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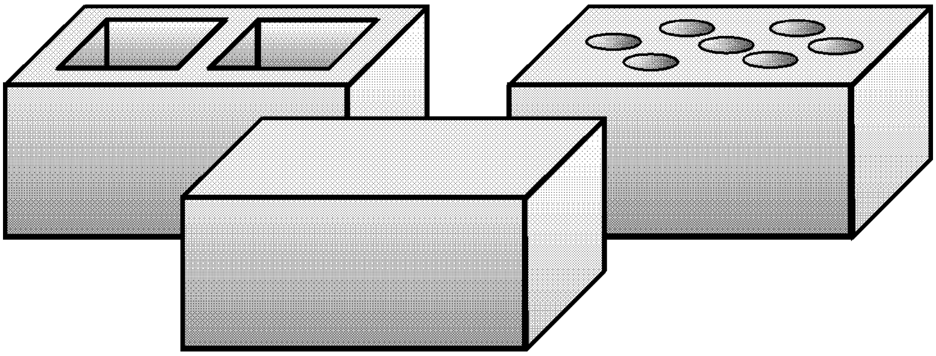
Stabilised Soil Research Progress Report SSRPR06



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

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These reports cover 'work in progress' by research students in the Development Technology Unit (DTU) of the School of Engineering at Warwick University. Their primary purpose is internal - a format for recording ideas and data in a way that allows them to be better discussed before their incorporation into theses, DTU Working Papers or external publications. However they also have a secondary purpose, that of facilitating the sharing of our research with other innovators in the field of building with stabilised soil. Each report, after some initial internal discussion and refining will be posted as a title and synopsis on the DTU web pages (home page= http://www.eng.warwick.ac.uk/dtu). Full copies can be obtained from the respective named authors.

Titles of Stabilised Soil Research Progress Reports Produced to date:

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

A dedication to someone special

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

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

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

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

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

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

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

Abstract

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

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

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

Nomenclature

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

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

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

Cement: Ordinary Portland Cement (OPC).

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

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

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

Fines: General category of silts and clays.

