

# **Bored piles with expansive concrete**

by

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I hereby declare that, except where specifically indicated, the work submitted herein is my own original work.

## Technical Abstract

Piled foundations are an increasingly common method of conveying loads from a structure built on soft ground to a strong bearing stratum. Bored piles, especially friction piles, rely on shaft resistance to carry vertical loads. The design load to be resisted determines the length and diameter of the bored pile, which in turn determines its cost. However, the skin friction may not be being maximised, meaning that piled foundations may be being built deeper or wider than necessary. Hence this project aims to investigate whether the shaft resistance of a bored pile can be enhanced using magnesia (MgO) expansive additive.

Magnesia has been used as an expansive additive in concrete for many decades, to control drying shrinkage and thermal cracking, but it has not yet been applied to enhancing pile capacity. Magnesia causes concrete to expand when it hydrates to form brucite ( $\text{Mg}(\text{OH})_2$ ), which has a larger volume. The literature review found that MgO is the most suitable expansive additive compared to ettringite and quick lime based additives, because its expansion occurs later and is more stable. Of the different grades of MgO available, light-burnt MgO hydrates the quickest, producing fast and large expansion.

An investigation into cement paste was conducted, in which the compressive strengths, expansions and drying shrinkages of specimens were recorded. The pastes used a 1:1 blend of Portland cement (PC) and ground granulated blast furnace slag (GGBS), with a percentage of the blend being replaced by MgO. The MgO contents tested were 0%, 5% and 8%. Higher contents were avoided so that strength was not adversely affected. Typical water-cement ratios of 0.33 and 0.37 were tested. Two different grades of MgO were studied: light-burnt 92-200 MgO and a hard-burnt Expansive MgO commercially available in China.

Unconfined Compressive Strength (UCS) tests were performed on 40mm cubes at 1, 7, 14 and 21 days. Measurements of shrinkage and expansion were made on 160x40x40mm prisms and taken at ages of 1, 3, 5, 7, 10, 14, 21, 65, 105, 165 days.

The cement paste investigation confirmed that an increase in MgO content leads to an increase in expansion. The addition of MgO was also observed to compensate drying shrinkage. An MgO content of 5% gave an increase in compressive strength compared to the plain specimen, but a further increase to 8% caused strength to fall.

Cement pastes with a water-cement ratio of 0.33 were stronger, shrank less but expanded less than pastes with a water-cement ratio of 0.37. The cement paste with light-burnt 92-200 MgO

expanded more, shrank less and had a higher compressive strength than the paste using hard-burnt Expansive MgO.

Following the cement paste investigation, lab-scale models of piles were tested. In this investigation pull-out tests were performed after 14 days of curing in a drum of sharp sand. The drum was 280mm in diameter and 500mm tall. Piles were approximately 110mm in diameter and 300mm in length. The piles were made from cement paste with MgO contents of 0% or 8% or concrete with MgO contents of 0%, 5%, 8% or 11% in its binder. The cement paste piles were in moist or saturated sand. The concrete piles were in sand which was saturated either to half of the pile's depth or the entire depth of the pile, to investigate whether the water table would have an effect on shaft resistance.

During the pull-out tests, the force lifting the pile and its displacement were recorded. After the tests, the piles were removed from the drums and measured to assess expansion. The bases of the piles were trimmed, in order to perform UCS tests on short cylindrical samples of cement paste or concrete at an age of 28 days.

The investigation concluded that MgO causes piles to expand which compresses the surrounding soil and increases shaft resistance, hence pile capacity. This means that there can be a reduction in the design length or diameter of bored piles, which would reduce construction costs and timescales.

The pull-out resistance increased with MgO content. For instance, a concrete pile made using a binder with 5% MgO had a pull-out resistance 1.61 times higher than the pile without MgO, so only has to be 0.62 times the length of a conventional bored pile. The pile with a binder that was 11% MgO had a pull-out resistance almost 4 times higher than the pile without MgO, so could be a quarter of the length of a conventional bored pile.

Furthermore, the compressive strength of the piles did not reduce when MgO was added to the concrete, and was actually shown to have improved in most piles with MgO. The highest strength observed for a concrete pile used a binder with a 5% MgO content. The density and diameter of the piles generally increased with MgO content.

This project has shown that MgO can be added to concrete to improve the pile capacity and compressive strength of bored piles in granular soils. Further work can be undertaken to verify the results and advance this field of research.

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# Chapter 1: Introduction

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## 1.1 Background

Non-displacement or bored piles are becoming more common as buildings become ever taller. They are constructed by boring a hole in soil, lowering in a reinforcement cage and pouring in concrete to fill the hole, which sets to form the pile. The piles carry the vertical load from the superstructure by two means: end bearing resistance and shaft resistance, together known as pile capacity. Friction piles are those where the majority of the load is carried by shaft resistance, typically when the pile is not bearing on bedrock. For such piles, and for piles where the base capacity is generally low, the shaft resistance is usually very important. Shaft resistance is dependent on the length and diameter of the pile and the unit shaft friction: a combination of the friction angle between the soil and the pile, and the effective stress profile in the ground.

Pile length and diameter are usually the design variables that are manipulated to achieve the required shaft resistance to support the building. As construction costs increase with pile length or diameter, it would be advantageous if the unit shaft friction could be increased, allowing the length or diameter of the pile to be reduced.

By casting the pile using concrete containing expansive additives, the friction angle at the interface between the soil and the concrete pile could be increased, therefore increasing the unit shaft friction and, consequently, the shaft resistance.

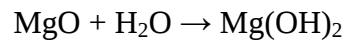
Expansive additives are not commonly used in standard concrete practice in the UK, despite use in the construction industry in the US and other countries, including China and Japan. The expansive additives used in the US are mainly ettringite based (Hoff, 1972), those in Japan are quicklime (CaO) based (Chen, 2006) and those in China are magnesia (MgO) based. Hence, there is very little experience in the UK with the use of expansive additives in concrete. Furthermore, there is very little published on the use of expansive additives in concrete for piling applications.

Magnesia, or MgO, is the expansive additive used throughout this project. It was first used in dam construction in China, where discovery of its expansive properties was discovered accidentally (Du, 2005). It was observed that the Baishan dam had not suffered from thermal shrinkage cracks and this was the result of a high MgO content in the cement that had been

used. The slow hydration of the magnesia had produced late-age expansion (Mo et al, 2012). MgO was then added to concrete on several successful dam projects thereafter.

When added to Portland cement, the effects of drying shrinkage and thermal cracking can be reduced while having very small impacts on the concrete's strength, stiffness or durability. This has meant that less steel reinforcement has been needed for crack control. Also, its expansion profile has been reported to closely mirror the shrinkage profile of mass concrete (Du, 2005), so MgO is well suited to counteract drying shrinkage compared to other expansive additives.

MgO causes autogenous expansion in concrete through its expansive hydration when mixed with water to form magnesium hydroxide (brucite).



|                               | MgO  | H <sub>2</sub> O | Mg(OH) <sub>2</sub> |
|-------------------------------|------|------------------|---------------------|
| Mass (g/mol)                  | 40.3 | 18.0             | 58.3                |
| Density (g/cm <sup>3</sup> )  | 3.58 | 1.00             | 2.34                |
| Volume (cm <sup>3</sup> /mol) | 11.3 | 18.0             | 24.9                |

The formation of brucite results in chemical shrinkage ( $11.3 + 18.0 > 24.9$ ) but the volume of solids has more than doubled. Without the hydration of magnesia, the free water would evaporate from the fresh cement, which leads to drying shrinkage. However, in moist curing conditions, hydration using external water leads to a Mg(OH)<sub>2</sub> molecule 118% larger than that of MgO (Xu and Deng, 2005).

There are different grades of MgO available: light-burnt, hard-burnt or dead-burnt, which have different expansive characteristics because of the temperature that the MgO was burned, or calcined, at during production.

This project conducts research into the use of expansive additives in concrete bored piles. If successful in showing that shaft capacity can be increased with expansive additives, there can be implications for the construction of deep foundations in the future. Shorter expansive piles could be able to achieve the same pile capacity as a longer conventional pile. This would lead to reductions on the volume of concrete poured, the amount of steel reinforcement used and

the amount of soil excavated. Therefore, construction costs can be decreased and construction times can be shortened.

## **1.2 Aim and Objectives**

The aim of this project was to investigate how MgO as an additive in concrete can increase the shaft resistance of a bored pile.

The objectives of this project were to:

- Investigate the influence of magnesia in cement paste in shrinkage, expansion and compression tests
- Observe the effects of varying water-cement ratio and curing conditions on the performance of the cement paste
- Investigate the effects of magnesia and curing conditions on laboratory-scale models of piles in pull-out tests
- Compare the test results to calculated shaft resistances for conventional piles
- Observe the effects of magnesia and curing conditions on the expansion of the piles
- Identify the key attributes of a concrete mix using expansive additives, for application in pile construction
- Estimate the percentage by which pile length can be reduced if expansive additives are used

## **1.3 Structure of Report**

This report is divided into six chapters. Chapter 1 introduces the project, the motivation for the research and states the aim and objectives. Chapter 2 is a literature review of research papers covering the theories of pile capacity and expansive additives in concrete. Chapter 3 explains the apparatus, experimental procedure and results of the investigation into cement paste behaviour. Chapter 4 covers the apparatus, experimental procedure and discusses the results of the pull-out tests on lab-scale piles. Chapter 5 presents the conclusions drawn from this project and suggestions for further research in the future. Chapter 6 lists the references used, followed by the risk assessment retrospective.

# Chapter 2: Literature Review

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A review of technical papers was conducted to determine what relevant research had already been done, in order to guide this project's research and form an experimental plan. There is very little work in the literature on the use of expansive concrete in bored piles. Hence the papers mostly cover the properties and behaviour of MgO and other expansive additives in cement pastes, with the key theory presented below.

## 2.1 Shaft capacity of bored piles

The unit shaft friction on a pile is equal to the horizontal effective stress at that depth multiplied by the tangent of the friction angle between the pile and the soil,

$$\tau_s = K \cdot \sigma_v' \cdot \tan \delta$$

Total shaft resistance is calculated by integrating the unit shaft friction on the surface area along the length of the pile.

$$Q_s = \int_0^L \tau_s \cdot \pi D \cdot dz$$

Bored piles are widely used for deep foundations and are constructed by boring a hole in the ground, by loosening a column of soil with a cutting tool or auger and transferring the loose spoil to the ground surface with a grab bucket or by lifting and spinning it off the auger. A continuous flight auger can loosen and remove soil simultaneously. In soft soils, once excavated, the hole must be kept open using heavy bentonite slurry to prevent collapse. The reinforcement cage is lowered and concrete is poured into the hole through a tremie pipe, so it enters at the base and pushes the bentonite mud out. The pipe is raised slowly as concrete is poured.

Horizontal stresses in the ground are relieved as the hole is opened. This leads to negative pore pressures that dissipate, reducing the horizontal effective stress. Consequently, the soil swells and softens, which would lead to a reduction in shaft resistance. Drilling muds, such as bentonite slurry are therefore used to maintain a lateral pressure and reduce the drop in total stress. However, soft soil cuttings leftover from excavation at the base of the hole may reduce base resistance (Haigh, 2013).

There are a few techniques available to increase the pile capacity of a bored pile. Shaft and base grouting has been widely reported to increase pile capacity by 1.5 to 3 times compared to a plain bored pile by improving the end bearing and shaft resistances.

Once the concrete pile has set, water is injected through *tube a manchettes* (TAMs) installed in the reinforcement cage of the pile, to crack the cover concrete and form a path for the grout. Grout is injected through the TAMs to fill voids in the pile and between the pile and the soil. As the grout is injected, the soil around the pile is compressed, increasing the stiffness and lateral earth pressure. In sands, grout increases the strength of the soil it permeates into. The grout is a mixture of water, cement, bentonite, admixtures and superplasticisers to ensure good flow, durability and that the grouted pile acts homogeneously. The grout will have a 28-day strength of 20-25 MPa. For the Rupsa Bridge project in Bangladesh, this process had been found to increase pile capacity by up to 5 to 7 times compared to plain bored piles. This sharp improvement has been attributed to the higher volume of grout injected: 50 litres/m<sup>2</sup> instead of the normal 25-35 litres/m<sup>2</sup>. (Manai, 2010).

If there is a strong bearing stratum, base enlargement, or under-reaming, can be used to increase pile capacity. This technique uses a cutting tool that is lowered down the excavated hole and opens out to excavate a chamber in the soil. When the pile is cast, it will have a wider base and a greater surface area, so end bearing and shaft resistances will be higher.

Another method of increasing shaft resistance could be the use of expansive additives in concrete. They have already been applied to controlling the shrinkage of concrete through use in expansive cements.

## 2.2 Concrete shrinkage

Autogenous or chemical shrinkage is caused by hydration of cement as it sets and is the shrinkage without loss of water to the surroundings. It occurs when water-cement ratio is low, i.e. less than 0.42, and demand for more water creates capillaries within the cement, the surface tensions of which cause shrinkage. If wet curing is used, autogenous shrinkage will not occur because water will be drawn into the capillaries from the surroundings. Otherwise it can lead to shrinkage cracking (The Concrete Society website).

Drying shrinkage is different and concerns the shrinkage with loss of capillary water to the surrounding environment, such as bleed water and excess internal water that evaporates from the surface (Concrete Basics website).

The heat generated by hydration in concrete, combined with concrete's low thermal conductivity, can produce large temperature differences between the interior and exterior of mass concrete. As it cools, the concrete undergoes thermal shrinkage, which leads to large thermal stresses and cracking. Expensive and time-consuming methods are sometimes used to control the temperature of the concrete in order to reduce thermal cracking. Expansive cements and/or additives can be used instead (Mo et al, 2012).

## 2.3 Expansive additives

Expansive additives have been added to cement to compensate shrinkage and reduce cracking on dams, bridge decks, slabs, liquid storage tanks and grouting operations. These cements can be classed as ettringite-based or hydroxide-based.

Three ettringite-based expansive cements - Type M, K and S - are in the ASTM C845-04 standard and were given those designations by the American Concrete Institute. They have been used in the US since the 1963. Their expansion comes from the formation of ettringite - which has the chemical formula  $(\text{CaO})_6(\text{Al}_2\text{O}_3)(\text{SO}_3)_3 \cdot 32\text{H}_2\text{O}$  - that results from the reaction of an aluminate with calcium sulphate. The expanding reactants in Type K cement are anhydrous calcium aluminosulphate ( $\text{C}_4\text{A}_3\text{S}$ ), calcium sulphate and quick lime. In Type M, they are calcium aluminate (CA) and calcium sulphate. In Type S, they are tricalcium aluminate ( $\text{C}_3\text{A}$ ) and calcium sulphate. The quick lime in Type K cement also forms portlandite to give expansion. Ettringite formation should not occur too early because it will not compensate shrinkage if expansion occurs when cement is still plastic, and this can cause more cracking later on. Conversely, if it expands too late, the ettringite will damage the concrete structure and reduce its strength. So the type of aluminate and amounts of aluminate and calcium sulphate are regulated to control ettringite formation (Hoff, 1972; Chen, 2006).

Quick lime ( $\text{CaO}$ ) is an expansive additive predominantly used in Japan. Its hydration product is calcium hydroxide ( $\text{Ca}(\text{OH})_2$ ), also known as portlandite. The volume of the calcium hydroxide molecule is 96% larger than that of the calcium oxide molecule. It can compensate concrete shrinkage but the hydration of quick lime releases a large quantity of heat, which can intensify thermal shrinkage (Chen, 2006). All of its expansion occurs in the

first 30 hours from set, but some shrinkage occurs after this period. CaO contents of 4 to 10% were found to show a net expansion after 28 days. Quick lime additives do not influence drying shrinkage (Samdariya et al, 2009).

Magnesia (MgO) has been used mainly in China and hydrates to form magnesium hydroxide ( $\text{Mg}(\text{OH})_2$ ), or brucite. It has been used to as a temperature-control measure and to reduce cracking on several dams.

Compared to the Type M, K or S expansive cements, concrete with added MgO has a higher compressive and tensile strength, higher tensile strain capacity and a higher modulus. The ettringite-based expansive cements also expand most before 7 days, which is too early to compensate the shrinkage of concrete as it cools, but MgO expands most after 7 days, so it is better suited for this purpose (Du, 2005). Type M, K and S cements cost much more than Portland cement (Chen, 2006).

