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Dynamic Compaction of Soil for Low-cost Building Blocks

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David E Montgomery and Terry Thomas

Development Technology Unit
School of Engineering, University of Warwick
Coventry, CV4 7AL, UK
Tel: +44 (0) 2476 523122 Fax: 2476 41892
email: dtu@eng.warwick.ac.uk
http://www.eng.warwick.ac.uk/DTU/

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Abstract

This paper reports the results of experiments carried out on the process of dynamic compaction of stabilised soil blocks. The interest in this area has been fuelled by the previous research that has shown the dynamic technique of compaction has significant advantages over quasi-static compaction. During the experiments emphasis was placed on determining the wet compressive strength obtained after curing of the formed material. The results lead to a greater understanding of the different factors that affect this strength and suggest a means of predicting the strength without applying a destructive test. The "green" density of the newly formed material was found to be a good surrogate for its subsequent wet compressive strength.

The discovery that density was a good indicator for strength led to further investigation into the factors affecting the achieved density. It was noted that the moisture content of the soil mix was an important variable. The concrete and the soil literatures both give very inappropriate guidelines for a suitable moisture content; around 6% water by mass was found to be optimum for the production of stabilised soil samples. The energy used to compact the material is another key factor in generating a high density. The same energy applied via dynamic and quasi-static compaction was found to achieve similar densities, a disappointing result as larger scale tests indicated dynamic methods uses less energy for compaction than quasi-static methods. The lower efficiencies could however be a result of non-optimum dynamic compaction as the variables within the method of energy transfer, were not specifically optimised for the small (200g) samples used.

Finally, the different findings have been interpreted into a possible machine specification for the dynamic compaction of stabilised soil blocks. The most notable advantage that dynamic compaction has over quasi-static is its potentially lower machine cost. The impulsive blow to compact a soil sample does not exert massive forces for sustained periods of time during the compaction process. Consequently dynamic compaction has shown to be possible with thinner mould walls and using low-tech mechanisms than hydraulically assisted high-pressure quasi-static compression, yet to achieve similar levels of densification (and subsequent strength). It is therefore envisaged that a machine capable of producing high-strength building blocks can be made at a tolerable cost whilst also requiring a tolerable input of human energy into the production process.

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.

Bulk Density: Density calculated including any moisture present in the material.

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.

Green Density: The density calculated immediately after ejection prior to any curing, drying or soaking.

Inferred Dry Density: The calculated density at ejection assuming no moisture is present in the formed sample, only solid matter.

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.

SSB: Stabilised Soil Block

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.

Religious dedication

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 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 cometh unto the Father, but by me.*” John 14:6.

1. INTRODUCTION

This report describes the experiments carried out that investigate the characteristics of soil samples stabilised by different methods of compaction. The effects of such variables as water content, compaction energy, mixing delays and method of compaction are examined. Particular emphasis is given to the dynamic compaction method of soil stabilisation.

1.1 Motivation for this work

It is well documented that there is a massive and growing shortage of low-cost housing for the urban and peri-urban poor in developing countries. Several technological solutions that use local soil as the basic building ingredient have been proposed to help alleviate this problem. Currently two devices are widely available for the manufacture of stabilised soil blocks (SSB), namely high and low pressure block-making presses. The high-pressure (e.g. 10 MPa) press is capable of achieving sufficient densification to allow the quantity of stabiliser (cement) to be reduced to a low level (<6%) while still achieving adequate block properties. Low-pressure (<2 MPa) machines do not achieve such high densification and consequently the quantity of stabiliser in each block needs to be increased to a higher level (8-12%). However, the saving in cement when the high-pressure machine is used does not outweigh the significantly higher machine cost. What the market requires is a machine that achieves the same level of densification as the high pressure machine whist costing little more than the low-pressure one. *Dynamic* compaction of soil samples has in the past been shown capable of achieving high levels of densification and promises to provide a basis for designing the required machine.

1.2 Dynamic compaction

The basic principle behind dynamic compaction is the simple one of using a fast impact to transfer the energy of a falling mass into the object being hit. One can cite the parallel of the superiority of impact over pushing when driving a nail into a piece of wood. How the energy is transferred is however quite complex to describe as it depends on the characteristics of both the impactor (falling mass) and the object hit. Furthermore, the energy transfer will not be 100% efficient as other outputs such as noise, vibration and air resistance will subtract from the total energy delivered into the object being hit.

Dynamic compaction of building blocks is of interest to us for a number of practical reasons. We believe that it has some significant advantages over the existing method of slow squeezing (‘quasi-static compression’) of soil blocks that greatly outweigh the potential problems within the process. The first and perhaps most important advantage is that dynamic compaction doesn’t require the same level of machine cost or complexity as high-pressure quasi-static compaction does. The absence of large levers, associated bearings and a hydraulic circuit represent a significant savings in machine cost. Furthermore the forces transmitted through the press are less, so that the machine can be made from thinner sections of steel and consequently be lighter and cheaper. The disadvantages of the process are that the safety implications of a falling mass are significant and the time taken to deliver a number of dynamic blows may be longer than a ‘slowly’ applied quasi-static force.

The instantaneous force generated during a dynamic blow can exceed, by a factor of up to 1000, the weight of the mass used for the blow and hence the force needed to lift it. We therefore have a sort of ‘dynamic lever’ capable of turning the pull of a human operator into a force of many tonnes. With these possibilities in mind, research into the dynamic compaction of soil for low-cost building began in the 1980s. This chapter reviews where the research in the field had reached prior to the commencement of this project and the current goals of the project.

1.3 Previous research at Warwick

Research has been carried out world-wide for many years into both the process of *quasi-statically* compacting stabilised soil blocks (SSBs) and that of *dynamically* compacting unconfined soil for the civil engineering industry. Unfortunately a bridge between these two spheres of activity did not seem to exist and there was virtually no information on dynamic compaction of constrained soil in order to produce building blocks. Other researchers at Warwick had noted this and hence dynamic compaction of blocks became an area of interest for the DTU. However almost no research into the technique has been identified elsewhere.

In 1984 Agas Groth carried out a final year student project investigating the potential of compacting soil within a mould by dropping weights onto it. The research included varying the mass of impactor and the drop height, but keeping the energy transfer and the material constant throughout the project. He aimed to achieve (with a 95% confidence) a block density of 1870 kg/m^3, a density that corresponded to a cured dry compressive strength of 3 MPa. With his particular soil type, he found he had to apply at least 1.63kJ to form a standard size block of 290 × 140 × 90mm (mass $\approx$ 6.8 kg), i.e. about 240 J/kg. Using the technique, Groth subsequently built two houses in Botswana which after 15 years are still in good condition.

Bearing in mind the limitations he faced, some comments can be made on his findings. Several blocks must have been made, but there was no record of their characteristics after compaction, only the method of transferring the energy into the block. The recorded density is not defined as wet or dry density, which with 12% moisture would make a significant difference. However, the research did pave the way for future research to be carried out on the process of dynamic compaction.

Dominic Gooding undertook research for his PhD during 1993-6, looking at methods of soil stabilisation for low-cost building. He investigated how various aspects of quasi-static SSB production affect the output characteristics of the block. Factors such as mould wall taper, mould wall surface smoothness and whether single or double-sided compaction were used were examined and all found to have only a minor effect upon densification. He also generated a pressure/cement/strength relationship for his quasi-statically compacted samples.

However the main thrust of his work was an investigation into the dynamic compaction of approx. 1.6kg cylindrical samples. Like Groth he kept the energy transfer constant and varied the method of applying the energy to a given quantity of soil. The results indicated that there were optimum arrangements for transferring the energy into the soil with respect to the number of blows applied and the mass and velocity of the impactor used. They also showed that impact was a more energy-efficient method of compaction than slow squeezing.

None of the dynamically compacted samples that Gooding produced were stabilised with cement. Moreover the soil he used for his tests was recycled several times and that may have caused unintended variations in block properties (subsequent testing indicated the soil had progressively lost most of its fines content). After graduation, Gooding undertook a review of SSB production in 6 developing countries.

David Montgomery (the author) continued this research during another undergraduate project, whose emphasis was upon the design and development of a test rig to manufacture full-size dynamically compacted blocks. The design kept in mind the developing country environment in which such a block press might be both manufactured and used and employed an appropriately low level of technology. Applying a number of blows from a 36kg impactor produced several blocks with varying characteristics. Density was the main measurement made of the finished blocks as they were also unstabilised to conserve materials. The primary discovery was that the impacting process and Gooding’s findings could be extrapolated onto full size samples (approx. 8kg) with a high degree of confidence. Even at full size the impacted blocks required much less energy to form (to a specified density) than quasi-statically pressed blocks.

1.4 Current Goals

The present (PhD research) project can be divided up into two distinct parts; a materials science part and a manufacturing process one. The materials part started with a review of criteria for selecting a suitable soil and such a soil was selected for research purposes and for comparing dynamic compaction with quasi-static compaction whilst a number of variables where manipulated. The objective of this was to gain a better understanding of the material and to determine which variables are of greatest influence in the production of compacted samples.

The manufacturing process part of the project will take the findings from the material analysis and develop a systematic method for block production using the beneficial aspects of dynamic compaction. Variables discovered to be of importance will either be optimised to a single value or will be kept as alterable variables within the production regime where it is possible to do so. This part of the project will involve the design and manufacture of a machine capable of producing full-size dynamically compacted blocks. The design will be selected to ensure that it is appropriate for SSB producers in developing countries to manufacture and maintain.

Another aspect of the whole research project is to clarify the actual physical processes underlying dynamic compaction, as these are still poorly understood. Several process models have been suggested already but none of these have proved to be very accurate. Dynamic compaction of unconfined soils has been modelled as a one-dimensional problem (Scott & Pearce, 1975), but the theories within his paper do not cover compaction of confined samples as is the case in block production. Some analysis of the dynamic forces will be required for the machine design but full analysis of the dynamic compaction process may be outside the scope of this project.

2. VARIABLES OF SIGNIFICANCE IN THE MANUFACTURE OF SABILISED SOIL BLOCKS

The production of blocks suitable for low-cost building involves many different stages from the extraction of raw materials via block manufacture to the transportation of the finished blocks to the building site. The purpose of this paper is to look only at block formation (compaction), its associated constraints and the resultant block characteristics. Selection, extraction of raw materials, pre-processing of them, curing techniques and transportation constraints will be considered either briefly or not at all.

Blocks manufactured from different materials and by different methods have significantly different characteristics. Below is a table showing some common building materials and their respective key characteristics. Unfortunately the large range in values makes useful comparison difficult.

Property	Fired clay Bricks	Calcium Silicate bricks	Dense concrete blocks	Aerated concrete blocks	Lightweight concrete blocks	Stabilised soil blocks (SSB)
Wet compressive strength (MN/m²)	10 to 60	10 to 55	7 to 50	2 to 6	2 to 20	1 to 40
Reversible moisture movement (% linear)	0 to 0.02	0.01 to 0.035	0.02 to 0.05	0.05 to 0.1	0.04 to 0.08	0.02 to 0.2
Density (kg/m³)	1400 to 2400	1600 to 2100	1700 to 2200	400 to 900	600 to 1600	1500 to 1900
Thermal conductivity (W/m°C)	0.7 to 1.3	1.1 to 1.6	1.0 to 1.7	0.1 to 0.2	0.15 to 0.7	0.5 to 0.7
Durability under severe natural exposure	Excellent to very poor	Good to moderate	Good to poor	Good to moderate	Good to poor	Good to very poor

(International Labour Office, 1990)

Desirable block characteristics are:-

- a high wet compressive strength – to permit both single and multi-storey construction,
- a low moisture movement – to lessen expansion/shrinkage potential,
- a low density – lighter blocks to make construction easier,
- a low thermal conductivity – for greater dwelling comfort and
- a high durability – securing a long-term investment.

