ADVANCED MASTERS IN STRUCTURAL ANALYSIS
OF MONUMENTS AND HISTORICAL CONSTRUCTIONS

Master's Thesis

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Study of earth-grout mixtures for rehabilitation

This Masters Course has been funded with support from the European Commission. This publication reflects the views only of the author, and the Commission cannot be held responsible for any use which may be made of the information contained therein.

Portugal | 2009

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ACKNOWLEDGEMENTS

This thesis could never have been completed without the support of many people. First of all, I would like to thank the European Union for providing the essential financial support through the Erasmus Mundus Scholarship, as well as the selection committee of the Advanced Masters in Structural Analysis of Monuments and Historical Construction who selected me to take part in this program. My most sincere gratitude for my supervisor, Prof. Rui Miguel Ferreira, for his professional guidance and precious suggestion to make this work possible. My sincere appreciation for Prof. Joao Paulo C. Gomes and Prof. Luiz Oliveira of the Centre of Materials and Building Technologies of the University of Beira Interior, for their support with the tests. I would like to extend my thanks to Prof. Luiz Oliveira who provided me useful suggestions and comprehensive edits in part of the work. My earnest gratitude to Filipe, Rui and to all laboratory technicians of the Construction Materials Laboratory of the University of Minho especially to Carlos Jesus, Fernando Pokee and Mr. Matos of providing me technical suggestions and friendship. I greatly acknowledge the help of Elisa Trovo, Sandra Pereira and Dora Coelho for their friendship and help through this master course. I would like to thank to Alejandro, Füsun, Habtamu, Murat, Tibebu, Visar and Ziba for all your companionship and discussion during this four months in Portugal. I would like to thank my endearing class of SAHC 2008/2009 Padova, Italy, especially Dechen and Patricia for your warmly friendship and support. A very special thanks to my flat mates in Italy, Anna, Jeremy and Raphael, for providing me a warm home and support to help me complete the intense courses in Italy. Great thanks to Prof. Kou K.P and Walter Wan for providing me information about this master course that let me have a meaningful year. Life-long thanks go to my parents and brother for providing me a strong foundation, toleration and trust which helped me to pursue my dreams.

ABSTRACT

Earth is one of the prevalent building materials and heritage built with earth can be found on all continents. Lack of maintenance and deterioration caused by environment have often led to fragmentation, cracking and durability problem. The grout injection method of strengthening masonry structures has been suggested as a viable and economical method to restore the earth structure. However, since grout injection technique is somehow irreversible, the compatibility between the grout and substrate is essential. Until recently, the strengthening of monuments was carried out with less adequate material like Portland cement, polymers or mixture of both; however, those materials have been proved incompatible with the original materials of the monuments. The incompatibility even causes further damages and durability failures of the repaired structures.

The requirements of the grout mixture for earth construction are quite similar to that of masonry structure. It should be with good injectability, bonding properties, similar strength as the substrate, adequate rate of strength development and low undesirable chemical reactions. Another important requirement is the moisture and air permeability. Thus, adding soil to the traditional grouting materials is proposed. This may improve the bonding properties while also possesses similar properties as the substrate. Given the unique approach presented, little knowledge exists on the appropriate mix design.

It is proposed in this research to study the performance of grout mixtures with different proportion of saturated clay, sand, hydraulic lime and cement. The aim is to verify if grout with earth can be a physico-chemcial compatible with the earth structure but at the same time fulfill the requirement based on structural viewpoint.

Finally, it is found that grout mixture with earth can obtain adequate fluidity, porosity and similar compressive strength as the substrate. A drawback is that the clay/sand mixture affects the fluidity and will lead to a quicker loss in workability which requires further study on the mix design and composition proportions. However, in this research it was found that adding earth to the grout is feasible and deserves further development.

RESUMO

A terra é um dos materiais de construção prevalentes sendo que património construído com terra pode ser encontrada em todos os continentes. A falta de manutenção e a deterioração causada pelo meio ambiente, resultando na sua fragmentação, fissuração e consequentemente os problemas de durabilidade. O método de injecção de caldas utiliza-se no reforço de alvenarias estruturais tendo sido sugerido como um método viável e económico para reforçar estruturas de terra. No entanto, como a técnica de injecção é irreversível, logo a compatibilidade entre a calda e o substrato é fundamental. Até recentemente, o reforço de construções antigas era realizado com materiais menos apropriados como o cimento Portland, polímeros ou uma mistura de ambos. Porém, esses materiais têm sido provado incompatíveis com os materiais originais constituintes das construções antigas. A incompatibilidade pode mesmo provoca maiores danos e roturas por durabilidade da estrutura.

Os requisitos para exigidos às caldas com terra são semelhante aos das estruturas de alvenaria. Deve possuir boa injectabilidade, propriedades de aderência semelhantes à do substrato, um adequado desenvolvimento de resistência e poucas reacções químicas indesejáveis. Outro requisito importante é a humidade do ar e a permeabilidade ao vapor. Desta forma, propõem-se a adição de solo a caldas de cimento e cal hidráulica tradicionais. Espera-se desta forma melhorar as propriedades de aderência ao mesmo tempo que também as possui propriedades semelhantes às do material a reforçar. Dada a inovação desta abordagem, existe pouca investigação publicada sobre as composições destas caldas.

Propõe-se investigação estudar o desempenho de caldas misturadas com diferentes proporções de argila saturada, areia, cal hidráulica e cimento. O objectivo é verificar se a caldas com terra possuem propriedades físico-químicas compatíveis com as estrutura de terra, enquanto que, ao mesmo tempo, cumprem com as exigências mecânicas.

Por último, verificou-se que as caldas misturadas com terra podem obter fluidez adequada, porosidade e resistência à compressão semelhantes à do metrial a reforçar. Uma desvantagem reside na influência da proporção argila/areia que afecta a fluidez e conduzirá a uma rápida perda de trabalhabilidade, logo que requer um estudo mais aprofundado sobre a composição. No entanto, nesta pesquisa, verificou-se que a adição da terra para a argamassa é viável e que merece maior aprofundamento.

摘要 (ABSTRACT)

土壤是其中一種很普遍的建築材料，在世界各地的古蹟中均不乏土建築。可惜很多土建築都因為缺乏維修保護或其他外來環境因素而導致損毀、開裂和耐久性等問題。應用於強化磚體結構之灌漿技術被視為其中一種修護土建築既經濟而可行的方法。然而，由於灌漿是一種不具可逆性的技術; 因此，灌漿物與土建築材料的兼容性是相當重要。直到最近，矽酸鹽水泥、聚合物或兩者的混合物開始被用於修復古建築。然而，這些物質被證實未能與原建築物料兼容，反而會加劇損毀及耐久性等問題。

應用在土建築及磚體建築的灌漿物料有相同的準則。灌漿物料需具備良好的流動性、黏附能力、與原材料相當的強度、足夠的早期強度、水及空氣滲透性和適當的化學特性。因此提出把土壤加入傳統的灌漿物料中，從而使灌漿物料具備土建築材料相似的特性及提高其黏附力。鑑於其獨特性質，此灌漿仍存有很多未知因素。

本論文提出對具備不同比例的飽和黏土、沙粒、石灰泥及水泥的灌漿物料作出一系列的實驗，從而探討及考證含有土壤灌漿物料是否能同時滿足兼容性和結構學上的要求。

實驗結果顯示，含有土壤的灌漿物料能具有足夠的流動性、透氣度和與原材料相近的強度。當中一項缺點為含有土壤的灌漿物料會加速流動能力的流失，因此應在物料成份及比例上作更深入之研究。然而，綜合所有實驗之結果，把土壤加入灌漿物料中有其可行性並應加以研究和發展。

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1. INTRODUCTION

Earth is a natural building material which can be found all over the world, therefore, it is one of the prevalent building materials. Heritage of earth building can be found on all continents. It exists in different types of building such as homes, wells, religious buildings, and even for defensive structures as castles and walls.

Nowadays, there is still one third of the human population living in earth structures. These consist of different types and can be differentiated according to the construction technique applied. There are seven main classes of technique to built earth structures: adobe, rammed earth, straw clay, wattle and daub, direct shaping, compressed earth blocks and cob (Houben & Guillaud, 2008). However, the first two methods are the typical methods being applied. These two techniques will be further discussed in the following sections.

Due to the widespread of modern construction material, earth is replaced by other modern building materials, like concrete and steel. Thus, the engineers in developed countries disregard earth as a construction material, and as a result, much related knowledge has seemed lost. Lack of maintenance and deterioration caused by environment have often led to fragmentation, cracking and durability problems.

The grout injection method of strengthening masonry structures has been suggested as a viable and economical method to restore the earth structure. However, since grout injection technique is somehow irreversible, the compatibility between the grout and substrate is essential. Until recently, the strengthening of monuments was carried out with less adequate material like Portland cement, polymers or mixture of both; however, those materials have been proved incompatible with the original materials of the monuments.

The requirements of the grout mixture for earth construction are quite similar to that of masonry structure. There are two main categories of requirement that are the mechanical behaviour and the durability of the injected structure. The first one is related to the physical behaviour of the injected structure. This includes, the injectability, bonding properties and the mechanical properties. The grout mixtures should consist of low yield value and viscosity, good penetrability, low bleeding and shrinkage and adequate rate of strength development. The other requirement is related to the durability of the injected structure. This includes the compatibility microstructure and limited undesirable chemical reactions. The grout to fulfill this should have compatible porosity and pore size distribution, limitation of diffusion of sulphate and chlorides, etc.

Since existing grout mixtures cannot fulfill these requirements, it is needed to develop a new mixture which can be physico-chemical compatible to the substrate. For earth structure, there is one more criteria that is the water and air permeability. Therefore, adding earth to the traditional grouting materials is proposed which seems can improve the bonding properties but also possesses similar properties as the substrate. Given the unique approach presented, little knowledge exists on the appropriate mix design.

1.1 Objectives

It is proposed in this research to study the performance of grout mixtures with different proportion of saturated clay and sand, hydraulic lime and cement. The mixture stability, physical, mechanical and rheological properties are then studied.

Based on the various mix design (parameter studied), the following is proposed:

- identification of physical properties of the specimens including fluidity, segregation, porosity, capillary absorption and electrical resistivity;
- identification of mechanical properties of the specimens including retraction mechanism, compressive strength, flexural strength and elastic modulus;
- identification of rheological properties including the flow curve, flow resistance and cohesion coefficient.

1.2 Thesis Structure

In addition to the introductory chapter, the dissertation is divided into seven additional chapters and appendix.

In Chapter 2: an introduction to the history of earth construction, structural pathology, and the rehabilitation of earth structure. In this chapter, the history, construction procedures and characteristics of the adobe structure and the rammed earth structure are briefly introduced. Furthermore, the cause of deterioration (such as water, biodeterioration and improper rehabilitation) and the common methods of restoration are reviewed.

In Chapter 3: present a literature review on grouting. In this chapter, the principle of grouting is reviewed. Literature review is done related to the characteristic and composition of the grout.

In Chapter 4: description of the material used and the mixing procedure for the grout mixes. In this chapter, the characteristic of the material used are present, the materials include sand, clay, hydraulic lime, cement and superplasticizer. Follow by the mixing procedure of the grout mixes.

In Chapter 5: a brief explanation on all the test procedure is given. In this chapter, all the test procedures are described. The test include fluidity test, segregation/bleeding test, electrical resistivity test, porosity test, oxygen and water permeability test, capillary absorption test, shrinkage test, test for determining flexural and compressive strength, elastic modulus and the rheological test.

In Chapter 6: the composition study, the test result and analysis of the test result are given. In this chapter, the calibration result of the grout mixes is present. All test results are then analysis and compared with reference values.

In Chapter 7: concludes on the test result and present the future work to study. In this chapter, the conclusion is made based on the test result. The effect of adding soil into the grout mixes is discussed. Furthermore, comments are made related to the content of future studies.

In the appendix, the raw data from the test procedures is presented.

2. EARTH CONSTRUCTION

Earth is a natural building material that can be found in most regions of the world. As a result, it is one of the prevalent building materials. Heritage of earth building can be found on all continents. Constructions exist in different types and shapes of buildings such as homes, wells, religious buildings, and even for defensive buildings. However, in developed cities, earth is replaced by other modern building materials, like concrete and steel. Nevertheless, one third of the human population lives in earth structures.

2.1 History of Earth Construction

Earth has been used as a construction material for as long as 8000 years (Minke, 2006). Earth construction exists on different continents, like Africa, Asia, Europe and America. The oldest adobe houses dating from 8000 to 6000 BC discovered in Russian Turkestan region (Pumpelly, 1908). Adobe structure is one of the oldest earth constructions techniques. In Iran, the Arg-é Bam, as shown in Figure 1, is the largest adobe building in the world located in Bam being built before 500BC.

Figure 1: The citadel of Arg-e Bam ("UNESCO World Heritage Centre," n.d.)

Another common earth construction technique is rammed earth structure. The early use of this technique can be traced to 5000BC in Neolithic archaeological sites of the Yangshao culture and the Longshan culture in China (Liu, 2002). Yet another earth construction technique, contemporary to this period is rammed earth applied in foundations in Assyria. An existing rammed earth structure is shown in Figure 2, the castle at Banos de la Encina which was built in 967AD in Spain. The most well-known existing ancient rammed earth structure is probably the 400-year-old Great Wall of China, which was built of rammed earth but later being covered by stones and brick. Another old example of mud brick walls is in Heuneburg Fort near Lake Constance, Germany and dates back to the 6th century BC (Minke, 2006). As mentioned above, the existing heritage found all over the world is a good proof that rammed earth construction is long lasting.

Figure 2: The castle at Banosde la Encina in Spain (rammed earth structure) (Jaquin, 2007)

Earth construction technique was well developed in dry region where other types of construction material cannot be found easily. Except for the rammed earth and adobe, there are other different earth construction technique of which constructions are made such as direct shaping and compressed earth blocks. Earth construction can accomplish delicate structural and architectural features such as domes and arches. The bazaar quarter of Sirdjan in Persia is one of the examples as shown in Figure 3.

Figure 3: Baraaz, Sirdjan, Iran (Minke, 2006)

Underground building was the other type of construction technique. In China, the climate of some regions, like eastern part of Gansu Province and Shaanxi Province, are dry and the soil is consolidated, people built their homes by digging caves in the silt and soil. Figure 4 shows the earth-well type cave in Shilipu Village in China.

