distance of (0.1571 − 0.1364) = 0.0207m. This is the deformation of the soil during impact (x). The velocity of the impactor prior to impact can be assumed to be

$$V = \sqrt{2gh} = \sqrt{2\times9.81\times0.1364} = 1.64 \text{ m/s ...etc.}$$

Below is a calculation table with the rest of the calculations for multiple blows during a compaction cycle using the above formulae.

|  | 1 blow | 2 blows | (3 blows) | (4 blows) | (8 blows) | (16 blows) | (32 blows) |
|---|---|---|---|---|---|---|---|
| Velocity prior to final impact (m/s) | 1.64 | 1.76 | 1.81 | 1.83 | 1.88 | 1.91 | 1.94 |
| Stopping distance (m) | 0.0207 | 0.0090 | 0.0043 | 0.0044 | 0.0016 | 0.0006 | 0.0003 |
| Mean deceleration (m/s²) | 64.6 | 171 | 375 | 384 | 1070 | 2800 | 6380 |
| Calculated stopping time (s) | 0.025 | 0.010 | 0.005 | 0.005 | 0.0018 | 0.0007 | 0.0003 |
| Pressure generated (MPa) | 0.057 | 0.152 | 0.332 | 0.341 | 0.948 | 2.488 | 5.656 |
| Dynamic mod of deformation | 2.768E+6 | 1.687E+7 | 7.635E+7 | 7.835E+7 | 5.743E+8 | 3.828E+09 | 1.925E+10 |
| Mean force in tonnes (final impact) | 0.233 | 0.616 | 1.35 | 1.38 | 3.85 | 10.1 | 23.0 |

N.B. The velocities and stopping distances for the blow numbers in brackets have been linearly estimated from compaction data for multiple blows. These figures are probably accurate to ±10% and despite not being spot on experimentally they do show the continued trend.

Two things are immediately obvious from the table of results above. Firstly, the dramatic increase in force that is applied during impact between the first blow and much later ones. Secondly, the dynamic modulus of deformation for a soil compacted in a confined manner will increase as it becomes compacted. Therefore the characteristics and behaviour of the soil will change during the compaction process. This will make accurate modelling the compaction significantly more difficult than an unconfined soil with a constant dynamic modulus of deformation.

Another thing to consider from these results is the magnitude of the force that can be delivered using a bigger dynamic compaction machine. For example: a 50kg impactor with a maximum velocity of 2m/s stopping in 0.0001m will deliver an instantaneous force of 100 metric tonnes! Delivering forces of this magnitude will necessitate a secure foundation for the machine, perhaps even larger than originally anticipated.

### 3.2 Dynamic compacting equipment as used in civil engineering

Within the field of civil engineering there are many different types of equipment that have the capacity of compacting a mass of soil. Many of these will not be of interest as they possess

very little dynamic properties that help to compact the soil. Even smooth vibrating rollers and vibrating sheep's foot rollers are outside of the field of interest as compaction via vibration is quite different to dynamic compaction.

Of the remaining equipment that is regularly used in civil engineering there are no devices that compact soil in a confined fashion. At a stretch of the imagination, one could say that some pneumatic and power rammers could be classed as being semi-confined if they were compacting soil in a trench. The dynamic compaction equipment almost always compacts the soil in an unconfined state, and there are several examples of these that can be looked at.

(a)      (b)      (c)
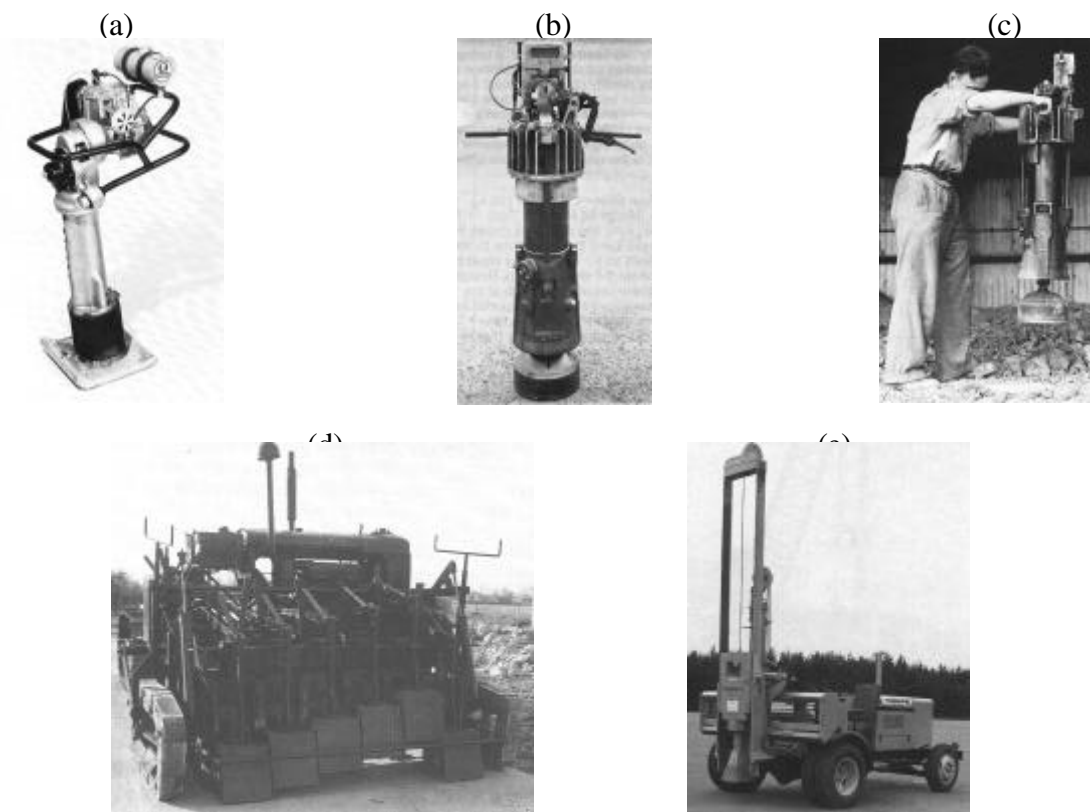


Vibro-tampers

These devices are essentially an engine driven reciprocating rammer that bounces up and down on the surface of the soil with its location controlled by an operator. They range from 50 – 150 kg in weight and vibrate at a frequency of around 10 Hz. The amplitude of vibration can vary depending on the machine anywhere between 10 – 80 mm. A picture of a Vibro-tamper can be seen in part (a) of the above diagram.

Power rammers

A controlled explosion of a petrol/air mixture is used to force a piston ground-wards. This causes the power rammer to jump up into the air compressing the soil beneath it and compacting the soil on its descent. A photo of a power rammer can be seen in part (b) of the above diagram, and a power rammer in use can be seen in part (c). Power rammers typically have a mass of about 100 kg with a circular base of about 250 mm in diameter. These rammers are manually controlled and guided around the ground surface. They jump between 300 – 360 mm into the air and deliver a blow of between 315 – 370 J/blow. This equates to an energy transfer per unit area of compacting base of between 6.3 – 8.1 kJ/m².

A much larger variety of power rammer is the frog rammer, typically around 600 kg with a 750 mm compacting base. This machine 'hops' along the surface of the soil compacting it with each 'hop'. It also moves forward with each 'hop' in order to reduce the directive force required by the operator. The operator turns the rammer into the direction that (s)he wants it to travel and the rammer hops along in that direction. Must be a fascinating machine to watch! Although this machine delivers 1835 J/blow  it delivers a smaller 4.3 kJ/m² than the other type of rammers.

