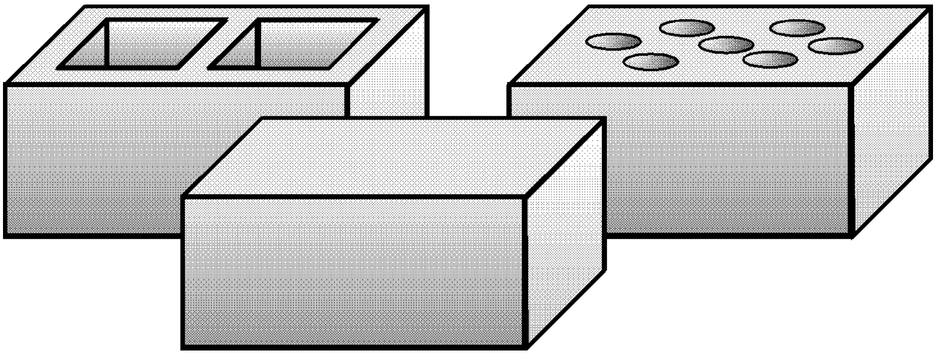
Development Technology Unit
School of Engineering
University of Warwick
Coventry CV4 7AL UK
Tel (Office) +44/0 1203 522339
Director 523122, Fax 418922
Email dtu@eng.warwick.ac.uk

Web site at http://www.eng.warwick.ac.uk/DTU/

Stabilised Soil Research Progress Report SSRPR2



How does cement stabilisation work?

Author: Mr D E Montgomery
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E-mail: d.e.montgomery@warwick.ac.uk

A dedication to someone special

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

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

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

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

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

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

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

Abstract

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

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

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

Nomenclature

Aggregate: Pieces of crushed stone, gravel, etc. used in making concrete.
Brick: An object usually of fired clay used in construction, usually of rectangular shape, whose largest dimension does not exceed 300mm.
Block: A larger type of brick not necessarily made of fired clay, but stabilised in some way, sometimes with central cores removed to reduce the weight.
Cement: Ordinary Portland Cement (OPC), a finely ground clinker which sets hard after mixing with water.
Clay: The finest of the particles found in soil, usually of less than 0.002mm in size and possesses significant cohesive properties.
Clinker: A slag formed when clay and lime a burnt in a furnace together.
Concrete: The finished form of a mixture of cement, sand, aggregate and water.
Dynamic Compaction: A process that densifies soil by applying a series of impact blows to it.
Gravel: A mixture of rock particles ranging from 2mm to 60 mm in diameter.
Green: Describing the state of material containing cement and water before it reaches the critical time, after which further plastic deformation hinders the final set strength.
Gypsum: A hydrated form of calcium sulphate.
Mortar: A mixture of sand, cement and water.
Sand: A mixture of rock particles ranging from 0.06mm to 2 mm in diameter.
Sandcrete (Cured Mortar): The finished form of a mixture of cement, sand and water.
Sharp Sand: Describes the angular nature of sand particles that are very good for making concrete or mortar.
Silt: Moderately fine particles of rock from 0.002mm to 0.06mm in size.
Slaked Lime (Lime): Quicklime (calcium oxide obtained by burning limestone), that has been mixed with water creating calcium hydroxide which has further setting qualities.
Soil: Material found on the surface of the earth not bigger than 20mm in size, not including rocks and boulders and predominantly non-organic. If soil is to be used for building material it must not contain any organic material and it can be a natural selection of particles or a mixture of different soils to attain a more suitable particle distribution.
Soil-cement: Similar to mortar, but prepared from soil with a wider particle distribution.
Stabilised soil: Soil which has been stabilised (treated to improve structural characteristics) by using one or more of the following stabilisation techniques: mechanical, chemical and physical.