The last column above shows the characteristics for SSB's and the very large ranges that each characteristic has for SSB's. During the research reported here, the wet compressive strength was taken to be the key characteristic and production sought to maximise the strength achievable with tolerable physical effort and machine cost.

During the production of an SSB many different variables will be of importance. We will regard as 'independent' those variables that can either be controlled by the operator, such as moisture content, or are a result of environmental conditions, such as temperature and can be monitored. The 'dependent' variables are values that are determined by interactions between the independent variables. From the viewpoint of the SSB manufacturer, several of the independent variables, including cement content, are of major concern; whereas to the end-user only the dependent variables, such as durability and strength, are of any great interest. For the purposes of this research both the dependent and the independent variables were monitored. The research endeavoured to identify which independent variables have the greatest effect on the dependent ones and what might be the optimum values of controllable variables. The aim of this was to minimise the demand on the manufacturing inputs without compromising the desired block characteristics.

2.1 Dependent variables of interest

This section discusses five key *dependent* variables, identifying values for them that are achievable and desirable in the production of SSB's. Since they are associated with different stages in the production and use of a block, they are presented in 'chronological' order.

De-moulding force – After compacting an SSB in a mould it must be successfully removed from the mould without damage. Moulds that come apart in some way to easily release the finished block are more complex to manufacture and take more time to open and close than simple straight-sided moulds: they are therefore unattractive both from the complexity and time aspects. The compacted material can instead be pushed up out of a cheaper fixed mould, however a certain de-moulding force will needed to overcome the cohesion/friction between the SSB and the mould walls. The size of this force will depend on the mould's surface finish, the moisture content of the material, the level of compaction achieved and the method with which the energy was transferred into the SSB. For manufacturing purposes we desire the de-moulding force to be as low as possible to make the production of the block easy. Currently a full-size block quasi-statically compressed with 10 MPa requires a de-moulding force of slightly under 2 tonnes. For a human to generate such a force a significant leverage must be employed. Reducing de-mould forces well below this 2 tonnes would be advantageous to both the machine designer and the block manufacturer.

Ease-of-handling – A freshly formed block has a low 'green' strength and must be handled with care. If the block had a greater 'ease of handling' there could be a lower rate of block breakage both before and after curing. Furthermore high ease-of-handling would permit green blocks to be stacked immediately upon demoulding, which in turn helps to reduce the floor area required for curing. Stacking also reduces the surface area for moisture-loss from the freshly formed block and thus helps to ensure a good curing regime. This ease-of-handling of a block is not a characteristic that can readily be measured directly. However it correlates with green strength which can be measured. A penetration test is usually used to determine the green strength of a formed block. This involves pushing a rod a specified distance into the surface of the block and recording the force required (or conversely measuring the penetration distance resulting from using a specified force). The green strength of the block will not depend on its cement content as the cement particles will not have had time to hydrate and add any strength to the material. The green strength is largely dependent on the particle size distribution (soil type), the moisture content and the level of compaction achieved. These factors work together to give the material the cohesion that enables ease of handling.

Green density – In the same way that the green strength is of interest to the block producer, the green density is another characteristic that can be easily and quickly measured immediately after production. This measurement can serve two purposes, firstly it checks that the block passes a certain standard prior to curing and secondly it can be part of a longer term feedback loop to improve control of the manufacturing process (discussed in Chapter 4). Where a known amount of material has been used to generate a sample, measurements are taken on the overall size of the sample after compaction has taken place. Several different density calculations can be carried out (as is discussed later) but usually either the ‘bulk’ or the dry density is recorded. The bulk density is always higher than the dry density due to the presence of water in the block and so it is important to record which of the two has been calculated. Bulk densities between 2000 and 2200 kg/m³ are considered to be excellent for SSB manufacture (Houben & Guillaud, 1989). A number of the process inputs (independent variables), but most specifically the energy transfer and the method of compaction, influence the green density of the block. Other factors such as moisture content and cement content have a lesser effect on it.

Wet compressive strength – This characteristic is high on the list of user priorities. Existing low-cement SSB’s manufactured by low-pressure compaction have compressive strengths adequate for the majority of low-rise structures *provided that* water penetration is kept to a low level. Using an external render or paint, both of which require regular maintenance, will reduce the moisture penetration considerably. However, when saturation of SSBs has occurred it has often proved to be too harsh for the material to withstand whilst maintaining a load: surface flaking or even collapse has followed. If the wet compressive strength can be improved then environmental effects such as running water will not cause such early failure to occur in the building material. The wet compressive strength is measured by placing a cured and water-soaked sample into the jaws of a compression machine and slowly squeezing the sample until the maximum load applied is reached. After the maximum the sample has been crushed and will no longer support a load of that magnitude again: it has been tested to destruction. The predominant factors that affect the wet compressive strength are cement content and the level of compaction achieved during moulding. The strength achieved by the cement content depends in turn on the moisture availability for cement hydration and curing regime applied to the finished block. Wet compressive strengths of over 2 MPa are considered to be excellent for SSB’s (Houben & Guillaud, 1989).

Durability – The most desirable of all the dependent variables is durability, taken to be the measurement of how long the material will survive before environmental attack jeopardises the integrity of the building material or renders it unsightly. Unfortunately no measurement of SSB durability is currently available, as real long-term tests need to be carried out. Current literature describes durability via the terms ‘poor’ to ‘excellent’, hardly a quantitative approach. Other research currently underway at Warwick is exploring durability. However it is generally accepted that the durability of stabilised soil blocks is closely linked to their wet-compressive strength: blocks with higher wet-compressive strengths last longer.

2.2 Controllable independent variables

This section briefly describes the different controllable variables that are involved in the SSB manufacturing process. A summary will be given of the ranges used for the controllable variables in previous work and mechanisms by which they might affect the dependent ones will be outlined.

Soil type – In the field this can vary considerably and it is known that some soils are more suitable than others for the production of SSB’s. The United Nations guideline for suitable soils for SSB production requires “a well graded soil consisting of 75% sand, the remainder being fines of which more than 10% is clay”. Soils with more than 30% clay will be very expansive with the addition of water and hence will exhibit excessive dimensional variation with the seasons. To counteract this a larger degree of stabilisation than normal is necessary, either by extra compaction or by increasing the amount of cement. Very high clay contents (over 50%) are unsuitable for stabilisation with cement, so either lime has to be used or sand must be mixed with the soil to reduce the clay fraction. There is therefore a literature about soil selection for block making. For the purposes of the research reported in this paper, the soil type has not been treated as a variable but instead been kept constant. All the experiments have used the same soil, one selected to be quite suitable for SSB manufacture.

Moisture Content (MC) – Different sources gave conflicting information about the selection of suitable moisture content for the process of SSB manufacture. A drop test is usually given by the SSB manufacturing texts as an approximate method for checking that the MC is suitable. For research purposes a better definition is required.

The *soil mechanics* literature indicates that maximum density is achieved if compaction occurs at what is termed as the Optimum Moisture Content (OMC) but we should rename *Density Optimising Water Content* (DOMC). Compaction tests need to be carried out to determine what the DOMC is for each soil used: values around 11% are typical for the soils of interest.

The *concrete* literature (Neville, 1995) - which however effectively assumes use of a ‘soil’ having a total absence of fines - indicates that for ideal compaction the Water/Cement (W/C) mass ratio should be extremely low. For practical levels of compaction, W/C ratios of 0.3 to 0.5 normally yield the greatest strength. For the low cement contents (<6%) characteristic of SSB manufacture, such ratios corresponds to around 2% water content. Thus the DOMC and W/C criteria give widely differing values for optimum water content, and a compromise needs to be made. A further complication with SSBs is that too high a moisture content (say >9%) so reduces the “green” strength of the block that its ease-of-handling becomes inadequate and post-compaction breakage rates become intolerable.

Cement content – Cement is usually the dominant variable cost in SSB production, so the reduction of its quantity is very desirable. How much cement is necessary depends on three factors, the clay content of the soil used, the degree of compaction during moulding and the required wet compressive strength of the finished block. The higher the clay content the more cement is required and conversely the higher the compacting effort (as measured by the densification achieved) the less cement is required for adequate stabilisation. If a higher wet compressive strength is necessary then either the compacting effort or the cement content will need to be increased. To some degree increase in the one can be traded for a reduction in the other - a fact that has driven a trend towards increasing the moulding effort in SSB manufacture. Previous stabilised soil research (Rigassi, 1995) has indicated that cement contents below 2 or 3% will not actually enhance the wet compressive strength or improve stabilisation. Consequently 5% by weight is probably the smallest amount of cement practical to employ for SSBs.

Energy transferred – This is a highly significant variable as it can have a marked effect on the final material strength regardless of the route by which the energy is applied to the material. Dynamic compaction has consistently proved to be more efficient in improving SSB properties than quasi-static compaction using the same energy transfer. Previous experiments with dynamic compaction kept the energy transfer, or the energy transfer per unit mass, constant. This generated samples with varying characteristics from the same energy transfer. Producing samples with fixed characteristics via different compaction methods and energies was not carried out. However, it is to be expected that different amounts of energy will be required to produce samples with similar characteristics via the two different compaction methods (dynamic and quasi-static).

Quasi-static compaction involves a certain pressure being applied to the ends of the material confined in a mould of either rectangular or circular cross-section. The pressure can be applied in one or more cycles and the speed of compression can also be varied (5-100mm/min). (Speed of compression is only varied for convenience and accuracy to ensure a good result in a short cycle time.) Previous research indicates that the increase in compaction achieved by having more than one compression cycle is so small that it is not an efficient use of energy (Gooding, 1993), five pressure cycles only increase the density by less than 2%. Generally the applied pressure is calculated in MPa and samples created between 8 and 12 MPa are of most interest for comparison with dynamic compaction.

Dynamic compaction uses the energy from a falling mass to compact the sample. The process entails a number of variables but these can easily be summarised as the number of blows and the impactor momentum per blow. The number of blows applied to the sample can be varied within a pre-determined optimum range of 8 – 32 blows. The impactor momentum ($mv = m\sqrt{2gh}$) and the impact energy ($e = mgh$) both depend on the mass m of the impactor, and the height h through which it is lifted. The lifted height will control the final velocity of the impactor at contact with the soil. Previous research showed that impact velocities of over 2 m/s were potentially damaging to the compacted material as the initial compressive shock wave could reflect at the bottom of the mould into a tensile wave, whose subsequent travel upwards can shatter the sample.

Mould-wall thickness –The mould-wall thickness required for dynamic compaction is different to that needed for quasi-static. It is found that for comparable energy transfer and densification, the forces applied to mould walls during dynamic compaction are smaller and of much shorter duration than those occurring during quasi-static compaction. If mould-wall thickness is chosen on the basis of achieving a particular strength safety factor, the dynamic moulds can be significantly thinner and therefore lighter than quasi-static compaction moulds. For example for highly-densified full-size blocks, the respective mould-wall thicknesses might be 8 mm and 25 mm respectively. This difference is economically significant, since one of the barriers to the take-up of quasi-static presses operating up to 10 MPa pressures has been their excessive weight and cost.

Size and shape – A standard block size is 290 × 140 × 90 mm whereas the standard sample size for compression testing is either a 150mm or a 100mm cube. Previous research has also been carried out on 100mm diameter cylinders with an approximate height of 100mm. All these different sizes and shapes will have an effect on the apparent characteristics of the finished sample. For research purposes it is inconvenient to manufacture full size blocks to check every little variable and characteristic. Furthermore the dynamic compaction of a full size block requires strict safety procedures to be followed and these become much less stringent if the sample size is smaller. For these reasons the research was performed using smaller size samples. Extrapolation of findings to full-size blocks is not straightforward, however the *ranking* of alternatives at one scale is likely to be the same as the ranking at a different scale.