Multi-dropping weight compactor

A picture of this machine is included in part (d) of the diagram above. The unit is towed behind a suitable traction unit and is designed to provide adequate compaction in a single pass over the surface. It uses an arrangement of six 200 kg cast iron weights that are lifted and dropped onto the surface of the soil by rotating cams driven by an on board diesel engine. Each weight is lifted through 330 mm and delivers around 515 J/blow. The base of the rammers are 330 ×305 mm and therefore have a specific energy of about 5.1 kJ/m².

Mobile dropping-weight compactor

This machine is called the Arrow D500 dropping-weight compactor and is self propelled with a hydraulically lifted impactor at the front of the machine. A picture of the machine can be seen in part (e) of the above diagram. This device can lift the impactor through a variable height up to a maximum of 2.2 m. A 36 kW diesel engine drives a pump for the hydraulic

system to lift the 588 kg mass to the desired height. This can then deliver a maximum of 11167 J/blow, and with a 305 × 305 mm base this equates to a considerable specific energy of 120 kJ/m².

All of the above information is taken from research carried out at the Transport Research Laboratory as reported by A. W. Parsons 1992. At TRL tests were carried out using the above machines on different types of soil and their different compaction abilities were noted. Some of the different types of soil that were used were; heavy clay, sandy clay, well-graded sand, gravel-sand-clay and silty clay. Different machines within the same class of compactors were assessed relative to each other in the different soil types. TRL also developed an experimental falling weight compactor that was used to help determine the efficiency of the other falling weight compactors that were available.

## 3.3  Research done by Gooding for his PhD

This source of information has proved to be highly valuable in the planning of future research in this field. Gooding has been the sole available reference for dynamically compacted soil samples that are compacted in a confined manner. Although Gooding thoroughly investigated the dynamic compacting process, he didn't actually stabilise any of the dynamically compacted samples with cement. The characteristics and effectiveness of the combined processes was not looked into. Other samples were stabilised using both compaction and cement but in these circumstances quasi-static compaction was always used.

### 3.3.1  Quasi-static compaction

Before Gooding began to investigate dynamic compaction, he looked into the process of quasi-static compaction (i.e. pressing). His research included varying the cement content, the applied pressure, mould taper, double and single sided compaction, pressure cycling and mould wall roughness. Throughout his tests he used a fabricated soil called *soil A* with a constant moisture content of 8%.

Gooding looked at the relationship between pressure verses wet compressive strength, cement content verses wet compressive strength and developed a model to estimate the wet compressive strength of a sample with known cement content and applied pressure. This model was based on actual experimental results taken from tests carried out using a range of pressures and cement contents. A small cylindrical mould specified in BS1924 was used for all of these tests. All the cylinders had their wet compressive strength tested after seven-day curing and subsequent soaking for 16 hours.

The model that Gooding developed suggests that a sample of *soil-A* with 5% cement and a compaction pressure of 10 MPa should have a wet compressive strength of around 1.6 MPa. Initial tests by the author using the Bre-pack machine have yielded blocks with compressive strengths of slightly less than this value, (1.5 MPa for a block with 4.9% moisture content). This apparent similarity has to be discounted for two reasons. Firstly, the test specimen the author used was a 100 mm cube instead of a 50 mm cylinder. And secondly, the difference in moisture contents would lead to considerably different results. Whereas Gooding was able to test the compressive strengths of the finished cylinders, the author found it more advantageous to cut the full size blocks into two 100 mm cubes. This resulted in generating two tests for the same block and it also uses a standard sample size, as used in the concrete testing procedures.

### 3.3.2 Dynamic compaction

Gooding investigated the efficiency of impact compaction using <u>un</u>stabilised *soil – A*. Consequently the wet compressive strength of compacted stabilised soil samples could not be measured as unstabilised soil breaks down when immersed in water. Instead each sample received the same energy but by different impact arrangements and the achieved density was measured. Density was calculated by measuring the final cylinder height ($\pm$0.05mm) and mass ($\pm$0.1g) on ejection from the mould. Each cylinder received a constant 279 J/kg and the mass of each cylinder was kept at around 1.66 kg. Other factors such as the number of

blows and momentum of impactor were varied to find any optimum parameters for this technique.

Each sample received one of 1, 2, 4, 8, 16, 32 or 64 blows. The optimum number of blows (number that yielded the greatest density) was found to be at 16 blows, but it was also noted that only a 3-4% reduction in compaction efficiency occurred when this was varied from 8 to 32 blows for each of the different masses.

If different number of blows and different masses were used to compact the samples then the height through which each mass was lifted had to be varied. A lighter mass had to be raised higher to transfer the same energy per blow as a heavier mass dropped from a lower height. Similarly, if less blows were being applied then the mass had to be raised higher to transfer the same total energy. This has the effect of changing the momentum of each blow applied as momentum depends on the mass and the velocity of the mass prior to impact and velocity depends on the distance through which the mass falls. Three different masses were used in the experiments on the samples (23.35, 35.00, 46.80 kg) and it was noted that the bigger masses dropping at slower speeds were more effective. Yet, the 23.35 kg mass and the 35.00 kg mass were only 0.4% and 0.2% less efficient respectively at the 16 blow configuration than the 46.80 kg mass.

This area needs to be further investigated using cement and doing proper compressive tests to suggest better accuracy for the environment in which the samples will finally be placed.

### 3.3.3  Other research that was done

Gooding 1995 was involved in producing "Survey of the potential for cement-stabilised building blocks as a building material in developing countries". During this field survey of many countries he encountered a couple of structures that were made out of cement stabilised dynamically compacted material. He compares them with other structures in the area, constructed using similar appropriate techniques, with some interesting observations. Below is an extract from that survey, pg 58 covering Botswana.

One soil-cement house is of particular interest. In 1985 a soil-cement house was constructed at the Camphill Community Centre in Otse using the Ranko Block Maker. This is a manual machine which uses impact to compact the soil-cement to high pressure. It was designed by Agas Groth, a Botswanan national. The house has now been standing for ten years without any maintenance work having been carried out and is in excellent condition. The blocks were produced with a cement ratio of 1:16 and having been well cured and laid in the wall were rendered with a low-cement bagwash. This should be compared with houses constructed by BTC for their experimental staff housing project using imported quasi-static machinery; the Hydraform and Ceratec machines which cost 60,000 P (£14,000) and 100,000 P (£24,000) respectively. The blocks were produced with a cement ratio of 1:10 and powered mechanical soil sieving and mixing were used. These houses have now been standing for only two years but are already deteriorating.  In the case of the Ranko block walling production was estimated to cost  between 20 and 30 % less than the prevailing price for sandcrete blocks (Enyatseng 1987). In comparison the blocks produced using the Ceratec machine were found to be 18% more expensive than stock cement bricks and 46% more than sandcrete blocks (BTC 1995). The high cost of the Ceratec blocks was attributed to the low productivity of the machine.  Although this  machine was capable of producing 1200 blocks/hour this figure was never achieved as two motorized mixers would have been required to continuously supply the machine with soil. If a lower cost machine were available, capable of high pressure compaction but with a useable maximum output then the economics of production would be significantly improved.

The author is currently trying to get a copy of the research work done by Agas Groth to compare it with Gooding's investigations.

### 3.4  The author's previous research

As part of an undergraduate degree programme the author had to do some research on a subject that was suggested by one of the resident lecturers. The author discovered that Gooding had a small project that would be suitable both for the project requirements and for the author's abilities. This project was subsequently undertaken and labelled "Design and realisation of a test rig to research the production of full size dynamically compacted soil-cement blocks". This project was completed in 1997 and achieved the following results. A full size dynamic compaction test rig was designed and manufactured. The design chosen was suited to the level of appropriate technology available in developing countries. Several blocks were produced and their densities and surface resistance was measured. Two blocks were stabilised using cement, but these were not used in the experimentation as they were only intended to be demonstrator blocks. This means that up to date there has not been any research done on dynamically compacted cement stabilised soil blocks.