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

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

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

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

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

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

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

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1. Introduction

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

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

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

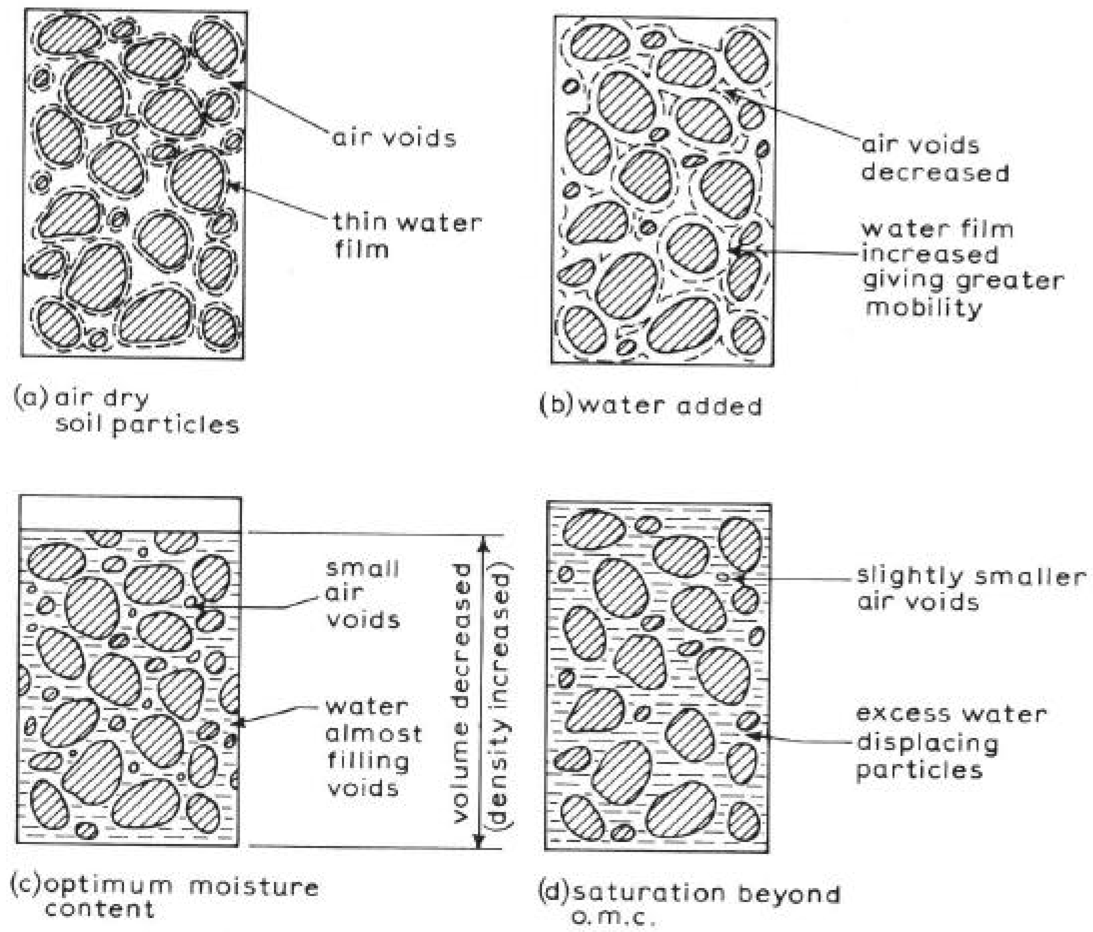
2. Principles of soil compaction

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

2.1 Air void reduction

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

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



2.2 Compacting methods

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

2.2.1 Soil compaction tests

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

BS Ordinary Test (or the Proctor test)

This test uses a 2.5 kg metal rammer with a 50mm diameter face that falls into a cylindrical mould of 105mm diameter. The drop height is kept at a constant 300mm to ensure consistent energy transfer between blows. The blows follow a pattern over the face of the sample to ensure repeatability and consistent compaction of the entire sample. Each sample made up of three layers of soil that has passed through a 20mm sieve and each layer is given 27 blows of the rammer. After compaction the sample is trimmed off to a set height that gives a constant volume of 1000cm^3. This is then weighed and the density can be calculated.

BS Heavy Test

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

Compaction by Vibration

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

Dietert Compaction

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

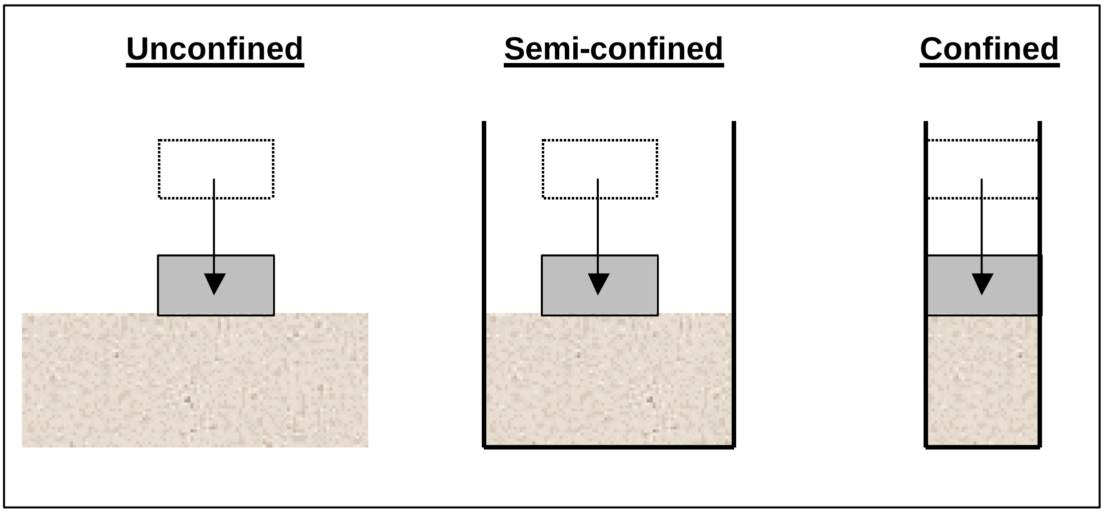
Harvard miniature compaction

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

2.2.2 Compaction test analysis

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

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



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

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

3. Previous dynamic compaction research

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

3.1 Mathematical modelling

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

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

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

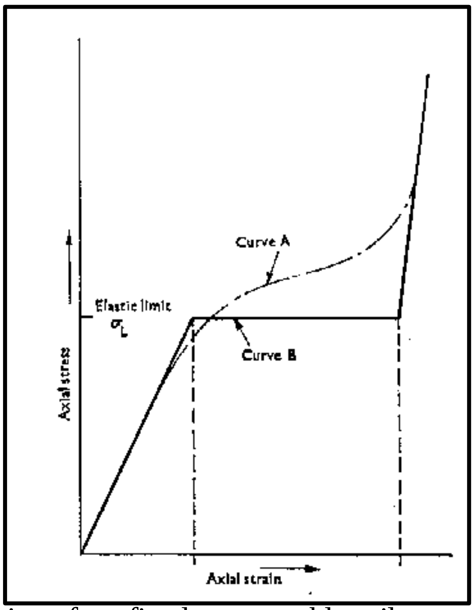


Fig. 2. Axial deformation of confined compactable soil

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

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

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

$$\sigma_L = \rho c v$$

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

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

$$-m\frac{d}{dt}(\dot{u}-v) = \rho_c \frac{d}{dt}\left[(z-u)\frac{d}{dt}(u-vt)\right] + \sigma_L \qquad (8)$$