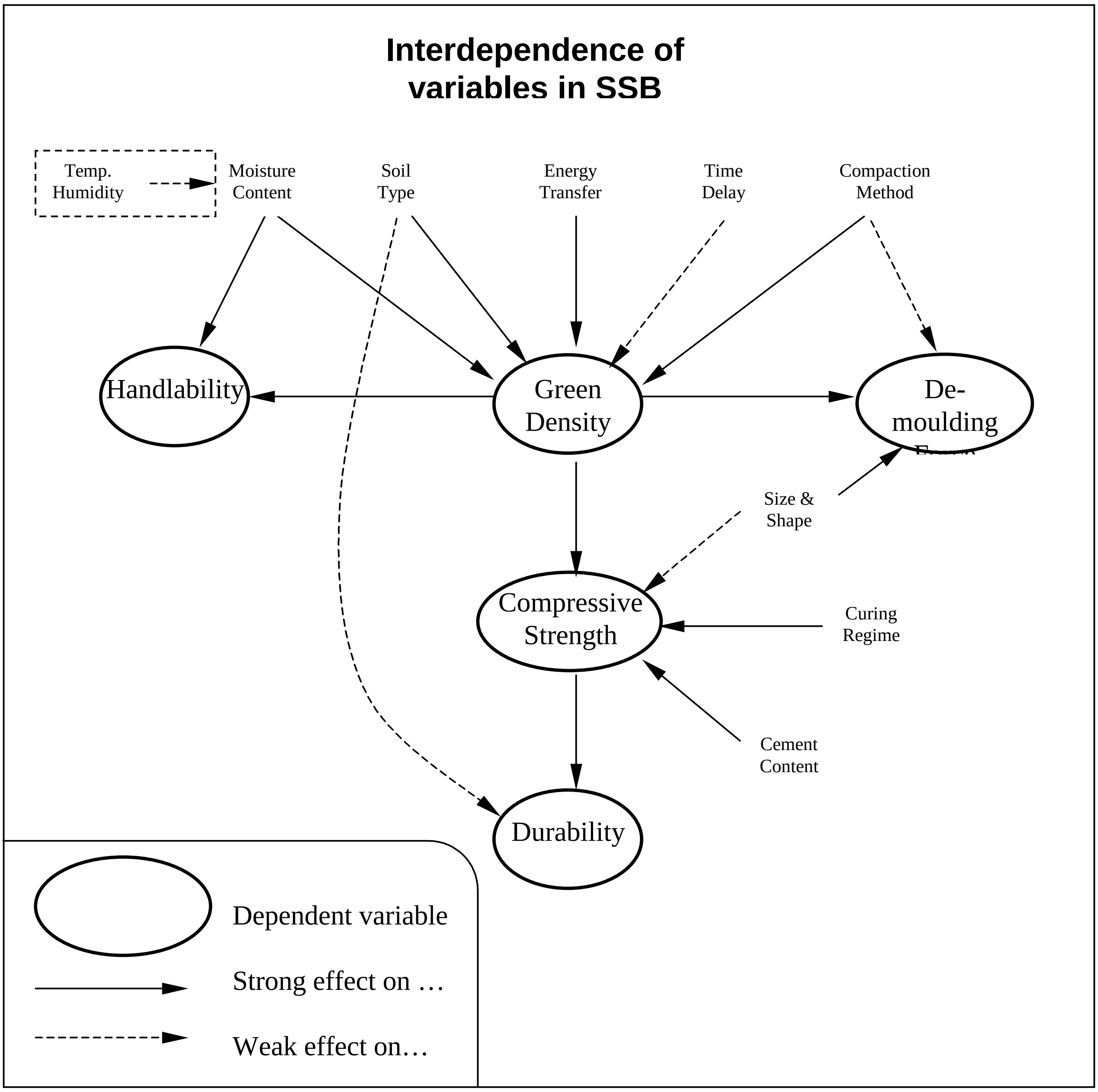
Delay before compaction – As soon as moisture is added to the dry soil/cement mixture the cement will begin to react with the water. As the cement begins to hydrate the moisture levels in the soil available for lubrication becomes less, hindering the compaction process. Meanwhile the crystallisation that is beginning to occur with the cement after the critical period has passed (roughly defined as 15 minutes after adding water) further hinders the compaction. Following the manufacture of a batch of material some parts of the batch are made into blocks before other parts. This variable delay between mixing and compaction has an effect on the ejected density. The order of production within a batch will thus have an effect on the final sample characteristics and while this is not large it is a factor that requires addressing. Indeed it is very useful to know whether a significant loss-of-strength penalty is incurred when a period as long as say 1 hour elapses between mixing a batch and using all of it.

Curing period – Ideally the compacted samples should be left to cure for an adequate time in an environment of nearly 100% relative humidity. The normal period for concrete curing is 28 days, although test data also records 3 and 7 day strengths as well. In reality SSB production seldom includes block curing for 14 days: 7-day or even shorter curing is more normal. Water scarcity and poor understanding of curing concrete often leads to blocks being left out and allowed to dry in the open. This is a very poor production practice as keeping blocks moist in a humid environment will improve their final strength significantly. The majority of previous experiments have been carried out under laboratory conditions, typically at 20°C and with a low relative humidity. During this research samples were cured in sealed bags containing water-saturated air.

2.3 Summary of variables and their interactions

Each independent variable has *some* effect on every dependent (output) variable. Below is a schematic chart that attempts to illustrate the this dependence of the outputs on the inputs. The term ‘significant’ is used to denote a output-to-input sensitivity commonly exceeding unity.

In order to check this interdependence a significant number of different samples needed to be manufactured. As full-size block production was not viable, for reasons rehearsed above, a smaller sample size had to be chosen. In fact a small sample, an approximately 200 gram cylinder, was selected. This permitted fairly rapid production even up to quasi-static pressures of over 10 MPa using existing laboratory facilities. An existing mould with an internal diameter of 54.4mm was found and was used as a standard for other moulds. The sample height was chosen to give the same ratio of mould-wall surface area to compaction (top surface) area ratio as a full-size block has.

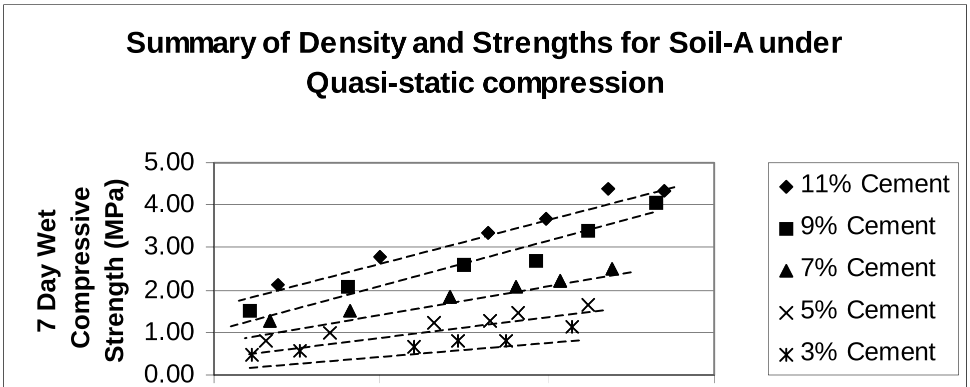


3. FACTORS AFFECTING THE STRENGTH OF CURED BLOCKS

One of the most important characteristics of an SSB is the durability of the finished product. Durability may, as discussed earlier, be thought of as how long the block will be able to support a load whilst experiencing normal environmental attack. Since durability measures do not currently exist for SSB's and the durability is closely linked with compressive strength, then determining the strength of an SSB is probably the best available indicator for its durability. Unfortunately compressive strength can only reliably be measured by rather complex and destructive testing of blocks prior to their incorporation in a wall. This is inconvenient both for research and for quality control in manufacture. Moreover compressive strengths of materials such as we are using here are inherently somewhat variable. As we shall see later, *block density* (which can be measured non-destructively) may sometimes be considered a surrogate for wet compressive strength in research work. In production a simpler modulus-of-rupture (flexural) test may be used instead of a crushing test although both are equally destructive in nature.

The flow chart in Section 2.3 showed the main factors that affect the strength to be the cement content, the curing regime and the green density. If the cement content and the curing regime are kept constant then the only factor affecting the strength should be the density achieved during moulding the block. We already know that the cement content and the curing regime have a significant effect on the final strength, but we don't know fully how other factors affect the green density.

Gooding established that the 7-day wet compressive strength of pressed blocks is directly related to the cement content and the compaction pressure applied to form them. He developed an equation to determine the expected strength if a known pressure and cement content were applied to a specific soil with a moisture content of 8%. Below is a summary graph of his results for wet compressive strength tests on 50mm diameter x 100mm long samples made from his 'soil-A'.


Summary of Density and Strengths for Soil-A under Quasi-static compression

After Gooding 1994

E_D_E_QS_gooding

Although cement content is not one of the variables that have been addressed in this paper, Gooding's work clearly illustrates the significant gain in strength that can be achieved by adding extra cement. The graph above also illustrates that increasing moulding pressure increases both density and strength. Each locus, representing a particular cement content, has 6 points representing moulding pressures of respectively 1, 2, 4, 6, 8 and10 MPa. Not unexpectedly the lowest pressures resulted in the lowest densities and strengths. Another feature visible from this graph is that the sensitivity of the wet strength to cement content is much higher than it is to moulding pressure.

A number of new experiments were carried out, in each of which the wet compressive strength of the sample was measured after compaction and subsequent curing. The effect on strength of varying (a) moisture content, (b) compacting pressure *or* number of fixed energy dynamic blows and (c) time delay before moulding was measured. Other factors such as mould wall thickness and energy transferred were also investigated for their effect upon green block density but not upon cured block strength.

Certain variables were kept constant (at realistic values) during the production of samples, partly because there are too many variables to consider and partly because some of them have already been investigated. The cement content was set at 5% by weight. Rather than vary the type of soil a large batch of stable (and reproducible) soil was manufactured that could be used for all of the experiments. This research soil is gap graded with 80% builder's sand and 20% kaolin clay and is called Soil-B. All samples were cured for a total of 7 days in a humid environment that included a 1-day soaking period followed immediately by wet crushing. Unless otherwise stated the selected sample size was a cylinder of 54.4mm diameter with a dry soil mass of 200g. Moulding and strength testing were conducted in the laboratory at temperatures around 20^{o}C and relative humidity levels around 60%.

3.1 Inherent variability of strength

Two seemingly identical concrete samples will have slightly different strengths. The different arrangement of the particles and the cementitious bonds that join them create a variation in the strength of the material. In order to determine this inherent variability an experiment was carried out in which almost every independent variable was held constant and the coefficient of variation of wet-strength was estimated. This indicated the inherent variability of strength so that future results could be assessed more accurately and sample sizes chosen wisely. For practical reasons, one input variable was allowed to vary, namely the time elapsed between mixing the soil mortar and compacting it. The results were processed in a way that allowed this variability to be compensated for.

During the experiment 35 samples were produced, 18 via quasi-static compaction and 17 via dynamic compaction. The quasi-statically formed samples were compressed to 10MPa and the dynamically compacted samples received 16 blows of a 5kg impactor falling through 200mm. The quasi-static samples received approximately 100J of compaction energy whilst the dynamic samples received 157J (i.e. 0.2m×9.81×5kg×16 blows). Both sets were manufactured at 6% moisture content and in the 54.4mm diameter mould with an 8mm wall thickness. A batch of material was made up to produce three 200g samples and the order of production of each sample within the batch was recorded.