Sulfo-aluminate and CaO additives expand concrete at an early age (before 14 days), so are less well suited to compensating drying and thermal shrinkage. Sulfo-aluminate additives, including AEA and UEA, cause expansion by forming ettringite. But ettringite is dangerous, as it may decompose at temperatures over  $70^\circ\text{C}$  and lead to a loss in strength. Conversely, MgO requires less water to hydrate and  $\text{Mg}(\text{OH})_2$  is more stable (Mo et al, 2010).

As ettringite requires a lot of water to form, it normally requires at least 7 days of continuous wet curing in order for expansion. Also, the required volume of external water may not be able to penetrate to the centre of mass concrete, so hydration may not complete, even in wet curing conditions. On the other hand, MgO can cause expansion without wet curing as its hydration has a much lower water demand: a water-MgO ratio of 0.45 is needed for complete hydration to brucite, while ettringite requires a water-AEA ratio of 0.85.

Ettringite expands at very early ages and AEA gave no expansion to compensate thermal shrinkage; MgO was found to be the best additive for compensating shrinkage at later ages because of its slower hydration rate. (Mo et al, 2012).

## 2.4 Magnesia (MgO)

### 2.4.1 Calcination

Magnesia can be produced by decomposing magnesite (magnesium carbonate) rock,  $\text{MgCO}_3$ , which has been mined and crushed. The magnesite is burned to remove  $\text{CO}_2$  and leave  $\text{MgO}$ . One kilogram of pure magnesite can yield 0.48kg of magnesia. Similarly, a filter cake of magnesium hydroxide,  $\text{Mg}(\text{OH})_2$ , produced in a seawater or brine process, can be calcined to remove  $\text{H}_2\text{O}$  so that  $\text{MgO}$  remains. One kilogram of pure magnesium hydroxide can yield 0.69kg of magnesia (Shand, 2006).

The properties of  $\text{MgO}$  depend on the temperature it is burned, or calcined, at. If it is calcined at  $1400^\circ\text{C}$  or higher, the  $\text{MgO}$  is dead-burnt and has low activity. Portland cement contains a small, controlled amount of dead-burnt  $\text{MgO}$  (periclase) as its clinkering temperature is  $1400^\circ\text{C}$ .  $\text{MgO}$  grain size increases with calcining temperature, so dead-burnt  $\text{MgO}$  has a large grain. This reduces specific surface area and increases neutralisation time, which leads to slower hydration. The same effects occur if the  $\text{MgO}$  is calcined for a longer residence time (Mo et al, 2010). Dead-burnt  $\text{MgO}$  gives small expansion at early ages although a larger final expansion is reached when hydration is complete after 6-8 years (Mo and Deng, 2007).

Light-burnt, or reactive,  $\text{MgO}$  is calcined between  $700^\circ\text{C}$  and  $1000^\circ\text{C}$  and has higher activity so gives large, rapid expansion at an early age (Mo et al, 2010). Light-burnt  $\text{MgO}$  takes 3-6 months to complete hydration and for its ultimate expansion to be reached (Mo and Deng, 2007). Calcining at intermediate temperatures ( $1000^\circ\text{C}$ – $1400^\circ\text{C}$ ) produces hard-burnt  $\text{MgO}$ , which takes longer to hydrate. Light-burnt and hard-burnt  $\text{MgO}$  grades are used in concrete as expansive additives.

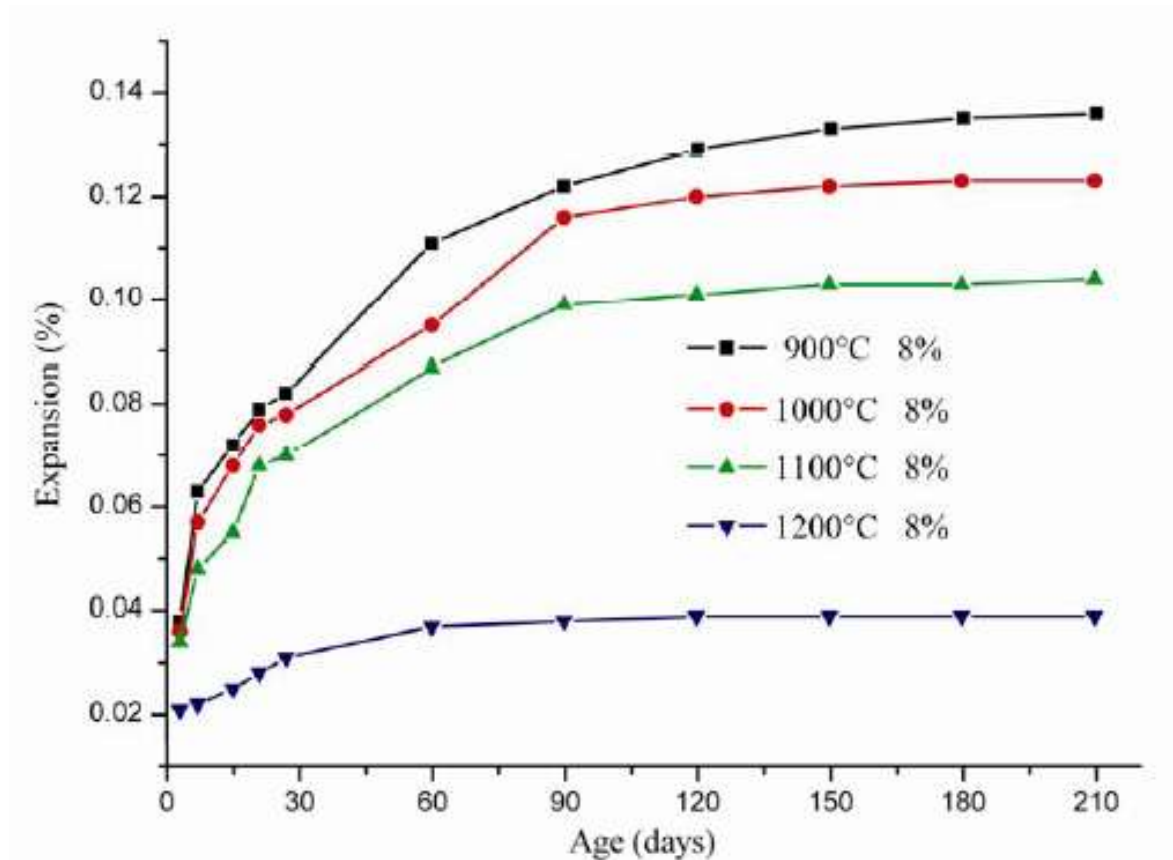
The hydration of hard-burnt  $\text{MgO}$  does not compensate the shrinkage of concrete as well as light-burnt  $\text{MgO}$ , because it expands less.  $\text{MgO}$  calcined at lower temperatures ( $900^\circ\text{C}$ ) consist of smaller particles so hydration is faster and expansion is greater.  $\text{MgO}$  should be ideally calcined at  $900$ - $950^\circ\text{C}$  (Li et al, 2010).

Table 2.1 shows the amount of  $\text{MgO}$  hydrated after 1, 3, 30 and 360 days for three different calcining temperatures of  $800^\circ\text{C}$  (light-burnt),  $1200^\circ\text{C}$  (hard-burnt) and  $1400^\circ\text{C}$  (dead-burnt), displaying hydration time increasing with temperature.

Figure 2.1 shows the expansion of cement pastes with 8% MgO, calcined at temperatures from 900°C to 1200°C, displaying expansion increasing as calcining temperature decreases.

*Table 2.1: Effect of burning temperature on hydration rate of MgO powder (from Du, 2005)*

| Hydration time<br>(days) | Burning temperature (°C) |       |       |
|--------------------------|--------------------------|-------|-------|
|                          | 800                      | 1200  | 1400  |
| 1                        | 75.4%                    | 6.5%  | 4.7%  |
| 3                        | 100%                     | 23.4% | 9.3%  |
| 30                       | -                        | 94.8% | 32.8% |
| 360                      | -                        | 97.6% |       |



*Figure 2.1: Expansion of cement pastes with 8% MgO expansive agent (from Li et al, 2009)*

#### 2.4.2 Expansion

There is a volume expansion of 118% when MgO hydrates to form  $\text{Mg}(\text{OH})_2$  (Xu and Deng, 2005). The amount of concrete expansion that will be achieved depends on the quantity of MgO added, the type of MgO used and the curing temperature (Du, 2005).

There is a slight difference between the amounts of expansion observed between cement paste and concrete that have the same MgO content, because of the aggregate and restraint from reinforcement bars (Li et al, 2010).

The ultimate expansion and the time taken to reach that ultimate expansion increase with MgO content (Mo and Deng, 2007). Figure 2.2 shows the increase in expansion with MgO content for cement paste cured in 20°C water. By comparing MgO contents of 5% and 8%, the higher content showed a faster rate of expansion (Mo et al, 2012). With MgO contents over 8%, expansion is large and fast before 14 days, although expansion is stable after 28 days (Xu and Deng, 2005).

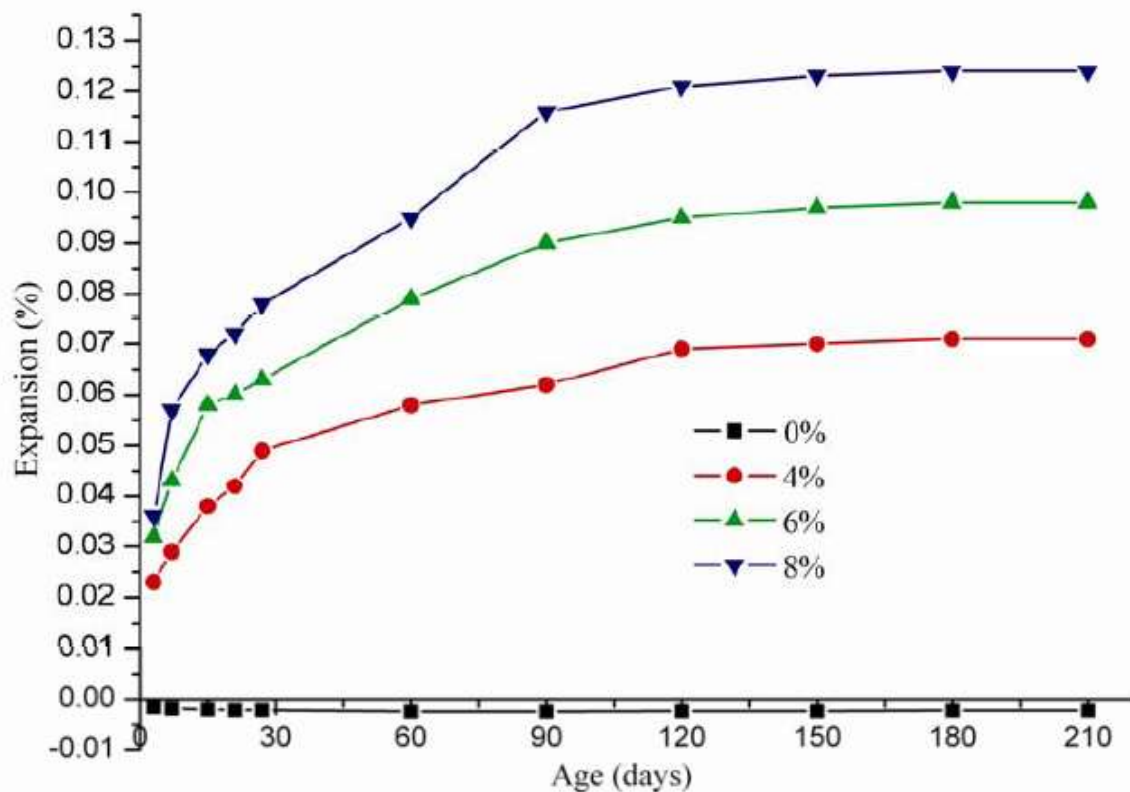


Figure 2.2: Expansion of cement paste with MgO cured at 20°C in water (from Li et al, 2009)

Light-burnt MgO, with high activity, gives a faster and larger early-age expansion but this ceases soon afterward. Dead-burnt MgO, with low activity, gives a slower and smaller early-age expansion but a fast and large late-age expansion, taking much longer for expansion to plateau. This is because, after an induction period, expansion on the grain boundary breaks apart the large MgO grains, opening up more surface area for reactions to take place. With lower activity MgO having longer induction periods and greater ultimate expansions (Mo et

al, 2010). However, this very slow hydration and late-age expansion is harmful to the hardened paste and weakens the integrity of the concrete (Du, 2005; Chen, 2006).

When concrete samples were cured in water of different temperatures, it was found that an increase in curing temperature produced an increase in expansion (Mo et al, 2010). Curing at higher temperatures also accelerates hydration, so that ultimate expansion is attained in a shorter time (Mo and Deng, 2007). Expansion also increases with curing age (Li et al, 2010).

### **2.4.3 Physical and mechanical properties**

Expansion leads to the number of microcracks in the concrete decreasing, so compressive and tensile strength of MgO concrete is higher than for conventional concrete. The concrete's tensile strain capacity increases as MgO content or curing temperature is increased. MgO concrete also creeps more than ordinary concrete so the cracking resistance of the concrete is improved. The expansive additive must be distributed uniformly throughout the mix, so that harmful over-expansion does not occur in localised areas of abnormally high concentration and weaken the concrete structure (Du, 2005).

Cracks appeared in concrete when there was an excessive addition of MgO, said to be more than 6-8%. Additionally, there was a loss in compressive and flexural strength for concrete with a high MgO content of 6-8%, caused by excessive expansion weakening the concrete structure, and this was a sign of unsoundness in the concrete (Mo and Deng, 2007). Greater expansion leads to a drop in compressive strength if there are no restraints. However, mortar samples that expand more in restrained conditions will have a higher compressive strength because of a denser microstructure (Chen, 2006).

The setting time of concrete with MgO becomes longer as the quantity of MgO is increased, because the initial hydration is retarded: the  $\text{Mg}(\text{OH})_2$  crystals precipitate on the surface of cement grains, forming a layer that slows further hydration. Increased MgO content delays the occurrence of the fastest period of hydration (Liu et al, 1992).

Cement pastes with a higher MgO content were found to produce a more porous cement structure, but the number of large pores decreased and density increased. However, in restrained conditions, the structure can be less porous with MgO. (Li et al, 2010). A high water content in the mix will lead to a more porous structure, and a higher porosity leads to a reduction in strength (Li, 2012).

## 2.5 Expansive additives in bored piles

One study compared the behaviour of UEA, AEA, MgO and no expansive additives in concrete bored piles. This was to see how best to address the defects of reducing diameter and strength shortage in piles. UEA and AEA are sulpho-aluminate additives widely used to deliver expansion by forming ettringite. Concrete with MgO was shown to perform better than concrete with other additives in most tests.

The study considered how the concrete performed in compressive strength. All of the expansive concretes gained their strength slightly slower than ordinary concrete, before reaching similar design strength at 28 days, as shown in Table 2.2, as a consequence of the pores being gradually filled by the expansive products. However, MgO concrete always had a higher strength than concrete with sulpho-aluminate additives because of its uniform and stable expansion. Concrete with MgO also had the highest stiffness, so can reduce pile settlement.

*Table 2.2: Compressive strengths of concrete cubes with different expansive additives*

|                         | No additives (C-30) | MgO (M-30) | UEA (U-30) | AEA (A-30) |
|-------------------------|---------------------|------------|------------|------------|
| 28d cube strength (MPa) | 45.2                | 43.5       | 39.8       | 41.8       |

Figure 2.3 shows all expansive concretes shrinking less than plain concrete in dry curing conditions because a limited amount of hydration was still possible, forming some ettringite or brucite. MgO concrete also had its drying shrinkage stabilising in later ages while concrete with UEA or AEA continued to shrink. Furthermore, Figure 2.4 shows MgO concrete to expand the most in confined conditions and to do so stably.

The expansion of MgO compensates the drying shrinkage deformation, so will compress the soil around the pile. This will reduce the soil's porosity and moisture content and increase cohesion, leading to greater friction between the pile and the soil.

MgO concrete had the least slump loss, greatest cohesiveness and lowest bleeding rate of the expansive concretes. Concrete with MgO was the least permeable to chloride ions, making this concrete the most durable against corrosion of reinforcement. It also had the best resistance to frost because of its dense structure (Wang and Zhang, 2009).