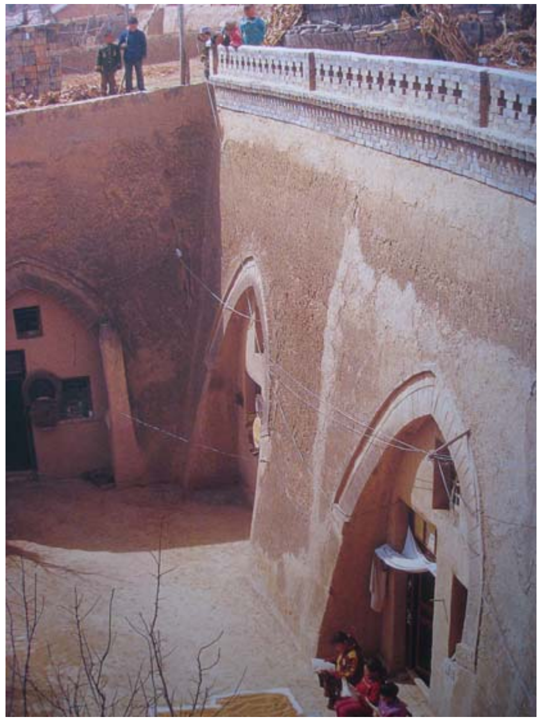


Figure 4: Earth well type cave, Shilipu Village, China (Lou, 2008)

There are different types of earth constructions that can be differentiated according to the technique applied. There are seven main classes of technique to built earth structures: adobe, rammed earth, straw clay, wattle and daub, direct shaping, compressed earth blocks and cob. However, the first two methods, adobe and rammed earth, are the most typical methods being applied. (Houben & Guillaud, 2008). In the following section these two techniques will be further discussed.

2.2 Adobe Structure

2.2.1 Building Materials of Adobe Structure

Adobe building materials used in historic structures include sun-dried brick or block, adobe mortar and cast adobe. Adobe is made by putting the loam into a formwork and drying naturally. The loam is composed of sand, silt, clay and water. Other materials, such as animals' hair and straw, are sometime added to improve the strength of the adobe. Small stones or gravel will be added in varying quantity. The material and the production process affect the quality of the adobe. The earth used to produce adobe can be well control by the particle size of the components. Furthermore, the amount of clay play an important role in the adobe structure since the clay content is the parameter which affect the expansion, moisture absorption and the shrinkage. Therefore, excess amount of clay will reduce the resistance to wetting and drying cycle and result in changing the dimension of the structure. In addition, the higher amount of clay will also lower the flexural strength of the adobe. However, clay is the main components which give the adobe the dry compressive strength. Silt is also working as a binder in the adobe composition; it works with clay to hold the sand particles to form the loam. Sand, especially coarse sand, is the material which provides high porosity and high compressive strength with minimum shrinkage (Minke, 2006). As mentioned above, gravel is added in certain amount, however, if the gravel is too large, its weight will overcome the binding forces of the silt-clay and will flow downward to cause disruption. Therefore, to obtain the dimensionally stable adobe, it should contain high sand to silt-clay ratio while with minimum amount of gravel. Furthermore, to obtain durable adobe structure, the loam used should 62% sand, 2% gravel, 22% silt and 14%clay (Minke, 2006).

2.2.2 Construction technique of Adobe Structure

The construction procedure and technique of adobe construction is very simple. This is the reason why it is widely spread all over the world. No special engineer is needed to build a simple adobe structure. The tools required are very common. The main apparatus is the form. There are different types of form for producing single block, but two- or four block forms are more efficient. The material of the form should be strong and long-lasting made from 2-inch thick planks. The dimension of the form is controlled by the weight of the block. To facilitate the building process, the block should be kept small enough about 23kg which can be moved easily. Therefore, the common dimension of the form is about 10~15cm thick and the width of the block should match the desired thickness of the wall between 23~46cm, the length is controlled by the weight of the block. The two typical sizes of blocks are 12.7x 25.4 x 50.8 cm with a weight about 25kg and 10.2 x 30.5 x 45.7 cm with a weight about 23kg. The common compressive strength of adobe block is about 1.0~5.0 MPa (Torrealva, 2009a).

The optimum number of workers to build an adobe structure is four. Two men prepare and mix the soil while the other two molds and remove the blocks and then clean the forms.(Handbook for building homes of earth, 1981) The procedure for making adobe block is routine. First, mix the soil with water to form loam and leave it to stay for two to three days such that allowing the activation of the clay particles. Then the loam is placed into the forms. It is suggested to drop or throw the mix in the forms so it packs tightly and can improve the strength. The mix is then kneaded by hand to fill all of the corners and remove all air bubbles within the loam. The kneading procedure should be done with great care so the corners and edges of the block gain sufficient strength. After kneading, a small board or trowel is used to cut off the extra soil and smooth the top edge of the molded block. A little water sprinkled on top of the block will help in smoothing it. As soon as possible, the forms are lifted from the freshly made blocks. There is no special time standard to remove the forms but to try it. If the blocks slump or bulge too much, either the forms are being removed too soon or the mix is too wet. If the mix sticks to the forms when they are removed, it is too dry or the forms have not been oiled enough.

The freshly made adobe blocks must be cured or sun-dried before they can be used. After removal from the mold, it is needed to leave them in place for two to four days so that it can gain enough strength to hold the shape. Then the adobe block should be placed on edge to finish curing. The time for curing may be almost a month, which depends on the weather and the material. The time may vary according to the stabilizers applied. If the lime or cement is used a stabilizers, the block should be either cover by straw or a wet cloth so to keep the moisture before turning them on edge for further curing. Finally, the blocks are stacked on edge so they occupy fewer space while curing. Figure 5 shows a worker making the adobe and how the adobe blocks are dried under the sun.

Figure 5: Worker producing adobe in Bam, Iran (Torrealva, 2009a)

2.3 Rammed earth structure

2.3.1 Materials used for rammed earth structure

Rammed earth structures are made by mixing sandy-clay soil with water that is very similar to the loam for making the adobe structure. The main difference is the water content and the absence of silt. The loam used is consisted of 50%~60% of sand, 10~20% of clay and 12~15% of water (Brown & Clifton, 1978). Loam contains more than 50%~60% of clay will lead to shrinkage. The compressive strength of rammed earth block is about 1.0~3.0 MPa (“www.bath.ac.uk,” n.d.).

Compared with other earth construction, rammed earth buildings consisted of higher construction cost due to the high labour costs. However, it also results in lower shrinkage ratio and higher strength compared with wet loam techniques. Furthermore, it is more long lasting compared with the adobe structure due to its monolithic characteristic.

2.3.2 Construction technique of rammed earth structure

Rammed earth structure is built by compacting the loam or moist soil into position between heavy wooden forms. In this method, continuous wall are built layer by layer. A short section of wall is completed first and then the forms are moved upward or sideways and repeat the compaction process again. The rams used can be in conical, wedge-shaped or flat bases. It will achieve a better bond if the wedge-shaped or conical rams are used. Flat-based rams will result in lower lateral shear resistance.

As previously mentioned, rammed earth structures are built layer by layer. This leads to different properties between the upper layer and the lower layers. It is found that the upper layer is usually contains higher moisture, so higher shrinkage. Therefore, it is common to find horizontal crack due to the higher shrinkage in the upper layer, which results in horizontal shrinkage cracks at the joint. This kind of horizontal crack will trap the capillary water and lead to swelling of the structure. This problem can be prevented by using the French pise technique (Minke, 2006).

A layer of lime mortar is applied above each layer so that it cures over several weeks and will remain plastic until the loam has stopped shrinking. Rammed earth wall can be provided a smooth surface if it is sponged with a moist felt trowel immediately after dismantling the formwork. For the exterior surfaces, roof overhangs should be used to protect it from rain and plinths should be used to prevent the splashing of water.

Rammed earth construction requires the most careful selection of the soil type, or the walls will shrink and crack after they dry. The amount of water used in the soil during the ramming must be carefully controlled to get proper ramming of the soil. If carefully done, the finished wall may look well without any coating. However, it is common practice to stucco or paint the finished wall to produce a pleasing finish. A well-made rammed earth wall is one of the most durable earth walls that can be made. Some have lasted for centuries.

2.4 Deterioration of Earth Construction

Earth construction built with natural materials is subjected to different types of deterioration. The degradation of earth structure in fact is generally caused by the combination of many factors that prompts deterioration processes. The various factors are as listed as followed:

Water

Water is the most deleterious factor leading to deterioration of earth construction. The water can attack the buildings in different forms and from various sources. Rain is one of the main sources of water, the rain penetration at the wall heads will lead to cracking at the top and vertical surfaces when the water running down from the top of the wall. The rain will also saturate the wall and leads to failure. Another source is ground water, which will lead to capillary action as shown in Figure 6. If there is salt in the ground water, salt crystallization will happen at the wall and lead to spalling at the wall base.

Figure 6: The capillary action in Plaza de Acho in Peru (Torrealva, 2009b)

Moisture, in another form of water that can greatly speed up the decay of earth construction. Building materials consisting of high clay content will be more susceptible to damping since it will lead to the dispersal of the clay and lead to a dramatic decrease in tensile and compressive strength of the wall. Another problem cause by moisture is that it will lead to swelling of the unit and shrink when it is dried. This type of varying dimension leads to formation of cracks. Continuous wet and dry cycles will result in crack propagation and imperil the structure integrity. In cold region, excess moisture can affect the earth structure because of the freeze-thaw damage. Thus, shrinkage, cracking, erosion, under-scoring and mechanical damage occur as a result due directly or indirectly of water. Some example of deterioration due to water is shown in Figure 7.

(a) (b)

Figure 7: (a) Swallowing at the lower part of the wall. (b) Erosion at the lower part of the wall (Torrealva, 2009b)

Biodeterioration

As earth is a natural building material it is more susceptible to biodeterioration namely vegetation growth than other building materials. It is very common to have deterioration due to the impurities of the materials, such that cause the salt efflorescence biological growth (Avrami, Guillaud, & Hardy, 2008) . The action of living organisms such as plant parasites (mosses, lichens), rodents, insects (termites) and rats will also lead to deterioration of the structure.

Inappropriate rehabilitation

Earth construction can survive for a long time if it is preserved properly. However, problems arise if inappropriate restoration techniques are applied. Introducing damp coursing is sometimes made. However, this should not occur before all the sources of damp have been correctly identified and eliminated. In fact, some type of earth construction, like rammed earth construction, can even survive in short severe rainfall and even a short period of cold weather. The main criterion is that the water should be able to evaporate so that it will not persist within the structure. Thus, the air and water permeability of the structure is one important factor. The material used for renewal and strengthening the earth structure should be carefully chosen. The material should match with the original one such that it can keep the permeability of the earth structure. Wrong technique includes using less permeable skin to protect the earth building. This is detrimental to the survival of the structure and whilst it is very common and favored repair technique for rammed earth in Spain.

Another common improper rehabilitation is using incompatible materials. This happens because people restore the structure without fully understanding its nature. The new materials should not cause any side-effect from their physical or mechanical contact. It should not cause any chemical deterioration and rheological phenomena which lead to further damage. Furthermore, the new materials should behave similar to the original material when subjected to environmental variations. Using Portland cement is one of the examples. It will lead to expansive salt crystallization and its high stiffness will cause cracking or even crushing. Another example is installing reinforcement in the structure. Since installing heavy steel reinforcement in earthen walls actually creates cracking in the walls as the earthen material continues to shrink during the drying process over a long period of time and the unyielding steel tries to hold it from shrinking, thus creating tension stresses that the earthen material cannot sustain(Chaudhry, 2007).

Improper Design and Construction

Earth construction like all structures required careful design and construction. Since earth can only resist to compressive loading. There should be other components to take the other stress such as tensile and bending stresses. Without those components, earth structural defects will be formed easily be formed. Poor design also includes improper foundation design, drainage design, inadequate bracing system, too many openings or made of composite materials. The location of the structure should be carefully decided. Collapse will be result if the building is situated at the site which cannot take the load and lead to settlement. Careless design will also weaken the resistance of the structure during natural disaster. For poor construction, it includes the low quality material such as loam with too high water content and clayey soil. Poor implemented construction techniques may also lead to formation of cracks.

Natural Disaster

Earthquake, flooding and storms can lead to the collapse of the earth construction. When there are earthquakes, the motion of the ground will transfer to the building horizontal loads. The horizontal and vertical movement of the ground causes damage to the structures as these are not design to resist this type of loading. The earthquake motion not only increases the compression and tensile stresses but also make the building component subjected to bending, diagonal tension, in-plane flections and even twisting. Thus, it is very often to observe diagonal cracking, out-of-plane failure or even the collapse of the earth constructions after earthquakes. In Figure 8, an example of damage to a building after earthquake is shown. For flooding and storm, the wind and water in addition to additional loading create a violent dynamic loading that may result in the structural collapse.

(a)

(b)

Figure 8: Two exterior views of Pio Pico Mansion, Whittier, Calif., after the 1987 Whittier Narrows earthquake. (Tolles, Webster, Crosby, & Kimbro, 1996)

2.5 Structural Pathology

As mentioned above, there are lots of sources that will lead to the deterioration of earth construction. Structural defects are usually first become apparent in forms of cracks. The typical structural pathology is as listed below:

1) Structural cracking: This is the most common and apparent observation of earth structure. It can cause by all the factors mentioned in the previous section.
2) Shrinkage cracks: These are usually the result of poor quality of construction material or construction process. Examples of these include high amount of clay and inadequate curing. Shrinkage cracks can be easily recognized, being vertical and regularly spaced (Houben & Guillaud, 2008). Repeated cycles of wetting and drying will result in shrinkage cracks.

3) Bulging: This is mainly caused by high loading. This observation is conjunction with cracking.
4) Collapse: This is the worst result that can lead to fatality. It can be due to inadequate strength of materials, increasing stress, loss of strength due to moisture or weathering, sudden shock such as earthquake. Two examples are shown in Figure 9 and Figure 10.
5) Decomposition of the material: Earth as a building material is susceptible to water and the environmental factors. Thus, lead to variation in chemical and mineralogical structure of the material. This will result in losing the bonding and coherence of the material.

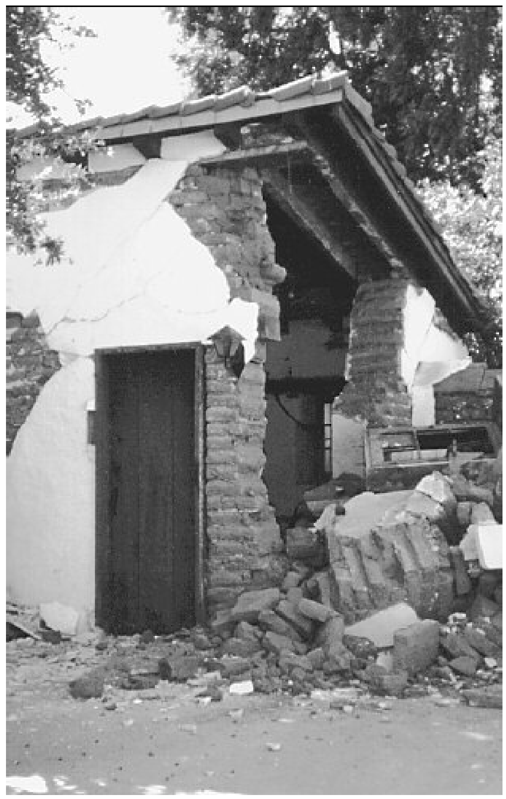


Figure 9: Collapse example due to the cracks at window openings (Andres Pico Adobe, Mission Hils, Calif.) (Tolles, Kimbro, & Ginell, 2002)

Figure 10: Collapsed wall of Ramona's room, Del Valle Adobe. (Tolles et al., 2002)

2.6 Rehabilitation of Earth structure

The deterioration of the earth structures can be prevented by introducing different measures such that protect the structure from the deleterious sources. A proper conservation can not only prevent the deterioration but also improve the resistivity against the natural disaster.