Gooding quasi-statically compressed a block to 9.7 MPa and noted that it achieved a density of 2038 kg/m³. This compaction pressure equated to a transfer of 279 J/kg. By comparison, the author dynamically compacted a full size block to a density of 2040 kg/m³ by applying 32 blows to it from a 36 kg impactor. This block received a total of 2035 J from the falling impactor. For a 10-kg block this equates to approximately 204 J/kg, some 26% less energy required than the quasi-statically compressed block, which is still a significant saving. This research indicated that the savings in energy that Gooding had found could be extrapolated onto full size blocks and warranted further research.

The author also did not stabilise any of the full size dynamically compacted blocks as these were trials to test the feasibility of full size compaction. Consequently there are not any known characteristics of the produced blocks apart from a handful of penetrometer tests done on the freshly demoulded block. These give little indication of the core strength and only sought to establish the level of uniformity of density throughout the block.

## 4. Discussion of research

The experiments done by the Research Transport Laboratory, Gooding and the author can in some way be compared with each other. The experiments described in section 3.2 can be compared to the tests carried out by Gooding, but only with the soil that is closest to the soil used by Gooding during his research, which are the sandy clays. Even this soil has a much higher percentage of clay than the soil used by Gooding, but the other soils are vastly different. It can be noted from these compaction results that greatest compaction was achieved with the experimental rig when it delivered 4, 5 or 7 blows with the same total energy transfer at the optimum moisture content as discovered by the 2.5 kg rammer test (described in section 2.2.1). The compaction was about 4% better in this configuration than the big multi-weight machine (described earlier), and about 8% better than the experimental rig delivering 2 blows, (40% of the energy as transferred compared to the 4,5 or 7 blow arrangement).

The author during his previous research also noted the slight reduction in compaction from a massive reduction in energy transfer. The graph below shows several blocks that were made by dynamic impact. Each blow had approximately equal energy after the first few blows so 40% energy of a block that received 32 blows should equate to about 12 blows. Block C2 achieved a density of around 1975 kg/m³ after 12 blows, but its density only increased to 2070 kg/m³ after a further 20 blows. Thus a decrease of 60% in energy transfer only led to a decrease in density of less than 5%.

However a small drop in density can have a significant effect on the final compressive strength of a compacted block. From Gooding's research it can be noted that a cylinder stabilised with 5% cement that was compacted to a density of 2124 kg/m³ achieved a cured wet compressive strength of 1.63MPa. Another cylinder compacted to 2032 kg/m³ (a drop of less than 5% in density) only yielded a cured wet compressive strength of 1.20MPa, (a drop of over 25% in strength). This trend of high gains/losses of strength for small increases/decreases in density fits throughout the results that Gooding received from his experiments.
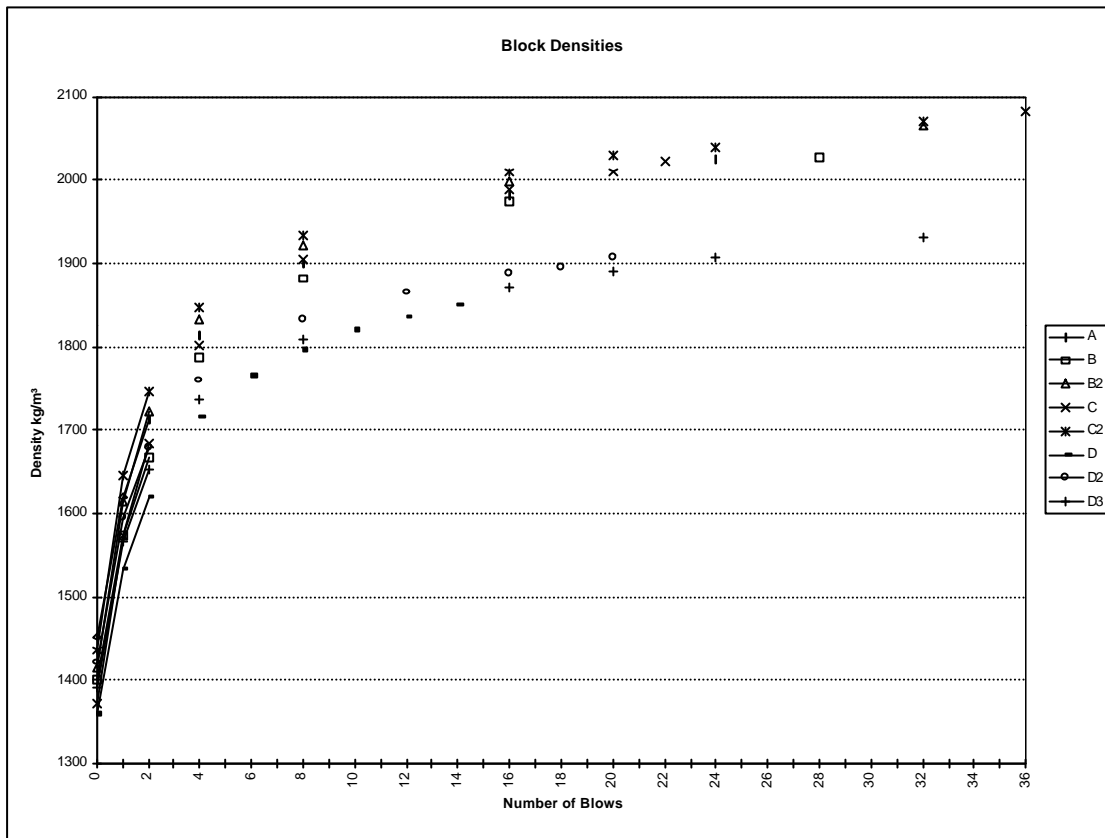
*Graph showing block density against number of blows received*

From the above results that have been highlighted for comparison, there are a few trends that can be noted and will help in further research. Final cured strength of cement stabilised blocks is highly dependent on the final compacted density. It is also true that small changes in density can only be achieved by much greater changes in energy transferred into the block. Dynamic compaction has proved to be a more efficient compaction process than quasi-static and it also has the added advantage that it is relatively easy to increase the energy transfer by simply applying more blows.

Any quasi-static compaction machine will have a working limit and will be unable to compress to a higher compaction pressure than that. Gooding suggested that pressure cycling would yield a small increase in final density and subsequently a higher strength, pg. 137, but this is time consuming and is still highly limited. Dynamic compaction would only be limited by the time required to produce each block, and even then the impact time could be reduced by modifying the machine design. Dynamic compaction, therefore, has a much

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greater potential for increasing the energy transfer and consequently increasing density and final cured strength.

Furthermore there is agreement among all the sources that compaction via multiple blows is more effective than with a single or a few larger blows. This characteristic is highly advantageous with dynamic compaction as larger numbers of blows can deliver the same energy into a block as a much larger impactor falling from a greater height. This method of energy transfer is much easier to design into a machine than a very large compactor falling through a great height.

# 5. Conclusions and recommendations

There is still more information that needs to be found and investigated. This will continue throughout the project and will be written up in due course. Several other sources are already being sought and they will help to shed new light on this relatively undocumented field of research.

The limitations of the existing information are significant and these need to be tackled during the project if a better understanding of the dynamic process is to be achieved. Dynamic compaction of cement stabilised samples needs to be undertaken, both for cylinders and for full size blocks. These will need to be tested according to the seven day wet compressive strength test and their performance noted. It is known that dynamic compaction provides better and more efficient compaction, but it is not clear if these will in turn reap significant benefits when the addition of a cement stabiliser is included in the stabilisation process. Will a dynamically compacted and quasi-statically formed block perform similarly if they both achieve the same density and contain the same amount of stabiliser?