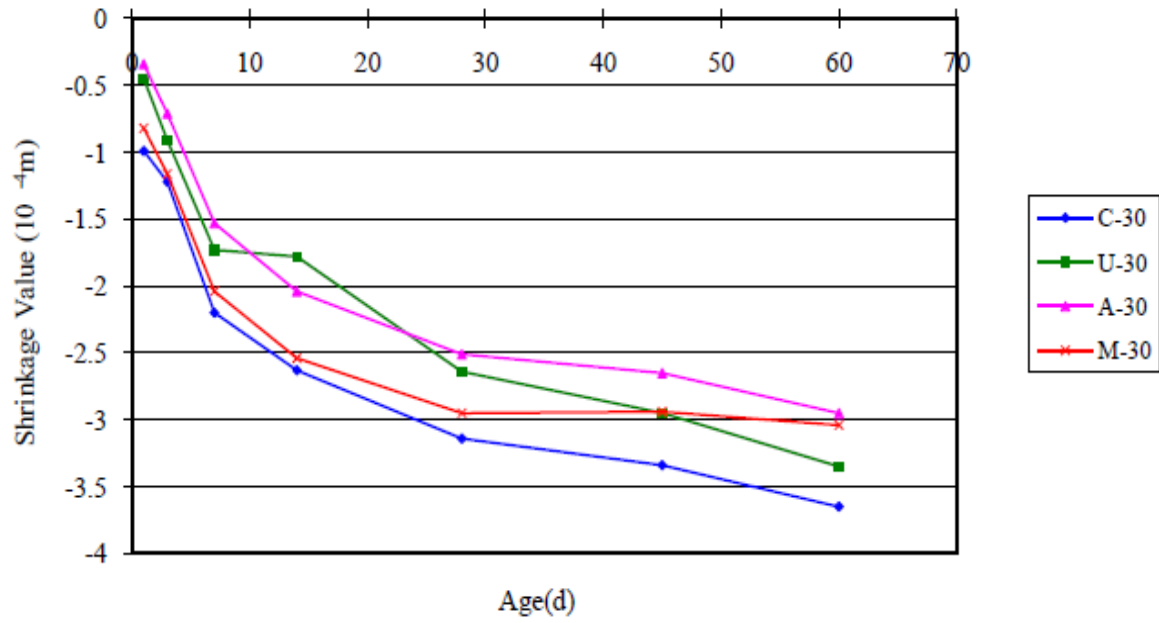


Figure 2.3: Shrinkage tendency of expansive concrete (from Wang and Zhang, 2009)

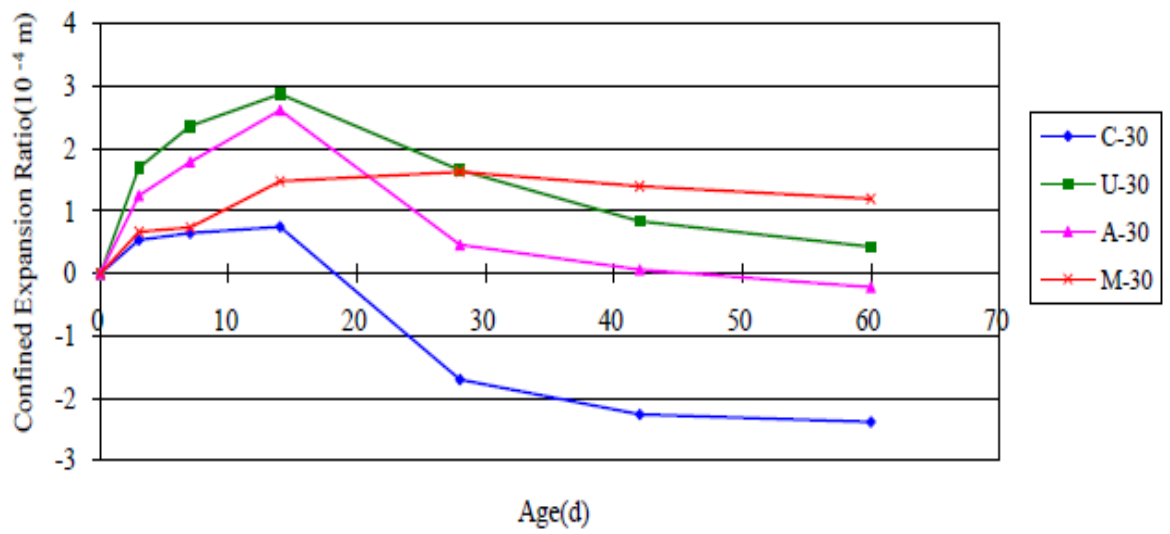


Figure 2.4: Confined expansibility of expansive concrete (from Wang and Zhang, 2009)

# Chapter 3: Cement Paste Investigation

## 3.1 Materials

The cement used was CEM I 52.5 N Portland Cement (PC), supplied by Hanson, UK, and conforms to BS EN 197-1:2000.

The ground granulated blast furnace slag (GGBS) came from the Purfleet works and was supplied by Hanson, UK and conforms to BS EN 15167-1:2006. It has a fineness of 505 m<sup>2</sup>/kg and a density of 2880 kg/m<sup>3</sup>.

The light-burnt 92-200 MgO was supplied by Richard Baker Harrison Ltd, UK. The chemical compositions of those three raw materials are shown in the Table 3.1. The hard-burnt Expansive MgO is commercially available and is sourced from China. The technical data for the Expansive MgO is not available.

De-ionised water was used to cast the specimens in the cement paste experiment, as stated in the method for testing cement strength in BS EN 196-1:2005.

*Table 3.1: Chemical composition of PC, GGBS and MgO, in percentage weight, from supplier information*

|      | MgO  | CaO   | SiO <sub>2</sub> | Al <sub>2</sub> O <sub>3</sub> | TiO <sub>2</sub> | Na <sub>2</sub> O | K <sub>2</sub> O | SO <sub>3</sub> | MnO  | Fe <sub>2</sub> O <sub>3</sub> | L.O.I. |
|------|------|-------|------------------|--------------------------------|------------------|-------------------|------------------|-----------------|------|--------------------------------|--------|
| PC   | 1.01 | 64.24 | 19.55            | 5.32                           |                  | 0.24              |                  |                 |      | 3.48                           | 3.05   |
| GGBS | 7.74 | 38.74 | 34.68            | 14.16                          | 0.89             | 0.46              | 0.65             | 0.21            | 0.42 | 0.05                           | 0.58   |
| MgO  | 93.5 | 1.9   | 0.9              | 0.1                            |                  |                   |                  |                 |      | 0.8                            | 2.8    |

## 3.2 Method

The experiments observed the shrinkage and expansion behaviour of cement paste prisms, and tested cement paste cubes for compressive strength.

### 3.2.1 Mix Design

The binder composition was a 1:1 blend of PC and GGBS, with a percentage of this blend's mass replaced by MgO. To investigate how a change in the MgO content would affect cement paste performance, two different MgO contents (5% and 8%) were used in the mixes, in addition to control specimens without added MgO. Two different water-cement ratios, 0.33

and 0.37, were used to observe what effects the ratio has on the behaviour of the cement paste. These ratios were chosen as they are within the typical range that would provide adequate workability. Differences between the light-burnt and hard-burnt MgO were studied by preparing one set of specimens with a mix containing 8% Expansive MgO and a water-cement ratio of 0.37, so that its performance in the tests could be directly compared to the specimens containing 8% 92-200 MgO and a water-cement ratio of 0.37. An MgO content of 8% was chosen to show the greatest expansion and a water-cement ratio of 0.37 for ease of workability.

Shrinkage prisms and cubes were numbered from 2 to 9 and expansion prisms were lettered from B to H. Table 3.2 shows the different mixes that were tested.

*Table 3.2: Composition of cement paste mixes*

| Mixes  | MgO grade | MgO content (%) | Water-binder ratio | PC (g) | GGBS (g) | MgO (g) | Water (g) |
|--------|-----------|-----------------|--------------------|--------|----------|---------|-----------|
| 2, B   | 92-200    | 5               | 0.33               | 665    | 665      | 70      | 462       |
| 3, C   | 92-200    | 5               | 0.37               | 665    | 665      | 70      | 518       |
| 4, D   | 92-200    | 8               | 0.33               | 644    | 644      | 112     | 462       |
| 5, E   | 92-200    | 8               | 0.37               | 644    | 644      | 112     | 518       |
| 6, F   |           | 0               | 0.33               | 700    | 700      | 0       | 462       |
| 7, G   |           | 0               | 0.37               | 700    | 700      | 0       | 518       |
| 8,9, H | Expansive | 8               | 0.37               | 644    | 644      | 112     | 518       |

### 3.2.2 Procedure

Each cement mix was prepared in a small bench-top high powered food mixer, in batches with a binder mass of 1.4kg. One batch of cement paste was enough to cast 3 prisms or 12 cubes. The dry ingredients of the binder were mixed together for 2 minutes. Then, water was added through a hatch while the mixer was running, and mixing continued for a further 3 minutes. Halfway through both of the mixing cycles, the mixer was paused and the contents of the mixer were manually stirred with a palette knife, from the edge of the bowl to the centre, to help improve mix homogeneity.

Each set of prism moulds was able to produce three 160x40x40mm specimens (Figure 3.1a). They allow gauge studs to be embedded into the ends of the prisms so that changes in length

can be measured. The cube moulds each produce six cubes with a side length of 40mm (Figure 3.1b). All moulds were milled from steel and coated in mineral oil prior to filling to seal in the cement's moisture.



*Figure 3.1: (a) Moulds for cement paste prisms, (b) Moulds for cement paste cubes*

The cement paste was scooped into the moulds in three layers. The paste in the moulds was agitated with a palette knife after each layer, to ensure cement filled the corners of the mould, good compaction and removal of air voids. After the final layer had been applied, the top surface of the paste was smoothed over with a palette knife. The filled moulds were then covered in cling film and left to set for  $22 \pm 2$  hours in curing conditions of  $20 \pm 1^\circ\text{C}$ , 90% RH (Figure 3.2).



*Figure 3.2: Cement paste in moulds undergoing curing*

The prisms were removed from the moulds and their initial lengths and masses were recorded. Since, shrinkage occurs when concrete is cured in non-wet conditions, the prisms used to investigate drying shrinkage were cured in room conditions ( $19\pm 2^{\circ}\text{C}$ ,  $55\pm 10\%$  RH) (Figure 3.3a). The prisms used for recording expansion were cured submerged in water at  $19\pm 2^{\circ}\text{C}$  to facilitate the expansive reaction (Figure 3.3b).



*Figure 3.3: (a) Dry curing of prisms on racks in room conditions, (b) Wet curing of prisms submerged in a water tank*

Measurements of mass and length were taken at several time intervals over six months - after 1, 3, 5, 7, 10, 14, 21, 65, 105 and 165 days from casting. Changes in length were measured using a calibrated digital length comparator with a precision of 0.001mm (Figure 3.4). Low shrinkage and high expansion is desirable.



*Figure 3.4: (a) Calibration of length comparator with standard rod, (b) Measuring the length of a prism with the digital length comparator*

Twelve 40mm cubes were cast for each mix composition to perform unconfined compressive strength (UCS) tests on. The cubes were cured in water to allow the MgO to hydrate. Tests were performed on three cubes at four different ages - after 1, 7, 14 and 21 days. Prior to each UCS test, the dimensions of the cube were measured using a digital calliper, with a precision of 0.1mm, to calculate the area of the compression face.

UCS testing was done in a Control Advantest 9 compression test machine, produced by Controls Testing Equipment Ltd (Figure 3.5a). Each cube was placed in a smaller compression rig for 40mm cubes (Figure 3.5b) that fits between the larger platens of the test machine. The load was increased at a constant rate of 2400N/s and recorded by a data logger until failure. The failure load was divided by the area of the compression face to obtain the UCS. Low compressive strength is undesirable.



(a)



(b)

*Figure 3.5: (a) Controls Advantest 9 machine, (b) Cube in compression rig, before UCS test*

Cubes could only be tested using the compression machine from Monday to Friday, which commanded the testing schedule somewhat. Casting of new mixes and testing of earlier mixes had to be carefully timetabled on certain days when both occurred. The results were then tabulated and graphed for comparisons to be made.

### 3.3 Results and Discussion

#### 3.3.1 Strength

The cubes were tested in triplicate for each mix and age to obtain an average strength. Table 3.3 shows the standard deviations of the triplicated results for each age. Photos of the tested cement paste cubes are shown in Figure 3.6a and 3.6b.

*Table 3.3: Standard deviations of triplicated strength results*

| Age (days) | 1    | 7    | 14   | 21   |
|------------|------|------|------|------|
| SD (MPa)   | 0.28 | 1.87 | 2.66 | 3.05 |



*Figure 3.6: (a) Cement paste cube after UCS testing, (b) Collection of UCS tested cubes*

Figure 3.7a and 3.7b show the development of compressive strength over 21 days for the cement pastes with water-cement ratio 0.33 and 0.37 respectively for different MgO contents of 5% and 8%, compared to plain cement paste without added MgO.

By comparing all the mixes that used a particular water-cement ratio, it can be seen that substituting 8% of the binder's mass with MgO leads to a small reduction in ultimate compressive strength compared to mixes without MgO. The loss in strength was more pronounced with a water-cement ratio of 0.33. This loss in strength with high MgO content is because of cracks and pores (unsoundness). Although, there was a gain in strength with a 5% MgO substitution compared to a mix without MgO. This is because some expansion will reduce the number of microcracks in the cube.

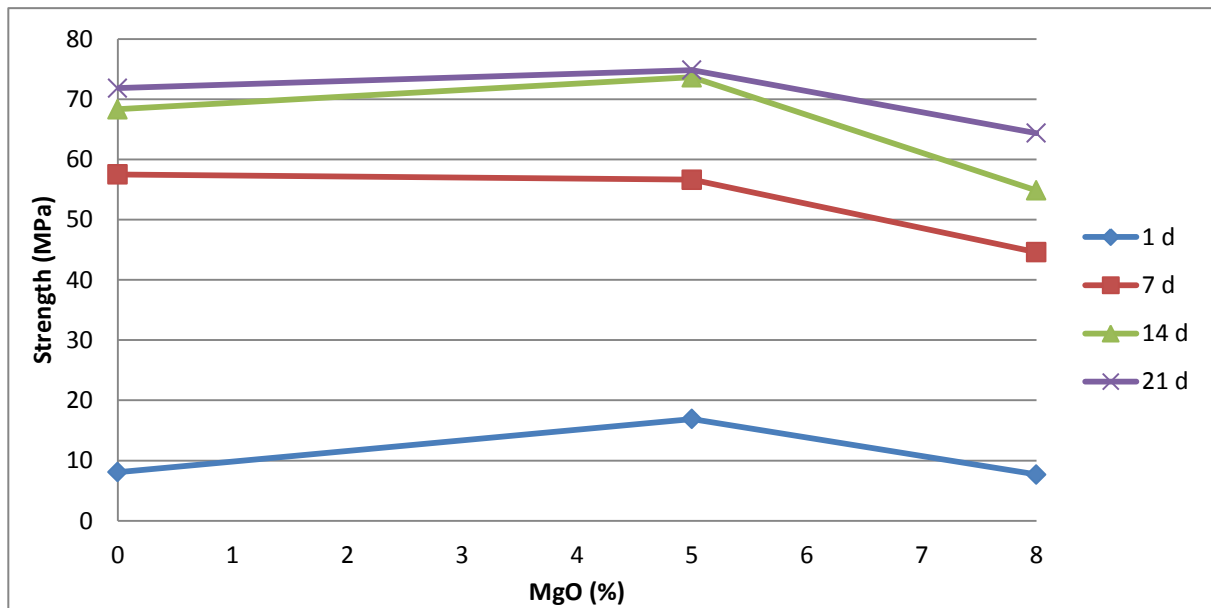


Figure 3.7a: Compressive strengths of cement paste with a water-cement ratio of 0.33

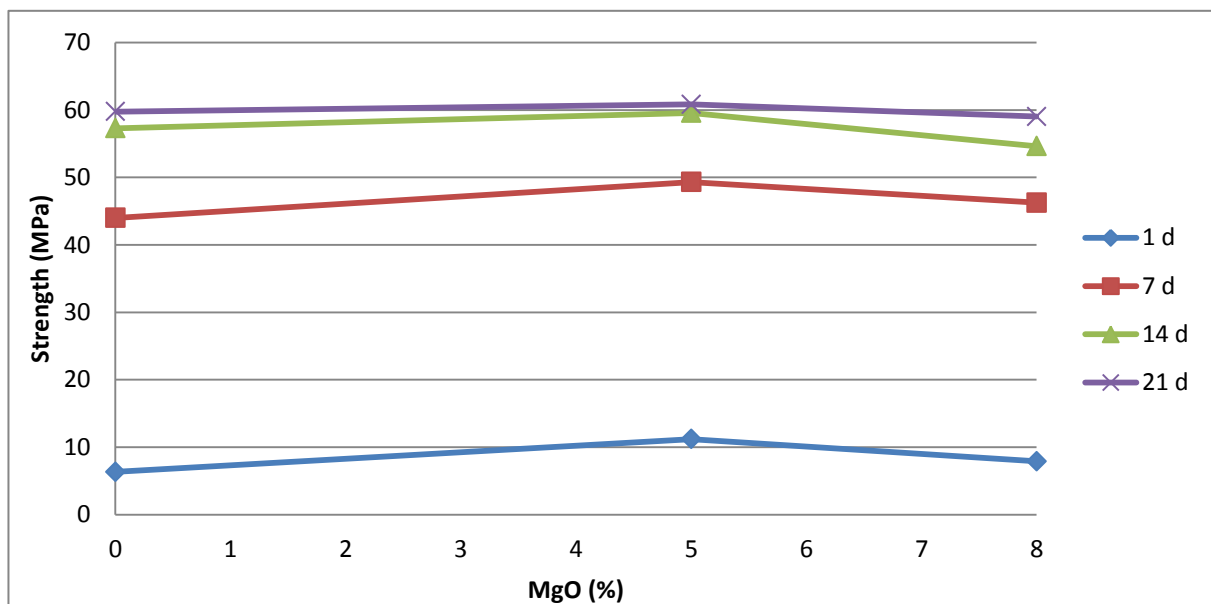


Figure 3.7b: Compressive strengths of cement paste with a water-cement ratio of 0.37

Figure 3.8a, 3.8b and 3.8c show the development of compressive strength over 21 days for the cement pastes with MgO contents of 0%, 5% and 8% respectively with different water-cement ratios of 0.33 and 0.37.