A few common intervention approaches will be briefly discussed as followed:

1) Introducing system to protect the structure from water: this included installing roof and eaves, waterproof course and drainage system. However, all this measure should be carried out with great care. It should first check the source of water and be sure that there is no more damp within the structure before installation.
2) Introducing reinforced system to strengthen the structure: this is used when there exists serious deterioration or damages to the structure. Also for the structure located in region suffered with earthquakes There are different methods to strengthen earth structure such as introducing straps and cables or using the center core rod that can prevent a specific type of failure. For the straps and cables, it can competently prevent the out-of-plane failure and maintain the stability of a cracked structure. The application of center core rod works efficiently in in-plane walls to stop the propagation of crack. It works well in adobe structure.
3) Introducing new material to protect the structure: this included the consolidation, surface coating. Consolidation is the other most widely used treatment for earth structures. For example, clay walling can be consolidated by spraying ethyl silicate. It will react with the clay particles forming a layer which can increase the water resistance of the material but maintain the original porosity. However, this technique should only apply after all water penetration has been dealt

with and there is no soluble salt problem present (J. Ashurst & N. Ashurst, 1998). Surface coatings can be categorized as either hydrophobic materials, sealers, or sacrificial coatings, but their fundamental purpose is the same: to increase the water resistance of earthen materials. There are different types of material used for surface coatings such as inorganic, natural organic, and synthetic organic materials. The surface coating materials are usually very thin and transparent or opaque which attach to the earthen materials.

4) Introducing new materials to restore the deteriorated structure: this included replacing with new unit and grouting. Crack stitching is a technique that is applied in fixing structure with large crack. The mud brick 'staple' is located across the crack then two staples were cut, and the surface material then wetted and hemp matting placed inside the cut. Mortared sun dried brick were then placed within the cut forming a solid staple inside the wall (Jaquin, 2007). If the original unit is seriously damaged, it is possible to replace it with new unit. However, it is necessary to identify the characteristic of the existing material in order to form the new unit. There are lots of suggestion on the new unit, such as the stiffness, the water content, the compressive strength and the composition. For example, new unit should not be harder than the original unit and Portland cement should not use as stabilizer because it is incompatible with the earth material (Garrison, 1990). Another type of technique is by grouting. It is mainly apply when there are cracks and voids in the earthen structure, grouts can be used to fill the cracks. This can reintegrate integrity and to prevent water to enter into the crack and cause further damages.

3. GROUTING

The literature related to the development of grouting in earth structure is limited. Thus, literature reviewed is more related to that applied in masonry structure. Furthermore, the literature reviewed also involved the material characteristic of the grout such as the mixing procedure, the effect of superplasticizer and rheological properties. Most of the published works involved were from Italy, Belgium and Greece, mainly related to the strengthening of masonry structure.

3.1 Compatibility of grouting and the original material

The compatibility of the grout with the substrate is a crucial factor to provide an efficient strengthening. The importance of this is proved after the 1997 Umbria-Marche earthquake. Studies had been carried out after the 1997 Umbria-Marche earthquake leading by Binda L showing that the actual efficiency of the retrofitting techniques for repairing and strengthening historic masonry are studied. It was found that most of the failures were due to lack of knowledge of the materials and of building construction details. It was found that the incompatibility of the structure and the material. In this study, they stressed that repair, retrofitting techniques should always respect the original existence, and that any intervention not respectful of it, can create incompatibility with the original structure and materials. Furthermore, some comments on the grouting techniques based on the damages surveyed after the 1997 earthquake, was provided. It stated that the aim of grouting is to improve the continuity and hence the strength of the masonry structure. However, this aim can be fulfilled only if the material constituting the wall and their composition are known such that can prevent the incompatibility of the materials. (Binda, Modena, Valluzzi, & Penazzi, 2000).

Considering the compatibility, Filip Van Rickstal, Eleni-Eva Toumbakari, Sven Ignoul and Dionys Van Gemert had further discussed on the compatibility of grout. They suggested that the grout should be suited the substrate in three aspects: chemical compatibility (including durability aspects), mechanical/structural compatibility and historical compatibility.

Chemical compatibility

The chemical compatibility is the most important requirement. If the injected materials are not chemically compatible, sooner or later the strengthening in fact will deteriorate or damage the structure. For example, when replacing the deteriorated adobe unit, the new unit should have less soluble salts.

Since salt accumulation will cause wall deterioration. Thus, it is necessary to first detect salts by looking for efflorescence. Furthermore, if there is damping, laboratory analysis becomes necessary to determine the water-soluble salts like sulfates, chlorides, nitrates and nitrites to know their concentrations of the original materials. After that, new unit should be tested to guarantee a lower level of soluble salts (Garrison, 1990). Some materials will have chemical reaction with the original materials. Portland cements are one of them. It will free salts after penetrating lime mortars or stone and will lead to expansive crystallization and cause cracking ("Guidelines for the conservation of historical masonry structure in seismic areas," 2006).

Mechanical compatibility

Mechanical compatibility includes compressive strength, tensile and flexural strength, ductility, shrinkage and the adhesion to the substrate. They stated that cementitious grouts provide very good strengthening, but not in ductility. This loss of ductility will obstruct the self-healing properties of masonry. Furthermore, the new material or strengthening devices should have a similar stiffness and strength to that of the original material. For example, Portland cement and concrete is not suggested to apply in strengthening adobe structure because of its high strength which will cause the original structure to crack or crush due to different deformation (Garrison, 1990).

Historical compatibility

The new material should be compatible with the substrate. Lime based grouts are widely agreed to be the most compatible material for restoring monuments. Filipe Van Rickstal stated that cement also provides hydraulic properties to the grout. However, it can be replaced by hydraulic lime that will provide the early strength and the required ductility. However, it is needed to play attention to the water content since it was found that fluid lime based grout would require a very high water content without the use of an appropriate superplasticizer. As a conclusion, lime is preferred to use in restoring the historical structure. Compare lime and polymer, cement is preferable because the physical properties with regard to moisture transport, thermal expansion, temperature household etc.. are much closer to those of the historical materials than in case of polymers. There is real example that being restored satisfactory by using cement-based grouts.(Van Rickstal, Eleni-Eva Toumbakari, Ignoul, & Van Gemert, 2003)

Furthermore, there is also study on the compatibility of grout mixes of historic masonry. The study was done by E-E. Toumbakari, et al. They suggested that there are two main categories of requirements were defined regarding the mechanical behaviour and the durability of the injected structure. They proposed that the rate of strength development is more important since replacing Portland cement by lime-pozzolan mixtures will lead to a slow increase of mechanical strength. Considering the durability, the bonding properties and the undesirable chemical reactions are two main factors. These requirements are further detailed in the tables below.

Table 1: Requirements relative to the Physical behaviour of the injected structure (E.-E. Toumbakari, Van Gemert, & Tassios, 1999)

Injectability
- low yield value and viscosity - penetrability: in voids with a diameter smaller than 0.3 mm (300 µm) - stability: no density gradients along the height of stored grout - low bleeding: lower than 5% after 120 min rest
Bonding with the existing materials
- relatively low shrinkage (although autogeneous shrinkage is unavoidable) - minimal heat of hydration - setting and hardening in dry as well as in wet environment
Sufficient mechanical properties within a defined time span
- development of the required mechanical properties in 90 days - compression and flexural strength dictated from the structural analysis

Table 2: Requirements relative to the Durability of the injected structure (E.-E. Toumbakari et al., 1999)

Compatible microstructure
- compatible porosity and pore size distribution: they depend on the porosity of the existing materials as well as on the required strength of the new materials - type of the hydration products: similar (though not necessarily identical) to the existing
Bonding with the existing materials
- limitation of diffusion of SO_2, chlorides etc. - resistance against deterioration due to environmental factors
Properties of the raw materials
- minimal content in gypsum and soluble salts (especially in releasable alkali)

3.2 Application of grouting in Earth construction

Grouting is more common in strengthening masonry structure. Limited resources can be found related to grouting in earth construction. In fact, earth structures demonstrate similar deterioration as masonry structure. Cracks and voids are the most often damage found in earth structure and lead to the decrease in integrity. There is various ways to improve the structure integrity; grouting is one of the most common methods to fill the cracks or voids such to improve the homogeneity.

The Getty Conservation Institute, Los Angeles has been contributed a lot to the conservation of earth structure. There is a publication Terra Literature Review, which compiles thirteen essays on different topics germane to earthen architecture research. As a summary of different existing research, the grout for strengthening earth construction should be lightweight to reduce the load on the bond between surface finish and substrate. Be able to bond between dissimilar materials (e.g., a lime plaster and an earthen substrate). Furthermore, the grout should be of low water content, adequate thixotropy, low shrinkage, and low soluble salt content, mechanical properties similar to original material, and no settlement prior to setting. The composition of the grout, which has been studied, was composed primarily of soil with the addition of a stabilizer to reduce shrinkage, increase strength, and possibly promote adhesion. Stabilizers included bentonite and lime (Fagundes de Sousa Lima and Puccioni 1990), hydraulic lime (Nardi 1986), lime and fly ash (Roselund 1990), and a very finegrained and stable "mercula" clay (Sharma, Gupta, and Kanotra 1995). In all cases, the strength of the grout was equal to or slightly greater in hardness than the original earthen material. A technique for grouting was well elaborated in one publication (Roselund 1990), and practices are probably rather uniform: fine cracks are filled with syringes, while larger cracks and voids are filled with a low-pressure pumping system (Avrami et al., 2008). There are also practical examples of applying grouting to strengthen earth structure which can be found in The Getty Conservation Institute Los Angeles publication "Survey of Damage to Historic Adobe Buildings after the January 1994 Northridge Earthquake". The Pio Pico Adobe was a structure which being repaired by grouting. It suffered extensive damage during the Whittier earthquake of 1987 then in 1991, the existing cracks were repaired by injection of an adobe-flyash grout. The wall strengthened by the grouting technique was found to suffer little damage during the January 1994 Northridge Earthquake. In Figure 11, it shows the photos of the wall which was repaired in 1991 with adobe-flyash grout after the Northridge earthquake (Tolles et al., 1996).

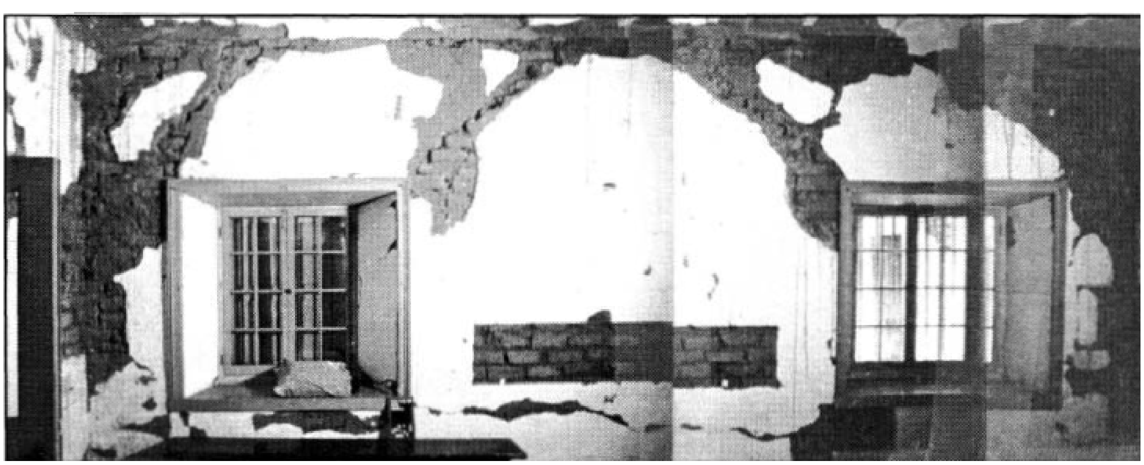


Figure 11: Interior elevation of the east wall of Room 8. This wall was repaired in 1991 with an adobeflyash grout and appears to have suffered little additional damage in the Northridge earthquake (Tolles et al., 1996).

3.3 Principle of grouts

As mentioned in the last chapter, traditional restoration methods in earth structures are not that efficient. Applying new elements or materials will lead to discontinuities in the structure and result in incompatibility. Furthermore, those methods strengthen the earth structure by introducing elements that take the tensile loading. However, the integrity of the structure is still insufficient because of the presence of cracks and discontinuities that greatly weaken the resistance. Grouting is a method that can obtain the homogeneity of the element and thus improves the strength and the stability of the structure. Furthermore, it is a technique which can improve the stability but at the same time without changing the appearance of the historical monuments.

Improving the homogeneity of the elements especially earth wall is especially important for earth constructions located at seismic region. Since during earthquake, there is great scale of lateral deformations happen in the earth structure. Structure with better homogeneity can transfer the forces to the member that can bear it.

The main purpose of grouting is to fill the cracks and voids such that to prevent the earth structure damage by water. Another purpose is to improve the structural integrity by bonding the separated segments together. Grout injection is carried out after a rinsing and preparation of hidden surfaces by pumping clean water into cracks and voids with the same equipment. The purpose is to make the wall become well and thus slow down the setting of the grout and improve the adhesion. The process always begins low in the wall and proceeds in lifts according to different condition. There are four different methods to carry out grouting in masonry structure, they are either manually, by pump, gravity and vacuum.

However, it was found that the size of the cracks and voids would affect the grouting procedure. A technique for grouting was well elaborated in one publication of Roselund, that and practices are probably rather uniform: fine cracks are filled with syringes, while larger cracks and voids are filled with a low-pressure pumping system (Avrami et al., 2008). Furthermore, it is suggested that the smaller the crack, the higher pressure or more closely spaced injection is needed. For large cracks, it is needed to first seal with mud and an observer armed with a bucket full of stiff mud monitors for discharge on the opposite side of the wall (Crocker, 2000). In fact, it is not easy to standardize the grouting parameters for earthen structure because there are various characteristics of different construction technique and material in different countries.

3.4 Composition of grout

A satisfactory grout should fulfill a few criteria. In 2003, Filip Van Rickstal, et al. published a paper related to the development of mineral grouts for consolidation injection. They stated that the ability to inject the mineral grout was the first requirement for a grout. Since filling the cracks and voids will improve the homogeneity and such that the masonry will behave monolithically. The next criteria for grout is its stability. Stability can be shown in two forms: bleeding and segregation. Bleeding means the separation of water and cement, if a bleeding grout is injected, the upper part of the strengthened structure will not be satisfactory because that part is only will with bleeding water. Segregation means that the heavy particles being sink at the bottom. In fact, stability can be improved by varying the water cement ratio or by adding stabilizing agent or by adding ultra fine admixtures (Van Rickstal et al., 2003).