In order to achieve a higher density a significant amount of extra energy has to be transferred into the block. Reducing this energy transfer, or changing the way it is transferred has a marked effect on the final density that can be achieved. Small changes in density have large repercussions with other important characteristics of the finished block, such as the compressive strength and porosity. Consequently the greatest factor in the production of a cement-stabilised block is the final density and maximising this characteristic should be done in wherever possible. If cement is the expensive commodity and this has been reduced to an absolute minimum, then the application of extra energy in the most efficient manner is surely justifiable.

Optimisation of the number of blows for small cylindrical samples was done by Gooding for a constant moisture content. This optimisation needs to be extrapolated onto full size blocks to determine if there are any better arrangements for delivering a fixed amount of energy into

a sample of stabilised soil. The moisture content has not been altered with respect to the cement content and this may be of significance. A lower moisture content may not yield the block with the greatest density, but it may yield a block with a higher wet compressive strength and durability. Parsons reported small changes in moisture content around the optimum to try and discover if the different compacting method yielded a different optimum moisture content. A similar exercise needs to be done with confined stabilised soil samples.

Gooding never used cement to stabilise his dynamically compacted cylinders and consequently nothing is known of the effect that the presence of cement has on the compacting process. It has been suggested in that cement will hinder the compacting process when the cement crystals are forming. Furthermore, compaction of the soil during crystal growth will be detrimental to final strength as bonds that have already formed will be broken and will need to be reformed again. It is the author's experience with the two dynamically compacted blocks that were stabilised with cement that slightly lower densities were achieved using similar compaction regimes. It was also noted that the ejection of the block from the mould was considerably more difficult than with the blocks formed without the use of cement.

# 6. Summary

The dearth of information on dynamically compacted soil blocks has only been a preliminary setback for the purposes of this research project. In one sense it gives complete freedom to explore any other area of the field that may be of interest as very little has been done before. The specific areas that have been covered provide adequate information and analysis and leave the author in no doubt of their accuracy. These areas do not need to be covered again, but they need extending to include other areas within the research field.

Dynamic compaction has been studied mainly for use within the civil engineering industry for ground compaction. This research gives helpful pointers to the behaviour of soil when it is compacted by an impact blow and also provides examples of equipment that are used within the industry. This research does not fit the same model as the fully constrained soil that would be used for dynamic compaction of soil blocks, but much of the data for impact delivery, energy transfer and soil deformation can be applied to this situation.

The understanding of what happens to the soil during an impact blow is still in infancy. It is dangerous to assume linear deceleration during the impact as the calculations in the latter part of section 3.1. This is probably not the case as the soil will act as a highly damped spring with variable damping and spring constants. A thorough investigation of the actual energy dissipation and resistive forces applied by the soil on impact may not be possible within the scope of this project. It would be good to know a bit more about this mechanism and the author intends to try and work this out, but he feels that the substance contained with such a study may warrant the commitment of a whole project on its own.

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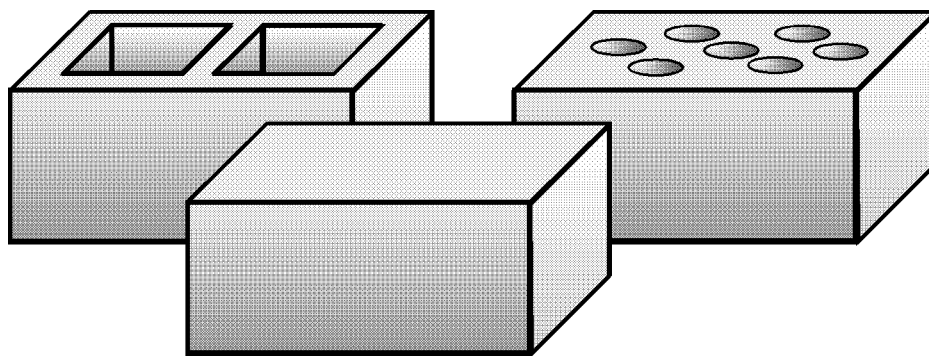{Loc: Author's personal copy}

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## Stabilised Soil Research Progress Report
## SSRPR03



# Physical characteristics of soils that encourage SSB breakdown during moisture attack

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## November 1998

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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.

"*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

Soil is the major component of a stabilised soil block and consequently its properties are of great interest to the Stabilised Soil Block (SSB) manufacturer. Some soils are considered to be unsuitable for manufacturing SSB's and need to be modified or discarded, whilst satisfactory soils have certain physical characteristics that can be generally suggested. The soil properties that have been found to yield satisfactory SSB's are only a small selection of the wide range of different soil characteristics. The properties of the soil used will partly determine the way it performs under moisture attack. Other factors such as the forming technique and any stabilisation process applied will also affect the performance of the SSB during moisture attack.

The general characteristics of soil are listed in this report and special emphasis is placed on those that are known to cause detrimental effects to the SSB's during moisture attack. If the poorer characteristics of the soil can be isolated and rectified by some means, then the result will be an enhanced product with better qualities. Those factors that cause expansion on wetting are the ones that prove to be the most negative of the characteristics. Those can be isolated into three parts, the presence of a clay fraction, the presence of porosity and the presence of moisture movement. Only with all three parts present will expansion occur and the removal or minimising of any of them will result in the removal or minimising of potential expansion of the SSB. How this can be done is the matter for another study.

## Nomenclature

**Aggregate:** Pieces of crushed stone, gravel, etc. used in making concrete.

**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.

**Gravel:** A mixture of rock particles ranging from 2mm to 60 mm in diameter.

**Green:** Describing the state of material containing cement and water before it reaches the critical time, after which further plastic deformation hinders the final set strength.

**Permeability:** Describing a material that permits a liquid or gaseous substance to travel through the material.

**Porosity:** A measure of the void volume as a percentage of the total material volume.

**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

Of the 29% of the earth's surface that is not covered with water, the vast majority has a soil layer on top of the underlying rock. It is this soil that supports life, man and his structures and will be the main focus of this report. Soil is a general term for particles formed by the gradual wearing away of parent rock material that is then deposited into layers onto the surface of the earth. The parent material of the rock from which the soil has been formed will largely define the composition of the soil present.

Between the top layer of soil and the rock structure there is usually a series of bands that each contain a soil with slightly different characteristics. The very top layer of soil usually contains organic material from the vegetation that has fallen to the ground and is slowly breaking down. Under this layer, one can find a mixture of organic material and small soil particles or "fines". The particle size grows as one digs deeper until the rock structure is reached. Size distribution in the soil is approximately dependent on depth. Larger particles dominate lower levels whilst finer particles the upper levels.

The basic composition of all of these layers may be the same as the underlying rock. Alternatively, material from elsewhere could have been deposited there by natural means, causing a different composition of the top layers to the bottom ones. Glaciation, floods and volcanic activity are some mechanisms through which soil from another area may be deposited locally. The composition of the small particles (sands) found in soil can generally be assessed as minerals that are silicas, silicates or limestones. As well as the solid rock particles and fragments, soil will have a proportion of water and air that fill the gaps between adjoining particles in the soil. This gives natural soil a non-homogenous and porous characteristic.

Soil that is used for building can undergo detrimental physical changes when it becomes wet. Soil will swell and contract when the water content changes and this usually leads to cracks forming in the structure. These physical changes are dependent on the characteristics of the soil both before and after processing to make the building material. The characteristics of the soil that cause these physical changes are the ones

that are going to be investigated in this report. The majority of these physical changes are due to the presence off very small particles called clays. Clays perform a valuable function in the production of building blocks, but they can have a detrimental effect on the stability of the material if they get wet.

Clay is necessary to achieve sufficient green strength in a freshly formed block to enable de-moulding and handling without excessive breakage. The low moisture content and the clay particles act as a bonding agent throughout the mixture of other particles before any chemical stabilisation process has had a chance to occur. In the example of using cement as a stabiliser, a considerable period of time must pass before there is any significant gain in strength offered by the cement. A partnership of the clay and cement must be entertained, but their proportions need to be carefully monitored so that the clay gives sufficient initial strength and yet does not blind the cement particles or provoke excessive material expansion upon wetting.