Table of Contents

1. Introduction

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

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

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

2. Some facts about cement.

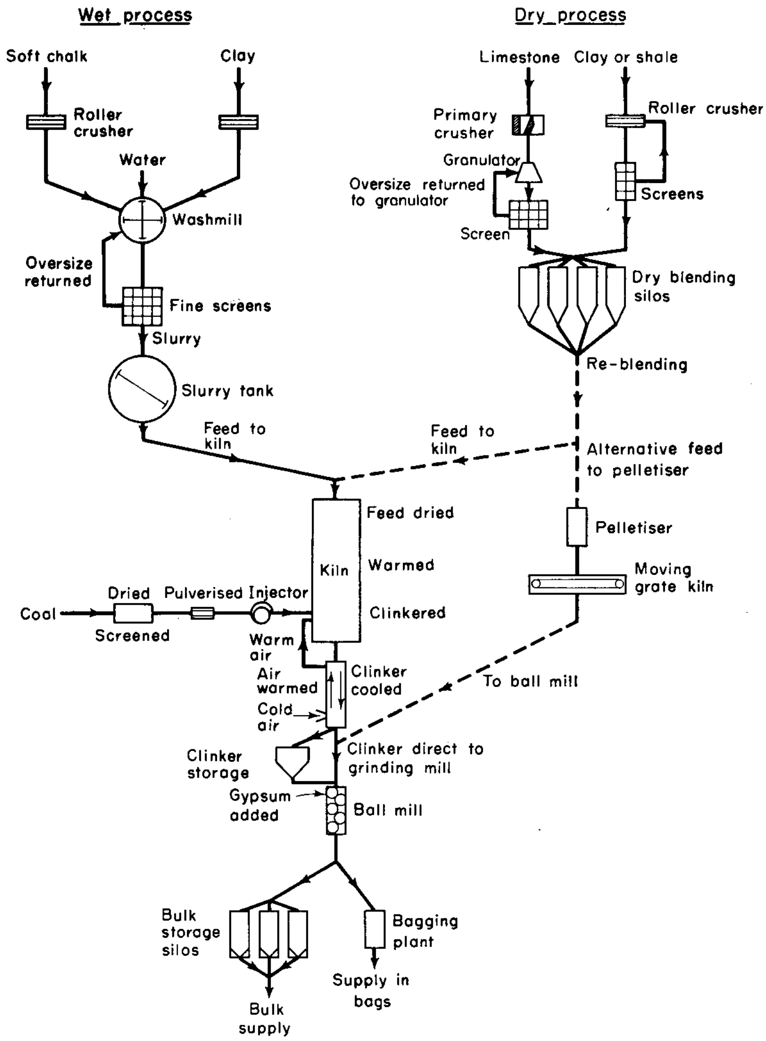
This section will concentrate on establishing the properties and composition of cement. This knowledge will provide a simple foundation for understanding the way that cement works. It will not describe in too much detail the characteristics or production of cement, as this has already been previously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

2.1 Chemical composition and production

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

	Percent (%)	Average(%)
Lime (CaO)	59 -67	64
Silica (SiO_2)	17 -25	21
Alumina ($A1_20_3$)	3 - 9	7
Iron oxide (Fe_2O_3)	0.5-6	3
Magnesia (MgO)	0.1-4	2
Sulphur trioxide ($S0_3$)	1 - 3	2
Sodium potash	0.5-1.3	1

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



2.2 Relative cost to other materials

The price per kilogram of cement will vary greatly depending on the distribution network and the proximity to the cement processing plant. Cement can usually be considered to be one of the more expensive materials necessary for building construction. In the field of low tech, low cost soil brick housing, it is crucial that the total cost of the cement as a proportion of the entire structure is kept as low as possible. One would ultimately like to minimise the cement content and maximise the strength and life of the structure. Through a variety of procedures the amount of cement necessary can be reduced and these may be investigated in more depth separately later on in the research. For the moment, the author is taking previous research to suggest that a nominal 5% cement is sufficient for good stabilising of soil blocks.

2.3 Distribution problem

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

3. Making concrete

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

3.1 Material selection and requirements

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

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

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

3.2 Mixing quantities and preparation

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

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

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

3.3 The effect of compaction

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

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

As yet the author has not found little information (other than previous work at Warwick) on the compacting of a green mix using a moving mass, such as a hammer or weight. This process has been hinted at in (Akroyd, 1962), (p. 196), but no details were given, as the compaction process has been replaced by internal and external vibrators to reduce the labour costs of manual compaction. It is precisely this manual compaction that is of interest to this project as the stabilised soil samples are to be compacted and hence the cement also is compacted. What we can learn from the references Akroyd and Gooding, is that compacted concrete has stronger characteristics than un-compacted concrete.