Each batch consisted of a ‘first’, ‘second’ and ‘third’ sample manufactured at different times. Six of each were produced for each (dynamic and quasi-static compaction) process. The strengths of the firsts, seconds and thirds can all be compared and analysis carried out on the results.

Below is a table of results from the dynamic compaction tests.

Table 3.1a

Number of samples	Position in Batch	Bulk density mean kg m^{-3}	Bulk density s.d. kg m^{-3}	Bulk density Coef of var %	7-day wet strength mean MPa	7-day wet strength s.d. MPa	7-day wet strength Coef of var %
5	1st	2140	8	0.38	2.38	0.14	6.1
6	2nd	2131	5	0.26	2.23	0.15	6.5
6	3rd	2118	5	0.24	2.12	0.18	8.3

E_D_E_DS_den-ref

It is immediately clear that there is a very low variation in the bulk density (under 0.5%) but a more significant variation in the wet compressive strength (6 to 8%). From this we infer that either strength is highly sensitive to density or that there is an inherent variation in the compressive strength of identically formed materials.

Below is the table of results from the quasi-static compaction tests.

Table 3.1b

Number of samples	Number in Batch	Bulk density mean kg m^{-3}	Bulk density s.d. kg m^{-3}	Bulk density Coef of var %	7-day wet strength mean MPa	7-day wet strength s.d. MPa	7-day wet strength Coef of var %
6	1	2067	9	0.44	1.76	0.09	5.3
6	2	2054	13	0.65	1.61	0.13	7.8
6	3	2050	9	0.44	1.63	0.11	7.0

E_D_E_QS_den-ref

The same feature can be noted in these results: a very low variation in the density and a larger variation in the compressive strength. Despite the lower densities and strengths of these samples, the coefficients of variation of strength are similar to those for the dynamically compacted samples. This suggests that variability in strength is not closely related either to the density achieved or to the method of compaction. The above results indicate that the strength coefficient of variation will be not more than 8% under normal conditions or not more than 5% if the average of 3 samples is taken. Consequently a sample size of 3 was adopted and any averaged change in strength of more than 10% was be considered to be significant - i.e. the result of a change in an input variable.

3.2 Effect of moisture content on strength

Early on in the project some full-size blocks were manufactured using a “Bre-pak” high-pressure block-making machine. Three blocks were manufactured from old ‘soil A’ at each of the moisture contents: 4, 5, 6 & 7%, making a total of 12 blocks. All the blocks were stabilised with 5.2% cement by weight and their production and curing cycles were virtually identical. Their measurements were taken at ejection and the bulk density was calculated for each block prior to curing it in a humid environment for 7 days. To make the compression tests comparable with standard concrete tests each block was cut in half and each half was cut to the size of a 100mm cube. This gave 24 samples for compressive testing instead of 12. Then each half of the same block was subjected to different tests. One half was soaked for a day whist the other half was left to dry out for a day prior to crushing. This gave a ‘wet’ and ‘pseudo-dry’ compressive strength test for each of the blocks.

It should be noted at this time that blocks continue curing after being removed from the humid curing environment. This resulted in a curing period of one day more than intended. A block crushed after 7 days curing and one day soaking or drying will have effectively been curing for 8 days total because the core moisture will not evaporate entirely in 24 hours. The concrete literature (Akroyd, 1962) suggests an adjustment of around -7% should be applied to an 8-day strength figure to generate the corresponding 7-day strength. The figures given below have been adjusted in this way to standardise them into 7-day wet compressive strengths.

Table 3.2a

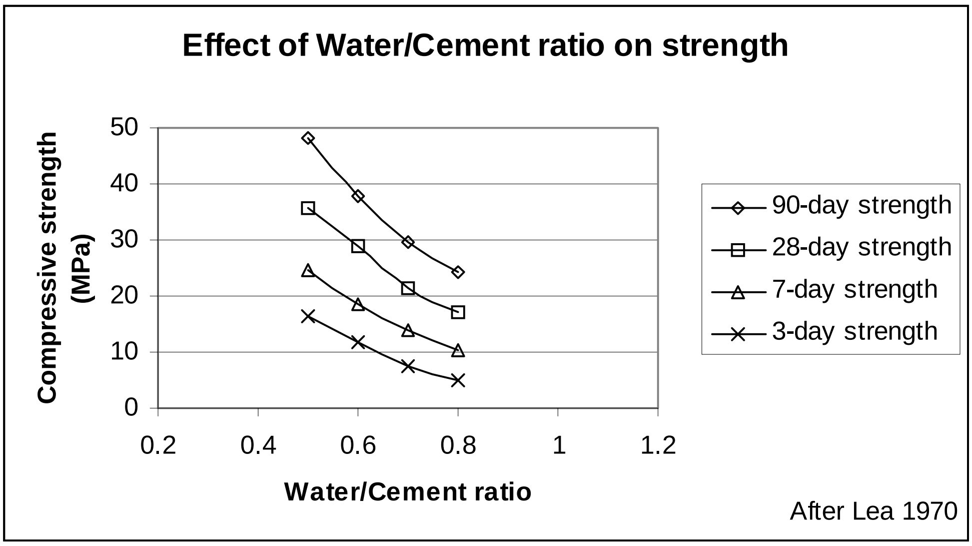
Moisture content % by wt	Bulk density mean kg m^{-3}	Bulk density s.d. kg m^{-3}	Bulk density Coef of var %	7-day wet strength mean MPa	7-day wet strength s.d. MPa	7-day wet strength Coef of var %
4	1943	3	0.15	0.86	0.04	4.41
5	1971	14	0.72	1.40	0.03	2.40
6	1995	2	0.09	2.10	0.08	3.87
7	2020	11	0.56	2.32	0.10	4.13

E_D_E_QB_strength

The above results seem to be consistent with the soils literature in that as the moisture content is increased up towards the DOMC the density also increases. These results follow that trend very well since 7% moisture is still below the DOMC for the soil (discovered to be between 9-10% moisture). The greater variability of wet compressive strength compared to that of bulk density can be seen here again. If we were to ignore the effect of the cement present we would be excused for thinking that the increase in strength is caused solely from the increase in bulk density resulting from compaction closer to the DOMC. This assumption cannot be made and consideration of what is happening between the cement and the water must also be included.

The cement literature suggests that a Water/Cement (W/C) ratio of between 0.3 – 0.5 is the best for concrete strength, provided that the mix is "fully compacted" (i.e. that all air is expelled). The above results unfortunately do not confirm or contradict that statement. The increasing *density* at higher water contents brings about an increase in strength; this may outweigh the loss in strength caused by the W/C ratio being too high. An alternative explanation is that (given the high water-affinity of the clay fraction of the soil) the higher moisture content mix has more free water to hydrate the cement and this, combined with the increase in density, helps to generate a higher compressive strength.

Data taken from (Lea, 1970) on the water-cement ratio and resulting strength (of sand-cement-water mixes containing no fines) is shown below.



E_D_MCTesting

For the experiments done only one of the above W/C ratios could be matched. One sample had a cement content of 5% and a moisture content of 4% giving a water-cement ratio of 0.8. It is obvious from the graph above that reducing the W/C ratio below this 0.8% should increase the strength, whereas the experimental data presented earlier showed strength *increasing* as W/C ratio was raised above 0.8. It must therefore be assumed that the W/C ratios recommended by the concrete literature are inappropriately low for soil stabilisation - either because of the presence of fines in the mix or because of the unusually low cement levels used in SSB manufacture.

In order to try and illustrate the effect of the water on cement curing for very low moisture contents (supposedly best for concrete strength) the 'pseudo-dry' strength was also measured. 'Pseudo-dry' is defined as removing the sample from the humid curing environment and allowing the free water to escape to the atmosphere in the laboratory for 24 hours. This does not dry the block entirely as much of the core moisture is still present. The table below shows the compressive strengths of these samples.

Comparing Tables 3.2a and 3.2b enables us to compare 'wet' and 'pseudo-dry' 7-day compressive strengths over a range of water contents. One normally expects a wet block to be weaker than a dry one, because there is more lubrication between particles and a slip plane can develop more easily causing failure at a lower stress level. The above results are initially contrary to this assumption. For the 4% M/C case the wet strength (0.86MPa) was actually higher than the corresponding pseudo-dry strength (0.77MPa). This difference is statistically significant (>95% as the difference in the sample means exceeds twice the standard error of difference). One possible explanation is that the extra water available during the soaking process preceding the wet-strength test so advanced the cementitious reaction that it overcame the loss in strength due to the sample being wet. This suggests that the cement had been starved of moisture and more moisture would have been of greater benefit.

Table 3.2b

Moisture Content %	'Pseudo-dry' compressive strength Mean MPa	s.d MPa	Coef of var %
4	0.77	0.02	2.79
5	1.36	0.11	8.08
6	2.12	0.18	8.29
7	2.48	0.16	6.64

E_D_E_QB_strength

For the 4% MC condition the significance test is as follows:

Standard error (wet) = $\frac{0.04}{\sqrt{3}} = 0.023$

Standard error (pseudo-dry) = $\frac{0.02}{\sqrt{3}} = 0.011$

Standard Error of Difference (SED) = $\sqrt{0.023^2 + 0.011^2} = 0.025$

Difference of Means (DoM)= 0.86 – 0.77 = 0.09

DoM/SED = 0.09/0.025 = 3.6 (3.6 > 2 $\therefore$ significant)

Penetrometer tests were also undertaken to determine the surface strength of 'green' blocks. Greatest penetrative resistance, and hence the greatest ease of handling, was found at moisture contents between 4-6%. Penetrative resistances above 0.4MPa were achieved in this moisture range but the penetrative resistance was found to reduce significantly where the water content was increased above 6%. Consequently, 6% water was selected for many of the experiments carried out.

3.3 Effect of 'Effort of moulding' on strength

Densification of material increases the effectiveness of stabilising additives like cement. This densification can take place in many ways, but for the purposes of this paper only two methods will be considered: quasi-static and dynamic compaction.

Quasi-static compaction can be most easily defined by the peak pressure applied to a block causing densification, whereas dynamic compaction can more easily be defined by the number of blows applied and the momentum of each blow. (For purposes of directly comparing the two methods however a common measure may be calculated, namely moulding energy applied per kilogram.) This sub-section will be looking closely at the difference between the two types of effort applied and how they respectively affect the strength of the sample created.

3.3.1 Quasi-static compaction

Different compacting pressures have been selected in the past for the stabilisation and densification of soil blocks. Low-pressure machines apply between 1 and 3 MPa via a lever mechanism, whilst high-pressure machines would apply between 8 and 16 MPa using a lever and a supplementary hydraulic circuit (Houben et al., 1994). The experiment carried out here looked at the effect of pressures within the high-pressure range on the wet compressive strength of samples produced.

Below is a table showing the summary of results from the compression tests of small samples (200g) produced by quasi-static compaction in a cylindrical mould with 8-mm walls and with a soil moisture content of 6%. The soil used was Soil-B stabilised with 5% cement.

Table 3.3a

Compacting	Bulk density			7-day wet strength		
Pressure MPa	mean kg m^{-3}	s.d. kg m^{-3}	Coef of var %	mean MPa	s.d. MPa	Coef of var %
8	2047	12	0.57	1.48	0.05	3.60
10	2067	14	0.69	1.75	0.23	13.07
12	2102	15	0.69	1.92	0.30	15.78

E_D_E_DS_density2

As the results from Gooding showed (Chapter 3) the strength increases as the pressure is increased for a given sample and these results also follow the same trend. What is interesting to note is that a 50% increase in pressure (from 8 to 12 MPa) yields only a 30% increase in strength, giving a mean sensitivity of strength to pressure of 0.65. (Gooding, operating with a slightly different range of variables, found doubling the strength requires a tenfold increase in compacting pressure, i.e. a mean sensitivity of only 0.3.) This is a fair return providing the machine is designed to withstand the higher pressures. The significant variation of strength for an insignificant variation in density can again be seen in these results.