## 2. Characteristics of soils

During this chapter the author will outline some properties of soil. These properties will include particle composition, shape, size and surface texture, some of which have standards for defining them. Ranges of values for these properties will be suggested but the basic techniques for discovering the properties of a soil sample will be described in a later chapter. This chapter will provide a summary of the characteristics that are possible to determine from a sample of soil.

### *2.1 Physical*

Some of the physical characteristics that could be used to define soil particles are: colour, size, shape, surface texture, density and specific surface area. The variety of physical characteristics of soil particles that can be found is considered to be virtually infinite. The analysis of some of these characteristics can been done using a simple set of field tests and personal interpretation, or, more complex and accurate tests can be carried out in the laboratory. Systems for identifying some major characteristics have been developed to define different ranges of soil characteristics. The most common of these is the size distribution of the soil particles. Below is a list of physical characteristics than can define a sample of soil. See (Houben & Guillaud, 1989), (p. 30,31) for more details.

*Colour:* Can range from white through to black with shades of tan, brown, red, grey and even blue and green. This is however an arbitrary and trivial description that is not standardised and based entirely on personal interpretation. Good for quick visual identification and can even suggest chemical composition of the soil, but accurate measurement is not defined.

*Shape:* Broadly defined as three different categories; angular, sub-angular or rounded. This can be assessed using visual interpretation and/or the feel of the soil. Only used as a general descriptive term, as accurate measurement is not a viable option. The ratio of particle surface area to the surface area of a sphere of the same mass can be an indication of shape and is defined as:

$$\lambda = \frac{Surface\_area\_of\_particle}{Surface\_area\_of\_sphere}$$

Where:        Rounded – $1 < \lambda < 1.2$

                    Semi-Angular – $1.2 < \lambda < 1.5$

                    Angular – $1.5 < \lambda$

Note: a four faced pyramid has $\lambda$ value of 1.49.

*Apparent bulk density:* This is a measurement of the overall density of the soil sample including air and/or moisture present within the sample. The measurement of apparent bulk density is a trivial exercise, as one only needs the volume of a sample and its mass. Apparent density of a block is simply

$$\rho_{apparent} = \frac{M_{sample}}{V_{sample}}$$ (measured in kg/m³).

*Specific bulk density:* Can be accurately measured following British Standard BS7755: 1998. This method splits up the soil into two sections and measures the density of the two sections in different ways. For particles smaller than 2 mm in size a small sample is placed in a pyknometer and the displaced water at a known temperature will give the volume occupied by the soil. The sample is also accurately weighed to give the mass of the sample. The specific bulk density is calculated from the mass of the sample and the displaced volume of water in like manner to the apparent bulk density. For particles over 2 mm in size the sample is weighed and is then suspended in water that is resting on a set of scales. The mass of the displaced water gives the volume for a known ambient temperature and the specific bulk density can be calculated from these two values, (also measured in kg/m³).

*Size or texture:* One of the most common methods of identifying the size of particles that can be found in a sample of soil is to use the British Standard BS7755: 1998 classification for particle sizes. This separates the soil into different fractions depending on physical dimensions by means of a number of different meshes and sieves. The sample of soil is passed through the largest mesh first and each subsequent mesh until all the soil has been separated off at a level

appropriate to its size. For laboratory testing the soil needs to be dry and any particles deflocculated to ensure accurate results. The size ranges as defined by the British Standard along with their common names are listed below.

| Trivial name | Size range in mm |
|---|---|
| **Boulders** | > 200 |
| **Cobbles** | 60 – 200 |
| **Gravel  (Coarse)** | 20 – 60 |
| **Gravel  (Medium)** | 6 – 20 |
| **Gravel  (Fine)** | 2 – 6 |
| **Sand     (Coarse)** | 0.6 – 2 |
| **Sand     (Medium)** | 0.2 – 0.6 |
| **Sand     (Fine)** | 0.06 – 0.2 |
| **Silt       (Coarse)** | 0.02 – 0.06 |
| **Silt       (Medium)** | 0.006 – 0.02 |
| **Silt       (Fine)** | 0.002 – 0.006 |
| **Clay** | < 0.002 |

*Moisture content:* Soil is very seldom totally dry, and how much moisture is present is important for determining the properties of the soil in general. Measuring this moisture content is done through a process of weighing and drying in an oven. Following British Standard BS1377: 1990 the sample must be weighed at regular intervals until the difference between consecutive weights are less than 0.1% of the whole sample mass. This usually means drying the sample for about 24 hours to ensure that it is virtually dry. The difference in mass from the initial weighing to the last weighing will be the mass of water. The moisture content is calculated as a percentage of the total mass of the sample before drying.

*Porosity or voids ratio:* A substance is considered porous if it has a matrix of voids throughout it. A very simple and common example of a porous object is a sponge. Soil is another such substance, but the porosity of soil can vary enormously depending on the particle size and distribution within the soil sample. To calculate the porosity of a sample of soil one needs to know both the apparent bulk density and the specific bulk density of the sample. The porosity or voids ratio is unity minus the ratio of the volume of soil alone to the volume of the sample, both of which will have been found when the apparent bulk density and the specific bulk density of the sample were measured. Porosity:

$P = 1 - \dfrac{V_{soil}}{V_{sample}}$  (generally expressed as a percentage).

***Permeability:*** A porous material becomes permeable when these air pockets are arranged in such a way so that a gas or fluid can pass through the substance. The permeability will largely depend on the porosity present in the sample. A sandy soil will be considered highly porous and will have a low resistance to the passage of water through it. A clayey soil is the opposite and will resist the penetration and passage of water. Permeability is a measure of how fast a fluid moves through a substance. The British Standard BS 8004:1986, (Craig, 1997), (p. 40) gives a list of coefficients of permeability and also tests for permeability that can be carried out in the laboratory. A falling head test and a constant head test are two ways that permeability can be measured. The flow of water through a sample is measured and described as a flow rate per unit of time. (Permeability of stabilised soil is too low to be measured by these means).

***Effective surface area:*** Particles that are so small that they will pass through even the finest sieve usually have a different means of identification. This is called the effective surface area of the particles in question and is usually measured in $m^2/g$ of material. This helps to distinguish between small and large clay particles for which any other classifications are useless. Three appropriate examples of this analysis are the three main types of clays Kaolinites, Illites and Montmorillonites that have approximate effective surface areas of $30m^2/g$, $80m^2/g$ and up to $800m^2/g$ respectively, (Houben & Guillaud, 1989), (p. 27).

***Adhesion:*** Described as the ability of soil to stick to other objects at a given humidity. It will increase as the humidity increases up to a point after which it will then decrease as the humidity continues to rise. Of interest usually with soil sticking to metallic tools.

***Specific heat capacity:*** Defined as the amount of energy required raising one kilogram of the soil by one degree Kelvin. Units are J/kgK, (joules/kilogram Kelvin).

***Dry strength:*** Highly dependent on the quantity and type of clays present in the soil sample. Measured in MPa to crush (effectively describing the shear strength of

the soil sample). The dry strength of clays varies from around 0.07 MPa to 7 MPa, (Craig, 1997), (p. 31).

*Linear contraction:* Sometimes described as the shrinkage of a particular sample. Linear contraction is highly dependent on the clay type and content and the water content. Standard shrinkage tests start with a soil at it's liquid limit. It is usually tested in a long narrow trough that is filled with moist soil and allowed to dry out. The contraction is limited to one direction and the linear quantity can be measured as either a percentage or as a ratio of overall length. The general rule is, the greater the shrinkage the greater the clay content.