4. Curing process

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

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

4.1 Inter-particle bonds, Why are they formed?

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

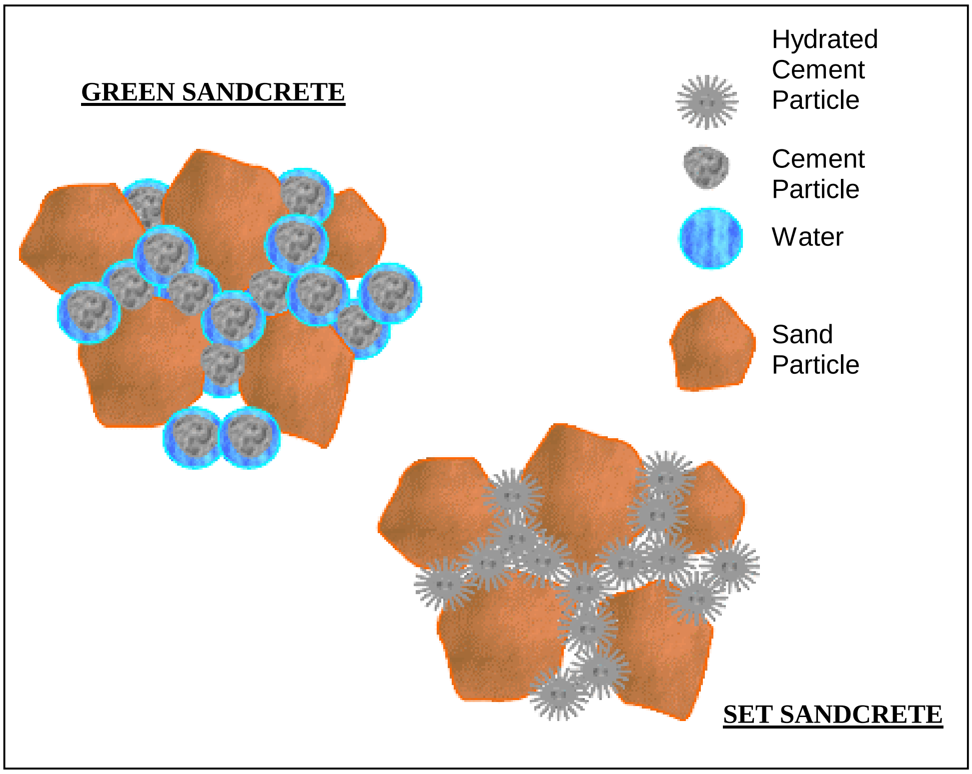
Once cement, sand, aggregate and water are mixed thoroughly the mixture gains a certain cohesion with itself. This cohesion greatly depends on the amount of free-water present as an excess of water will lead to a more runny consistency. Assuming the correct amount of water is applied to ensure complete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

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

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

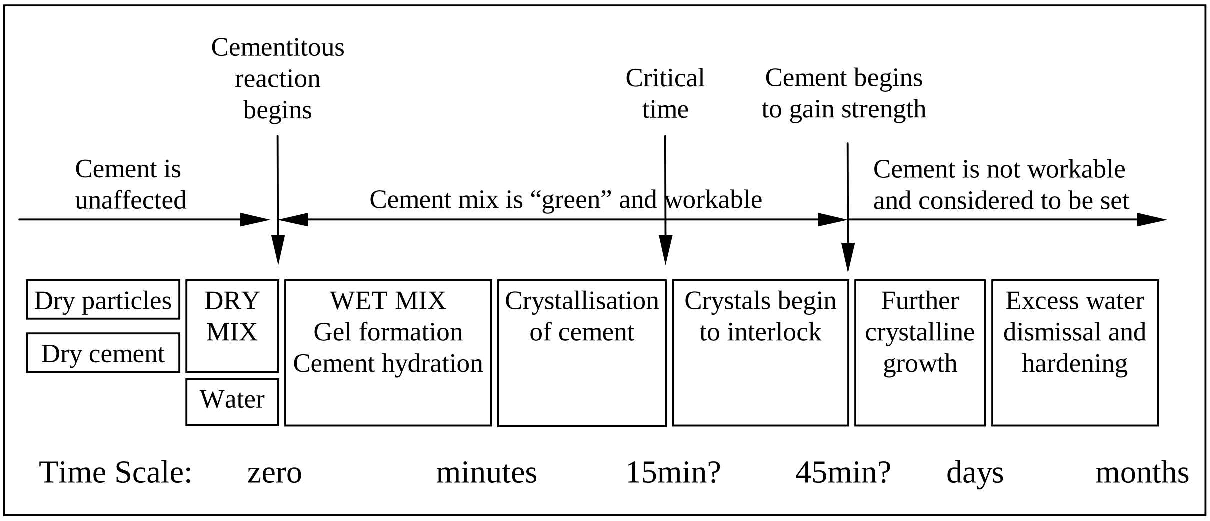
The difference between the strength available in tension and compression is suggested to be that in tension the particles are held together with relatively weak Van der Waal forces. However, in order to separate the particles in compression the forces are acting against the much stronger hydrogen bonds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