3.3.2 Dynamic Compaction

Previous research had already indicated that dynamic compaction was more efficient at increasing the density of a sample for the same energy transfer, but that research did not include any strength testing of the samples produced. Consequently a series of small samples (200g) was produced by dynamic compaction in a cylindrical mould with 8-mm walls and with a soil moisture content of 6%. The soil used was Soil-B stabilised with 5% cement. These were manufactured in the same manner, as the quasi-statically compressed samples described in the previous section. The method of densification and the energy transfer were the only variables altered. The aim was to try and achieve the same density via different methods and to see if the resulting strength was significantly different.

One of the negative aspects of the process of dynamic compaction is the large number of blows that often need to be applied to the sample to achieve sufficient densification. If this number could be reduced then the processing time for making a block would be shortened. Clearly this is desirable, but sacrificing strength to accomplish it is not acceptable. Direct comparison with quasi-static compaction suggests that 16-20 blows should be sufficient to achieve the same strength as using 10MPa quasi-static compaction. This experiment set out to confirm this. Three blocks were manufactured at each of the following number of blows: 8, 12, 16, 20 & 24, making a total of 15 samples. Each blow is from a 5kg impactor falling through no more than 200mm. An analysis of energy transfer will be considered in later chapters.

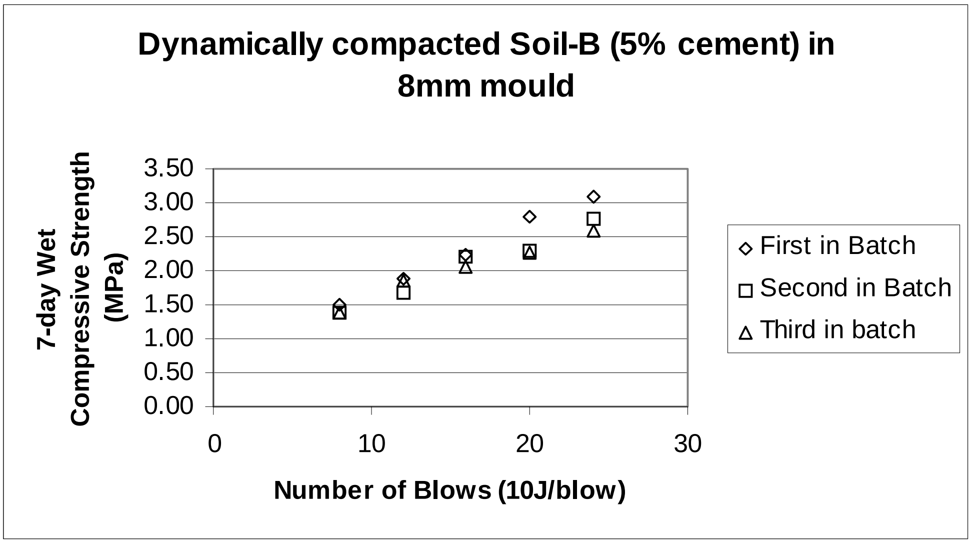
Table 3.3b

Number of Blows	Bulk density			7-day wet strength		
	mean kg m^{-3}	s.d. kg m^{-3}	Coef of var %	mean MPa	s.d. MPa	Coef of var %
8	2053	18	0.86	1.43	0.07	4.76
12	2097	13	0.61	1.81	0.11	6.19
16	2113	16	0.75	2.17	0.10	4.79
20	2133	13	0.59	2.44	0.29	11.98
24	2162	19	0.86	2.81	0.25	9.06

E_D_E_DS_density2

As the blow number, and hence moulding energy, are increased the bulk density and wet strength also increase. As noted previously, density is less variable than strength. Increasing the number of blows applied by 50% (from 8 to 12 or from 16 to 24) generates an increase in strength between 25 to 30% - giving a mean sensitivity of strength to effort of 0.6. This is a good return especially considering the machine design does not need to be altered to accommodate the higher number of blows.

These results are represented in the graph below with indicating the order of production for each batch. The graph shows another feature that may be of interest. The strength achieved seems to be related to the position within the batch, with the first sample produced being the strongest and the last generally the weakest. This trend seems to become more pronounced as the number of blows is increased, possibly due to the longer production time necessary for more blows to be applied.



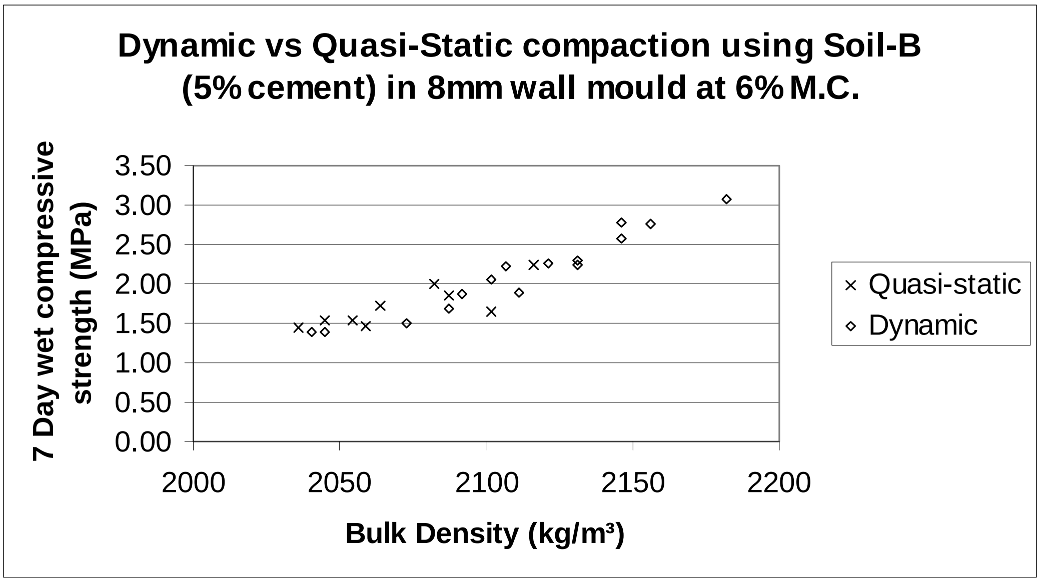
E_D_E_DS_density2

A direct comparison between the dynamic and quasi-static compaction results, show that dynamic compaction is significantly better than almost all of the compacting pressures. The strength achieved with 12 or more blows exceeds the strength achieved with 10MPa pressure. Looking at the highest applied pressure of 12MPa a resulting strength of 1.92MPa is achieved whilst the 12 and 16 blow samples achieve 1.81 and 2.17MPa respectively. A quick significance test shows that there is no significant difference between the 12MPa sample and either of the 12 or 16 blow samples, (E_D_E_DS_den-ref). Consequently it can be suggested that the strength achieved by quasi-static compaction to 12 MPa is the same as the 12 and 16 blow dynamically compacted samples.

These results suggest that the goal of replicating the strength achievable with a 10MPa press should be possible with in order of 14 dynamic blows. This is a very pleasant discovery as Gooding showed that for a constant energy transfer the optimum number of blows is around 16.

3.4 Effect of method of compaction on strength

One of the important tests that needs to be carried out is whether or not the method of compaction makes any difference to the strength of the sample compressed to a similar density. In order to check this, a set of results from dynamic and quasi-static compaction tests were compared. Everything except the method of compaction and the corresponding moulding ‘effort’ is the same for these results, summarised in the graph below.



E_D_E_density2

The graph immediately shows the similarity in the results given by the two methods. What is also of great interest is that the two methods of compaction seem to lie in a similar region on the graph with the dynamic results extending beyond the scope of the quasi-static results.

If we look at the results that overlap (i.e. where density does not exceed 2120kg/m³) then we find the results for quasi-static pressures between 8-12MPa and dynamic blows between 8-16 are remarkably consistent. A significance test carried out on these results shows that there is no significant difference in the density-strength relationship between the two compaction methods. (In fact the difference is very low indeed with the Difference of Means/Standard Error of Difference equalling only 0.43). These results show that over the region of interest (for any given density in the range achievable by 10MPa compression) the strength achieved via either moulding method is highly similar.

3.5 Time delay between mixing and moulding

In the production regime of block manufacture it is customary to mix materials up into batches from which several blocks are moulded. The time delay between mixing and moulding will therefore increase from the first block made from the batch to the last one; this variation may be reflected in differing strengths of the blocks. As time passes the cement is progressing through the curing process and compaction should take place as soon as possible and certainly not after the critical time. (This critical time is defined by the concrete literature as the time after which working the cement mix causes damage to the cement crystals that have already formed.)

It is possible to see if the time delay has a significant effect on the characteristics of the finished sample by looking again at the results from the reference set of dynamic and quasi-statically compacted samples. For the production of these samples the time delay was in the order of about 15 minutes between the first sample and the third sample of the batch. The first sample in the batch was compacted after the moisture had been mixed into to the soil for about 3 to 4 minutes. Therefore the total processing time for a batch was around 20 minutes.

Below is a table of results from the dynamic compaction tests.

Table 3.5a

Number of Samples	Position within Batch	Bulk density mean kg m^{-3}	Bulk density s.d. kg m^{-3}	Bulk density Coef of var %	7-day wet strength mean MPa	7-day wet strength s.d. MPa	7-day wet strength Coef of var %
5	1st	2140	8	0.38	2.38	0.14	6.09
6	2nd	2131	5	0.26	2.23	0.15	6.53
6	3rd	2118	5	0.24	2.12	0.18	8.26

E_D_E_DS_den-ref

Below is a table of results from the quasi-static compaction tests.

Table 3.5b

Number of samples	Position within Batch	Bulk density mean kg m^{-3}	Bulk density s.d. kg m^{-3}	Bulk density Coef of var %	7-day wet strength mean MPa	7-day wet strength s.d. MPa	7-day wet strength Coef of var %
6	1st	2067	9	0.44	1.76	0.09	5.26
6	2nd	2054	13	0.65	1.61	0.13	7.84
6	3rd	2050	9	0.44	1.63	0.11	6.99

E_D_E_QS_den-ref

In both tables the mean wet strength falls with position within the batch. For the method of dynamic compaction there is a statistically significant difference between the first and third sample, but an insignificant one between the first and second or between the second and third samples produced. The quasi-static compaction results are slightly different as there is a significant difference between the first and second or third samples, but not between the second and third samples. (E_D_E_DS_den-ref).

These results seem to indicate that there is a significant drop in strength if a sample is produced more than 15 minutes after adding water to the soil/cement mixture. This poses some serious production problems and will need to be addressed and double-checked on the full-size block production to see if the same limitation exists.

The significant drop in strength could be a result of a variety of effects, some of which are as follows. (i) Some of the free water (useful for lubricating the particles causing better densification) has been absorbed by the fines content of the soil and partially used in the generation of the cement gel; (ii) there could be active cement crystallisation already occurring and this hinders the compaction process sufficiently to reduce the final strength; (iii) the compaction process actually breaks already-formed cementitious bonds. The last effect is probably of greatest concern as the crystalline growth is being damaged and wasting potential cement strength. The lack of lubrication or compactive effort could be remedied easily, but destruction of crystalline growth should be avoided if possible.

4. DENSITY AS THE SURROGATE FOR STRENGTH

The last chapter described the many tests carried out to determine how different factors affect the final strength of an SSB. We can now state with a degree of confidence that many of the independent variables affect both the cured strength and the green density of blocks. The understanding of the relationship between density and the strength can enable us to know how accurately and under what circumstances density at demoulding can act as a surrogate measure for the potential strength of a sample.