According to Van Rickstal, the material of the binder should be fine with the largest particles smaller than 0.15 times the smallest crack size. Superplasticizer was found to be necessary to provide the injectable grout. Since without using superplasticizers, the water content ratio will be so high and lead to the dramatic loss of the stability of the grout. However, he also stated that an adapted superplasticizer might enhance the conflict between fluidity and stability of lime based grouts. Other materials were suggested to improve the stability, these included ultra fines like fine hydrated lime or silica fume. It was stated that silica fume and bentonite are both good stabilizing agent.(Van Rickstal et al., 2003)

Another characteristic of earth structure is its penetrability that allows moisture to pass through. As mentioned above, it is common that wrong materials are used to strengthen the structure, which finally speeds up the deterioration. In 1987, Hughes stated in his article that a correct treatment of old buildings should use permeable materials such allowing moisture to pass through them and evaporate in front of the surface. Furthermore, lime-based mortars or very weak cement/lime mix were recommended. Finally, it is needed to check if there is deterioration if the building has already been treated with impervious material. It is also suggested to do nothing if the cement pointing is too hard. He stated that the difference between the modern buildings and the old buildings is that modern buildings prevent moisture to penetrate through. Old buildings built before mid of 19th century is the opposite, it allow the moisture which was absorbed by the material to evaporate. Thus, it is very critical to use the material which is permeable. Lime mortar is preferred because of its permeability. (Hughes, 1987)

As stated previously, the injectability is one of the important parameters of grout mixtures. Thus, there are lots of studies related to improving this parameter. One of them is related on how the mixing procedure affects the grout. In 1999, E.-E.Toumbakari, et al. studied the effect of different mixing procedure on the injectability performance of grouts composed of cement, lime, natural pozzolans, and silica fume of a usual particle size. It was found that the use of superplasticizer is not sufficient to improve injectability when penetrability in very fine voids is needed. Furthermore, it was found that although using superplasticizers will develop a repulsive forces to improve the fluidity. However, their action does not appear sufficient when the grout contains very fine materials silica fume and lime (calcium hydroxide).

In the study, cementitious grout is prepared by a high turbulence mechanical mixing procedure and an ultrasonic mixing procedure respectively. Then the fresh state properties are then studied. Finally, they concluded that using the high turbulence mixing procedure was not that good to deflocculating all the formed flocs. It cannot ensure a constant penetrability of grouts composed of cement and fine materials (hydrated lime, natural pozzolan). Grout contains silica fume and produce by high turbulence mixing procedure was found to be not fluid enough and is not injectable. Unless the water and superplasticizer contents are drastically increased. Grout produce by the ultrasonic mixing procedure can result a high penetrability grouts with a limited water/ solids ratio, even if Silica fume is used. The reason is that this procedure consisted of high dispersion capacity and can deflocculate the particles. Thus, they concluded that grout consisted of normal fineness materials (such as ordinary cement, natural pozzolan sieved at the cement fineness, commercially available lime, and Silica Fume) and was subjected to be injected to medium considered as high penetrability. Then ultrasonic mixing procedure should be used to produce an injectable grout with limited water and superplasticizer contents. (E.-E. Toumbakari, Van Gemert, Tassios, & Tenoutasse, 1999)

According to E.-E. Toumbakari, et al., considering the selection of materials, it is unavoidable to use hydraulic binders because of the required mechanical strength. The use of air-hardening binders cannot provide enough strength in a period of time meaningful from a structural viewpoint. A possible way is to reduce the percentage of cement such that can achieve a suitable level of strength. Furthermore, substitute Portland cement by lime-pozzolan mixtures will slow down the rate of increase of mechanical strength. On the other hand, using the natural or artifical pozzolanic admixtures enhances the durability properties of hydraulic binders. Therefore, it is suggested to use lime, natural pozzolans, ordinary Portalnd cement and if needed, silica fume to prepare the grouts. The rationale of the formulation of compositions was the combination and optimization of the various reactions that take place simultaneously (E.-E. Toumbakari et al., 1999).

3.5 Mechanical Properties of hydraulic lime, cement and sand mixture

Since the mixture of this study is a new trial, there is no reference data of similar mixture. Thus, literature study is carried out based on the mixtures which contain hydraulic lime, cement and sand. There is lots of reference value related to mortar. For porosity, it is found that hydraulic lime mortar consists of higher porosity than cement mortar, the former one is about 18~30% and the later one is 10~20%. There also study M.J. Mosquera on the porosity of lime-based mortar. In his study, the porosity of mortar with sand (0.5~2mm), hydraulic lime (NHL3.5) and cement (CEM II/B-V32.5) is about 24% (Mosquera, Silva, Prieto, & Ruiz-Herrera, 2004). Furthermore, the porosity value of cment paste and lime paste are about 30% and 60% respectively.

According to literature review, the 28-days capillary coefficient of mortar with air lime and sand is about 1.0 g/cm^2 (hr)$^{0.5}$ and that of mortar with air lime, metakaolin and sand is about 0.93~1.2 g/cm^2 (hr)$^{0.5}$ (Velosa & Veiga, 2007). The 28-days capillary coefficient of mortar with cement is about 0.15~0.3 g/cm^2 (hr)$^{0.5}$ (Lanzon & Garcia-Ruiz, 2009).

Considering the strength, the flexural strength, compressive strength and elastic modulus of hydraulic lime mortar is about 1MPa ,7MPa and 8Gpa respectively. The strength of cement mortar is much higher; the flexural strength is about 3.5~6MPa, the compressive strength is about 14~28MPa and the elastic modulus is about 30Gpa. There are also some studies on mortar with different proportions of cement and sand. One of them is done by M.J. Marques, the compressive strength and the elastic modulus of mortar with ordinary Portland cement and sand is determined. The compressive strength of samples with sand to cement ratio as 3:1 is 37MPa, 6:1 is 9.5MPa and 9:1 is 5.2MPa. The elastic modulus of samples with sand to cement ratio as 3:1 is 20GPa, 6:1 is 8.1GPa and 9:1 is 2.4GPa (Mosquera, Benitez, & Perry, 2002). According to E.-E. Toumbakari, et al., grout with hydrated lime, silica fume, cement and Rheinisch Trass were studied. The 28-days compressive strength of the grout is about 5.4~6.5MPa and 28-days flexural strength is about 1.2~1.7 MPa (E.-E. Toumbakari et al., 1999).

For the rheological properties, most of the rheological parameters are determined by using the Bingham model. The viscosity coefficient of the binder paste is about 0.05 to 0.1 Nmm min (Seabra, Pavia, Labrincha, & Ferreira, 2008) and that of mortar is about 0.3 Nmm min (Sicker, Huhn, Mellwitz, & Helm, 1997). For the flow resistance, that of the binder paste is about 25 Nmm (Seabra et al., 2008) and that of mortar is about 60Nmm or higher (Sicker et al., 1997). There are also studies related to grout with hydraulic lime, aggregate, air lime and metakaolin by Martins et al. The flow resistance of grout with hydraulic lime and aggregate and that with air lime, aggregate and metakaolin is about 2.5~4.5 Nmm

The viscosity coefficient is about 0.09~0.12Nmm min. For group A, the viscosity coefficient is about 0.12~0.15 Nmm (Martins et al., 2008).

4. MATERIALS AND MIX DESIGN

In this chapter, the properties of the materials that were chosen to form the grout are discussed. This is followed by the preparation process of the grout and a description of laboratory test procedures.

4.1 Materials

All the materials were chosen based on local availability, the present adoption of materials for historical construction restoration industry and also based on the existing research of grout materials. The grouts studied were based on a mixture of hydraulic binder grout and soil with varying quantities of clay and sand. In the following sections, the materials are briefly described.

4.1.1 Sand

The sand is extracted from a local river. Before use, the said is first dried in the oven at 100-110°C for approximately 24 hours. In Figure 12, the particle size distribution curve of the sand is shown and in Figure 13, a sand sample is shown.

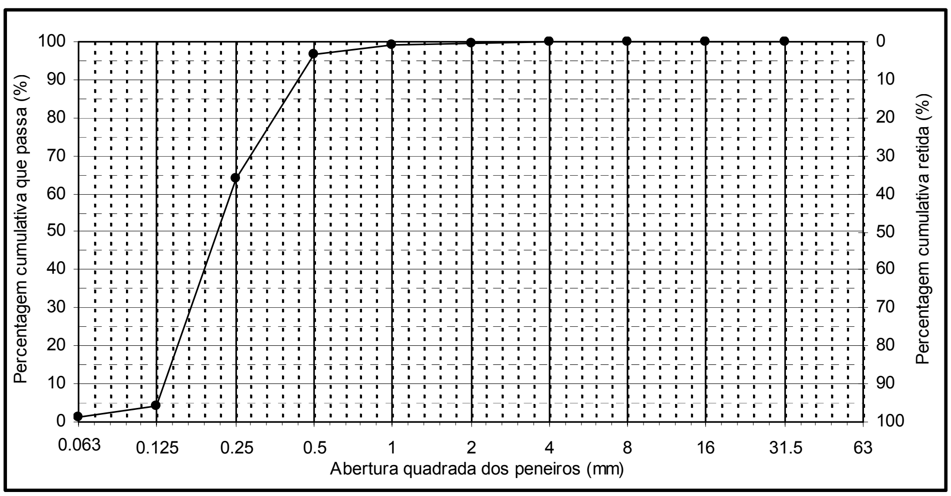


Figure 12: Particle size distribution curve

The sand has a fineness modulus of approximately 2.35. This indicates that the sand is rather fine. Prior to use, the sand was passed through the number 1 sieve to eliminate course and other particles.

Figure 13: Sand sample

4.1.2 Lime

A hydraulic lime was used, CAL HIDRAULICA (NHL5), from the company CIMPOR Industria de Cimentos, S.A. The hydraulic lime sample was as shown in Figure 14.

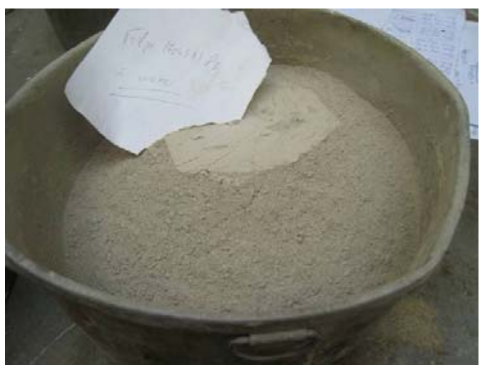


Figure 14: The Hydraulic Lime NHL5

In Table 3, the chemical, physical and mechanical properties of the hydraulic lime is given.

Table 3: Properties of Hydraulic Lime NHL 5

Chemical Properties	
Sulphates (SO_3)	$\leq$ 3.0%
Free Lime	$\geq$ 3.0%
Physical Properties	
Initial time of hardening	$\geq$ 60 min
Expansion	$\leq$ 20 mm
Residues at 0.09mm	$\leq$ 15%
Density	$\geq$ 600 g/l
Mechanical Properties	
Compressive Strength (7 days)	2.0 MPa
Compressive Strength (28 days)	5.0 MPa

4.1.3 Cement

The cement used was a CEM II/B-L 32.5N also from the company CIMPOR Industria de Cimentos, S.A.The sample is as shown in Figure 15. The properties of the material are given in Table 4.

Figure 15: Cement , CEM II/B-L 32.5N

Table 4: Properties of Cement, CEM II/B-L 32.5N

Constituent	
Clinker	65%~75%
Limestone	21%~35%
Other Constituents	0%~5%
Chemical Properties	
Sulphates (SO_3)	$\leq$ 3,5%
Chloride Content	$\leq$ 0,1%
Physical Properties	
Initial time of hardening (NP EN 196-2)	$\geq$ 75 min
Expansion (NP EN 196-21)	$\leq$10 mm
Mechanical Properties	
Compressive Strength (7 days)	16.0 MPa$\leq$7 days
Compressive Strength (28 days)	32.5 MPa$\leq$ 28 days$\leq$52.5 MPa

4.1.4 Clay

The clay used was from Quinta Grande Apulia, sponsored by MIBAL Minas de Barqueiros, S.A. The properties of the clay are as shown in Table 5. To facilitate the mixing procedure, the clay used was saturated clay. The saturated clay was formed by mixing 3 kg of clay with 6 kg of water and waiting for about 24 hours. Then, the saturated clay will have settled at the bottom with clear water on top. The extra water is then removed and the saturated clay is well mix by the stirrer again before used. The water content of the clay is checked everyday and it was found to be within the range of 1.55~1.85. The wet and dry clay samples were as shown in Figure 16.

(a) (b)

Figure 16: (a) Dry Clay (b) Saturated Clay

Table 5: Properties of Clay

Chemical Properties									
Element	SiO_2	Al_2O_3	Fe_2O_3 Total	CaO	MgO	Na_2O	K_2O	TiO_2	P.I
%	47.0	37.1	0.9	0.1	0.15	0.2	2	0.1	12.75

Properties	Values	Methods
Degree of whiteness (Axis of white– Black(L))	75 - 85	Colorímetro Dr. Lange
Density	2.4 - 2.7	ASTM D 1817 – 96
Absorption of oil	34 – 48	ASTM D 281 – 95
pH	6 – 9	ISO 789/9 – 1981 (E)
Sieve residue (53 μm)	< 0.3 %	ASTM D 4315 - 94

4.1.5 Superplasticizer

The superplasticizer used was of the brand CHRYSO®Fluid Premia 196 Superplasticizer – High Range Water Reducer. The properties of the superplasticizer are shown in the Table 6 and a sample is shown in Figure 17.

Table 6: Characteristics of CHRYSO®Fluid Premia 196 Superplasticizer – High Range Water Reducer

Nature	Liquid
Colour	milky green/grey
Density	1.055 ± 0.010
pH	7,5 ± 2,0
Cl^- ion content	≤ 0.10 %
Na_2O equiv.	≤ 1.5 %
Dry extract (halogen)	25.0 % ± 1.2
Dry extract (EN 480-8)	25.3 % ± 1.2

Figure 17: Superplasticizers sample

4.1.6 Water

The water used was tap water the public network of Guimarães.

4.2 Grout composition

The grout samples were composed of five or six materials: sand, clay, lime and/or cement, superplasticizer and water. Different mix proportions of the materials were tested. The calibration process that led to the final composition will be further mentioned in Chapter 6.1.

4.2.1 Combination of Grout

As mentioned previously, six combinations of grouts were chosen for testing. The mix proportions and the flow time measured with the Marsh cone are as shown in Table 7. There were three main groups of which each of them with similar proportions of soil/ binder and clay/sand that distinguishes these are:

- Different water content;
- Different superplasticizer content;
- Binder type (For the grouts 1A, 2A and 3A (GroupA) are lime-based grout, however, for grouts 1B, 2B and 3B (Group B) contained cement).

Table 7: Composition of grouts

Composition	1A	1B	2A	2B	3A	3B
W/B*	0.25		0.35	0.3	0.35	
SP/B**	1.6%	1.2%	1.4%	1.1%	1.6%	1%
Binder	50%	50%	50%	50%	40%	40%
Hydraulic Lime	100%	50%	100%	50%	100%	50%
Cement	0%	50%	0%	50%	0%	50%
Soil	50%	50%	50%	50%	60%	60%
Clay	50%	50%	30%	30%	30%	30%
Sand	50%	50%	70%	70%	70%	70%
Fluidity (s)	15.5 s	11.5 s	14.0 s	14.9 s	15.6 s	12.7 s
Fluidity after 15 min	18.2 s	16.1 s	20.8 s	17.6 s	19.7 s	14.7 s

* W/B = water- binder ratio ** SP/B= superplasticizer- binder ratio

4.2.2 Procedure of mixing and Preparation of samples

The grout was prepared at the Construction Material Laboratory, University of Minho, Guimaraes.