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



4.2 Wet strength and curing times or cycles

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



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

In order to maximise the green strength of the mixture one needs to ensure that the free-water content is as small as possible and to leave the mixture untouched for as long as possible to permit the cementitous action to bond the particles together. The exact length of time that is necessary to achieve this may be discovered by trial and error, but as mixture quantities and handling techniques may vary "as long as possible” may be a good initial estimate. Setting can take place in as little as 45 minutes, but useful hardening will take much longer, (Stulz & Mukerji, 1993), (p. 63). The green strength of mixed samples can be tested to give a more accurate answer, using both destructive, i.e. compressive tests, or non-destructive, i.e. scratch tests, to determine the approximate green strength of the formed mixture.

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

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

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

4.3 Moisture dismissal and shrinkage

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

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

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

To minimise shrinkage one must minimise the potential space between particles in the mixture. Clearly the sand and aggregate particles themselves do not shrink, and similarly the cement and formed cementitic crystals are not prone to shrinkage. This leaves the physical gaps between adjoining particles and the gaps left by excess water when it has evaporated off, being the primary cause for potential shrinkage.

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

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

4.4 Strength testing

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

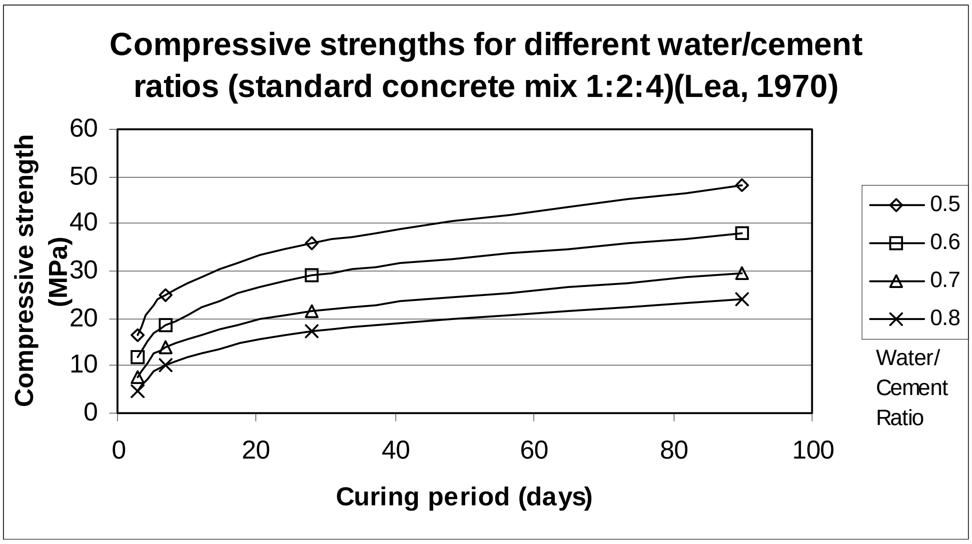
The final set strength of a concrete mix is directly proportional to the water/cement ratio, provided that the workable concrete is compacted so that it contain less than 1% by volume of air voids. This relationship can be expressed as $S = A/B^x$, where S is the compressive strength, x is the water/cement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

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

TABLE 59

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

Or viewed graphically:



4.5 Longevity, environmental attack

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

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

5. Application of cement to stabilise soil

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

5.1 Basic requirements of soil

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

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

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

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

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

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

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

5.2 Particle, particle interaction/intimacy

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

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

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

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

5.3 The curing process re-applied

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

5.4 Moisture attack

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

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

6. Conclusions and recommendations for further work

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

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

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

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

Topics for further investigation

- A more detailed account of the interaction between cement and clay and why too much clay in the mixture is detrimental to the effectiveness of the cement.
- A brief study of the effect of multi-stage curing or wetting cycles on cement stabilised soil. Is an environment of 100% humidity totally necessary? or can a series of wetting cycles be just as adequate?
- How critical is the moisture content for dynamic compaction? Can a drier mix of soil can be compacted by this method better than quasi-staticly compressed soil-cement?
- If a much drier soil is used for compacting, can wetting after compacting encourage further cement particles to hydrate and hence increase the overall strength?

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

7. Summary

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

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

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