## 2.2 Chemical

The chemical composition of the soil particles will be of interest when chemical stabilisation is taking place, or if the soil will be in an environment where the elements will be susceptible to chemical attack, (e.g. limestone is attacked by acid rain). Soil is generally a stable compound because it has been formed over a long period of time and any chemical changes will have already occurred to it in the environment. For the majority of cases the scientist can assume that soil will be chemically unaffected by the environment.

*Composition:* The soil particles will have roughly the same chemical composition as the parent rock from which the soil was formed. This chemical composition can range from salts or chalk composition through to iron and aluminium oxide composition. (Houben & Guillaud, 1989), (p. 36,37) gives more details on the many different types of soil that are present and their respective chemical composition.

*Mineral content:* Minerals present in the soil are unstable components that are being processed by the environment usually as a result of decaying organic matter. Any organic matter should be avoided and unstable components resulting from them should also be regarded as potentially detrimental to structure longevity.

*Metallic oxides:* Soil can contain a significant quantity of metallic oxides such that they are used to produce the metal through smelting the soil. Bauxite for aluminium and ferrous oxide for iron are two common oxides present in soils.

*pH levels:* Soils can be either acidic or basic in pH level, but they do not usually stray very far away from the neutral point. Their pH will depend on the $H^+$ and $OH^-$ ions that are present and these ions will depend on the chemical composition of the particles themselves and their interaction with one another.

*Sulphates:* These are soluble compounds of elements and will be affected by changes in moisture. Leeching of soil can occur if water passes through it removing any soluble salts or substances with it. Sulphates can cause problems with cement and soils with sulphates present should be avoided if cement is being used as a stabilising medium.

# 3. Measuring soil characteristics

In the previous chapter many different physical and chemical characteristics of soil were defined. However, most of the processes for measuring each of those different characteristics were omitted, that will be the focus of this chapter. It is not necessary for all of the above characteristics to be determined for every soil sample taken. The relevant ones will be discussed and listed. Following this some techniques for measuring these properties will be described. Some techniques are restricted to the laboratory, whilst other are considered to be sufficiently accurate for field tests using limited equipment.

## 3.1 Some relevant properties for making SSB's

With so many different characteristics that one could discover about a sample of soil, it would be foolhardy to try and discover them all in every situation that soil is to be used for making SSB's. Only a small number of different characteristics are of real relevance to the scientist testing the soil. The chemical composition of the soil is of little importance once the absence of unstable compounds and organic matter has been established. The physical properties are of greater interest for making SSB's as these will help to determine its ease of mixing, forming, de-moulding, porosity, permeability, shrinkage, dry strength and apparent bulk density.

The particle size distribution or texture of the soil is a necessary characteristic to determine, as it will help the scientist to measure the sand, fines and clay content. These are necessary to ensure that the material being used falls within the parameters suggested for making SSB's. The moisture content of the soil is another critical characteristic as it affects a number of factors in SSB production. What moisture content the soil has in relation to its optimum moisture content is of great interest to the SSB manufacturer as this will help determine potential shrinkage. For soil mechanics the Optimum Moisture Content (OMC) is defined as the maximum amount of water that can be added to the sample that completely fills all the air voids present throughout the material and no more. The moisture content also has a marked effect on material workability, cement curing, drying times, de-mould slump and porosity.

Consequently the OMC for a soil may not necessarily be the optimum moisture content for stabilised soil material.

### 3.2  Field tests

Field-testing methods are many and varied, and will depend vastly on the judgement and previous experience of the person carrying them out. There also seems to be conflicting information about what certain tests reveal about the characteristics of the soil. Gooding noted these differences in his thesis and the summary below is largely taken from his suggestions for interpreting the results received from each test. Assuming that the exact characteristics of the soil are not necessary, these field tests will give the user a reasonable idea of the type of soil that is present.

*Smell test:* Detects the presence of organic material if a musty odour is sensed. Soil with organic material is unsuitable for manufacturing SSB's and should be rejected. The organic layer usually exists on the top of the soil and can easily be removed to reveal more suitable soils underneath.

*Visual-touch test:* This test will determine the range of particle sizes present. A soil containing mostly large particles (over 2 mm in size) is a sandy and gravely soil, it will easily break up and run through the fingers. Such a soil has a low fines content and is unsuitable for making SSB's. Conversely a soil containing no sand particles and only smaller particles that is hard to the touch, difficult to break up and reveals a fine powder that is difficult to wash off is classified as a soil with an excess of fines and clays. This too is unsuitable for making good SSB's.

*Thread test:* If a mixture of sands and fines is present then the soil can be formed into a thread upon the addition of some water to increase its plasticity. If the thread can be rolled to a diameter of less than 3 mm then the fines content is too high and more sand will need to be added. If a thread of as little as 5 mm diameter cannot be formed then insufficient fines is present and more will need to be

added. A thread that breaks up at a diameter of around 4 mm has a sufficient fines content for making SSB's.

*Shine test:* After the above tests have been carried out the shine test indicates the level of fines present in the sample. A mixture with a high fines content will achieve a shiny surface if scratched with the fingernail. This shiny surface is caused by a moderately high presence of silt and clay and is be acceptable for making SSB's. A dull surface finish will indicate a sandy composition with a low fine content and this is also suitable for SSB production.

*Glass-jar test:* This test will give the investigator a rough idea of what percentage of each fraction is present in the soil sample. The test requires a glass straight-sided jar to be a quarter or a third filled with soil and the remainder filled with water. The jar is then sealed and rotated end over end for several minutes to ensure that all the particles have been broken up and held in suspension within the water. The jar is then placed on a flat surface and left undisturbed for some time. A cloudy mist of very fine particles may stay in the solution indefinitely, held there by Brownian motion, but these are only particles less than 0.0002 mm, (Craig, 1997, p. 7) and can be ignored. All the other fractions should have settled to the bottom within a few days and should be easily distinguishable from one another. A sandy layer should be present at the bottom with smaller particles at higher levels. The particles in suspension fall out of solution according to Stokes' law, which states the larger the particle size the faster the decent velocity and vice versa, (Craig, 1997, p. 6). The clay and silt fractions may not be distinguishable from one another and these can often be combined to yield a simple coarse to fines ratio for the soil sample. The quantity of the different fractions can be found by measuring the depth of particles within each fraction and calculating each fraction as a percentage of the whole settled depth.

A basic analysis of the results found from the glass-jar test can be summarised as follows:

- More than 80% sand and gravel (if present) indicates very low fines content and is considered unsuitable for making SSB's.
- Between 70 – 80% sand shows a low fines content and can be used for SSB's.

- Between 50 – 70% sand shows a high fines content and can also be used for SSB's.
- Less than 50% sand indicates very high fines content and should not be used for manufacturing SSB's.

*Shrinkage test:* A mould of dimensions $40 \times 40 \times 600$ mm is filled with soil near its liquid limit, (the point at which the soil passes from a solid state to a liquid state). This soil is then left to dry out slowly. The mould walls are treated with grease or a lubricant so that as the bar of soil shrinks in size it slides along the mould walls. The difference between the initial length and the final length is the linear shrinkage. This is usually represented as a percentage of the original length.

All the above field-tests it can be done on a relatively short period of time with simple equipment. The interpretation of the results is where the inconsistencies can arise, especially between different field scientists. Nevertheless these tests are sufficient as a preliminary check for initial analysis and use for even medium-sized projects. Small projects would be classified as the building of one or two dwellings undertaken by an individual or family. Larger projects would have significant funding and could justify further tests to establish soil characteristics more accurately.

## 3.3  Laboratory tests

The larger projects that require more careful analysis of the soil properties will find that field tests will be insufficient and laboratory testing will need to compliment these to ensure an accurate analysis of the soil present. Testing is usually only justified if a very large amount of soil will be used and an area of land is being surveyed for excavation. The survey will reveal the different properties of the soil in different locations and will help to direct the SSB manufacturer to the best source of soil for making the SSB's. Below is a list of characteristics and the methods for accurately measuring those properties.