To facilitate the mixing procedure, the sand was all sieved through a 1mm sieve to get rid of the bigger particles and the clay was left under water for at least 24 hours to form saturated clay. In this research, aerated lime is not used because according to literature study, using air-hardening binders cannot develop enough strength in a period of time meaningful from a structural viewpoint. Furthermore, aerial lime shows a thickening behaviour and unable to harden under water make it not so suitable to use in grout mixes.

The mixer used was Automatic Controller L5-025, as shown in Figure 18. The Speed of the mixer was 140rpm (low) and 285rpm (high). First the sand, cement and/or hydraulic lime and saturated clay were placed into the container and mixed well at a slow speed. Water and superplasticizer were then added slowly while keeping the grout mixing at slow speed. After adding all the water and superplasticizer, was switched the mixer to a high speed until a grout without flocs was achieved. The total mixing time (counted from the putting all the materials inside the container) varied from 3 min to 6 min. Longer mixing time was needed for Grout A because of more hydraulic lime which takes longer time to break the coagulate.

(a) (b)

Figure 18: (a) Mixer (b) The blade

The grouts were then tested with the fluidity test with the Marsh cone. The flow time for 1 L grout was recorded. According to the literature review and visual observation the range of the flowing time was set to be 15~18s. If the flow time of the grout fulfills the requirement then it will be used to prepare the sample for the different test. The number of sample prepared for each grout are as listed in Table 8.

Table 8: The list of samples and relative test for each grout

Type of sample	Number of sample	Test
4x4x16cm sample	3	Mechanical strength test (14 days)
	3	Mechanical strength test (28 days)
	3	Absorption and porosity test
2.5x2.5x25cm sample	3	Retraction Test
4cm height and Ø 4.5cm cylinder	3	O_2 and H_2O Permeability test
10cm height and Ø 4.5cm cylinder	2	Elastic Modulus Test

(a) *(b)* *(c)*

Figure 19: (a) 4x4x16cm samples. (b) Cylinder samples. (c) 2.5x2.5x25cm samples

(a) *(b)* *(c)*

Figure 20: All the test samples

The 2.5 x 2.5 x 25cm samples were always kept inside the humidity chamber, at 20°C and 69% humidity; they were removed from the mold until they gained enough strength after two to three days. The other samples were kept indoor overnight then removed from the mold and kept inside the humidity chamber until the date of testing.

5. LABORATORY TEST PROCEDURE

5.1 Physical Test

5.1.1 Fluidity Test

The fluidity test was carried out after preparing each grout. The test was done according to BS EN 445 (1997). The setup of the apparatus is as shown in Figure 21. This test is to study the workability of the grout. The cone was first dampened. A finger is used to close the lower orifice of the cone. Grout is poured into the cone slowly. After open the lower orifice, the stopwatch is started at the same time. The time to collect 1L of grout is recorded. The grout then left aside without mixing for 14min and then mix at high speed with the mixer for 1min. The fluidity test was done again and the flow time to collect 1L of grout is recorded.

Figure 21: Apparatus of fluidity test

5.1.2 Segregation/Bleeding Test

The segregation/bleeding test is done by pouring the grout into a transparent container and observing its behaviour. This test shows the stability of the grout. The test is used to identify whether the heavy particles sink to the bottom and result in a colour difference between the bottom part and the upper part of the sample. In addition, the separation in distinct phases with water on top is also observed. Observations of this test are done at time interval: 15min, 30min, 1hour and 24 hour.

5.1.3 Electrical resistivity test

Electrical resistivity test is done by using the resistivimeter as shown in Figure 22 and was done according to LMC PE 002 ("RESISTIVIDADE ELÉCTRICA, Medição da resistividade eléctrica de uma superfície de um elemento de betão (PE-002)," 2005). The test was carried out every two days for the first two weeks and then once a week starting at the third week. The test was done on three surfaces of 4 x 4 x 16 cm sample, the bottom surface and the two lateral surfaces. Resistivity of a sample is expected to increase with time as a result of hydration of the binder and curing of the specimen.

(a) *(b)*

Figure 22: (a) Resistivimeter. (b) Usage of resistivimeter

5.1.4 Porosity Test

This test was performed according to the LNEC E 394-1993 ("Betões - Determinação da absorção de água por imersão, Ensaio à pressão atmosférica LNEC E 394- 1993," 1993). The aim of this test is to determine the interconnected voids of the sample. The test was carried out with 4 x 4 x 16 cm samples. The masses of different states, including dry, saturated and immersed were measured. The porosity was determined by using the equation (1). The specimens were dried in an oven with 36~54°C for four days until the mass was stable. The mass of the dry samples are measured. Prepare the vacuum chamber by the dry and clean state, move the specimens to keep in vacuum state for 3 hour in order to remove the air inside the pore structure of specimens. The apparatus was shown in Figure 23. Then immerse the sample with water and maintain in vacuum state again for 3 hours. Finally, the saturated mass and the immersed mass are measured as shown in Figure 24.

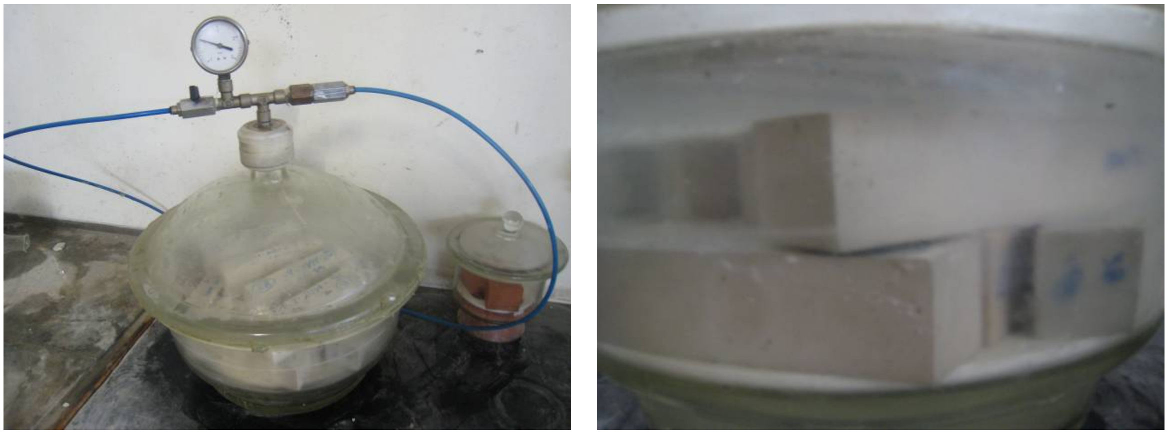
$$\text{Porosity}(\%) = (M_s - M_d)/(M_s - M_i) \times 100 \qquad (1)$$

where:

M_s = Mass saturated (g)

M_d = Mass dry (g)

M_i = Mass immersed (g)



(a) *(b)*

Figure 23: (a) The specimen in vacuum chamber. (b) The specimen immersed in water inside the vacuum chamber

(a) *(b)*

Figure 24: (a) Measuring the saturated mass. (b) Measuring the immersed mass

5.1.5 Oxygen and water permeability

The test was performed with the Leeds permeation cell (LPC) according to the test procedure LMC P004 for the oxygen permeability test and LMC P005 for the water permeability test. The sample was first dried in an oven of 50~60°C for 4 days until the mass of the sample is constant. Used the silicon to wrap the cylinder surface and left overnight. The apparatus of this test is as shown in Figure 25. The oxygen permeability test was first carried out and the time for a bubble to rise 10 cm in the pipette was recorded. The water permeability test was then carried out. Poured a solution of alcohol, phenolophthalein and water (about 15ml) into the cell valve. Applied a pressure about 2 to 3 bar and kept it for 3 hours. The time of the test was recorded. The sample was than split into two pieces and the penetration depth was measured. The water permeability can be calculated as followed.

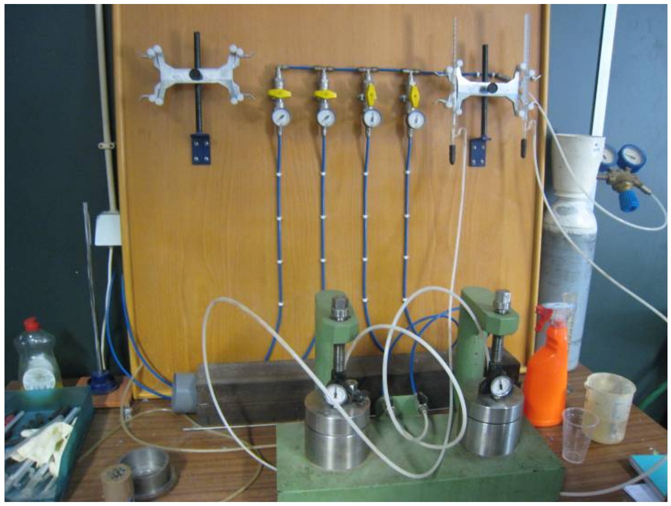


Figure 25: Appartus setup of oxygen and water pemeability test

$$k_W = \frac{d_p^2 \times \delta}{2 \times h \times t} \tag{2}$$

where:

k_w = coefficient of water permeability (m/s)
d_p= depth of water penetration (m)
δ= porosity of the sample
t= time to penetrate to depth dp (s)
h= head of water (mH2O); 1bar = 10.207mH2O

$$K_W = k_w \times \frac{\eta}{\rho \times g} = k_w \times 1.3 \times 10^{-7} \tag{3}$$

where:

Kw =coefficient of water permeability (m^2)
η = viscosity of water at 20°C
ρ =density of water, 1000kg/m^3
g = gravity: 9.81m/s^2

The oxygen permeability can be calculated according to modified Darcy's equation:

$$K_G = \frac{2Q \cdot L \cdot \eta \cdot p_f}{A \cdot (p_1^2 + p_2^2)} \tag{4}$$

where:

K_G = coefficient of gas permeability (m^2)
η = viscosity of oxygen (N s/m^2) = 2.02 x 10^{-16} N s/m^2 at 20°C
Q = volume of gas passing (m^3)
L = thickness of the sample (m)
A = area of penetration (m^2)

pf = pressure at which the volume Q gas is measured (N/m^2)
p1 = head pressure (N/m^2)
p2 = outlet gas pressure (N/m^2)

5.1.6 Capillary Absorption

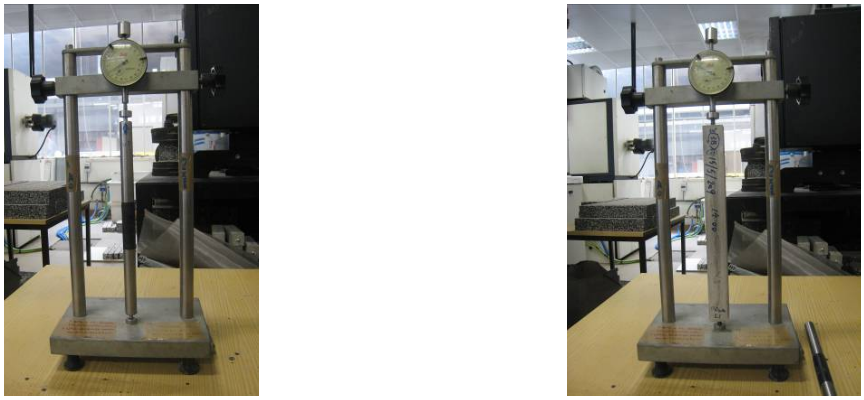
The test was performed according to LNEC E 393-1993 ("Betoes Determinacao da Absorcao de Agua or Capilaridade LNEC E 393-1993," 1993). The 4 x 4 x 16cm sample was being tested. The aim of this test is to determine the absorption by the sample of water through capillary rise. All the samples were first dry in an oven of 40~50°C for 4 ~5 days until the mass was stable. The dry mass of the sample was then recorded. The samples were put into a tray with a thin layer of water (about 0.5cm high). The mass of the wet sample was recorded at 3,6,24 and 72 hours. The capillary absorption rate was calculated by the equation (5).

Capillary Absorption rate = (Wet weight- Dry weight)/Area of section (5)

Figure 26: Samples setup of the capillary absorption test

5.1.7 Shrinkage test

This test was performed according to the standard LNEC E229-1979 ("LNEC E 229-1979 Cimentos Ensaio de Expansibilidade Processo da autoclave," 1979) and is used to study the retraction behaviour of the grout material. According to the literature review, it is found that the grout material should be of low shrinkage. Since high shrinkage grouting in fact will lead to further damage or even speed up the deterioration of the earth construction. The length of 2.5 x 2.5 x 25cm samples of each grout are measured by using the length comparator as shown in Figure 27. The test was measured two times a week for the first week and then starting at the second week, the measurement was taken once a week.



(a) *(b)*

Figure 27: (a) Length comparator with standard bar. (b) Length comparator with test sample

5.2 Mechanical Test

5.2.1 Flexural strength

This test was performed according to the BS EN 196-1:1995 ("BRITISH STANDARD: Methods of testing cement — Part 1: Determination of strength," 1995). The test was carried out both at 14 days and 28 days with the 4 x 4 x 16cm size specimens. The test was done by using the testing machine which is capable of applying loads up to 10 kN, at a rate of loading of (50 ± 10) N/s. The machine provided with a flexure device incorporating two steel supporting rollers of (10,0 ± 0,5) mm diameter spaced (100,0 ± 0,5) mm apart and a third steel loading roller of the same diameter placed centrally between the other two. The configuration of the sample was as shown in Figure 28. The flexural strength is determined by the equation (6).

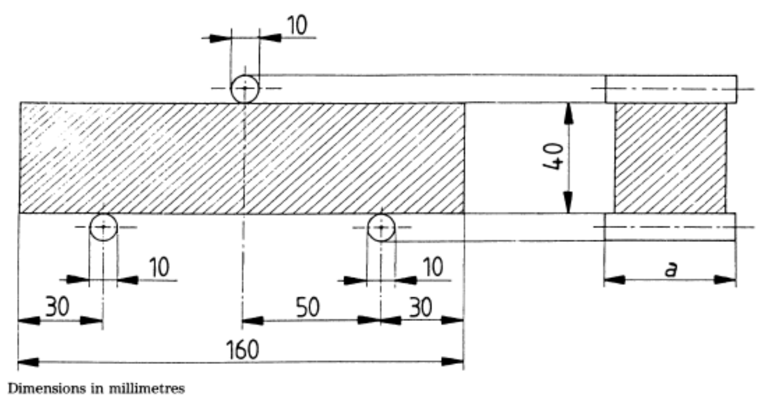


Figure 28:Arrangement of loading for determination of flexural strength

$$R_f = \frac{1.5 \times F_f \times l}{b^3} \tag{6}$$

where:

Rf = flexural strength (N/mm^2)
b = side of the square section of the prism (mm)
Ff = load applied to the middle of the prism at fracture (N)
l = distance between the supports (mm)

(a) (b)

Figure 29: (a) The machine to determine flexural strength (b) The configuration of the sample.