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

$$-m\frac{d}{dt}(\dot{u}-v) + k_{\rho}\frac{d}{dt}\left[(u-vt)\frac{d}{dt}(u-vt)\right] + \sigma_L = 0 \qquad (9)$$

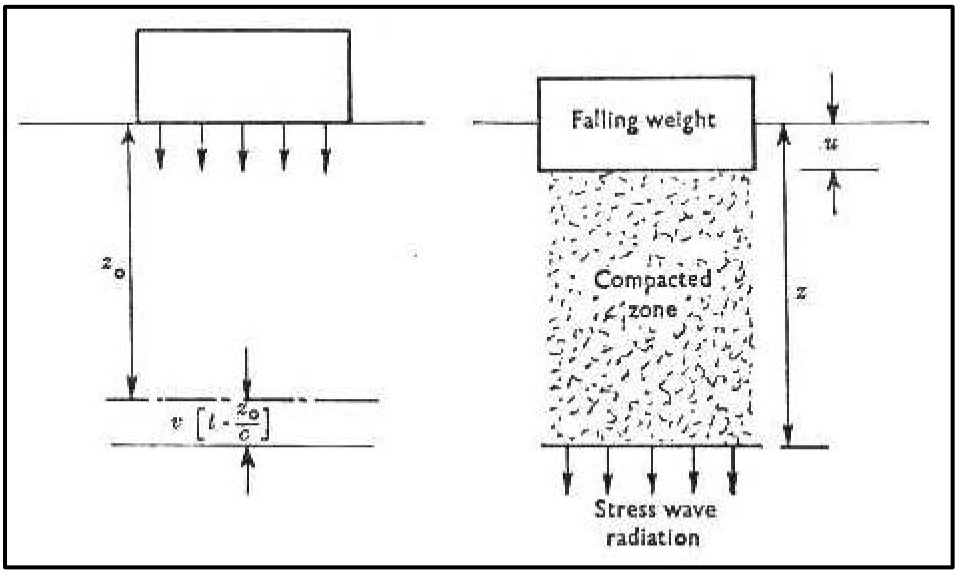


Fig. 3. One-dimensional compaction

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

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

where

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

The surface stress in the soil is then given by

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

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

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

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

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

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

"Theoretical analysis of the factors influencing the performance of dropping-weight compactors

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

12.28 From the well known equations of motion:-

$$V^2 = 2fx \qquad (1)$$

And $$pA = Mf \qquad (2)$$

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

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

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

=dynamic modulus of deformation of the soil

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

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

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

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

where g' = actual acceleration of the falling rammer.

$$p = \sqrt{E_s k_s} \qquad (6)$$

where E_S = specific energy

12.29 These relations indicate that the impact pressure is a function of the energy per unit area of the rammer base (specific energy) and the deformation properties of the soil under dynamic conditions of loading. The latter factor is also likely to be a function to some extent of the area and shape of the rammer base, but little information was available on that aspect at the time that the analysis was made. If it is assumed that the dynamic modulus of deformation behaves similarly to the static modulus of deformation in that the modulus is often found to be inversely proportional to the square root of the loaded area, then:-

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

where C is a constant

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

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

where C = constant for the particular soil conditions.

Thus, if the rammer area is changed, the compaction energy provided by each blow per unit area of rammer base (specific energy)

$\left(\frac{1}{2}M\frac{V^2}{A}\right)$ would have to be kept proportional to the square root of the area of the rammer base $\left(\sqrt{A}\right)$ for a constant pressure to be developed."

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

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

Between the initial resting place of the impactor and the resting place after one blow there is a distance of (0.1571 – 0.1364) = 0.0207m. This is the deformation of the soil during impact (x). The velocity of the impactor prior to impact can be assumed to be $V = \sqrt{2gh} = \sqrt{2 \times 9.81 \times 0.1364}$ = 1.64 m/s …etc.

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

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

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

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

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

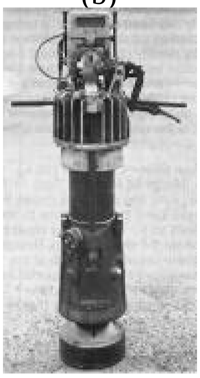
3.2 Dynamic compacting equipment as used in civil engineering

Within the field of civil engineering there are many different types of equipment that have the capacity of compacting a mass of soil. Many of these will not be of interest as they possess very little dynamic properties that help to compact the soil. Even smooth vibrating rollers and vibrating sheep's foot rollers are outside of the field of interest as compaction via vibration is quite different to dynamic compaction.