*Particle distribution:* Accurate measurement of the particle distribution has already been hinted at in chapter two, where the particle size distribution or texture of the soil was defined as a physical characteristic of soil. British Standard BS7755: 1998 classification for particle sizes describes a process that separates the soil into different fractions depending on physical dimensions by means of a number of different meshes and sieves. The exact method of this should be referenced from the British Standard as such standards are updated regularly, or its local or national equivalent.

*Apparent and specific density:* If these two values for the soil are known then the porosity can be measured. Measuring the apparent density is straightforward as only the overall volume and dry mass is required of the soil sample. The water must be removed from the sample before weighing as it will add to the overall mass of the soil and give an inaccurate density of the soil and air mixture. Suggested measurements and calculations are as follows:

Volume of undisturbed soil sample (including air voids that may be partially filled with water) = V

Mass of dried soil sample = M

Apparent Density $\rho_{app} = \dfrac{M}{V}$

The specific density has to be measured in accordance with British Standard BS775:1998 and again this should be referenced to include current changes and modifications.

*Porosity/permeability:* In simple terms the volume of dispersed air voids within a sample is proportional to the porosity. Porosity can be easily calculated from the specific and apparent bulk densities of the soil sample if they are known. The porosity can be calculated both before and after processing of the soil.

Permeability can be measured as a function of the flow rate of a fluid through a porous substance. Darcy's empirical law defines the permeability of soil, but this is only limited to one dimensional flow of water through a fully saturated soil, (Craig, 1997), (p. 39).

Darcy's law states: q = Aki

where q = the volume of water flowing per unit of time, A = cross-sectional area of the soil corresponding to the flow q, k is the co-efficient of permeability and i is the hydraulic gradient.

Darcy's law can also be written as:

$$v = \frac{q}{A} = ki$$

where v is the discharge velocity of the water through the soil.

# 4. Effect of moisture on soils

The fundamental problem with building with soil is that it will lose compressive strength when it becomes wet. This is not a desirable characteristic for walls supporting a roof structure with inhabitants underneath it. Consequently it is the responsibility of the designer to ensure that either the weakening effect that moisture has on the soil is greatly reduced, or the possibility of the soil getting wet is removed. For building with soil where there is little or no rain, then the problem is negligible, but for wetter climates it is a serious concern. Techniques used in the past to overcome the problems of building with soil in wet climates have included mechanical and chemical soil stabilisation, wall painting or rendering and use of wide roof eaves.

## 4.1 Detrimental characteristics

It is important to isolate the characteristics that are most useful for the SSB manufacturer to know about the soil that is being worked with, so that they can be closely monitored. These are usually the characteristics that greatly affect the resistance of the soil to moisture attack. Below is a list of these poor characteristics and how they might be improved for general use.

*High porosity/permeability:* These are two characteristics of soil that can cause the potential swelling and cracking that is so detrimental to SSB's durability. No matter how much clay is present, if water cannot penetrate then the clay will not swell and integrity can be preserved. Render or paint will provide such protection, but only at significant cost and regular maintenance is always required. A high porosity will permit moisture to penetrate the surface of the block and then subsequently flow into the internal structure of the soil particles distributing moisture to other soil particles. This process causes water to coat the soil particles and by the process of surface tension drive neighbouring particles further apart. This mechanism is particularly severe with the clay fraction of the soil. Reducing the porosity can be achieved by compacting the

soil and therefore increasing its apparent bulk density. Porosity of the soil itself can never be reduced to zero, but a significant improvement to the resistance of moisture penetration can result through compaction.

A very high level of porosity in the finished block will mean that the structure will no longer be able to keep out the elements, such as wind, rain and temperature variation. Clearly this is undesirable, as these are some of the most basic functions of a dwelling. As porosity cannot be removed completely from a basic building material such as soil, the level of porosity that is acceptable or even desirable needs to be identified. Taking the other extreme, in a hermetically sealed dwelling, there is no potential for the passage of air or moisture from the inside of the dwelling to the outside world. This is also unacceptable as humidity and oxygen levels from respiration will make the living space uncomfortable. A balance between the two extremes needs to be rationalised.

A major factor that would concern a dwelling designer is the time taken for the building material to respond to changes in climate both inside and outside the dwelling. For example, if outside has a very high humidity and the inside is kept comfortably dry, how long will it take (assuming the conditions are sustained until equilibrium is reached) for the inside of the wall to have the same characteristics as the outside. Perhaps a better analogy is using one of heat. If the outside temperature is 10°C and the inside temperature is 20°C then there is a thermal gradient of 10° between the internal and external faces of the wall. The thermal gradient exists because the wall possesses a thermal resistance and the internal temperature is being sustained by a heat source. If that heat source was removed the temperature of the wall would equalise and the gradient would be reduced to zero. The same principle can be applied to the moisture content of the wall. If the outside is wet due to rain, and the wall is porous then the moisture will migrate to the inside face of the wall saturating the wall. Ensuring that the internal face of a wall can remain dry and the wall itself can survive a 50-year storm would not be an unreasonable request for the average homeowner.

Depth of moisture penetration is another consideration that would concern the SSB builder as a small degree of penetration can be tolerated, but deeper penetration may be unacceptable in the long term. Moisture ingress affects the strength of SSB's but the effect on strength is usually not so significant to cause collapse. A more common mode of failure is spalling of the surface of the blocks as moisture has penetrated, caused expansion and subsequent contraction and cracks have occurred. These cracks permit further moisture penetration and cause more expansion and cracking to occur. These cracks if permitted to continue begin to jeopardise the integrity of the block surface initially and then the structural strength of the block itself. Over time the surface of the block falls away permitting deeper moisture penetration and progressive destruction of the block.

*High fines/clay content:* The smallest of the particles in the soil are the ones that exhibit the greatest expansion when they become wet. If there is a high percentage of this fraction of soil then the potential expansion will be significant as more particles become coated with water and drive neighbouring particles apart. There are two remedies for the effect of this type of soil, firstly to reduce the fines/clay content by mixing in coarser grains, or to add a stabiliser such as cement in such high quantities that the particles are restrained from moving when water is added. Both will work in practice, but the latter is an expensive exercise and the former should be attempted if possible.

The larger sized fractions of soil are generally unaffected by moisture. They will gain a thin film of water on their surface, but this will be small compared to the grain size. The smaller grain fractions achieve a similar thin film of water on their surface that is of the same order or magnitude or bigger than the grain size. The diagram below illustrates this phenomenon.
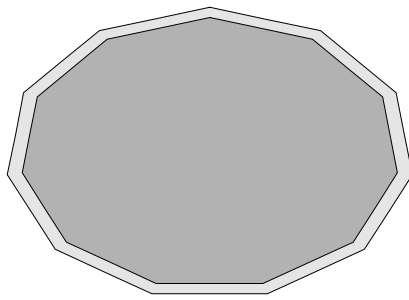
Large soil grain (2 mm)
coated with water
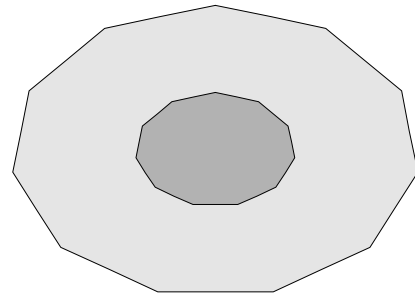
Small soil grain (0.02 mm)
coated with water

The Large soil grains will be coated with a thin layer of water, but this will not increase the size of the particle significantly. If thicker layers of water tried to coat the particle gravity would begin to have an effect and excess water would drip off the bottom of the grain. The surface tension that holds the water onto the grain surface will not be strong enough to create pore pressure that pushes other particles further away from each other. The small grains, on the other hand, will be significantly larger when coated with water and will cause a volumetric expansion of the particles. At this scale the surface tension will be strong enough to move particles further apart and to cause significant overall expansion.