Comparing mixes with equal MgO content shows that those with a water-cement ratio of 0.33 tend to have a higher ultimate compressive strength than mixes with a water-cement ratio of 0.37. This is because the lower water content leads to a less porous cement paste structure.

Compressive strength is also gained as the cement cures over time, with significant increases over the first 14 days. The strengths at 14 and 21 days are fairly similar.

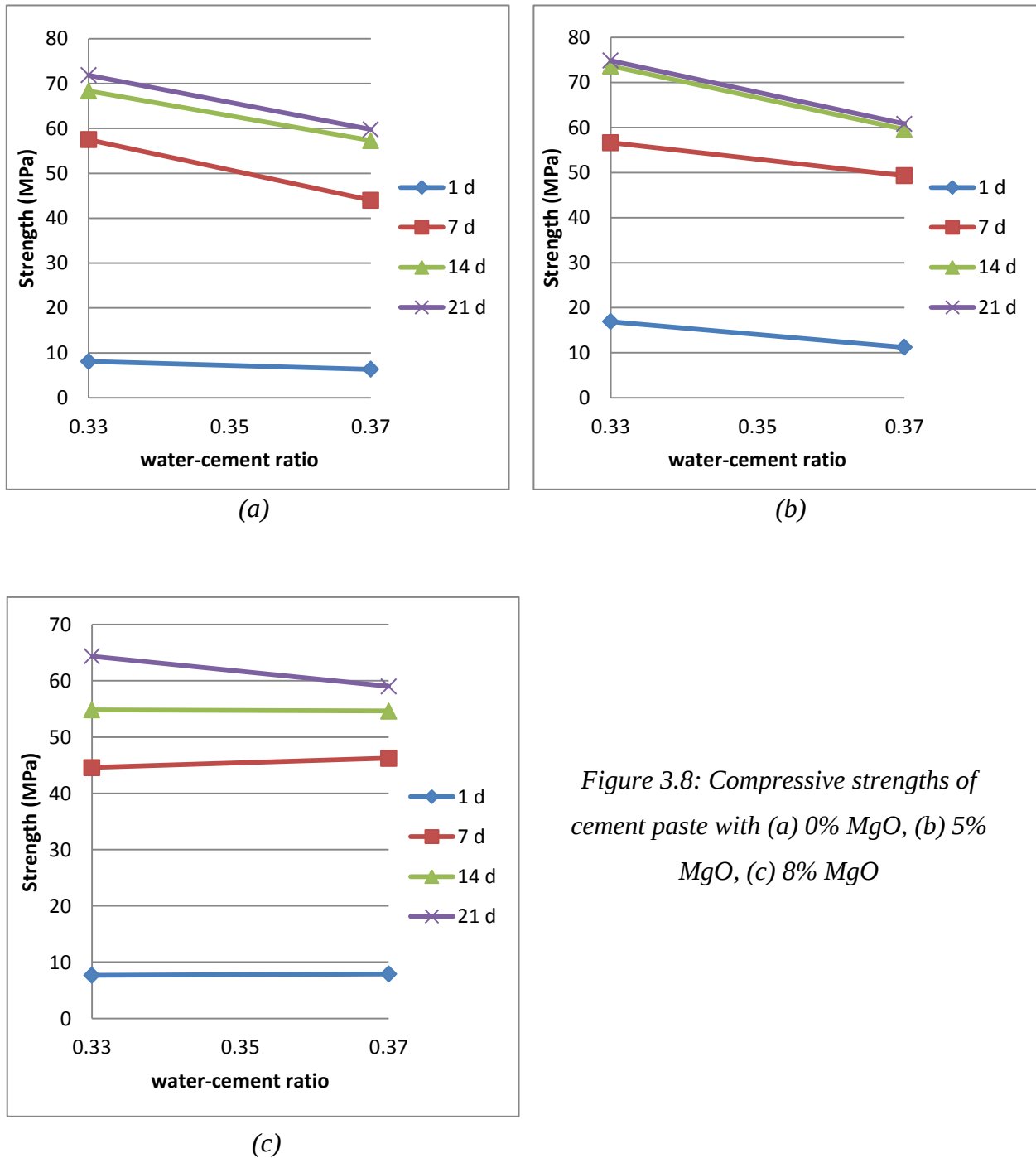


Figure 3.8: Compressive strengths of cement paste with (a) 0% MgO, (b) 5% MgO, (c) 8% MgO

Figure 3.9 shows the compressive strength values for cement paste cubes containing no added MgO, 8% 92-200 MgO and 8% Expansive MgO and all with a water-cement ratio of 0.37. The development of the cement paste strengths with different MgO grades is shown over the 21 day wet curing period.

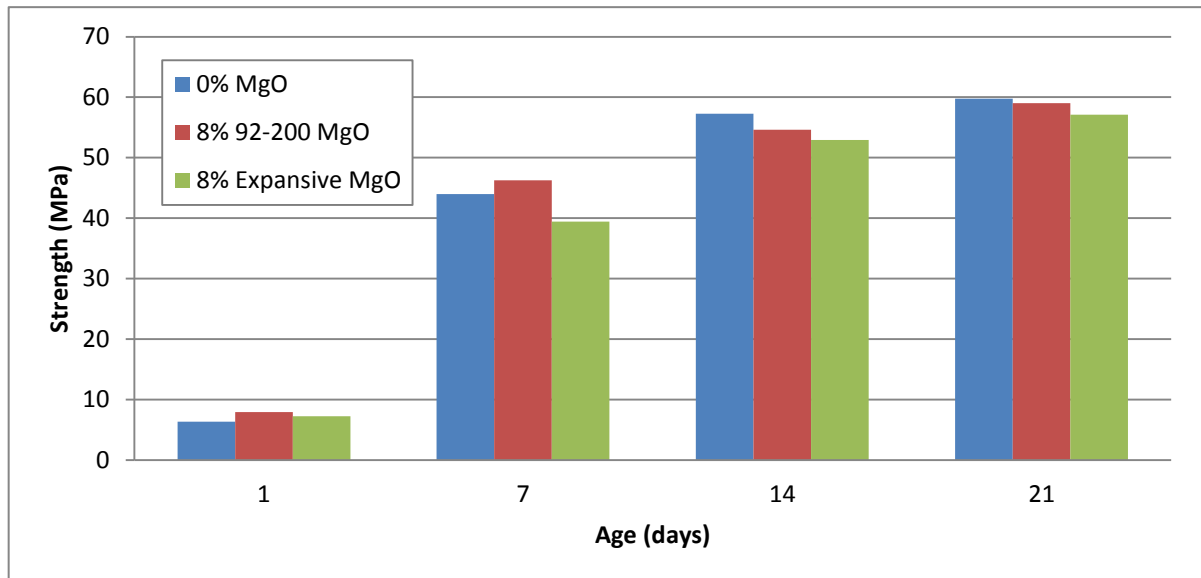


Figure 3.9: Compressive strengths of cement paste with different grades of MgO

The strengths of the specimens using Expansive MgO were 7 MPa lower than those using 92-200 MgO at an age of 7 days. However, apart from this, the cement paste made with 92-200 MgO had only a slightly higher compressive strength than the paste with Expansive MgO. The difference may be explained by the different densities of the two grades of MgO meaning that the MgO takes up different volumes within the mixes.

There was only a very small decrease in 21 day strength when 8% 92-200 MgO was added to the plain cement paste mix, suggesting its presence has not caused unsoundness.

### 3.3.2 Shrinkage

Three prisms were made for each mix. The standard deviations of the triplicated results are shown in Table 3.4.

Table 3.4: Standard deviations of triplicated shrinkage results

| Age (days) | 3     | 5     | 7     | 10    | 14    | 21    | 65    | 105   | 165   |
|------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| SD (mm)    | 0.009 | 0.025 | 0.029 | 0.030 | 0.031 | 0.032 | 0.033 | 0.039 | 0.038 |

A photo of all the cement paste prisms used to record shrinkage is shown in Figure 3.10.



Figure 3.10: Prisms used to observe cement paste shrinkage

All figures from Figure 3.11 to Figure 3.13 show changes in length of cement paste prisms, from an initial length of 160mm, over the six month period measurements were taken. Note the negative y-axis. Figure 3.11a and 3.11b show the change in length of the cement paste prisms for water-cement ratios of 0.33 and 0.37 respectively, using different MgO contents of 0%, 5% and 8%.

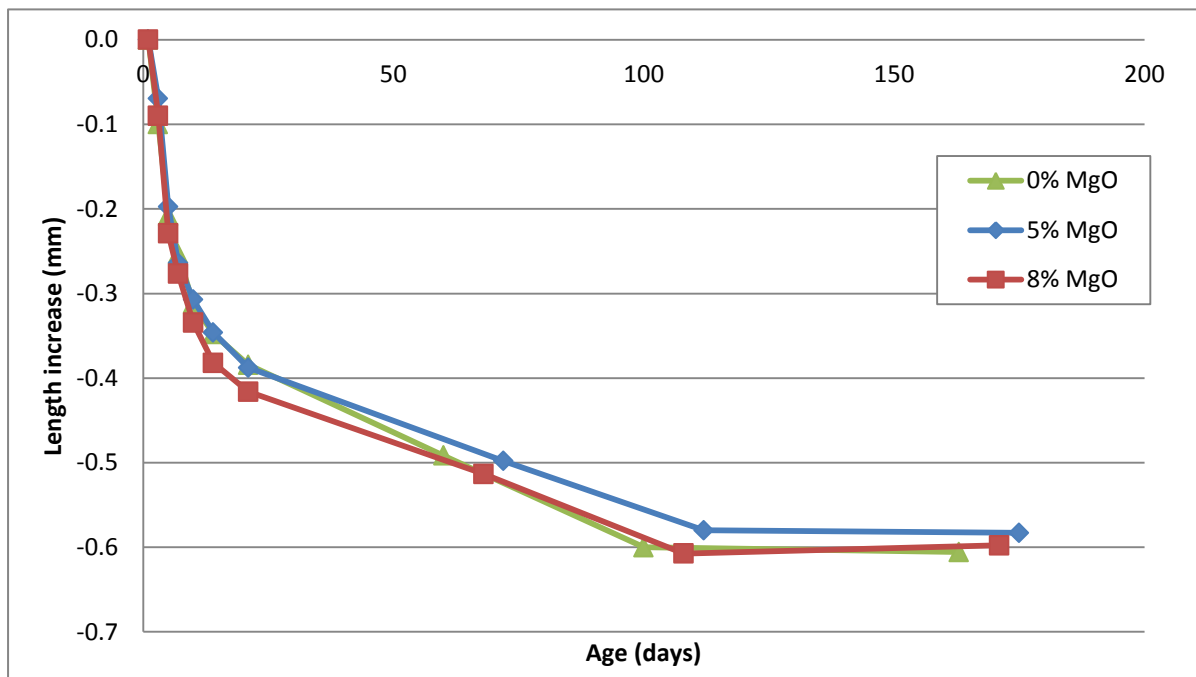


Figure 3.11a: Shrinkage of cement paste prisms with a water-cement ratio of 0.33

For a water-cement ratio of 0.33, after 21 days, the strain in the cement pastes with 0%, 5% and 8% MgO were 2400, 2425 and 2600 microstrain respectively. After 165 days, the strains were 3788, 3644 and 3738 microstrain respectively.

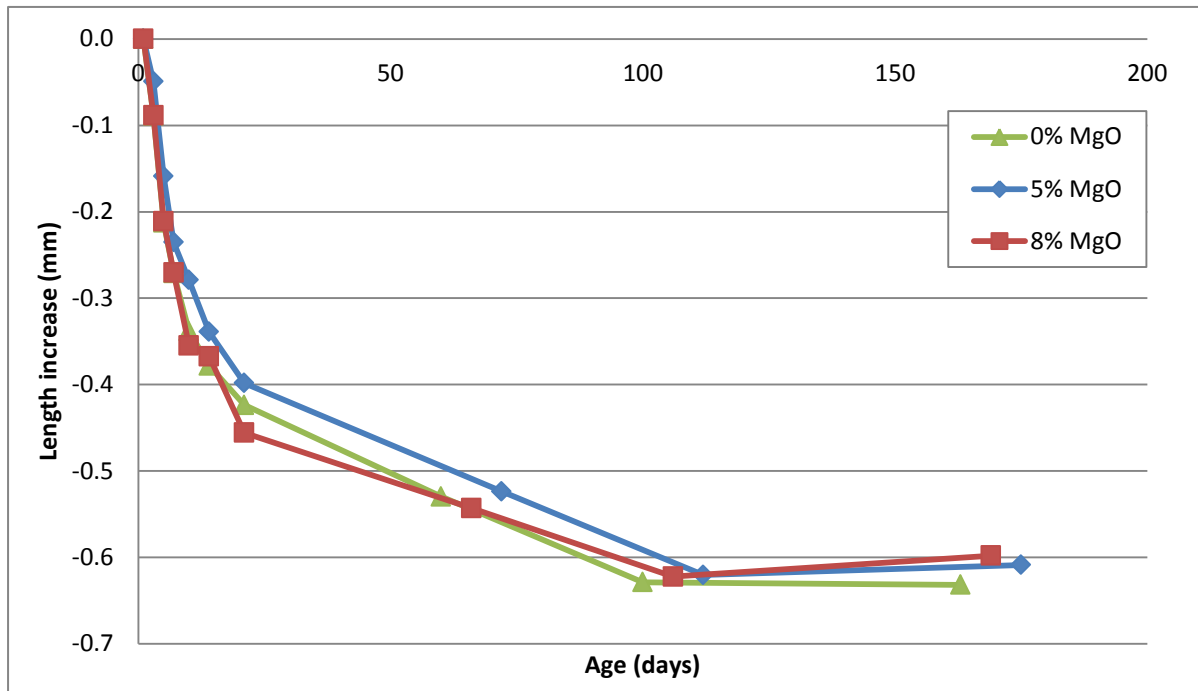


Figure 3.11b: Shrinkage of cement paste prisms with a water-cement ratio of 0.37

For a water-cement ratio of 0.37, the strains after 21 days for cement pastes with 0%, 5% and 8% MgO were 2650, 2488 and 2850 microstrain respectively. After 165 days, the strains for the same prisms were 3950, 3806 and 3738 microstrain respectively.

Shrinkage for cement paste with 8% MgO was generally the greatest in the early ages before it showed some shrinkage compensation after 105 days, showing that it was slow to hydrate when cured in room conditions. At the time of the final reading, the prisms with MgO showed less shrinkage than the prisms without MgO.

For both water-cement ratios, the paste with 5% MgO showed less shrinkage than the prisms without MgO at most ages. So the 5% MgO mixes were good at compensating shrinkage. In all cases, shrinkage was fastest over first 14 days and stabilised after 105 days.

Figure 3.12a shows the change in length of the cement paste prisms containing 5% MgO but with different water-cement ratios of 0.33 and 0.37. Figure 3.12b shows the change in mass for the same prisms.