5.2.2 Compressive strength

This test was performed according to the standard BS EN196-1:1995 ("BRITISH STANDARD: Methods of testing cement — Part 1: Determination of strength," 1995). The test is carried out both at 14 days and 28 days with the two fracture 4 x 4 x 16 cm samples from the flexural strength test. The test machine increases the load smoothly at the rate of (2 400 ± 200) N/s over the entire load application until fracture; the load is then recorded. The machine and the configuration is as shown in Figure 30. The compressive strength is then determined by using the equation (7).

(a) (b)

Figure 30: (a) Compression machine. (b) Configuration of the compression test

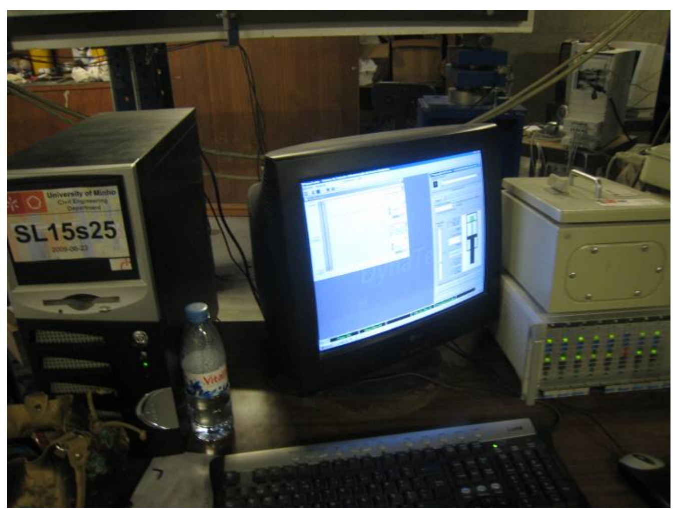
$$R_c = \frac{F_c}{1600} \tag{7}$$

where:
Rc = compressive strength (N/mm^2)
Fc = maximum load at fracture (N)
1600 = 40mm x 40mm is the area of the platens or auxiliary plates (mm^2)

5.2.3 Elastic modulus

This test was performed according to LNEC-E397-1993 (“Betões – Determinação do módulo de elasticidade- LNEC -E-397 -1993,” 1993). The test was carried out Ø 4.5cm cylinder. . The sample was fixed by two rings which connected to three displacement sensors. The apparatus setup of the test was shown in Figure 31. The diameter and the distance between the two rings were measured. The maximum load of each sample is 30% of the compressive load determined by the compressive strength test. The displacement, loading and time is recorded by the computer.

(a)

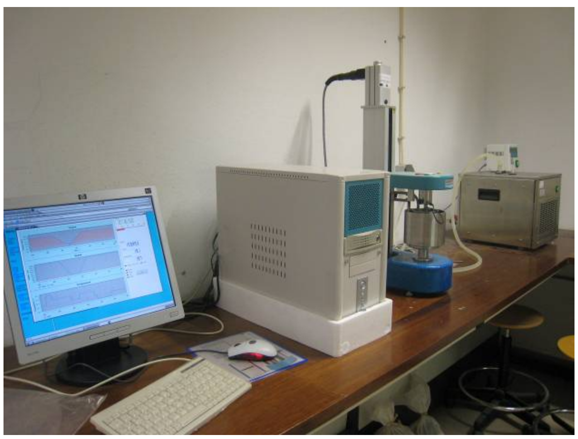


(b)

Figure 31: (a) Apparatus setup of elastic modulus test (b) Computer system for collecting the data

5.2.4 Rheological Test

The test was carried out at the Material Laboratory of the Universidade da Beira Interior. The rheological analysis was done by using the rheometer (Viskomat NT). The six grouts were prepared by the same procedure. The grout was then poured into the beaker; the volume of sample involved is approximately 370ml. The probe used was the modificated cement paste probe that can be used for mixture with maximum particle size of 2mm. The configuration of the apparatus was as shown in Figure 32. The grout was pour into a double wall beaker and the rheometer being connected to a temperature control unit such that the temperature was maintained to be 20°C. The speed of the rheometer was controlled with two speed profile respectively. The first one, here called ramp test, was performed with the speed profile by increasing the speed to 160rpm in 1 min and maintain 160rpm for 2min and returned to 0rpm in 1min. The second profile, here called dwell test, with the speed maintained constant, 160rpm, for 60min, with periodically decreases to zero rpm (in 30s) for every 15min. These two profiles were as shown in Figure 33. The grout was first tested with the ramp test profile followed by the dwell test.

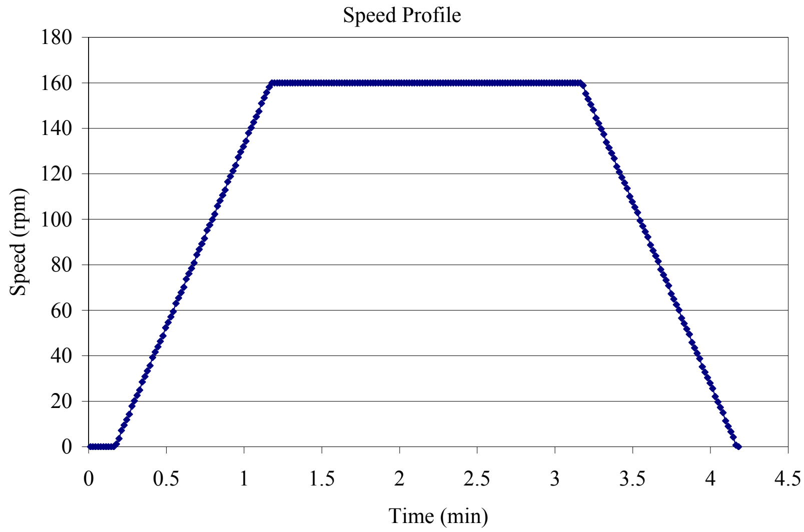

(a)


(b)

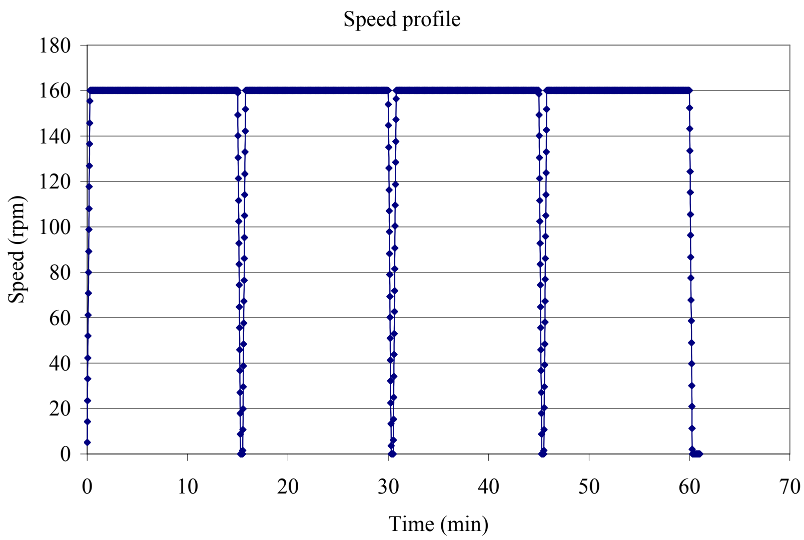

(c)


(d)

Figure 32: (a) The whole system of the rheological test. (b) Rheometer (c) Temperature Control Unit (d) Configuration of the double wall beaker and probe



(a)



(b)

Figure 33: The Speed Profile of (a) Ramp test and (b) Dwell test

In order to determine the rheological parameters, mathematical model will be used to fit to the decreasing speed flow curve. The most common model used is Bingham model which can provide the yield stress and plastic viscosity coefficient. In some case, Bingham model is not applicable when the grout behave non-linearly (Ferraris & Larrad, 1998). There are two other models, Herschel-Bulkley model and modified Bingham model which are used to fit high flowable mix (Ferraris & Larrad, 1998). The equations and the parameters of each model are shown below.

Bingham model

$$T = g + h\,N \qquad (8)$$

where
g = Flow resistance (N mm)
h = Viscosity coefficient (N mm min)
T = Torque (Nmm)
N = Speed (rpm)

Herschel-Bulkley model

$$T = T0 + K\,Nb \qquad (9)$$

where
K = consistency coefficient
b = flow behavior index
T = Torque (Nmm)
T0 = Initial torque (Nmm)
N = Speed (rpm)

Modified Bingham model

$$T = g' + h'\,N + T0 \qquad (10)$$

where
g' = Flow resistance (N mm)
h'= characteristic Viscosity coefficient (N mm min)
T = Torque (Nmm)
T0 = initial torque determined by Herschel-Bulkley model
N = Speed (rpm)

6. TEST RESULT AND ANALYSIS

In this chapter, the test result and the related analysis will be shown and studied.

6.1 Composition definition

Due to the lack of literature of grouts containing soil, an experimental phase was carried out to access some basic characteristics of grout workability and stability. The aim of this process was to determine the suitable proportion of materials in the grout and to obtain the proper W/B and SP/B ratio. In fact, in this study, two different clays had been attempted. The first type of clay was not as fine as the second type (the one provided by MIBAL Minas de Barqueiros, S.A.). Since there is no official data for the first type of clay no further information can be provided. Using the first type of clay, twelve different combinations were attempted. Two flow time readings, one just after mixing and one after mixing for more 10min, were recorded. Furthermore, the 6,7 or 8-day flexural strength and compressive strength were measured. The samples made during the calibration process were cured in water. The combinations and the result were as shown in Table 9 ~ Table 11.

Grout with 50% of binder and 50% of earth

In this group, the binder and earth ratio was 1:1. The clay content was dominant and varied from 80% to 95%. The SP/B ratio was within 3.5~6% and the W/B ratio was between 0.8~0.925. Within this six grouts, those with cement required less superplasticizer and water to achieve the fluidity. Furthermore, increase the amount of sand will also reduce the fluidity. Grout HH3B, which consisted of the smallest SP/B value showed a loss of workability (the flow time increases for almost 17%) after mixing for 10 min. Thus, superplasticizer can slow down the loss of workability.

Considering the strength, the grout with cement shows a much higher compressive and flexural strength. Compare HH1A and HH3A, reducing the clay result an increase in flexural strength. However, this conclusion does not apply to Grout HH2A and HH2B because it consists of higher W/B ratio which reduce both the compressive and flexural strength.

Table 9: Composition of trial grout with 50% binder and 50% of earth

Composition	HH1A	HH1B	HH2A	HH2B	HH3A	HH3B
W/B*	0.875	0.8	0.925	0.85	0.8	0.8
SP/B**	6%	4.75%	6%	6%	5.75%	3.5%
Binder	50%	50%	50%	50%	50%	50%
Hydraulic Lime	100%	50%	100%	50%	100%	50%
Cement	--	50%	--	50%	--	50%
Earth	50%	50%	50%	50%	50%	50%
Clay	95%	95%	90%	90%	80%	80%
Sand	5%	5%	10%	10%	20%	20%
Flow time for 1L of Grout (s)	18.54	18.74	23.39	27.51	26.45	25.78
Flow time after mixing 10min (s)	18.52	18.59	23.31	27.69	26.50	30.15
Average 7-days Flexural Strength (MPa)	0.26[1]	1.69[1]	0.45[2]	1.44[2]	0.28	1.63
Average 7-days Compressive Strength (MPa)	0.8[1]	5.86[1]	0.57[2]	4.18[2]	1.03	6.36

* W/B = water- binder ratio ** SP/B= superplasticizer- binder ratio

[1] = 8-days strength [2] = 6-days strength

Grout with 40% of binder and 60% of earth

In this group, the binder and earth ratio was 2:3. The clay content was dominant and varied from 70% to 95%. The SP/B ratio was 6% and the W/B ratio was between 0.925~1. Compare with the previous group (50% binder and 50% earth), both the SP/B ratio and W/B ratio were higher. This indicates that increasing the earth content will lead to diminishing in fluidity.

Consider the strength, those grouts with cement showed a higher strength. Furthermore, it could observe that increasing the amount of sand resulted in higher compressive strength and flexural strength. When compare the strength with the previous group, both the compressive and flexural strength were lower because of the less amount of binder.

Table 10: Composition of trial grout with 40% binder and 60% of earth

Composition	FS1B	FS2A	FS2B	FS3B
W/B*	1.0	0.95	0.95	0.925
SP/B**	6%	6%	6%	6%
Binder	40%	40%	40%	40%
Hydraulic Lime	50%	100%	50%	50%
Cement	50%	--	50%	50%
Earth	60%	60%	60%	60%
Clay	95%	75%	75%	70%
Sand	5%	25%	25%	30%
Flow time for 1L of Grout (s)	24.17	24.12	21.99	26.23
Flow time after mixing 10min (s)	27.89	24.83	22.67	26.68
Average 7-days Flexural Strength (MPa)	0.87[1]	0.28	1.31	1.36
Average 7-days Compressive Strength (MPa)	3.92[1]	0.68	4.41	4.37

* W/B = water- binder ratio ** SP/B= superplasticizer- binder ratio

[1] = 8-days strength

Grout with 25% of binder and 75% of earth

In this group, the binder and earth ratio was 1:3. The clay content was 80% and sand is 20%. The SP/B ratio was 6% and the W/B ratio was between 1.85~2.6. This combination with earth dominant at 75% seems not feasible. For Grout TS1A, grout without cement, it consists of 6% of superplasticizer and W/B as 2.6 but it still loss its workability after mixing 10 min and even could not carry out the fluidity test. For TS1B, the one which consists of cement, it could carry out the fluidity test but it showed an increase of 29% in flow time after mixing for 10 min. In fact, during the fluidity test of TS1B it could find that at the beginning only the more watery grout came out and those at the end of the test were very thick. This indicated that the W/B and SP/B ratio were at an improper standard that there were bleeding and segregation. Earth content at 75% will result in coagulation of mixture and dramatic drop in fluidity. Thus, this earth percentage seems to be the upper limit of earth content.

Table 11: Composition of trial grout with 25% binder and 75% of earth

Composition	TS1A	TS1B
W/B*	2.6	1.85
SP/B**	6%	6%
Binder	25%	25%
Hydraulic Lime	100%	50%
Cement	--	50%
Earth	75%	75%
Clay	80%	80%
Sand	20%	20%
Flow time for 1L of Grout (s)	29.27	23.85
Flow time after mixing 10min (s)	Impossible to flow	30.65
Average 7-days Flexural Strength (MPa)	--	0.67
Average 7-days Compressive Strength (MPa)	--	1.48

* W/B = water- binder ratio ** SP/B= superplasticizer- binder ratio

[1] = 8-days strength [2] = 6-days strength

After finished this twelve grouts, the first type of clay was out of stock, another type of clay provided by MIBAL Minas de Barqueiros, S.A. was used. The TS1B, was tried once again to see if this type of clay could work in this combination. Dry clay was used to prepare the TS1B, the required SP/B is 6% and W/B is 2.8%. Even at this SP/B and W/B ratio, the grout was still very thick. In addition, the fineness of this clay made the mixing process became more difficult. Therefore, it was decided to use saturated clay to ease the mixing process.