*High linear contraction:* Again, this linear contraction is due to the presence of clays and fine particles that shrink back together when the moisture around them is removed. The contraction will also depend on the moisture content when the soil is formed and then left to dry/harden/cure. Higher initial moisture contents will result in higher overall shrinkage of the soil. Clearly reducing the initial moisture content will help to reduce initial shrinkage, but ultimately it is the clay content that will determine the amount of expansion and shrinkage. Again the shrinkage can be limited by the addition of cement to the soil. The amount of shrinkage will determine the quantity of cement that will be required to effectively stabilise the soil. As described in (International Labour Office, 1987), (p. 38-39), the cement to soil ratio is as follows for a given shrinkage as determined by the shrinkage test described in chapter 3.2.

| Measured Shrinkage (mm) | Cement to soil ratio |
|---|---|
| Under 15 | 1:18 parts (5.56%) |
| 15 – 30 | 1:16 parts (6.25%) |
| 30 – 45 | 1:14 parts (7.14%) |
| 45 – 60 | 1:12 parts (8.33%) |

*Adhesion:* If the soil is moist and has a high adhesion to metallic surfaces, it will cause significant problems when de-moulding. The simplest way of reducing the adhesion exhibited by the soil is to reduce the moisture content when the soil is formed in the mould.

## 4.2  Significance to making SSB's

The above section detailed the characteristics that the SSB manufacturer would want to avoid. In practise these characteristics are impossible to remove altogether and a compromise needs to be made somewhere along the line. This section aims to explain the effects that the above characteristics have on SSB's produced in the field.

Expansion of a SSB can only occur if three characteristics are present: Clays or fines and Porosity & Permeability and Moisture movement. If any one of those is absent then expansion and contraction will not occur, (ignoring chemical and thermal expansion and contraction). The diagram to the right illustrates the idea.
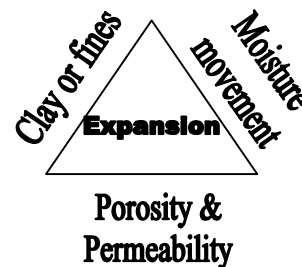


It is the job of the SSB manufacturer to minimise these characteristics in the blocks that are being produced so that potential expansion is reduced to acceptable levels. External environmental changes will cause the moisture levels to rise and fall over time. This will not have an effect on the SSB unless the moisture levels within the SSB also change.  Moisture will only be able to penetrate the SSB if porosity and permeability are present. Swelling and shrinkage will only take place if the moisture reaches a fraction of clay present within the SSB and sufficient cement is not present to resist the potential expansion offered by the clay or fines. Therefore there are three

factors that want to be controlled: the clay fraction, the porosity of the material and the rate of moisture movement.

***Controlling the clay fraction:*** Too much clay results in unacceptably high expansion upon wetting or excessive amounts of cement to combat this. Too little clay causes low adhesion between particles and hence causes high breakage rates on de-moulding of the SSB's. Either situation is unacceptable and this can only be achieved by monitoring the clay and moisture content when the soil is to be formed. How closely this has to be done to achieve satisfactory results is not clear. An optimum fines content for making SSB's was suggested by the United Nations to be about 25% of which more than 10% is clay, (Gooding, 1993), (p. 263). From the literature it is unclear how much a change of say ±5% to the clay content will have on the overall performance of the SSB.

***Porosity:*** An ideal for the level of porosity for any type of SSB would have to be zero. Since this is a physical impossibility a small amount of porosity needs to be tolerated. The greater the porosity the more susceptible the SSB will be to the elements and more specifically, the permitting of water penetration. In certain cases it is impossible to avoid water getting onto the face of the block, e.g. blowing rain, but what must be stopped is the water penetrating into the block itself. Water in the block will cause expansion and deterioration of compressive strength unless it is compensated for with a high cement content. If the level of porosity at the surface is much less than deeper into the block then this also is an acceptable situation. If water does not penetrate the surface then it will not matter if the porosity is lower where the water does not reach as this area will be unaffected. Using steel-sided moulds and dynamic compaction give good surface finishes and will result in a slightly lower surface porosity than deeper into the SSB core.

Possible moisture penetration models:

Capillary action without differential pressure - Unknown mechanism but very effective on small pored materials.

Gravitational force pushing water into pores of SSB - Surface water on SSB pushes water into SSB through pores.

Pressure difference flow - Low pressure internally in block with high pressure outside SSB drives moisture from one side to the other.

*Moisture levels:* More water means more shrinkage upon drying and potentially higher adhesion to metal surfaces, but some moisture is required to keep the soil in a workable state and also to hydrate any cement particles if they are used to help in the stabilisation process. Careful control of the moisture levels is also required to ensure that the soil has adequate adhesion to itself to reduce SSB breakage upon de-moulding. If the moisture level change during the life of the SSB, then moisture movement has occurred. Initially this happens when the block is dried out after it is formed. Subsequent moisture movement should be avoided. Moisture will only be able to enter or level the block if porosity and permeability are present and these can be reduced by adjusting the particle size distribution and the apparent density of the finished block.

## 5. Conclusions and recommendations

The characteristics that define soil are many and varied. Defining a soil with any degree of accuracy from all the different soils present in the world is a difficult task. With such a variable substance, one can appreciate the difficulties posed to the SSB manufacturer to ensure that the soil that is chosen will be acceptable for the intended task. An even greater problem is determining what effect slight changes to the soil's texture, porosity and moisture content will have on the finished product. This is not helped by the fact that these properties will affect one another as they are sometimes inter-dependant. For example, if the moisture content is high during manufacture then there will be a higher porosity when all the moisture has been removed. If the texture is carefully controlled then this will have an effect on the porosity and apparent density.

Further analysis of how different characteristics affect one another in general should be looked into more closely. A cause and effect chart displaying all the different characteristics and how each is effected by changes in different characteristics would be very helpful. It may be possible to determine that all the different characteristics are linked mathematically and any change in one property will result in changes in a number of others. This model may have to be limited to only a few simple characteristics as the overall variability and complexity of soil may be too difficult to model with any degree of accuracy.

The mechanism through which water penetrated a block is another area where further study should be undertaken. How and why water wishes to permeate a porous substance against the forces of pressure and gravity is a question that needs to be answered. The adhesion of water to surfaces and the internal cohesion that it has with itself are major factors in the situation. How these forces can be hindered so that water is less likely to penetrate a block would be very useful to know if it is possible. Water cannot penetrate certain porous objects because the pores are too small for the water to penetrate into them. At what level this occurs and whether it can be achieved by modifying soil characteristics physically is not known at the moment and should be investigated further.

# 6. Summary

 Some physical characteristics of soil have a major influence in the potential for expansion when it becomes wet. These can be isolated into the clay/fines fraction, the porosity/permeability and the moisture movement. Only with all three factors present will expansion occur. Monitoring the clay fraction and apparent density can be easily done using simple tests, but finding the porosity and hence the potential for moisture movement is a bit more complex. Cement will hinder expansion to a certain degree, but if the root problem can be eliminated rather than trying to constrain the effect of the problem then that would be much more advantageous.

As the SSB's will be in an environment that exhibits changes in moisture and clay is an important component of the block's composition then the only factor that can be reduced is the porosity and permeability of the SSB. The porosity cannot be reduced to zero, but there may be a point at which the SSB becomes impermeable to water. This is the desired condition and this may be achieved by monitoring the particle size and distribution, the moisture content and the apparent density of the final SSB. How exactly this can be done in practice is still open to further discussion. At least now we know the offending characteristics that cause material expansion and consequently we are better equipped to minimise their effects and to deal with their consequences.

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