After 21 days, the strains for water-cement ratios of 0.33 and 0.37 were 2425 and 2488 microstrain respectively. After 175 days, the same prisms had strains of 3644 and 3806 microstrain respectively.

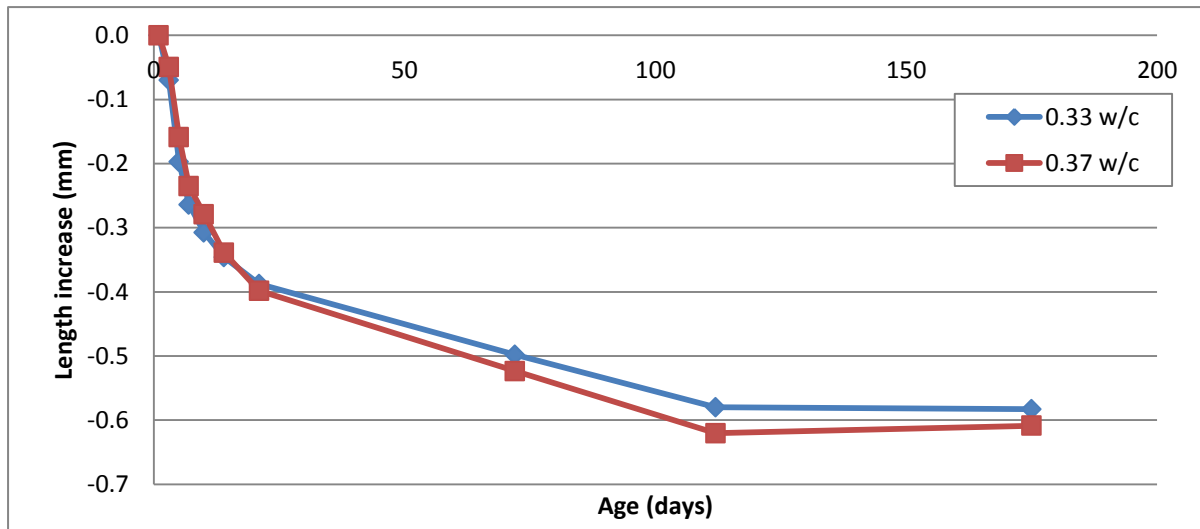


Figure 3.12a: Shrinkage of cement paste prisms with a 5% MgO content

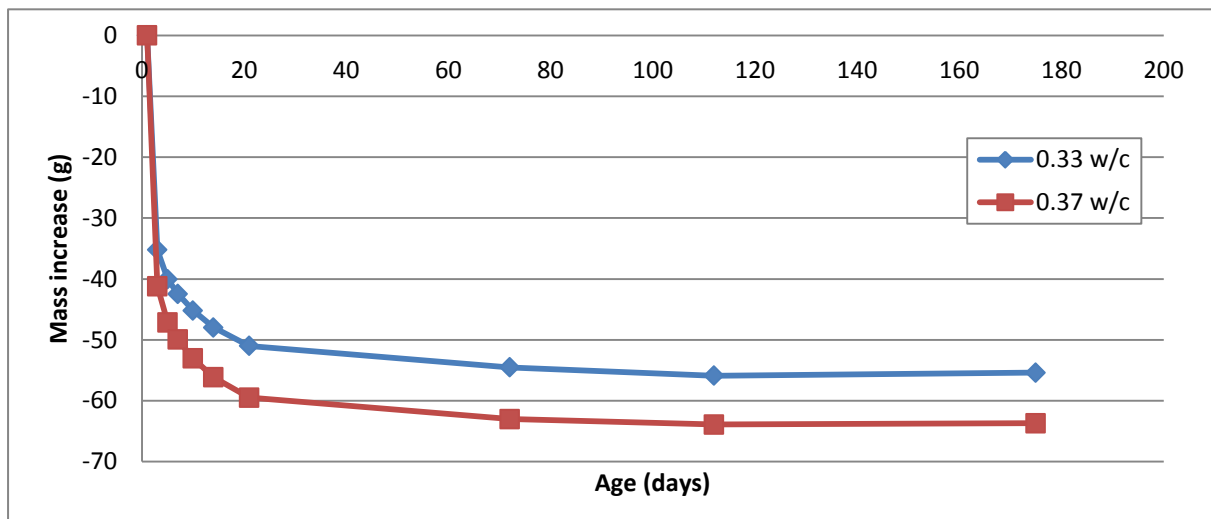


Figure 3.12b: Loss in mass of shrinking cement paste prisms with a 5% MgO content

Cement paste with a water-cement ratio of 0.37 ultimately shrank more than paste with a water-cement ratio of 0.33. This was because there was more excess water in the prisms to be lost by drying shrinkage. Comparing figures 3.12a and 3.12b show that the prisms that shrank more also lost the most mass, because of the water lost during drying shrinkage.

Figure 3.13 shows the change in length of cement paste prisms with a water-cement ratio of 0.37 but using 8% 92-200 MgO, 8% Expansive MgO or without MgO.

The sets of prisms containing no MgO and 92-200 MgO both had similar shrinkage profiles. But prisms containing Expansive MgO shrank fastest and by the most. So, hard-burnt MgO actually exacerbates drying shrinkage and should not be used to compensate it.

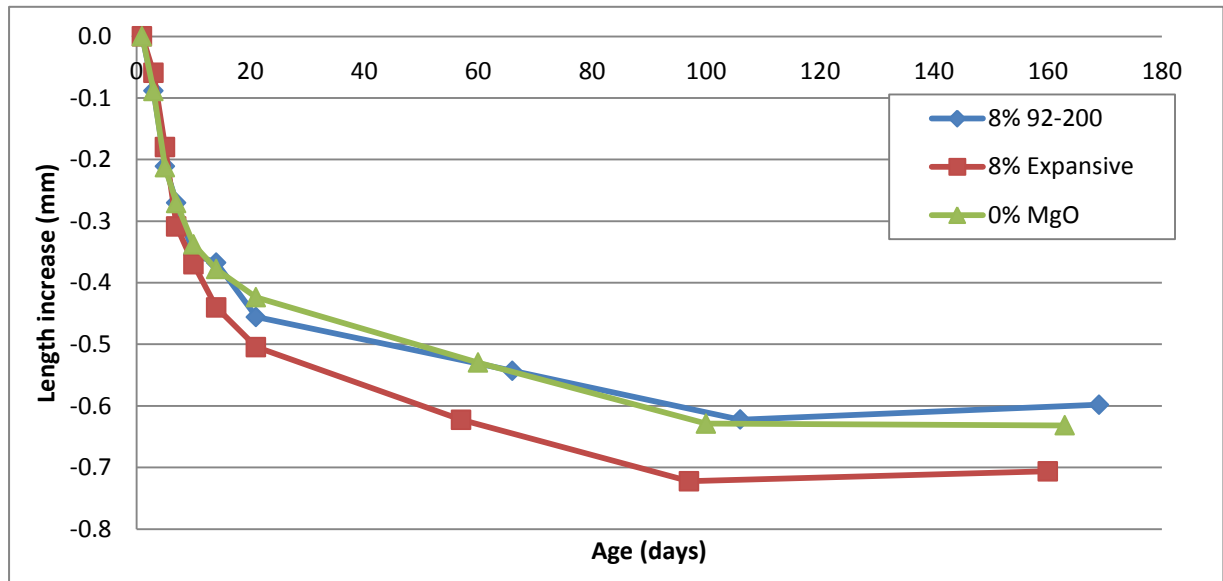


Figure 3.13: Shrinkage of cement paste prisms with different grades of MgO

The strains after 21 days were 2650, 2850 and 3156 microstrain for no MgO, 8% 92-200 MgO and 8% Expansive MgO respectively. After 165 days, the strains for the same prisms were 3950, 3738 and 4413 microstrain respectively.

### 3.3.3 Expansion

Three prisms were made for each mix. The standard deviations of the triplicated results at each age are shown in Table 3.5.

Table 3.5: Standard deviations of triplicated expansion results

| Age (days) | 3     | 5     | 7     | 10    | 14    | 21    | 65    | 120   | 165   |
|------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| SD (mm)    | 0.013 | 0.016 | 0.019 | 0.021 | 0.020 | 0.019 | 0.020 | 0.020 | 0.019 |

All figures from Figure 3.14 to Figure 3.16 show changes in length of cement paste prisms, from an initial length of 160mm, over the six month period measurements were taken.

Figure 3.14 shows the increase in length of cement paste prisms with a water-cement ratio of 0.37, but containing 0%, 5% or 8% MgO.

Strains of 313, 344 and 563 microstrain were observed after 21 days for MgO contents of 0%, 5% and 8% respectively. After 165 days, the strains observed for the same prisms were 519, 856, 1356 microstrain respectively.

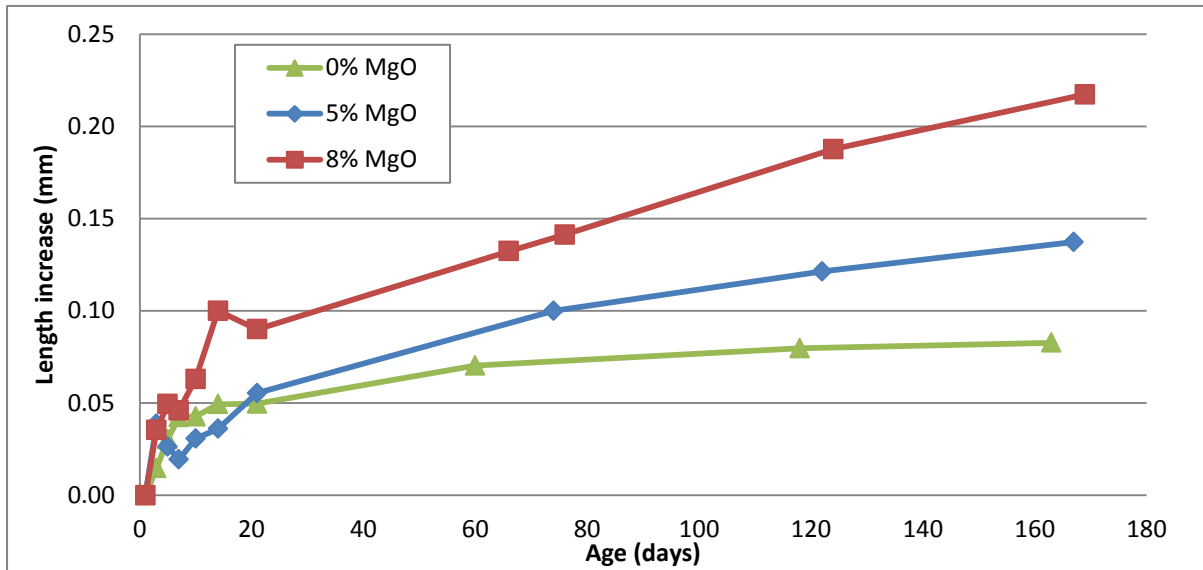


Figure 3.14: Expansion of cement paste prisms with a water-cement ratio of 0.37

All of the samples increased in length and the higher the MgO content, the greater the increase in length. This is because there is more MgO present for the hydration reaction, so more brucite is produced, expanding the cement paste matrix. The sample without added MgO expanded a little because Portland cement and GGBS largely consist of CaO, which also increases in volume after hydration in wet curing conditions.

Figure 3.15 shows the length increase of cement paste prisms containing 8% MgO with different water-cement ratios of 0.33 and 0.37. After 21 days, strains of 488 and 563 microstrain were recorded for water-cement ratios of 0.33 and 0.37 respectively. After 165 days, the same prisms had strains of 1263 and 1356 microstrain respectively.

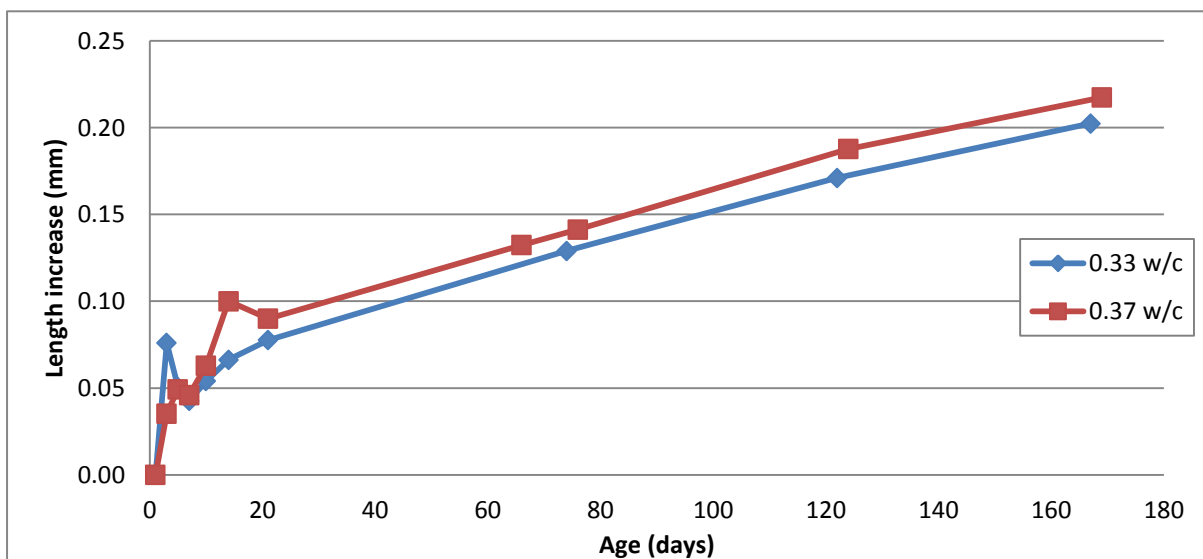


Figure 3.15: Expansion of cement paste prisms with an 8% MgO content

The tests showed that the higher the water-cement ratio, the greater the expansion. This is because there is more water readily available within the mix for the hydration of MgO. Samples with low water content draw in water from the surroundings for hydration and this can be slowed by the paste's low permeability

Figure 3.16a shows the length increase of cement paste prisms that contain 8% 92-200 MgO, 8% Expansive MgO or 0% MgO, all with a water-cement ratio of 0.37. Figure 3.16b shows the change in mass for the same prisms.

The light-burnt 92-200 MgO ultimately showed more expansion than the hard-burnt Expansive MgO, but the Expansive MgO expanded a little more than the 92-200 MgO during early ages. However, the light-burnt MgO had a rate of expansion continued to stay high after 70 days, because it is more reactive, whereas the hard-burnt MgO started to slow. Hence light-burnt MgO should be used to achieve greater expansion.

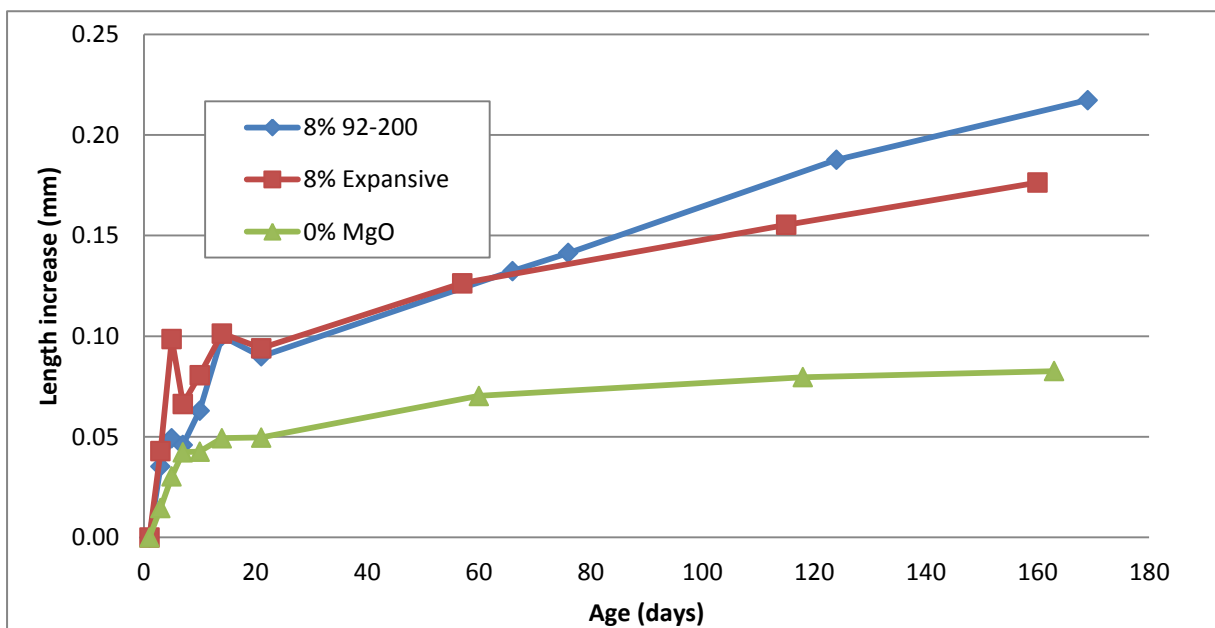


Figure 3.16a: Expansion of cement paste prisms with various grades of MgO

The strains after 21 days were 313, 563 and 588 microstrain for cement paste with no MgO, 8% 92-200 MgO and 8% Expansive MgO. After 165 days, the same prisms had strains of 519, 1356 and 1100 microstrain respectively.