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

(a)

(b)



(c)

(d)

(e)

Vibro-tampers

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

Power rammers

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

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

Multi-dropping weight compactor

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

Mobile dropping-weight compactor

This machine is called the Arrow D500 dropping-weight compactor and is self propelled with a hydraulically lifted impactor at the front of the machine. A picture of the machine can be seen in part (e) of the above diagram. This device can lift the impactor through a variable height up to a maximum of 2.2 m. A 36 kW diesel engine drives a pump for the hydraulic system to lift the 588 kg mass to the desired height. This can then deliver a maximum of 11167 J/blow, and with a 305 × 305 mm base this equates to a considerable specific energy of 120 kJ/m².

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

3.3 Research done by Gooding for his PhD

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

3.3.1 Quasi-static compaction

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

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

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

3.3.2 Dynamic compaction

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

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

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

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

3.3.3 Other research that was done

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

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

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

3.4 The author's previous research

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

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

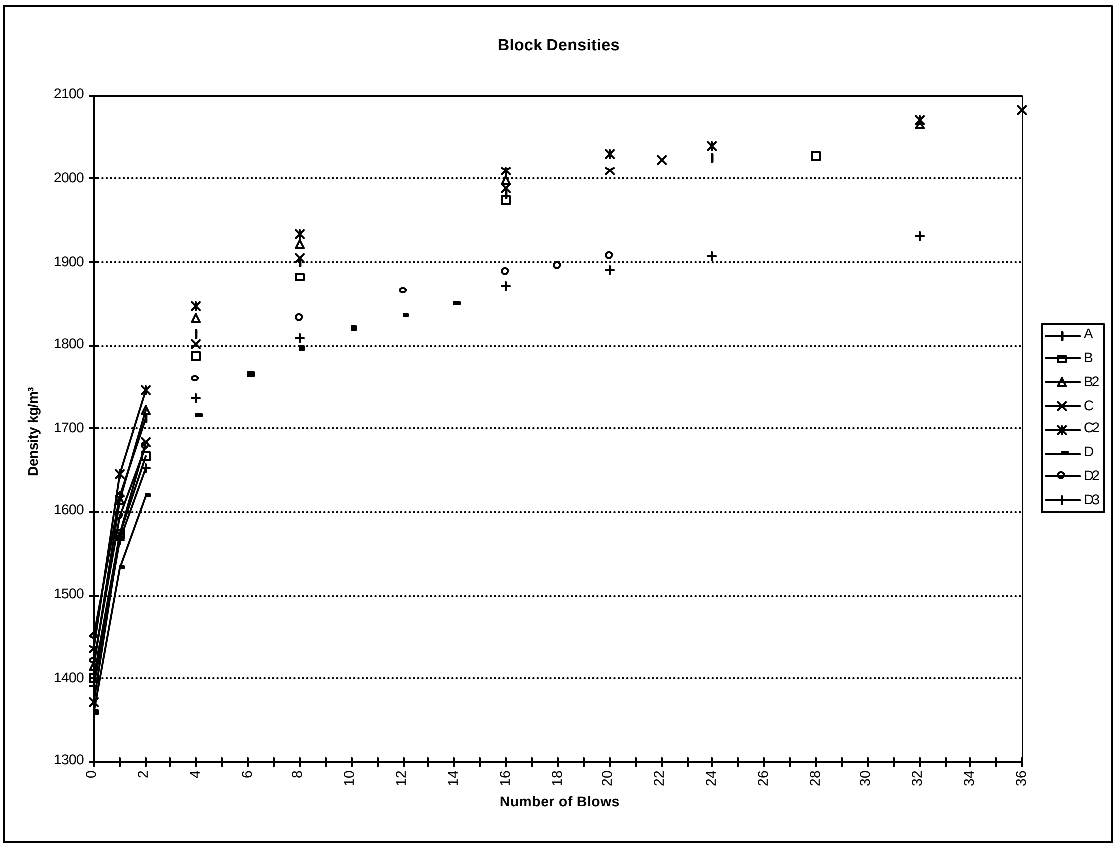
The author also did not stabilise any of the full size dynamically compacted blocks as these were trials to test the feasibility of full size compaction. Consequently there are not any known characteristics of the produced blocks apart from a handful of penetrometer tests done on the freshly demoulded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

4. Discussion of research

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

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

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



Graph showing block density against number of blows received

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

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

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

5. Conclusions and recommendations

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

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

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

Optimisation of the number of blows for small cylindrical samples was done by Gooding for a constant moisture content. This optimisation needs to be extrapolated onto full size blocks to determine if there are any better arrangements for delivering a fixed amount of energy into a sample of stabilised soil. The moisture content has not been altered with respect to the cement content and this may be of significance. A lower moisture content may not yield the block with the greatest density, but it may yield a block with a higher wet compressive strength and durability. Parsons reported small changes in moisture content around the optimum to try and discover if the different compacting method yielded a different optimum moisture content. A similar exercise needs to be done with confined stabilised soil samples.

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

6. Summary

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

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

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

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