If density is to be the surrogate for strength it is important to decide which density should be used. Several different densities can be measured or inferred during the production of an SSB. Below is a summary of them. As in every case density is taken as a mass divided by a volume, we define different densities by which mass and which volume each uses. In practice we use weight as the source of mass.

Green bulk density – weight is that of material (*including* water) placed into the mould for compaction; volume is that measured upon removal of the green block from the mould. This density is the most commonly used as its calculation is easy to accomplish using simple measurements taken at the time of moulding.

Inferred green dry density – weight is that of material (*excluding* water) placed into the mould for compaction; volume is that measured upon removal of the green block from the mould. This density is not commonly used but is helpful when determining the comparative compaction of different samples with different moisture contents as the moisture variation is removed from the density calculation.

Pre-ejection dry density - this is a similar measure to *inferred green dry density* except that the volume is based upon a block’s dimensions prior to its ejection from its mould. This measure is suitable for exploring density variations during moulding and is used in Chapter 5 below.

Cured bulk density – weight is that of the block after the curing process has just been completed, it includes the free water in the block as well as the absorbed water used in the curing of the cement; volume is as measured earlier on demoulding. Other current research has indicated that this density calculation may be the best indicator of the final strength of the finished sample.

Post-cure dry-density – weight is measured after both curing and driving off excess moisture (e.g. in a low-temperature oven); volume is measured at the same time. This is a difficult density to record during a research cycle of curing and subsequent crushing as time is taken to dry out the sample during which some curing is permitted to occur. Furthermore, the subsequent soaking prior to determining the wet strength (by crushing) will permit even more curing to take place, changing the characteristics of the sample.

Post-cure wet-density – uses the weight and volume measured after curing and then soaking for 24 hours (i.e. just prior to crushing). One can determine the voids ratio of the material by comparing the *post-cure wet* and *dry densities*. Their difference is due to the mass of the water filling any voids present.

For the majority of the experiments carried out the *inferred green dry density* was used as a working guide of densification, particularly where the moisture content was not held constant. For ease of communication and understanding these results have been converted into the ejected bulk density which is more commonly understood. Wherever a density is quoted it will be presented as either “inferred dry” or “bulk” density.

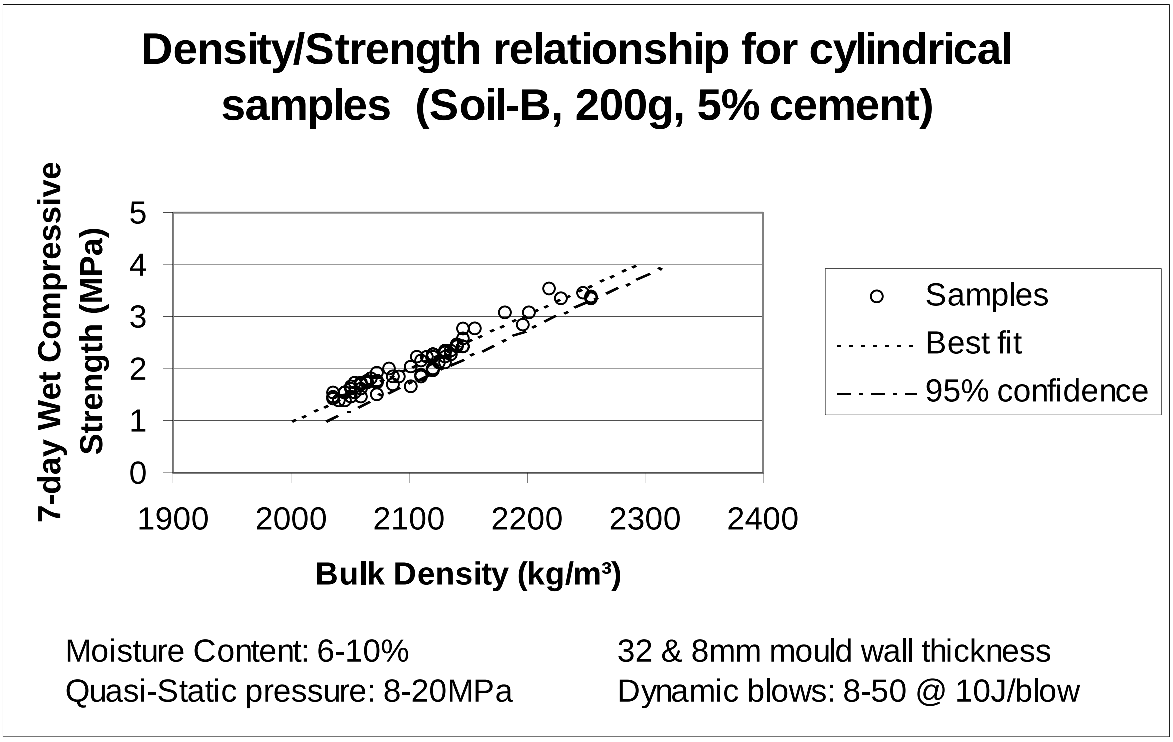
4.1 Summary of Density/Strength data

Before looking at specific variables to see whether or not their effect on the achieved density directly correlates with the effect on strength, a general overview of all the variables would be helpful. This section summarises the production of all of the samples generated and will show the relationship between density and strength even when several entities are varied.

In Section 3.4 above it was shown that at least under some circumstances green bulk density is highly correlated with cured wet strength regardless of the moulding method by which that density was created. That finding, however, does not help determine whether or not the density surrogate can be applied if other variables are changed. Many variables change the density achieved during the production process: these variables may have a greater or lesser effect on the change in strength. A simple method of checking this is to put the data from all experiments carried out in a graph and try to determine the general relationship for strength against density. Some variables (such as cement content) were however held constant because they were already known to have a significant effect on strength for similar densities.

The graph on the next page is a summary of all the tests carried out so far on small cylindrical samples that were stabilised and crushed. The variables include; moisture contents, number of blows, compacting pressure, mould wall thickness. Entities *not* varied were:- soil type, cement content, the size and shape of sample and in the case of impactive moulding, the impactor mass and drop height.

The graph shows a definite trend of strength against density with a reasonably straight-line relationship over the area of interest. The straight-line trend between strength and density is not a surprise because Gooding’s results (displayed in chapter 3) have a similar relationship. What we want to be able to do is to successfully predict with a 95% confidence that a sample compacted to a certain density will have a known strength. In order to do this a best fit line is drawn through the results using the least mean squares method. The results are then normalised to find the standard deviation and a new line is generated two standard deviations away from the best-fit line. This line is shown as the 95% confidence line on the graph and has the equation parameters described below.



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

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

For 95% confidence

The equation of this line: $y = mx + c$ is

Bulk Density (ρ in kg m^{-3}) $= 97 \times 10^{-6} \times$ Strength (σ in Pa) $+ 1993$

Or more helpfully: $\sigma = 10{,}300\ (\rho - 1933)$

From this we can suggest that over the relevant density range we can use density to predict the 7-day wet compressive strength. This is a very useful property. In research work it allows us to sometimes replace the destructive and cumbersome measurement of strength with a quicker measure that leaves the samples undamaged and hence available for other tests. In block manufacture, green density provides an immediate feedback on block quality that is fairly easy to interpret. Inadequate density points to using a larger charge in a fixed volume mould or more effort in a variable volume mould. Setting density targets is straightforward.

Note incidentally that at mid-range, e.g. σ = 2 MPa, the sensitivity of strength to density is only 0.092, or put another way a 1% increase in density corresponds to an 11% increase in strength.

Whereas the formula above (valid for a particular soil, cement content and thoroughness of curing) is very useful for predicting the strength of these 200g samples, the coefficients may well be different for full-size blocks. The range of values that the above relationship is correct for is only a small variety of possible combinations. The relationship above is only for 200g small cylindrical samples made from Soil-B and stabilised with 5% cement. The moisture can range between 6 and 10% and the mould wall thickness can vary between 32 and 8 mm. Compaction can be either from quasi-static compression between 8 and 20 MPa or from dynamic impact using between 8 to 50 blows at 10J per blow via a 5kg impactor falling through 200mm.

It is hoped that the relationship between these variables at this scale can be extrapolated and adjusted for full scale block manufacture and still exhibit the same trends that have been noted here. This will be examined later on in the project and cannot be reported here.

4.2 Other variables needing consideration

The accuracy and reliability of the results above certainly suggest that the density can be a very good indicator of strength. However, in the normal production of an SSB many different variables would be changing. Some of those would either be out of the range investigated here or be one of the variables that were not investigated. This section looks at some of the possible variables that could either affect the strength without changing the density or variables that will affect the strength that have not been considered earlier in this paper.

Cement content – We have reduced the cement content to the lowest possible value for production and assumed that the manufacturing process would control these quantities very accurately. In reality the cement content will vary and possibly quite significantly depending on the production method and the conscientiousness of the production team. If the cement content varies blocks produced with the same achieved density will have significantly different strengths because of the large effect that cement has on the strength. It is not possible to account for a badly controlled variable, so either a factor of safety must be applied or the cement content vigorously controlled for each block.

Curing regime – Similarly, the curing regime will not be constant in a real production situation. Inadequate curing of the cement is probably one of the most common mistakes in the production of cement SSBs. The difference in strength between a well and a poorly cured block will be highly significant and will not be obvious from the density alone. The achieved density will only successfully indicate the strength if the curing regime is consistent with the reference set and the produced blocks.

Soil characteristics – The soil type used in the manufacture of SSBs may also change during production. The samples produced for this paper were made from a stable and consistent material carefully measured and mixed with cement. A different soil type will have a direct effect on the density that can be easily noted, but it will also have an effect on the ability of cement to add strength to the block. Moreover, due to the expansive nature of certain clays, the soil type may affect the durability of the block even more than its strength. Only long term tests would be able to confirm this proposition and that is currently outside the scope of this project. It would be very useful to show that the particular soil used has only a small effect on block strength or at least that any *change* in density results in a similar *change* in strength regardless of soil type. This analysis has not been carried out and consequently a safety factor would need to be applied to accommodate the possible variation in the soil composition.

Size and shape – The dimensions of the sample produced will have a direct effect on the measurable strength achieved for the same density. Larger samples usually have a lower compressive strength and consequently the short small cylinders used in this research will show a higher strength than would a full-size block of the same density.

Correction factors for compressive strength of concrete samples with a cylinder length to diameter ratio other than 2 can be found in (Orchard, 1979) (p. 79). The 200g cylinders have a diameter of 54.4mm and a height between 41 and 45 mm. Therefore the ratio of length to diameter is between 0.75 and 0.83 giving a strength of between 136% to 125% that of a reference cylinder (with L/D = 2). So normalising to such a reference cylinder for compression testing requires the data in this paper to be multiplied by about 0.77. The small stabilised cylindrical samples that Gooding produced had approximately L/D = 2 and were the minimum size suggested for compression testing of concrete samples, (i.e.: 50mm diameter and 100mm length). Note: The sample size selected for this project is smaller than the recommended minimum, but was so chosen for two reasons. Firstly we wished to keep the ratio of side wall area to compaction surface area the same as for full size blocks. And secondly, the particle size distribution of the soil used contained much smaller particles than the normal aggregate mix used in concrete.

Type of strength test - The usual method of production-testing an SSB is to carry out a rupture test on it. This is done by supporting a block only at both ends whilst loading its centre (by stacking other blocks on top until it fails). This type of test is not as accurate as laboratory compression testing and indeed measures a *tensile* strength that is likely to be not more than 25% of compressive strength.

The principal finding above (that for a given soil, cement content, block shape and curing regime, green density is a good surrogate for strength) could be extrapolated onto full size blocks with a reasonable degree of confidence. Ideally a reference set of compacted blocks would need to be made on start-up of manufacture, the densities and strengths measured for each one and a target density thereby set. In practice cement content, block shape and curing regime may be standardised. This leaves the variation in soil type to be accommodated and hopefully future work will show this not to be a high sensitivity variable.