The graph of mass change shows a similar shape to the graph of length change, indicating that expansion causes an increase in mass. This result was expected as  $\text{Mg}(\text{OH})_2$  has a mass 45% greater than MgO.

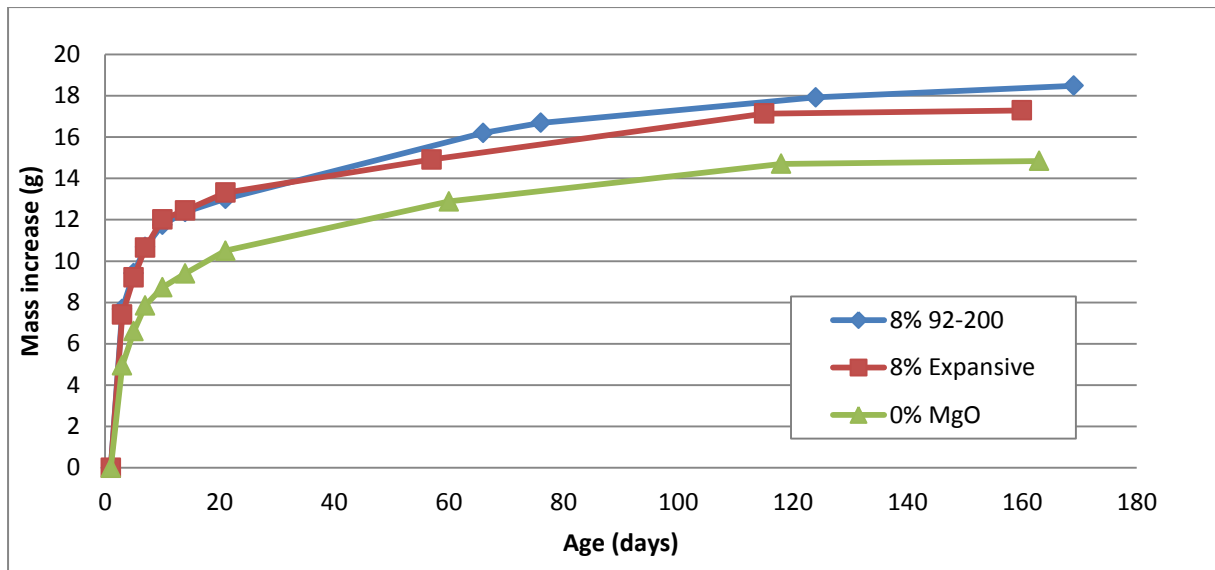


Figure 3.16b: Gain in mass of expanding cement paste prisms with various grades of MgO

### 3.3.4 Conclusions

The findings of the cement paste experiments guided the mix design for the lab-scale piles.

1. Cement paste is stronger with a 5% MgO content but slightly weakened with 8% MgO
2. Lower water-cement ratios produce stronger cement paste
3. Cement paste with 92-200 MgO has a higher compressive strength than cement paste with Expansive MgO
4. MgO compensates drying shrinkage
5. In wet curing, 8% MgO cement paste expands more than 5% MgO cement paste
6. The drying shrinkage of cement paste with a water-cement ratio of 0.33 was less than paste with a water-cement ratio of 0.37
7. In wet curing, cement paste with a water-cement ratio of 0.37 expanded more than paste with a water-cement ratio of 0.33
8. In dry conditions, cement paste with 92-200 MgO shrank less than paste with Expansive MgO
9. In wet curing, cement paste with 92-200 MgO expanded more than paste with Expansive MgO

Therefore, to show most expansion, the piles would use 92-200 MgO and cement paste piles would use a water-binder ratio of 0.37.

# Chapter 4: Lab-scale Pile Investigation

## 4.1 Materials

The same PC, GGBS and 92-200 MgO used to make the cement paste prisms and cubes were used to cast the lab-scale piles.

Sharp sand with a grain size of 0-4mm, including gravel component was used in the concrete. Its effective specific gravity was 2.651. This sand was also used as soil to fill the drums. The sand had water added and mixed to achieve a moisture content of 10% to form moist soil. The coarse aggregate used in the concrete was gravel with a size of 4-12mm. The particle size information for the sand and gravel is shown in Table 4.1. Both the sand and gravel would normally be used to mix concrete and were supplied by Ridgeons, Cambs., UK. Tap water was used in the mixes.

*Table 4.1: Sand and gravel particle size*

|        | D <sub>50</sub> (mm) | D <sub>90</sub> (mm) |
|--------|----------------------|----------------------|
| Sand   | 0.4                  | 1.9                  |
| Gravel | 6.5                  | 10.5                 |

## 4.2 Method

Lab-scale models of piles were made and pull-out tests were performed on them to investigate whether expansive additives could increase shaft friction.

The piles were made from either cement paste or concrete and installed in drums of sharp sand. MgO content was varied to see what effects an increase in MgO content would have on shaft resistance. In some of the test cases, more water was added to the sand in order to saturate it to a depth halfway up the pile (“Half-Saturated”) or to saturate it throughout (“Saturated”). This was done to replicate actual conditions where piles extend to below the ground water table and to study what effects this might have.

The drums were 280mm in diameter and 500mm tall, and sand was used to fill the drums to a height of 450mm. A 400mm length of plastic tubing with an internal diameter of 100mm was used as formwork to cast the piles. The drums of sand were prepared in stages: a 75mm thick layer of sand was laid at the bottom of the drum, and then the plastic tubing was pressed

gently into the sand in the centre of the drum. Sand was placed around the tubing until half of it was covered. Water was added if the sand around the lower half of the pile needed to be saturated. Then more sand was placed around the tubing until it was almost entirely covered (Figure 4.1a). Water was again added if the sand was to be saturated throughout and the drums were allowed to settle for 24 hours.

The cement binder was once again a 1:1 blend of PC and GGBS, with the MgO replacing 0%, 5%, 8% or 11% of the blend. Cement paste was made by combining this mixture with water, in a water-binder ratio of 0.37. Concrete was made using a typical mix design that had ratios of 1 : 2.5 : 3.5 for cement binder to sand to aggregates, with a water-binder ratio of 0.5. Table 4.2 shows the mix details of the piles and the soil conditions they were tested in.

*Table 4.2: Composition of lab-scale piles*

| Pile No. | Material | Sand           | MgO (%) | PC (g) | GGBS (g) | MgO (g) | Sand (g) | Gravel (g) | Water (g) |
|----------|----------|----------------|---------|--------|----------|---------|----------|------------|-----------|
| 1        | Cement   | Moist          | 0       | 2500   | 2500     | 0       | 0        | 0          | 1850      |
| 2        | Cement   | Moist          | 8       | 2300   | 2300     | 400     | 0        | 0          | 1850      |
| 3        | Cement   | Saturated      | 0       | 2500   | 2500     | 0       | 0        | 0          | 1850      |
| 4        | Cement   | Saturated      | 8       | 2300   | 2300     | 400     | 0        | 0          | 1850      |
| 5        | Concrete | Saturated      | 0       | 350    | 350      | 0       | 1750     | 2450       | 350       |
| 6        | Concrete | Saturated      | 8       | 322    | 322      | 56      | 1750     | 2450       | 350       |
| 7        | Cement   | Saturated      | 8       | 2300   | 2300     | 400     | 0        | 0          | 1850      |
| 8        | Concrete | Saturated      | 8       | 368    | 368      | 64      | 2000     | 2800       | 400       |
| 9        | Concrete | Half-Saturated | 5       | 380    | 380      | 40      | 2000     | 2800       | 400       |
| 10       | Concrete | Half-Saturated | 11      | 356    | 356      | 88      | 2000     | 2800       | 400       |
| 11       | Concrete | Saturated      | 11      | 356    | 356      | 88      | 2000     | 2800       | 400       |
| 12       | Concrete | Saturated      | 5       | 380    | 380      | 40      | 2000     | 2800       | 400       |
| 13       | Concrete | Half-Saturated | 8       | 368    | 368      | 64      | 2000     | 2800       | 400       |



(a)



(b)

*Figure 4.1: (a) Prepared drum awaiting concrete pour, (b) Rotary concrete mixer*

All of the dry ingredients were mixed at once in a rotary mixer for 2 minutes, before stopping to add water and then continuing with the mixing for a further 3 minutes (Figure 4.1b). The cement or concrete was then scooped into the plastic tubing and a length of steel reinforcing bar, with a threaded tip, was inserted into the top of each pile to allow the pull-out test to be performed (Figure 4.2a). Finally, the tubing was pulled upwards and out of the drum so that the cement paste or concrete came into contact with the soil (Figure 4.2b). The drums were left for 14 days for the cement paste or concrete to cure and for the MgO to hydrate.



(a)

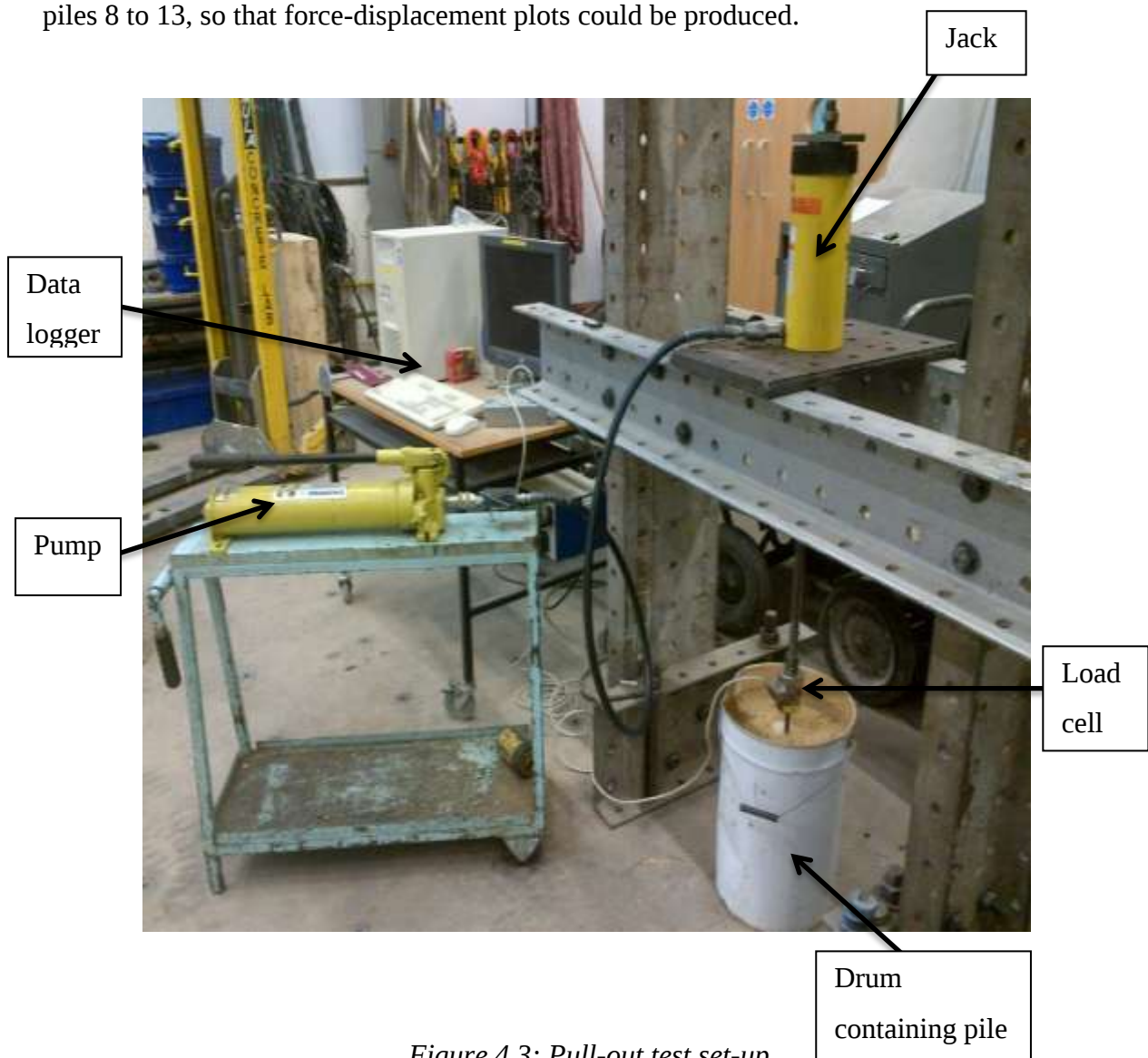


(b)

*Figure 4.2: (a) Concrete poured into tubing and steel bar positioned in top of pile, (b) Tubing between soil and pile removed*

The pull-out test apparatus (Figure 4.3) consisted of a manually-operated pump connected to a jack, which raised a length of studding screwed into a load cell. The threaded steel bar at the top of the pile was screwed into the opposite side of the load cell.

The load cell was connected to a data logger and the force required to overcome the pile's shaft resistance is measured and recorded during pull-out tests. Later, a linear variable differential transformer (LVDT) [not shown in figure] was added to the top of the jack and linked to the data logger to measure the vertical displacement of the piles during testing for piles 8 to 13, so that force-displacement plots could be produced.



*Figure 4.3: Pull-out test set-up*

The drums had to be restrained from lifting off the ground during the test using timbers (Figure 4.4a). Once the piles had been removed from the sand, they were weighed and measured to assess expansion and density after 14 days of curing (Figure 4.4b). A tape measure was used to measure length and bow leg callipers were used to measure the diameter

of the piles at the top of the pile, at a point one-third along its length, at a point two-thirds along its length and at the bottom of the pile.



*Figure 4.4: (a) Load cell and pile during pull-out test, (b) Removed pile after pull-out test*

UCS tests were then performed on samples from the piles, 28 days after they were cast. The samples were cylindrical and trimmed using a circular saw from the base of the pile, to avoid including the steel bar, so they were approximately 60mm in height (Figure 4.5a). Measurements of the samples' diameters were made using a digital calliper. Plaster was applied to the top and bottom faces of the samples to achieve a level surface for the UCS test. The samples were tested in the Controls Advantest 9 compression testing machine with the failure load recorded and failure stress deduced (Figure 4.5b).



*Figure 4.5: (a) UCS samples trimmed from base of piles (b) Sample after UCS testing*

## 4.3 Results and Discussion

### 4.3.1 Pull-out force

Table 4.3 shows the lengths and the pull-out forces for all the lab-scale piles tested.

*Table 4.3: Lengths and pull-out forces of lab-scale piles*

| Pile No. | Material | Sand           | MgO % | Length (mm) | Pull-out force (N) |
|----------|----------|----------------|-------|-------------|--------------------|
| 1        | Cement   | Moist          | 0     | 310         | 458                |
| 2        | Cement   | Moist          | 8     | 275         | 422                |
| 3        | Cement   | Saturated      | 0     | 290         | 982                |
| 4        | Cement   | Saturated      | 8     | 295         | 1376               |
| 7        | Cement   | Saturated      | 8     | 290         | 751                |
| 9        | Concrete | Half-Saturated | 5     | 290         | 973                |
| 13       | Concrete | Half-Saturated | 8     | 260         | 796                |
| 10       | Concrete | Half-Saturated | 11    | 280         | 1032               |
| 5        | Concrete | Saturated      | 0     | 275         | 369                |
| 12       | Concrete | Saturated      | 5     | 295         | 688                |
| 6        | Concrete | Saturated      | 8     | 265         | 561                |
| 8        | Concrete | Saturated      | 8     | 300         | 656                |
| 11       | Concrete | Saturated      | 11    | 260         | 1309               |

The table above suggests that concrete piles with 5% MgO performed better than piles with 8% MgO. However, the piles have slightly different lengths, affecting their shaft resistances.

The pull-out forces were normalised for the slight differences in pile length, by dividing the force by the pile's length squared. The average unit shaft friction on the pile increases linearly with average effective stress, hence  $L$ ; and total shaft resistance is also directly proportional to surface area, hence  $L$  again. Consequently, shaft resistance scales with  $L^2$ .