Furthermore, based on the previous experiment result, grout with soil percentage up to 75% cannot achieve adequate fluidity. It was decided to focus on the grout with binder to earth ratio 1:1 and 2:3. The next procedure was to calibrate the percentage of clay and sand. At the beginning, the percentage of clay was dominant; however, it was found that there was a sudden change in behaviour at certain percentage of water and superplasticizer. The flow time of the fluidity test was shown in Table 12. It could find that the grouts were either too fluid or lose fluidity in a short time. Thus, it was decided to change the composition of grout to be sand dominant.

Table 12: Combination and Flow time of Grout (Clay dominant)

Composition	A	B	C	D
W/B*	0.25	0.3	0.3	0.4
SP/B**	1%	1%	1.5%	3%
Binder	50%	50%	50%	50%
Hydraulic Lime	100%	100%	100%	100%
Cement	0%	0%	0%	0%
Earth	50%	50%	50%	50%
Clay	80%	80%	80%	80%
Sand	20%	20%	20%	20%
Flow time (s)	14.0	14.12	6.25	Too fluid
Flow time after mixing for 15 min (s)	>30	Cannot flow	6.23	--
Reason of elimination	quick loss of workabiliy	quick loss of workabiliy	too fluid	too Fluid

* W/B = water- binder ratio ** SP/B= superplasticizer- binder ratio

Finally, six combinations were chosen to continue further study. The selection was based on the principal properties of grout that was the fluidity. This test and the six combination will be discussed in the following sections.

6.2 Physical Tests

6.2.1 Fluidity Test

The aim of fluidity test is to determine the workability of the grout. In this study, it is used to define the water-binder ratio and the amount of superplasticizer. The fluidity test is served as a standard to determine the composition of the grout, the flow time to collect 1 L of grout is set to be within 15~ 18s.

Comparison between grouts 1A and 1B, 2A and 2B and 3A and 3B

The main difference between Grout 1A and 1B, 2A and 2B and 3A and 3B are the percentage of earth. Grout 3A and 3B, which consists of the highest amount of soil, required a higher W/B ratio and SP/B in order to fulfill the criteria of flow time. This shows that the increase in soil amount will reduce the fluidity of the grout.

Comparison of grout of group A and group B

This two groups of grout are different in the binder part. Group B contains both cement and hydraulic lime and group A contains only hydraulic lime. It can be found that the group B required lower SP/B and W/B ratio to archive the similar fluidity as group A. Thus, it can be concluded that the presence of cement and reduction of hydraulic lime can improve the fluidity of the grout.

Table 13: The flow time and composition of the test grout

Composition	1A	1B	2A	2B	3A	3B
W/B*	0.25		0.35	0.3	0.35	
SP/B**	1.6%	1.2%	1.4%	1.1%	1.6%	1%
Binder	50%	50%	50%	50%	40%	40%
Hydraulic Lime	100%	50%	100%	50%	100%	50%
Cement	0%	50%	0%	50%	0%	50%
Soil	50%	50%	50%	50%	60%	60%
Clay	50%	50%	30%	30%	30%	30%
Sand	50%	50%	70%	70%	70%	70%
Flow time (1L) (s)	15.5	11.5	14.0	14.9	15.6	12.7
Flow time (1L) after 15 min (s)	18.2	16.1	20.8	17.6	19.7	14.7
Range of flow time(s)	13.5~ 19.0	9.3~ 13.4	14.0 ~ 19.2	13.8~ 18.9	15.6~ 17.1	10.2~ 14.6

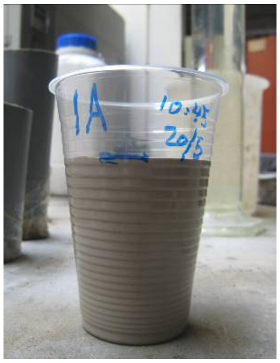
* W/B = water- binder ratio ** SP/B= superplasticizer- binder ratio

Effect of clay

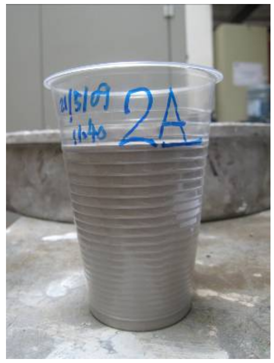
As mentioned previously, the water content of the clay varied from 1.55~1.85 but this variation of water content does not have significant effect on the fluidity test result. The flow time of each grout is still within the standard. The reason is that clay is not the dominant material in the mixtures. However, as listed in Table 13, there is an increase in flow time after left the grout without mixing for 15 minutes. All grouts lost workability without mixing. This will be further clarified by the rheological test in Section 6.3.4.

6.2.2 Segregation/Bleeding Test

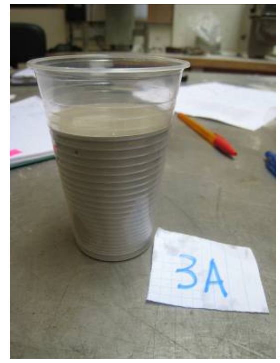
All the grouts show no segregation. As shown in the Figure 34, the stability of the grout are good. In fact, there is also no bleeding being observed. Thus, all six grouts performed very well in stability.



Grout 1A



Grout 2A



Grout 3A

Grout 1B

Grout 2B

Grout 3B

Figure 34: Segregation test result

6.2.3 Electrical resistivity

The electrical resistivity and the trend of the electrical resistivity with time are studied. Figure 35 shows the electrical resistivity readings. Group 3 consists of highest resistivity and then follow by group 2 and group 1. Hence, it can be concluded that the amount of sand and clay control the resistivity. Higher proportion of soil results in higher electrical resistivity.

Furthermore, the increasing rate of electrical resistivity of group A and group B are different. Group A shows a steeper slope and the resistivity is increasing more rapidly.

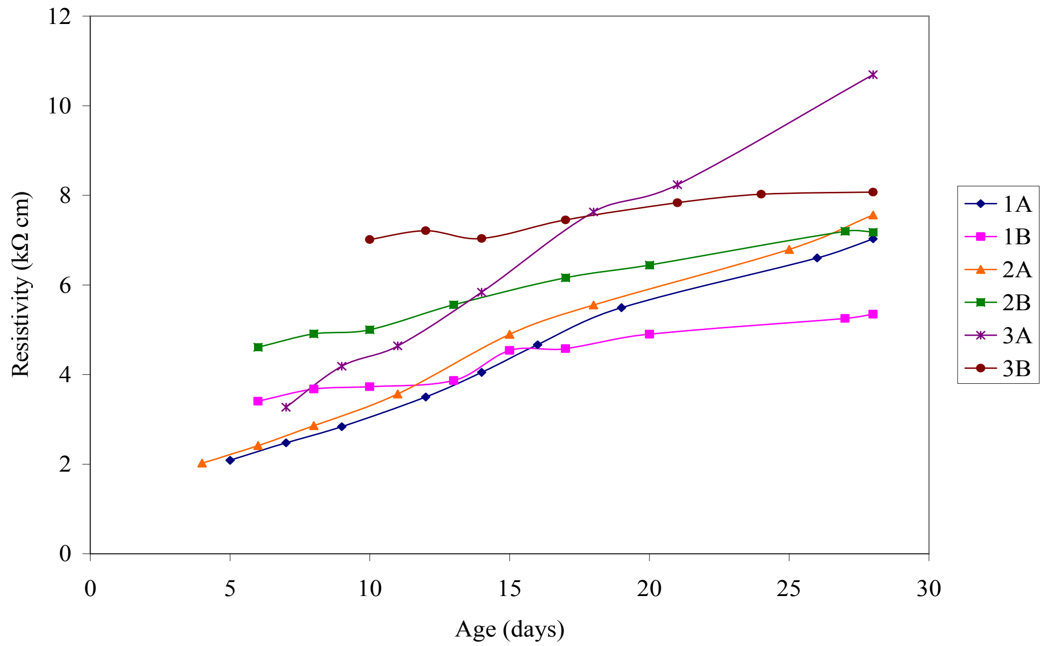


Figure 35: Electrical Resistivity versus age

The porosity, moisture and temperature are the factors which affect the electrical resistivity. It is an indirect method for assessing curing development. Therefore, the two observations mentioned above indicate that grout with soil and hydraulic lime may lose moisture faster and at the same time have more pores. The higher amount of soil seems will lead to a higher electrical resistivity.

6.2.4 Porosity test

The aim of this test is to determine the porosity of different samples. The test is carried out with one 4 x 4 x 16 cm sample. The result is shown below.

Table 14: The porosity result of the specimens

Group	Sample	Porosity (%)
Group A (with hydraulic lime)	1A	34.1
	2A	30.2
	3A	28.8
Group B (with hydraulic lime and cement)	1B	23.4
	2B	18.7
	3B	26.2

It is observed that group A has a higher porosity than group B. The presence of cement in group B causing the low porosity. Since the cement is very fine materials, it resists the pore increasing in manufacturing processes.

Comparing grout 1A, 2A and 3A, 1A consists of highest porosity. Although 3A consists of highest amount of sand, the porosity is the least. This indicates that the amount of hydraulic lime controls the porosity. For grout 1A and 2A, it is expected that grout 2A will result a higher porosity because of higher sand content but the result is not as expected. It is because of the higher percentage of clay. The viscous properties of saturated clay lock up the air bubbles formed during the mixing process.

Comparing group B, grout 3B which have more sand consists of highest porosity. When comparing 1B and 2B, Grout 2B consists of similar binder amount as 1B and even has higher percentage of sand but finally 1B consists of higher porosity. This again is due to the saturated clay.

Therefore, for grout with hydraulic lime and soil, the amount of hydraulic lime seems to be the main factor which affects the porosity and the saturated clay appears to be the minor factor. For grout with hydraulic lime, cement and soil, sand appears to be the main factor while saturated clay is the minor factor which affect the porosity.

According to literature review, the porosity of a few common types of mortar and paste are listed in Table 15. Compare the porosity test result with the reference value, the test result are similar to common paste and mortar. But all the result are lower than that of hydraulic lime paste.

Table 15: Porosity of common types of mortar and paste

Materials	Porosity
Cement mortar	≈10~20%
Hydraulic lime mortar	≈18~30%
Lime mortar	≈23%
Sand/hydraulic lime / cement mortar	≈24%
Cement paste	≈30%
Lime paste	≈50~65%

6.2.5 Oxygen and water permeability

The samples were dried in the 36~54°C oven, the mass was measured until the percentage difference is almost constant. After drying for five days, the percentage of water loss became smaller so the test was prepared to carry out on the next day. However, all the sample of group A cracked. Therefore, this test cannot carry out on time and cannot present the result in this study. The test is suggested to be carried out in the future studies.

1A

1B

2A

2B

3A

3B

Figure 36: The cracked sample of grou A and the sample of group B after drying for 5 days

6.2.6 Capillary Absorption

The aim of this test is to determine the capillary absorption of different samples. The result is shown below.

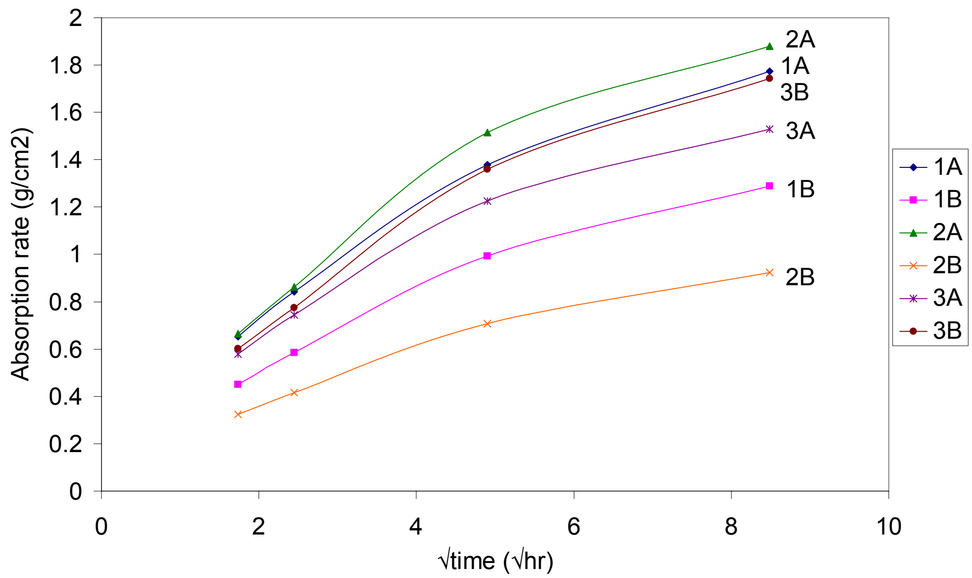


Figure 37: Capillary absorption rate of the sample

From Figure 37, it is observed that most of the group A result in higher capillary absorption rate than group B. This result agrees with the porosity result of which grout with hydraulic lime possesses more pores. Furthermore, the absorption rate is decreasing with time. The coefficient of capillary absorption of each grout is as listed in Table 16.

Table 16: The coefficient of capillary absorption of the specimens

Group	Sample	Coefficient of capillary absorption ($g/cm^2\sqrt{hr}$)
Group A (with hydraulic lime)	1A	0.165
	2A	0.180
	3A	0.140
Group B (with hydraulic lime and cement)	1B	0.124
	2B	0.089
	3B	0.170

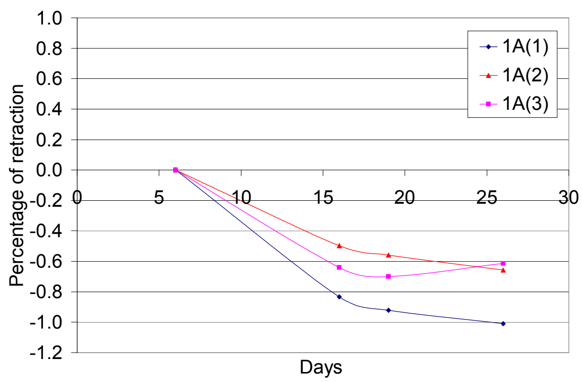
It is found that the capillary result does not totally agree with the porosity result. In group A, 3A consists of smallest coefficient which agrees with the porosity result. However, comparing grout 2A and 1A, 1A which consists of highest porosity is expected to have largest coefficent of capillary absorption but the result is not as expected. The reason is related to the pattern of pores. Saturated clay traps the air bubbles inside the sample but at the same time it means that those pores may be independent from each other.

Therefore, high porosity does not indicates that there is more capillary effect but it depends on the pore pattern. Therefore, for grout with saturated clay, it cannot make a good prediction of capillary absorption rate by knowing the porosity.