5. ENERGY INPUT AND CURED BLOCK STRENGTH

5.1 Energy Productivity

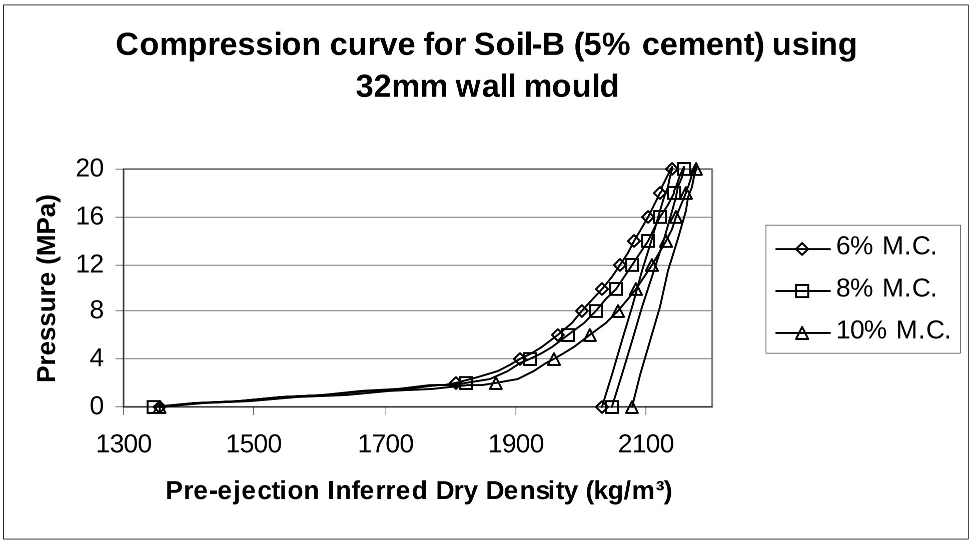
Establishing the factors that affect the final strength of a sample and the possibility of using density as a surrogate for strength were just some of the useful discoveries described in earlier chapters of this paper. To compliment these findings other aspects of the SSB production and performance were noted during these experiments. This chapter will give a brief description of the different observations that were made during the course of the project so far.

One of the variables little studied by previous researchers was ‘energy productivity’, namely the block strength achieved (in Pa) per unit of energy cost (in J/kg). For manual production, energy is of considerable interest, because labour time is a significant part of production cost. Labour time in turn s closely, although not solely, related to energy input needed per block.

During previous research Gooding discovered that the energy transferred into a full-size block quasi-statically compacted to 10MPa was 279J/kg and this achieved a density of 2038 kg/m³. The soil (‘Soil A’) he used to make this 8kg block was different from that employed in the current research, so his findings cannot be directly compared with newer data. However, Montgomery later used Gooding’s Soil A to make a 10kg block *dynamically* compacted 2040 kg/m³ using only 192J/kg of energy. This indicated a 30% energy reduction for full-size block compaction and is a trend that we would wish to confirm in these results here.

Calculating the energy transfer via dynamic compaction is a trivial calculation using the drop height, the mass of impactor, the number of blows and the gravitational constant. (However if the impactor is released from a constant height, suitable adjustment must be made for the fact that the block’s top surface drops, blow by blow, causing the drop distance for the later blows to be higher than for the earlier ones.) By contrast measuring the quasi-static energy transfer is far from straightforward. A force displacement graph needs to be generated during the compression process so that the area under the curve (i.e. energy applied) can be calculated. Doing this has proved quite difficult to achieve for full-size blocks and where necessary previous results have been used for reference.

Three different moisture contents were used in investigating the pressure-density relationship for quasi-statically compressed Soil-B reported above. We can employ the same data to investigate energy productivity. The samples were compressed up to a maximum of 20 MPa and 9 in total were produced. The results of the compaction can be seen in the graph below. Results from other dynamic compaction tests (mentioned earlier in this paper) are used in this comparison.



E_D_E_QS_press'den2

It is immediately clear that there is significant "spring-back" in the compressed material when the load is removed. It has already been established that the difference in achieved density from the different moisture contents is reflected in their respective strengths. We want to use this data to discover what is the approximate energy transfer for different compaction pressures. The cumulative energy transferred for each moisture content and at each pressure can be summarised in the following table.

Table 5a - Q-S compression of 200g cylinders

Pressure MPa	Force N	Average energy transfer (J) 6% M.C.	8% M.C.	10% M.C.
0	0	0	0	0
2	4649	37	39	41
4	9297	54	55	55
6	13946	70	71	70
8	18594	83	86	84
10	23243	97	99	96
12	27891	111	112	108
14	32540	125	126	119
16	37188	139	140	131
18	41837	154	154	142
20	46486	168	168	153

E_D_E_QS_press'den2

From the table it appears that moisture content does not have a great effect on the energy necessary to achieve a certain pressure. A pressure of 10MPa requires approximately 97J of energy to be applied to the sample (i.e. 500 J/kg). This would be equivalent to 10 blows of a 5kg impactor falling through 200mm. Actually the earlier impact blows fell less than 200mm; although the exact distance was not recorded, the energy applied during the first 10 blows was estimated at 95J and we may therefore treat 10MPa Q-S compression and 10-blow impact compression as requiring almost identical energy inputs.

In order to compare the efficiencies of the two methods of compaction the achieved densities of each process needs to be examined. Back in section 3.3.1 the results of several quasi-static compression tests showed an average bulk density of 2067kg/m³ could be achieved with a pressure of 10MPa. Then in section 3.3.2 the results of dynamic compaction tests indicated that 8 blows and 12 blows achieved a bulk density of 2053 and 2097kg/m³ respectively. Taking as a tolerable approximation the average of the 8 blow and 12 blow densities, we obtain a 10 blow density of 2075kg/m³. Thus there is an almost negligible density increase of 8kg/m³ when the same 97J of energy was applied dynamically rather than quasi-statically. The inferred strength improvement is less than 4% and lies within the variability of the strength measurements of the two processes. Consequently it can be stated that for this scale of production there is no significant difference in energy productivity between quasi-static and dynamic compaction.

This finding is a bit of a disappointment, because it was hoped that the higher energy productivity of dynamic compaction detected on a 10kg scale would also hold for smaller blocks. This phenomenon may be a possible result of the very small total energy transfer for these samples, or from probably sub-optimum momentum of the small impactor used in these tests. The better energy productivity of the impactive method may still exist for larger samples and full-size blocks, but this will have to be confirmed later in the research programme.

Combining data from tables 5a and 3.3a indicate that over the range 8 to 12Mpa Q-S compaction pressure, the energy productivity is fairly constant (at about 3500 Pa/J/kg) and hence that for this process the sensitivity of block strength to energy input is about unity. From table 3.3b the energy productivity for impactive formation falls from about 3600 Pa/J/kg at 8 blows to only about 2400 Pa/J/kg at 24 blows - a sensitivity of strength to energy input of only 0.6. Thus beyond a certain point, extra blows give diminishing returns of block strength.

5.2 A good use for excessive strength

The results so far have indicated that a wet compressive strength of around 2.0MPa is possible after 7 days of curing. This would be considered pathetic in the concrete industry, however, as we have already shown much of the concrete literature is not appropriate for the production of SSB’s. The earth building literature (Houben et al., 1994) suggests that a dry compressive strength of 2.0 MPa is adequate for single storey dwellings. This value already has several safety factors to cope with production defects, environmental effects and construction technique. Furthermore the text lists various materials and puts them into classes A, B, C, D; (‘A’ being the best and ‘D’ the worst).

Class ‘A’ building material is considered to have a wet compressive strength of 2.0MPa after 28 days of curing. The graph in section 2.2 shows how the strength increases with time from 3 to 90 days. As 7-day strength is approximately 60% of the 28-day strength for concrete samples, we may assume that blocks shown in the various tables above as having 7-day strengths of 2MPa would be likely to reach 3.3MPa by 28 days. This therefore puts these produced samples well into the ‘A’ class of building materials and a competitor to industrially-fired brick and superior to clamp-fired brick. Indeed they probably are too strong.

It might be said that there is no such thing as too much strength. However, in the efficient use of building materials it is unwise to make a brick several times stronger than necessary. If it turns out that the full-size blocks are much stronger than necessary then it may be beneficial to (i) use less cement for the same amount of material, (ii) use less energy in their production but the same amount of material or (iii) modify the shape of the block to save material. Which of these three options is best will depend on the sensitivity of strength to that input (cement, energy, volume) and the fraction of total cost attributable to that input. In fact the sensitivities of strength to cement, energy and soil volume are approximately 1.1, 0.6 (impactive) to 0.8 (quasi-static) and 1.0 respectively. As all these figures are close to unity, sensitivity alone does not distinguish which option to choose. However, reducing cement usage by 1% will usually save more money than reducing energy usage by 1%, which will in turn save more than reducing soil volume by 1%. Therefore if there is excess strength the most economic course is probably to reduce the cement content. (This conclusion holds less strongly for impactive compaction than for quasi-static because of the former’s somewhat lower strength-energy sensitivity.)

6. BLOCK EJECTION FORCE

As mentioned in section 2.1 the de-moulding force is a dependent variable of interest. The force required to eject a number of fully compacted 200g samples was recorded., and from this data we can make some useful observations. However the factors determining the size of demoulding forces have not been exhaustively investigated and the findings reported here are only provisional. In particular they depend upon data from samples much smaller than a normal building block.

These findings relate to machine design and production technique rather than to block characteristics. However, it could be said that the higher the ejection force the better the surface finish of the final block will be, as significant wiping of particles will occur and a smoother and less penetrable surface results. This characteristic may enhance the durability of the block and perhaps also reduce the rate of moisture loss from the block surface during curing.

We start with the expectation that the greater the achieved density, and hence the higher the moulding forces, the higher the potential force required to eject the block from the mould. Other possible determinants of that force are the compaction method used (quasi-static or impactive), the extent to which the cementitious action has progressed prior to ejection, the 'stickiness' of the particular soil used and the mould geometry (e.g. thickness, proportions, taper). We only have data suitable for investigating the first three factors, namely moulding force, moulding method and (indirectly) cement action.

For impactive compression, Table 6a relates ejection force to degree of compaction - as measured by moulding energy or by density achieved. It confirms that the required block ejection force rises with the degree of compaction. The sensitivity of that force to the *energy* input is quite high (over 0.8) so that we might crudely assume that ejection force is proportional to moulding energy. Unfortunately with impactive forming, we cannot easily measure the maximum moulding *force* and hence we cannot explore the interesting ratio of the ejection force to moulding force.

Table 6a Variation of ejection force with degree of compaction

Number of Blows	Energy Transfer J	Av. Bulk Density kg m^{-3}	Ejection Force Average kN	S.D. kN	C.o.V %
8	78	2053	0.77	0.10	13.36
12	118	2097	1.18	0.08	6.94
16	157	2113	1.28	0.08	5.90
20	196	2133	1.50	0.05	3.40
24	235	2162	1.91	0.11	5.98

E_D_E_DS_density2

Tables 6b and 6c allow us to assess the effect of choice of moulding method upon ejection force. We can see that the force required to eject the 200g cylinders formed by the two methods to very similar densities (means of 2054 and 2050 kg m^{-3} respectively) are significantly different. The quasi-statically compressed samples have an average ejection force of 1.07kN, whereas for the dynamically compacted samples it is only 0.77kN - 28% lower. A test on these results confirms that the two ejection forces are significantly different.