Figure 4.6 shows the normalised pull-out force for cement paste and concrete piles. The cement paste piles have MgO contents of 0% and 8% and are in moist or saturated sand. The concrete piles have MgO contents of 0%, 5%, 8% and 11% and are partly or wholly in saturated sand.

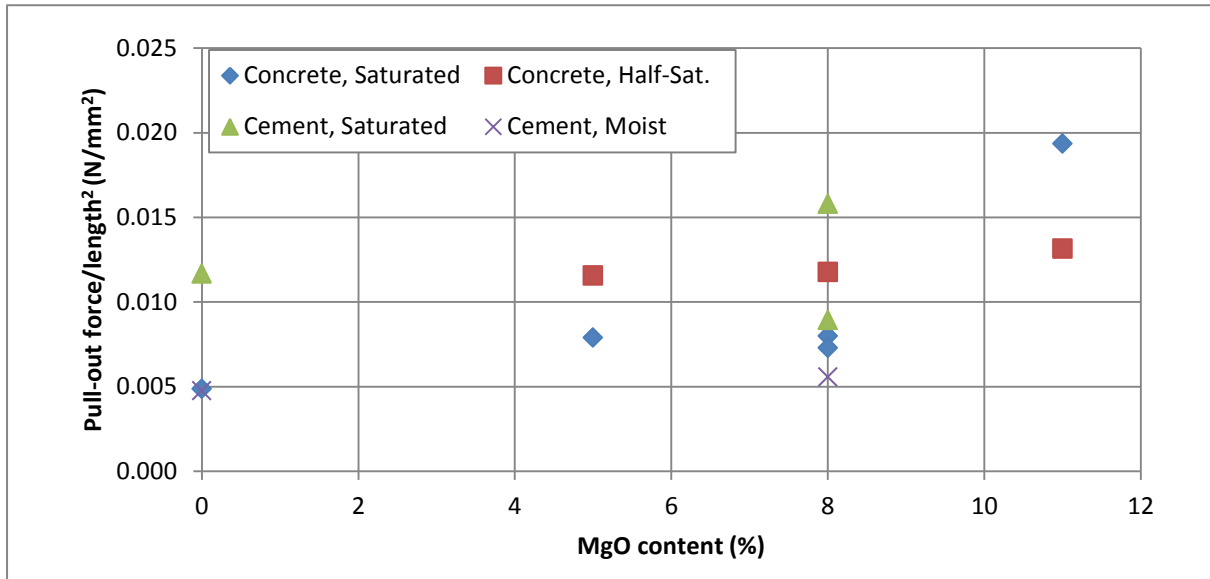


Figure 4.6: Normalised pull-out forces on piles

Cement paste piles in moist sand showed a slight increase in pull-out resistance as MgO content was raised from 0% to 8%. Although, the results for cement paste piles in saturated sand are inconclusive, as the pull-out resistance for one pile with 8% MgO was higher than for the pile without MgO, while the other 8% MgO pile had a lower resistance.

The pull-out force for concrete piles generally increased as MgO content was increased, although the resistances of the piles with 8% MgO were similar to those with 5% MgO. In saturated soil, the pile with an MgO content of 11% had a far higher shaft resistance than the piles with MgO contents of 5% or 8%. In half-saturated soil, the highest shaft resistance was again observed for the pile containing 11% MgO.

For the lower MgO contents of 5% and 8%, the pull-out force was greater when the bottom half of the pile was in saturated sand and the top half in moist sand, compared to when the entire pile was in saturated sand. This is because when a pile has its top half in moist sand instead of saturated sand, it experiences a greater horizontal effective stress there, increasing average unit shaft friction and total shaft resistance.

However, at 11% MgO a pile wholly in saturated sand had a greater pull-out resistance than a similar pile half in saturated sand. So if there is a higher MgO content, fully saturated conditions lead to greater shaft resistance than partly saturated conditions because there is more water present, enabling more hydration, thus increasing expansion.

All piles with saturated soil around their bases experience a base suction during the test, increasing the pull-out force. This is why the cement paste piles in saturated sand had a higher resistance than those in moist sand.

Table 4.4 shows the normalised pull-out forces of the concrete piles in saturated sand divided by the force for the 0% MgO pile.

*Table 4.4: Relative normalised pull-out forces of concrete piles in saturated sand*

| MgO content (%)                    | 0    | 5    | 8    | 11   |
|------------------------------------|------|------|------|------|
| Relative normalised pull-out force | 1.00 | 1.61 | 1.56 | 3.96 |

Piles with 5% or 8% MgO show around a 60% increase in shaft resistance, while the pile with 11% MgO shows almost a 300% increase.

#### **4.3.1.1 Comparison with calculated pull-out forces**

Taking approximate values for the sand's unit weight and  $K \tan \delta$ , it is possible to estimate the shaft resistance of a plain bored pile in the stipulated soil conditions.

While the drums were being prepared the medium sand was lightly compacted after each layer, making the sand dense. The dense medium sand's bulk unit weight was taken to be  $18.5 \text{ kN/m}^3$  and saturated unit weight  $21.5 \text{ kN/m}^3$  (BS 8002:1994, Table 1). The  $\beta$  value, or  $K \tan \delta$ , for bored piles in dense sand is 1.4 (Chitambira, 2000; Poulos and Davis, 1980). Table 4.5 lists the calculated and measured shaft resistances,  $Q$ .

All of the actual shaft resistances from the pull out tests are higher than the calculated resistances. The actual resistance for the concrete pile in saturated sand without MgO is 1.72 times greater than the predicted value. For a concrete pile with 11% MgO content in saturated sand the measured resistance was 6.42 times the calculated value because of expansion. The measured resistance of the cement paste pile with 0% MgO in moist sand was 1.03 times the calculated value. But the measured resistance of a similar pile in saturated sand was 3.98 times the predicted value because of suction.

Table 4.5: Calculated and actual shaft resistances for lab-scale piles

| Pile No. | Material | Sand           | MgO % | Length (mm) | Average Diameter (mm) | Average $\sigma_v'$ (kPa) | Calc. Q (N) | Actual Q (N) |
|----------|----------|----------------|-------|-------------|-----------------------|---------------------------|-------------|--------------|
| 1        | Cement   | Moist          | 0     | 310         | 113.7                 | 2.87                      | 445         | 458          |
| 2        | Cement   | Moist          | 8     | 275         | 114.7                 | 2.54                      | 353         | 422          |
| 3        | Cement   | Saturated      | 0     | 290         | 116.1                 | 1.67                      | 247         | 982          |
| 4        | Cement   | Saturated      | 8     | 295         | 116.6                 | 1.70                      | 257         | 1376         |
| 7        | Cement   | Saturated      | 8     | 290         | 116.8                 | 1.67                      | 248         | 751          |
| 9        | Concrete | Half-Saturated | 5     | 290         | 115.2                 | 2.43                      | 357         | 973          |
| 13       | Concrete | Half-Saturated | 8     | 260         | 120.4                 | 2.18                      | 300         | 796          |
| 10       | Concrete | Half-Saturated | 11    | 280         | 120.1                 | 2.35                      | 347         | 1032         |
| 5        | Concrete | Saturated      | 0     | 275         | 112.3                 | 1.58                      | 215         | 369          |
| 12       | Concrete | Saturated      | 5     | 295         | 112.0                 | 1.70                      | 246         | 688          |
| 6        | Concrete | Saturated      | 8     | 265         | 113.3                 | 1.52                      | 201         | 561          |
| 8        | Concrete | Saturated      | 8     | 300         | 111.8                 | 1.73                      | 254         | 656          |
| 11       | Concrete | Saturated      | 11    | 260         | 119.3                 | 1.50                      | 204         | 1309         |

#### 4.3.2 Pile diameter

Table 4.6 shows the diameter of each pile, taken at its top, at its one-third depth, at its two-thirds depth and at its bottom. The diameters of cement paste and concrete piles with differing MgO contents are displayed in the table. Figure 4.7 shows all of the average pile diameters as MgO content is varied, with points distinguished between cement paste and concrete piles and by soil saturation condition.

Table 4.6: Diameters measured at points along pile

| Pile No. | Material | Sand      | MgO % | Diameter (mm) |                 |                 |       |         |
|----------|----------|-----------|-------|---------------|-----------------|-----------------|-------|---------|
|          |          |           |       | Top           | One-third depth | Two-third depth | Base  | Average |
| 1        | Cement   | Moist     | 0     | 113.2         | 114.0           | 113.9           | 113.8 | 113.7   |
| 2        | Cement   | Moist     | 8     | 112.1         | 114.1           | 116.1           | 116.3 | 114.7   |
| 3        | Cement   | Saturated | 0     | 115.1         | 116.9           | 118.3           | 114.2 | 116.1   |
| 4        | Cement   | Saturated | 8     | 114.9         | 116.3           | 118.0           | 117.2 | 116.6   |
| 7        | Cement   | Saturated | 8     | 114.3         | 117.2           | 119.4           | 116.1 | 116.8   |
| 9        | Concrete | Half-Sat. | 5     | 115.7         | 111.0           | 113.5           | 120.6 | 115.2   |
| 13       | Concrete | Half-Sat. | 8     | 120.8         | 119.6           | 119.8           | 121.4 | 120.4   |
| 10       | Concrete | Half-Sat. | 11    | 118.3         | 119.3           | 118.8           | 124.0 | 120.1   |
| 5        | Concrete | Saturated | 0     | 111.3         | 112.6           | 112.9           | 112.5 | 112.3   |
| 12       | Concrete | Saturated | 5     | 108.0         | 112.2           | 113.0           | 114.7 | 112.0   |
| 6        | Concrete | Saturated | 8     | 112.6         | 115.8           | 110.7           | 114.0 | 113.3   |
| 8        | Concrete | Saturated | 8     | 105.2         | 109.6           | 114.4           | 118.0 | 111.8   |
| 11       | Concrete | Saturated | 11    | 114.8         | 115.9           | 121.7           | 124.8 | 119.3   |

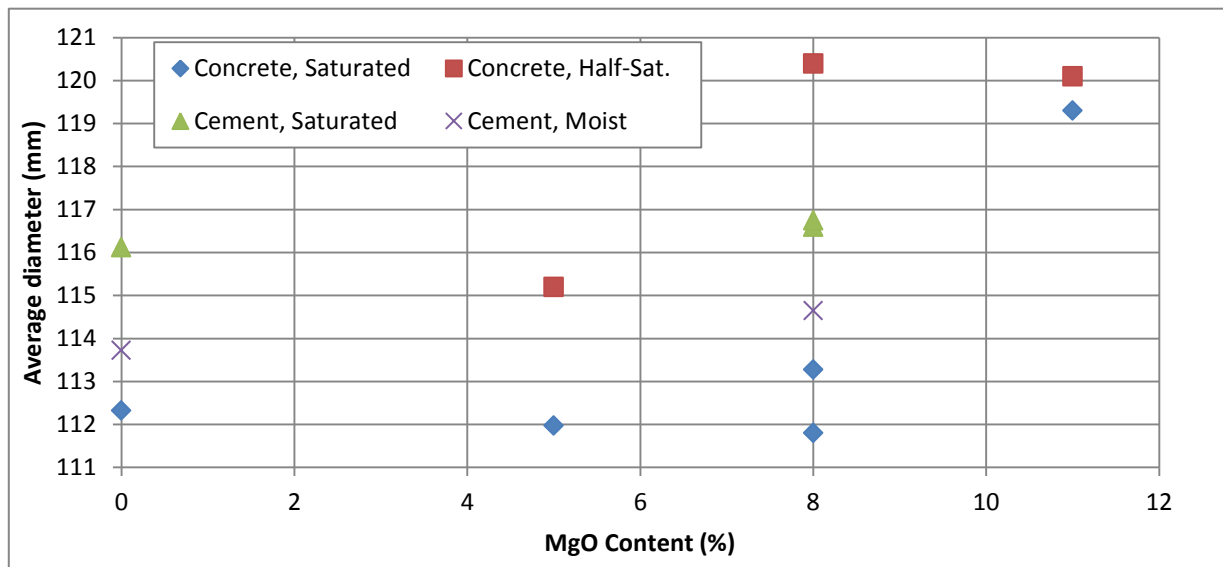


Figure 4.7: Average diameter along pile

Immediately after the plastic tubing is removed the cement paste or concrete fills a hole with a diameter equal to the tube's outer diameter, which is about 112mm. Some errors may have occurred in the measurement of pile diameter with the bow leg calliper because of the uneven

surface that measurements had to be taken across; the pile's cross-section is not perfectly circular so diameter varies in different orientations.

Pile diameter tends to increase with depth because the bottom of the drums keep saturated the longest. This trend occurs for most concrete piles wholly in saturated soil, which also tend to be narrowest at their top and widest at their bottom. The concrete piles that are “Half-Saturated” are widest at the base but not always narrowest at the top and expanded more than “Saturated” piles. Cement paste piles seemed to be widest around the middle of their length and the addition of MgO caused them to expand more near their bases.

As MgO content is increased, the average pile diameter measured along its length generally increases. This result is expected as a greater MgO content produces more expansion. Although the piles' initial diameters are not fixed by any rigid mould, assuming one of 112mm, the concrete pile containing 11% MgO produces a strain of 0.065, and cement pastes with 8% MgO have strains of 0.041 and 0.043. This is higher than the strain of 0.000625 observed in the cement paste investigation for cement paste containing 8% MgO.

Comparing the cement paste piles in moist sand with those in saturated sand, it can be seen that expansions are greater in saturated sand. This is because of the greater amount of water available for hydration and the lower confining horizontal effective stresses.

### **4.3.3 Force-displacement**

Figure 4.8a and 4.8b show the force-displacement behaviour during the pull-out test for concrete piles in soil saturated to half of the pile's depth and concrete piles entirely in saturated soil respectively.

As the peak pull-out force increased, the displacement at which the peak occurred also increased. The curves for the piles partly in saturated soil are similar in shape. But for piles wholly in saturated soil, the curve for the 11% MgO content has a sharper peak, possibly indicating a denser soil, while the other two MgO contents have a flatter peak. After all the curves peak, the force falls to a steady state, suggesting a drop in pile capacity as displacement continues to increase. The jaggedness of the lines is caused by the manually-operated pumping action, which applies load incrementally.

Where the sand is saturated, suctions are briefly generated as the pile is pulled out, increasing resistance.