Table 6b Ejection force for quasi-static samples

Number of samples	Position in Batch	Av. Bulk Density kg m^{-3}	Ejection Force Average kN	S.D. kN	C.o.V %
6	1st	2067	0.95	0.18	18.92
6	2nd	2054	1.07	0.14	13.40
6	3rd	2050	1.13	0.09	8.03

E_D_E_QS_den-ref

Table 6c Ejection force for dynamic samples

Number of samples	Position in Batch	Number in Batch	Av. Bulk Density kg m^{-3}	Ejection Force Average kN	S.D. kN	C.o.V %
5	1st	1	2140	1.29	0.14	10.61
6	2nd	2	2131	1.35	0.10	7.38
6	3rd	3	2118	1.36	0.12	9.02

E_D_E_DS_den-ref

It can also be noted from Tables 6b and 6c that the ‘stiction’ to be overcome by the ejector mechanism increases as the position in the batch increases. As successive samples are produced from a particular batch of mixed soil, their density decreases but the force to eject them increases. This increase in ‘stiction’ cannot be a result of the *fall* in density, but is probably an effect of moisture acting within the soil. As time progresses since mixing a batch, the moisture in the soil become redistributed or even lost, reducing the free moisture available for lubricating the sample against the mould walls. As mentioned in section 3.2, moisture content has a significant effect on the block characteristics, both in terms of achieved density and cement curing. Here we see water also having a significant effect the ejection force required during production. Other earlier experiments had also shown easier ejection with wetter mixes.

Earlier experiments had also shown qualitatively that ejection forces are lower with thick-walled moulds than with thin-walled ones, but that phenomenon needs further study.

7. IMPLICATIONS FOR MACHINE DESIGN

The second objective of this research project is to extrapolate the findings from experimentation with small-scale samples into full-size block manufacture. This requires the design and development of a machine capable of dynamically compacting full-size blocks. Several findings in the previous chapters are significant and should be implemented into a comprehensive machine design and production regime. This chapter summarises these findings and explores how the production of full-size SSB's could be modified to accommodate them.

The basic principle behind quasi-static compaction is an excellent one: the great majority of manual presses in developing countries are based on it. Low-pressure manual presses are readily manufactured and maintained in such countries using local materials and skills. High-pressure machines are more complex and robust, they are more difficult to locally manufacture and maintain and they are significantly more expensive. The higher forces in a high-pressure machine need to be dissipated thought stronger bearings and a thicker steel body. This adds considerably to the weight, production and material costs of the machine, probably putting it out of the reach of the urban poor in developing countries. The high-pressure presses yield a much stronger block and therefore permit production of blocks with only a low cement quantities. But the potential cement savings using the higher-pressure machines do not fully offset the greater machine cost. Gooding conducted a survey for the ODA in 1996 assessing the financial pro's and con's of increasing moulding pressure and reducing cement. He discovered that in every country investigated it was more economic to have a high cement content (8-15%) instead of increasing the compacting pressure.

Gooding's hope was that the high-pressure machines could be replaced with a dynamic compaction machine of comparable cost to the low-pressure manual machines. If this was possible then the reduction of cement content became a viable alternative and the overall cost of SSBs could be reduced. Research since then has shown that excellent stabilised samples can be made via dynamic compaction using only 5% cement. It remains however to show that *cheap* dynamic compaction machines can be devised.

7.1 Machine design specifications

Several dynamic compaction rigs have been manufactured throughout the different periods of research, but dynamic compaction of full-size block was only performed once and using a temporary test rig. A full-size machine should be manufactured both to facilitate research and to show that such a machine can be economically made and operated. The first design will of course not be the final design. There will be inevitable alterations to the design as extrapolation of smaller-scale experimentation to full-size block production takes place. The prototype full-size design therefore needs to incorporate more flexibility than a production model in order to continue effective investigation of the process of dynamic compaction.

Apart from the research requirements of the machine there are several other requirements that can be noted from the research carried out thus far. The safety of the machine is paramount. A falling mass of 50kg is a significant potential hazard and precautions need to be taken to ensure that the impactor cannot fall onto any part of an operators body. If possible the mechanism should be inoperable unless all necessary guards are in place and the operator is well away from the falling impactor. Neither ejection of the block nor routine cleaning of the machine should require operators to place any part of their body underneath the impactor.

Changing to dynamic compaction has shown some reduction in the force required to eject a compressed block. This force is still however substantial - perhaps 10% of the peak moulding force - and will need to be applied manually via a lever by a force not exceeding that which can be repeatedly applied with the hand or foot. Since existing machines require levers over one metre in length to achieve this necessary force *by hand*, it may be possible to use a smaller lever if the force is applied by foot. Either system is acceptable, but a foot-operated lever will be more compact and therefore require less material.

The design of the machine needs to be restricted to a level of complexity that lies within the user’s understanding, and requires only simple and sporadic maintenance. The machine’s construction should also be constrained to use materials and a level of production technology that is readily available in the countries where it is to be made and operated. In spite of the prototype being manufactured in an institution where advanced production facilities are available, the constraints above need to be applied to its design to facilitate its subsequent dissemination and acceptance in the field.

A feature of dynamic compaction is that the peak pressures generated are lower (for a specified final block density) than with quasi-static compaction. This means that the mould walls do not need to be as thick as in traditional presses. An experiment was carried out with dynamic compaction using four different moulds. Each had a different mould wall thickness that followed a geometric progression as follows: 32mm, 8mm, 2mm, 0.5mm. For the same energy transfer it was noted that the 8mm and 2mm moulds generated slightly higher density samples, which was an unexpected yet pleasant finding. Furthermore the samples compacted in the thinnest walled mould achieved a high density yet exerted a stress in the mould walls corresponding to only 30-40 microstrain. The yield strain for steel is around 1200 microstrain, so this shows that the material even when very thin is able to deal with the forces present during dynamic compaction. It should therefore be possible to design a mould for a high-densification impact machine that is comparable in thickness with those in traditional low-pressure quasi-static machines. Such a mould will be much cheaper and lighter than those required by the heavy 10 MPa presses needed to produce comparable densification by the quasi-static method.

7.2 Some production guidelines

This section will attempt to outline some of the key areas of concern in a production regime for manufacturing SSB's. Some of the issues have been discussed above whilst others are a result of past research and experience. As full-size block production has not been carried out as yet it is foolish to categorically state anything as being the most important aspect of production. However, it is possible to suggest some important requirements of the manufacturing process that have been revealed in this research.

Moisture content has proved to be a highly significant variable in the production of SSB's. The available water will have an effect on the workability of the soil/cement mix, the achievable density, the de-moulding force, the ease-of-handling and the curing of the cement. Since these are all important, it is difficult to say which has precedence over the others. Having said that, it is in the handling of green blocks that the greatest production losses can occur and therefore achieving adequate ease of handling might be made a first priority when choosing water content. Many experiments were carried out at around 6% moisture where blocks are both easily handled and readily brought to a high density, so this could be a good starting point for full-size block tests.

Thorough mixing of the materials prior to compaction is very important when the quantity of stabiliser is so small. For these experiments the soil/cement/water mixture was very carefully proportioned and mixed together to give a good consistency between experiments. This thorough mixing is difficult to achieve on full-size block and will be even more difficult to practise in the field. Nevertheless, it is advisable to include a measure of care when mixing the materials together as poor mixing will not bring out the full potential of the SSB. It has been said for concrete that "good concrete and bad concrete are made from the same ingredients, it's the method of production that will determine the finished product". The same could be said for the production of SSB's. It may be that it is one of the tasks of a machine designer to address not just moulding but also ingredient batching.

Handling after moulding - once the finished block is compacted it needs to be ejected and carefully moved to a curing area. Even where moisture content has been chosen to enhance ease of handling, design attention needs to be given to reducing breakage prior to curing. Boards can be used to carry blocks around and special block lifting apparatus can be employed to help transfer the blocks to and from these boards.

Curing - a book could be written about the use and abuse of cement in developing countries. Possibly the greatest and yet commonest mistake in a production regime for SSB's is to leave the freshly formed blocks out in the open to "dry out". This makes the cementitious reaction slow down and stop, as the moisture is lost to the environment. Consequently the crystalline growth does not get very far and very little strength is added to the material. Subsequent wetting of the material may help to further cure the cement, but this will not be as effective as thorough curing of the blocks immediately after moulding.

Batch size: Time delay in the production of the SSB's from a batch of soil has been shown to be of importance. If the time, between adding moisture to a batch of soil and the production of the final block from that batch, can be minimised then the SSB's produced will be both stronger and more consistent. The extreme case of having a batch size only large enough to produce one block at a time, is not economically viable and the material for several blocks will need to be made at the same time. However this will introduce unwanted variation in the characteristics of the finished blocks and the blocks produced later in the batch will be inferior to the ones made first. Consequently using a small batch size not only facilitates good manual mixing, but also gives consist block attributes with the batch itself. The ideal of continuous mixing and the design option of adding water only as the charge enters the moulding chamber will be investigated further.

8. CONCLUSIONS AND RECOMMENDATIONS

The first and most important conclusion to make is that the process of dynamic compaction works as effectively as the current method of quasi-static compaction in densifying stabilised soil building blocks. The tests described in this paper have shown that, at least on the small-scale used for tests, the dynamic method performs as well in terms of energy productivity (Pa/J/kg), achieved density and the wet compressive strength of cured blocks. We also have good reason to believe that larger scale dynamic compaction will achieve higher energy productivity than reported here. This finding will need to be confirmed on full-scale tests to be carried out in the future.

The research has also brought to light several factors that affect the stabilisation of soil blocks. Stabilisation is mainly concerned with adding durability and strength to a material that would otherwise be unsuitable for construction. Since the durability of the samples produced could not be checked then compressive strength was used as the best available surrogate. Using the same fraction of cement and the same curing regime, the wet compressive strength of samples was found to depend entirely on the level of compaction that they achieved. Consequently density on demoulding can be used for a satisfactory indication of the subsequent cured strength of a block.

Dynamic compaction brings one significant advantage to the process of heavily compressing soil: it requires much lighter equipment. High-pressure quasi-static compaction is much more complex and expensive than the lower-tech method of dynamic compaction. The experiments reported indicate that a machine for dynamic compaction could be similar in cost yet much superior in performance to the low-pressure quasi-static presses that are popular throughout developing countries. Thin mould walls, short levers and the absence of hydraulics make dynamic compaction available to a wide group of people in need of low-cost housing solutions.

Changing the method of compaction from quasi-static to dynamic is potentially straightforward. However comprehensive machine design is yet to be done and a full-size prototype is yet to be built and tested. This is should be achieved in the next year. The safety of the machine is the only major factor of concern as this needs to be fully addressed before a design can be propagated.

Once a prototype has been produced and laboratory tested then the technique needs to be fully tested in the field using potential users and readily available soils. This process will help to determine the obstacles to successful dissemination of the technology in the areas where it is most applicable. Possibly the largest issue is the public’s attitude towards soil itself. Soil, even when stabilised to perform as well as fired brick and concrete, currently has an unfavourable image and other alternatives still exist for the uneducated urban poor. Small brick clamps are currently the most popular method of soil stabilisation but these use increasingly scarce resources such as firewood in a very inefficient way. Substantial improvements in the performance and economics of the cement-stabilisation alternative are needed if it is to make much headway in the short term.

Future research will initially focus on the extrapolation of the findings to date onto full-size blocks. This should include the fabrication of some sample walling for realistic durability testing. The production process for full-size blocks needs to be carefully refined to ensure that the maximum benefit is obtained from the inputs of effort and cement. Once this research has been completed then it will be necessary to disseminate the findings (especially through demonstration) and to assess reactions to the new technology. The level of technology and understanding required for this technique is such that if the reaction to it is favourable its dissemination could occur by normal processes of copying and commercial initiative in urban areas of relevant low-income countries.

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