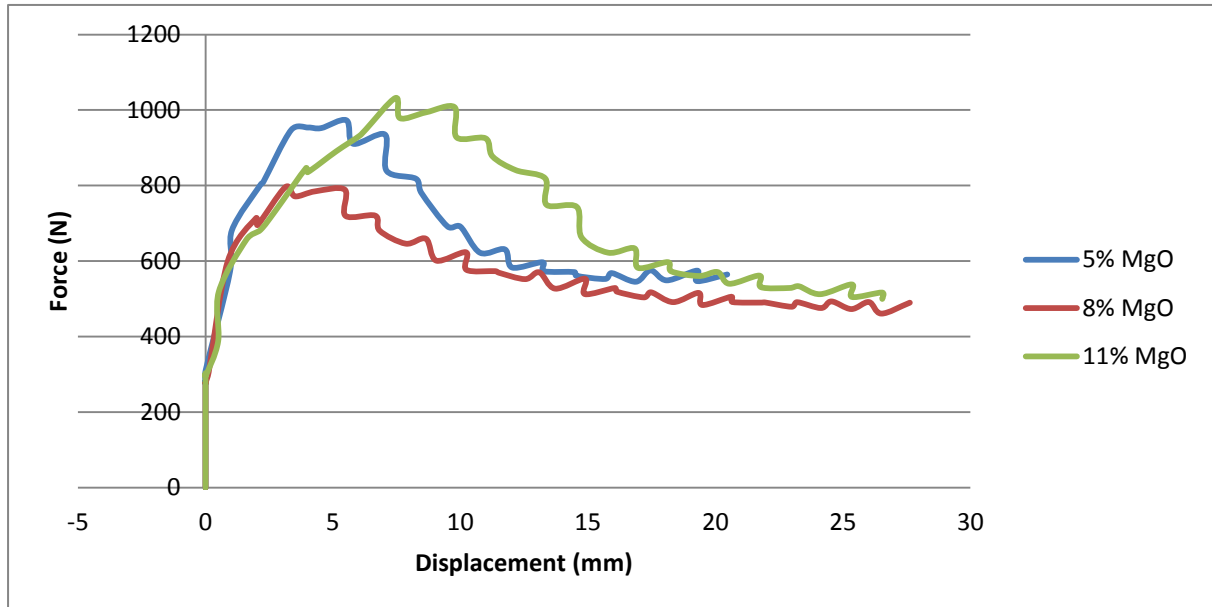


Figure 4.8a: Force-displacement plot of piles saturated to half-depth

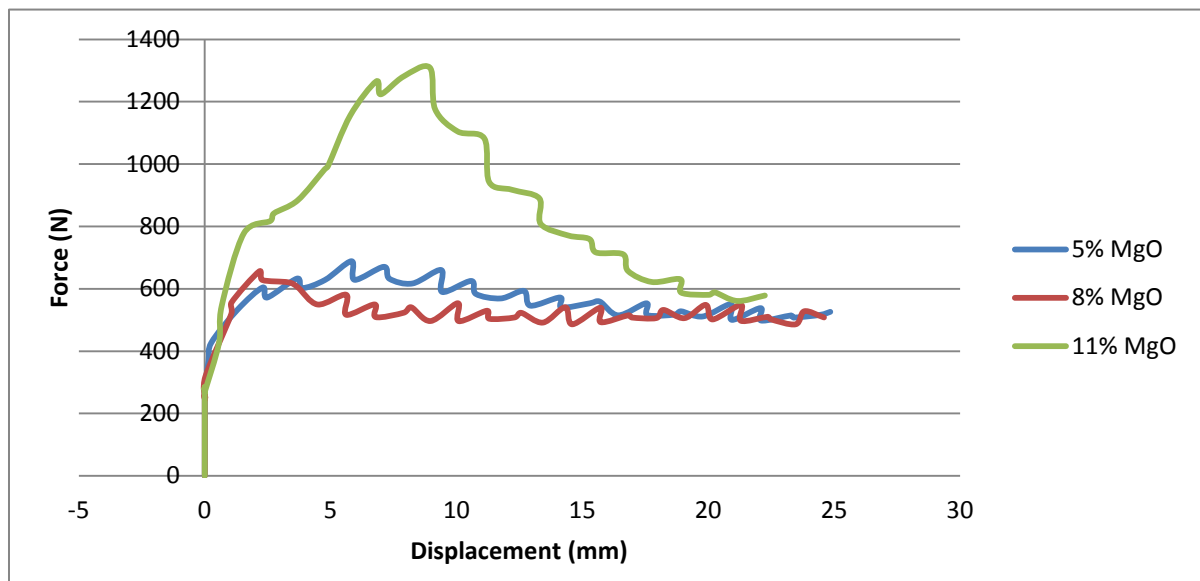


Figure 4.8b: Force-displacement plot for piles in saturated sand

#### 4.3.4 Density

Figure 4.9 shows the densities of all of the piles as MgO content is varied, with data points differentiated between cement paste and concrete piles and by soil saturation condition

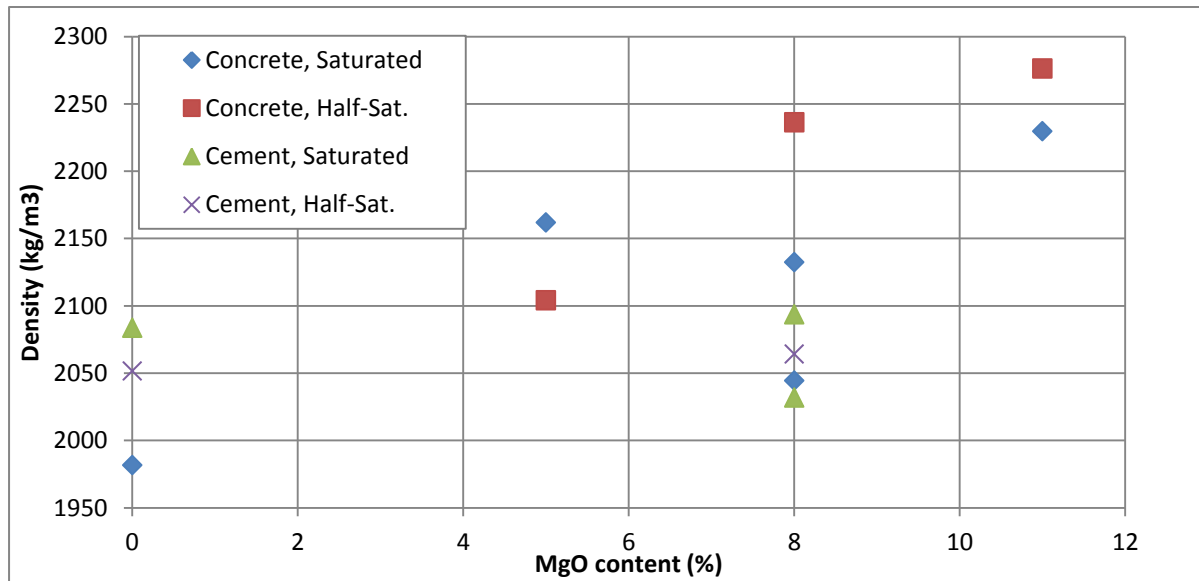


Figure 4.9: Density of piles

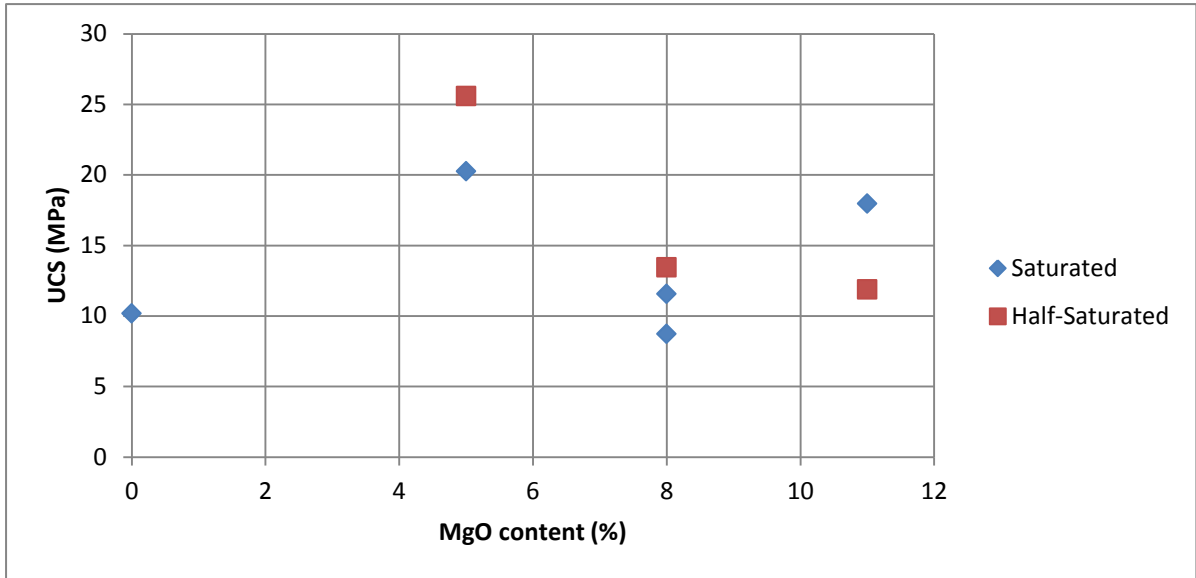
The scatter graph shows a general trend that the density of concrete increases with MgO content. This is because of the greater molecular weight of brucite produced during hydration and the volumetric expansion occurring in restrained conditions. Changes in density with MgO content were more noticeable in concrete piles than in cement paste piles. There is some error in the densities, as the pile was idealised as a perfect cylinder to obtain volume.

#### 4.3.5 Strength

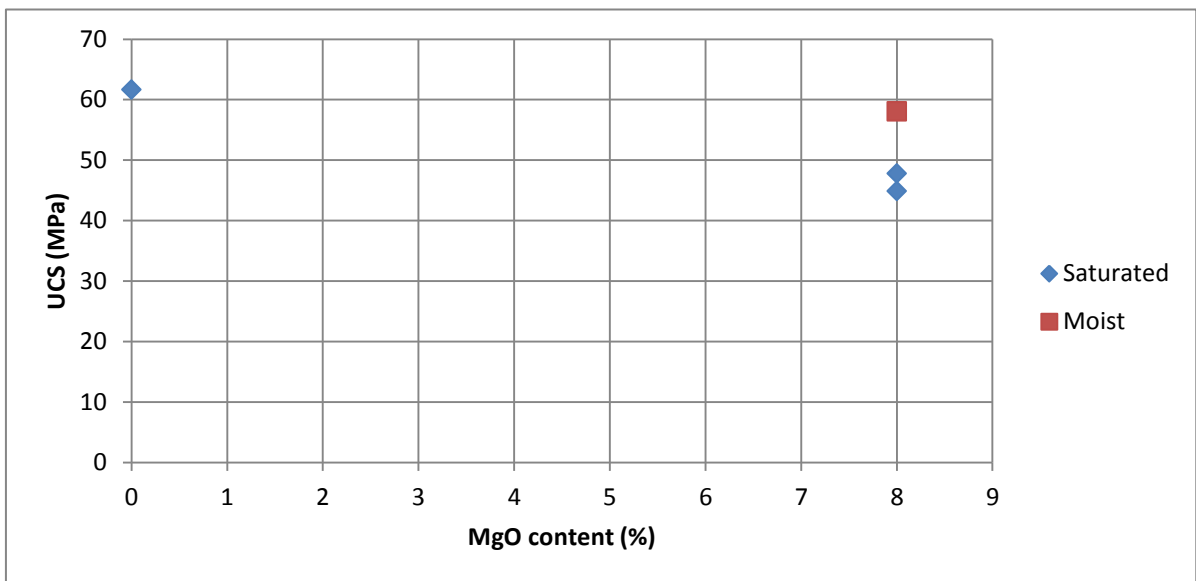
Figure 4.10a and 4.10b show the UCS of 60mm tall cylindrical samples trimmed from the base of the concrete piles and cement paste piles respectively. In figure 4.16a, the soil saturation conditions should not affect the strength of the concrete at the base of the pile, where it would be in saturated sand, but the two sets have been distinguished for completeness. In figure 4.16b, the soil at the base of the pile is either moist or saturated, so there is a difference in the amount of water available for MgO hydration.

The UCS of the cylindrical concrete samples taken from the base of the piles decreases as MgO content increases from 5% to 11%. Though, the sample without MgO has one of the lowest strengths recorded. This is because the addition of MgO can increase strength in restrained conditions, but excessive MgO addition then decreases strength, so there is an optimum MgO content around 5% that achieves high compressive strength.

The UCS of cement paste samples from the base of the piles decreases as MgO content increases. This supports the earlier UCS tests on cement paste cubes and the background theory that an MgO content of 8% can cause unsoundness.



*Figure 4.10a: UCS of concrete piles*



*Figure 4.10b: UCS of cement paste piles*

The cement paste cubes from the earlier investigation had a 21-day strength of 60 MPa and 59 MPa for a 0% and 8% MgO content respectively. While the pile specimens had a 28-day strength of 62 MPa for a 0% MgO content and between 45 and 58 MPa for an 8% MgO content. The differences in strength are affected by the difference in specimen shape; direct strength comparisons cannot be made between cubes and cylinders with a height to diameter ratio of approximately 0.5.

# Chapter 5: Conclusions

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Magnesia has been used as an expansive additive in concrete to reduce thermal cracking and drying shrinkage, most notably in the construction of dams.

The literature review summarised that MgO creates expansion in concrete by hydrating to form brucite, which has a larger volume. An increase in MgO content leads to a greater expansion. The late-age expansion of MgO is more stable and useful than the early-age formation of ettringite or portlandite from sulpho-aluminate additives or quick lime respectively.

Compressive strength normally decreases when high MgO contents are used in a phenomenon known as unsoundness. However, strength can be increased if the expansion of MgO concrete is restrained, as with bored piles, because a denser microstructure will be produced. A light-burnt MgO, calcined at 900°C, has strong expansive characteristics and will produce large and rapid expansion. Dead-burnt MgO, calcined at 1400°C, does produce greater expansions at a much later age, but its slow expansion leads to unsoundness and a drop in strength and concrete integrity.

Expansion of a bored pile will compress surrounding soil and increase friction between the pile and the soil, thus improving shaft resistance.

For expansion to occur, moist curing is required because water is drawn in from the surroundings to hydrate MgO. This is not a problem for piles in saturated soils but water may need to be added to dry soils in order to maximise expansion. A uniform distribution of MgO in the cement mixture is important for avoiding harmful over-expansion in localised areas, which would reduce compressive strength. As brucite has a larger volume than magnesia, its formation fills the pores within concrete so density will increase with MgO content.

This project's investigation into cement paste tested the compressive strength, drying shrinkage and wet-cured expansion of pastes with 0%, 5% and 8% MgO contents with water-cement ratios of 0.33 and 0.37. It confirmed that higher MgO contents produce larger expansive strains. A 5% MgO content was observed to have the highest compressive strength. The tests also showed that pastes with a low water content produced higher compressive strengths, smaller shrinkage and smaller expansion than pastes with a high water

content. A light-burnt MgO mix was found to produce higher compressive strength, more expansion and less shrinkage than one using hard-burnt MgO.

The addition of MgO to cement paste was shown to compensate drying shrinkage to a small extent after 6 months in dry conditions. Although its behaviour in the later ages seemed to suggest that, given more time, the shrinkage would be compensated further.

The addition of MgO to the concrete used to cast bored piles does increase shaft resistance. The greatest increase in shaft resistance for a concrete pile was observed when a binder with an MgO content of 11% was used. Improvements in shaft resistance were observed for piles either partly or wholly in saturated sand. Piles with MgO contents of 5% or 8% saw greater shaft resistances when partly in saturated soil but piles with an 11% MgO content produced higher resistances when entirely in saturated soil.

Measuring the pile diameters, more expansion was seen for cement paste piles in saturated sand than in moist sand, and more expansion occurred in concrete piles in sand saturated to half their depth compared to concrete piles entirely in saturated sand. Pile diameter increased with MgO content.

The strength of the concrete did not decrease with the addition of MgO because of the piles' confined conditions. In fact, compressive strength improved in some cases, with the greatest strength being observed when the binder contained 5% MgO.

The pull-out resistance of a pile using 5% MgO was 1.61 times the resistance of a plain pile. This means that piles can be 38% shorter if the cement binder has an MgO content of 5%. Piles using a binder with 11% MgO can reduce the length even further.

The relative costs of PC, GGBS, aggregates, steel and MgO need to be considered in industry when deciding whether there is a real benefit to using expansive additives in bored piles. MgO costs in the region of £150 to £200 per tonne.

An alternative method of increasing pile capacity is to use base and shaft grouting, which normally increases capacity by between 1.5 and 3 times and can increase it by as much as 5 to 7 times.

## 5.1 Future work

The results of this project have been encouraging but knowledge in this field can be improved. Possible extensions are listed in order of priority:

- More pile pull-out tests can be conducted, with a greater number of repeats, in order to verify the results of this investigation. The piles tested should have a range of MgO contents, including piles without MgO.
- Pile tests should be performed in clay to ascertain whether similar results are found for cohesive soils.
- Long-term studies into the durability of MgO concrete piles should be undertaken before use in industry
- UCS tests should be performed on 100mm cubes of MgO concrete to obtain more accurate results than from the trimmed samples, some of which had slight defects. Also, these tests should be performed at multiple ages to observe strength development.
- The cement paste investigation can be furthered to include another water-cement ratio and another MgO content to get clearer indication of trends as water-cement ratio or MgO content is increased.

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## Appendix I: Risk Assessment Retrospective

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A risk assessment was completed and submitted to the CUED Safety Officer before beginning the project. It was largely accurate in safeguarding against the risks encountered.

A 3M 8835 dust mask was needed when mixing cement, because of the fine particle sizes of PC, GGBS and MgO. A face fit test was done by the Safety Office to check that the dust mask fit securely and functioned effectively; this test was passed and has been certified. A lab coat was also worn when mixing cement.

Mechanical equipment included the concrete mixers and the compression machine. The debris from the crushed UCS samples was contained using a protective screen. Safety boots were worn in the Inglis structures and concrete laboratories. Latex gloves were worn at all times when cement and concrete was being handled.

In addition to the original risk assessment, a fixed circular saw was used to trim UCS samples from the piles. The saw had a guard and was fitted with an emergency stop. Instructions on how to operate the saw safely were received and care was taken when using this equipment. A dust mask, eye and ear protection were all worn when the saw was operated.

Also, handling of the drums required care because they were heavy when filled; a trolley was used to move them between the preparation area and testing area.