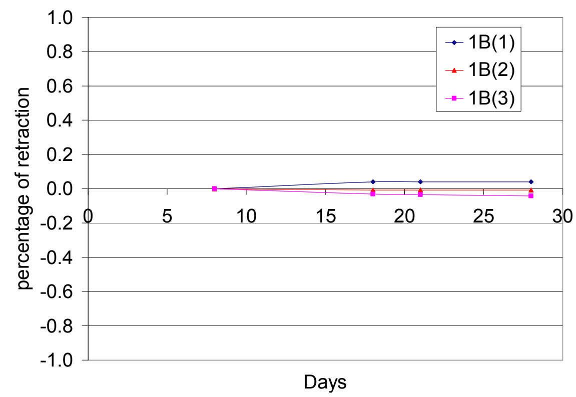
According to literature review, the 28-days capillary coefficient of mortar with air lime and sand is about 1.0 g/cm^2 (hr)$^{0.5}$ and that of mortar with air lime, metakaolin and sand is about 0.93~1.2 g/cm^2 (hr)$^{0.5}$. The 28-days capillary coefficient of mortar with cement is about 0.15~0.3 g/cm^2 (hr)$^{0.5}$. It can be found that the capillary coefficient of all the sample are more closed to cement mortar.

6.2.7 Retraction mechanism

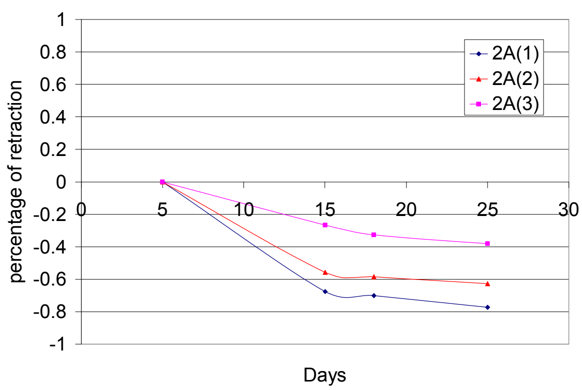
The shrinkage test is aimed in compared the change in dimension of the each grout. The percentage of shrinkage was found by compared the dimension with the first measurement. The negative percentage indicates a shrinkage mechanism and the positive value refers to expand mechanism.



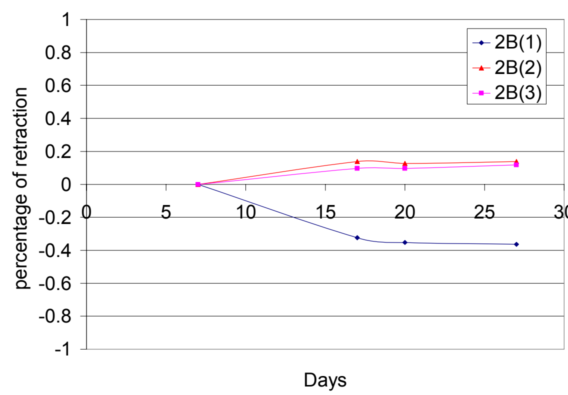
(a)



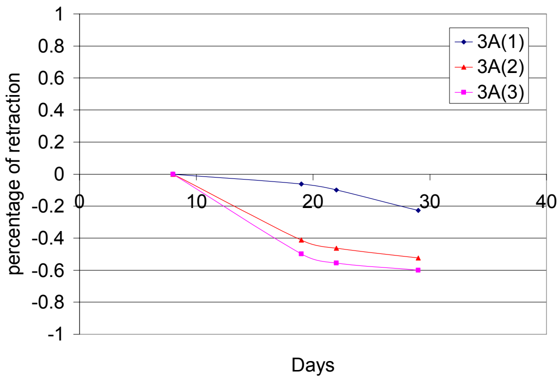
(b)



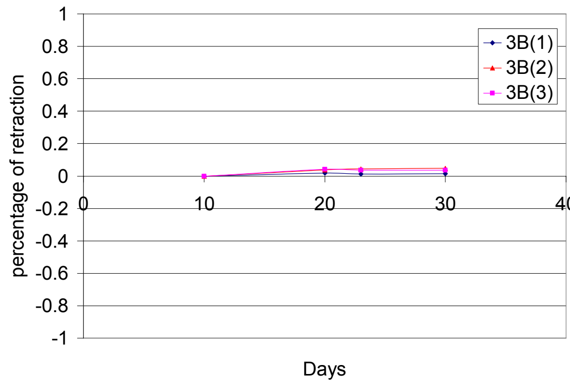
(c)



(d)



(e)



(f)

Figure 38: Percentage of retraction of all samples

All samples show a percentage of retraction less than 1.2%. The percentage of retraction of Grout 1A with the highest value. In fact, Group A shows higher percentage of retraction than that of Group B. Hence, the presence of cement and lower W/B ratio can reduce the retraction mechanism. Furthermore, comparing Grout 1, 2 and 3, it is observed that grouts with higher percentage of sand will have lower retraction. The dimension of all sample become stable after 15 days. Therefore, with the presence of cement and sand seems can result in lower retraction.

6.3 Mechanical Test

6.3.1 Flexural strength

The flexural strength of the samples was measured at 14 days and 28 days. The objective of this test is first to compare between the 14-day and 28-day flexural strength. Then to understand the effect of increasing the amount of sand and clay on the flexural strength and finally compare the result value with the reference value.

Table 17: Average Flexural strength of 14-day and 28-day

Grout	Average Flexural Strength (MPa)		
	14 days	28 days	Percentage increase (%)
1A	2.20	2.94	33.6
1B	4.56	5.03	10.4
2A	2.24	2.56	14.3
2B	4.43	5.85	32.3
3A	2.02	2.66	31.8
3B	3.57	3.77	5.6

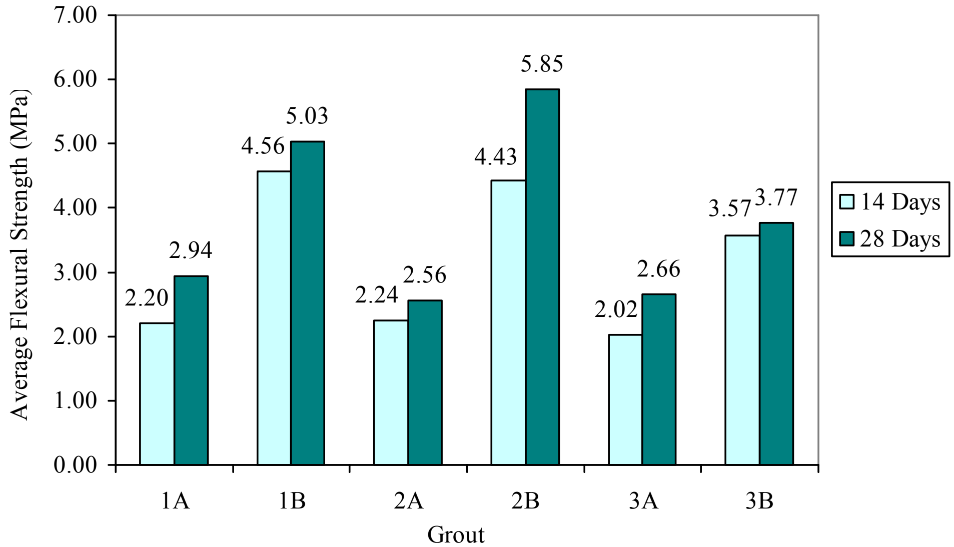


Figure 39: Average Flexural strength of all the grouts

As shown in Table 17, the 28-day flexural strength of all the samples is higher than the 14-day flexural strength. The highest value of 28-day flexural strength is that of Grout 2B and the lowest value is that of Grout 3A. The maximum percentage difference between Grout 1A, 2A and 3A is about 14.8%. However, the maximum percentage difference between Grout 1B, 2B and 3B is about 55.2%. Therefore, the changing in amount of soil will not affect the flexural strength in Group A.

Grouts with cement, Group B, is apparent that reducing the amount of cement will result in dramatic drop in strength. This can be observed by comparing Grout 2B and 3B. For Grout 1B, 2B and 3B, the cement is the main factors which affect the flexural strength. However, when comparing Grout 1B and 2B, keeping the cement amount constant, there is a strength increase with the higher proportion of sand. Therefore, it can be concluded that increasing sand is another factor which control the flexural strength after cement. Besides of sand, the saturated clay also influence the flexural strength since according to the porosity test, the saturated clay will somehow increase the porosity which will reduce the flexural strength.

Table 18:The 28-days flexural strength of common types of mortar

Samples	Flexural Strength
Hydraulic lime mortar	≈ 1 MPa
Cement mortar	≈ 3.5~ 6 MPa
Lime mortar	≈ 0.5MPa
Cement/ Sand mortar	≈ 4 MPa

According to literature review, the flexural strength of a few common types of mortar are listed in Table 18. Compare the test result with the reference values, the grouts with hydraulic lime and soil consist of higher strength than common hydraulic lime mortar. For the grouts with hydraulic lime, cement and soil they are similar to common cement mortar. Therefore, the presence of sand seems can improve the flexural strength of hydraulic lime based grout.

6.3.2 Compressive strength

The compressive strength of the samples was measured at 14 days and 28 days. The objective of this test is to compare the 14-day and 28-day compressive strength. Then to study the effect of increasing the amount of sand and clay on the compressive strength. Finally, compare the result with reference value.

Table 19:Average 14-day and 28-day Compressive Strength

Grout	Average Compressive Strength (Mpa)		
	14 Days	28 Days	Percentage increased (%)
1A	3.26	5.85	79.7
1B	13.04	15.66	20.1
2A	3.94	5.64	43.0
2B	17.86	19.41	8.7
3A	3.16	5.27	66.7
3B	10.57	12.45	17.8

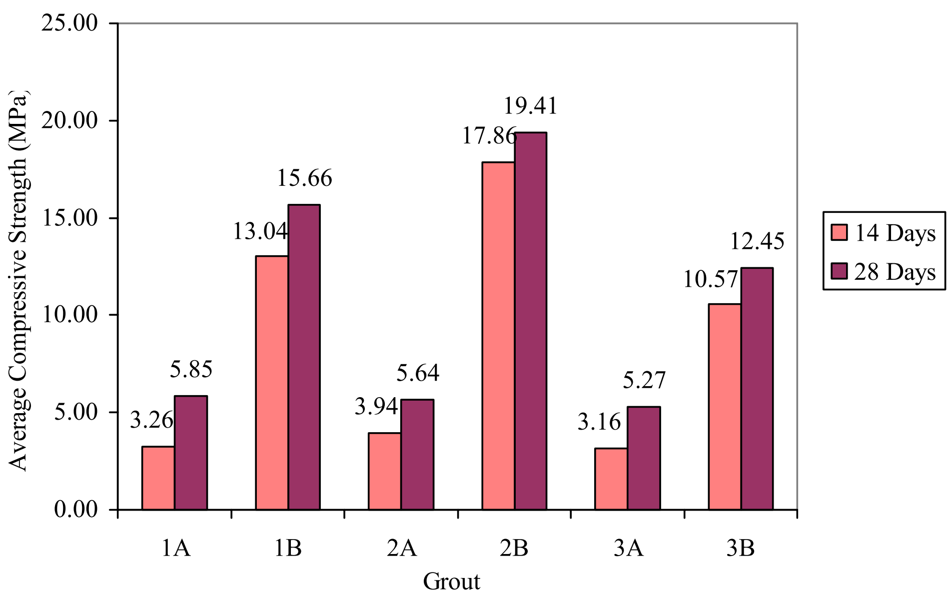


Figure 40: Average compressive strength (MPa) of different grouts

As shown in Table 19, the 28-day compressive strength of all the samples is higher than the 14-day compressive strength. The highest value is that of Grout 2B and the lowest value is that of Grout 3A. The percentage increase in compressive strength of Grout 1A, 2A and 3A is about 43~79.69%, which is higher than that of Grout 1B, 2B and 3B. Thus, cement is a factor which controls the gain of strength. The grout with cement will achieve a higher compressive strength and a higher rate of gain of strength.

Considering the 14-day and 28-day strength of Grout 1A, 2A and 3A, the maximum percentage difference is about 24.6%. However, the maximum percentage difference of Grout 1B, 2B and 3B is about 68.9%. Therefore, the soil is not a factor which affects the compressive strength in GroupA.

Grouts with cement, Group B, seems that reducing the amount of cement will result in dramatic drop in strength. This can be observed by comparing Grout 2B and 3B. For Grout 1B, 2B and 3B, the cement is the main factors which affect the compressive strength. Hence, reducing the amount of cement result in lower strength. When comparing Grout 1B and 2B, keeping the cement amount constant, there is a strength increase with the higher proportion of sand. Therefore, it can be concluded that increasing sand appears to be another factor that control the compressive strength after cement. Furthermore, similar to flexural strength, the saturated clay will somehow affect the compressive strength. Refer to grout 2B which consist of the lowest value of porosity have the highest compressive strength.

Table 20: The 28-days Compressive strength of common types of mortarand earth materials

Samples	Compressive Strength
Hydraulic lime mortar	≈ 7 MPa
Cement mortar	≈ 14~ 28 MPa
Lime mortar	≈ 2~3 MPa
Cement/ Sand (3:1) mortar	≈37 MPa
Cement/ Sand (9:1) mortar	≈ 5 MPa
Adobe block	≈ 4 MPa
Rammed earth	≈3 MPa

According to literature review, the compressive strength of a few common types of mortar are listed in Table 20. Compare the test result with the reference values, the grouts with hydraulic lime and soil consist of lower strength than common hydraulic lime mortar. For the grouts with hydraulic lime, cement and soil they are also lower than common cement mortar. Adding soil to the grout will reduce the compressive strength. It can also find the grouts with hydraulic lime and soil have more close compressive strength as the earth construction material.

6.3.3 Elastic modulus

The result of the elastic modulus of the samples are as listed below.

Table 21: Elastic moduli of the sample

Grout	Sample	Age (days)	Elastic Modulus (GPa)
1A	1	44	4.56
	2	44	7.01
2A	1	46	6.52
	2	46	6.42
3A	1	49	7.47
	2	49	6.55
1B	1	49	12.83
	2	49	7.95
2B	1	50	21.96
	2	44	14.36
3B	1	52	10.34
	2	52	10.59

The elastic modulus of sample of group B are much higher than that of group A. The elastic moduli of group B are about 40% higher than that of group A. The cement is a material which cause this.

Comparing the result of group A, all three results are very similar. For group B, 2B have a much higher result in sample 1, the reason may due to the different age of the two samples. However, still grout 2B has the highest elastic modulus. This agrees with the result of compressive and flexural strength test. Furthermore, it is found that the percentage of soil seems will not affect the elastic modulus of grout with only hydraulic lime and soil.

Table 22: Elastic moduli of common types of mortar

Samples	Elastic moduli
Hydraulic lime mortar	≈ 8 GPa
Cement mortar	≈ 30 GPa
Cement/ Sand (3:1) mortar	≈ 20 GPa
Cement/ Sand (9:1) mortar	≈ 3 GPa
Cement/Sand grout	≈ 14 GPa

According to literature review, the elastic moduli of a few common types of mortar are listed in Table 22. Compare the test result with the reference values, the grouts with hydraulic lime and soil consist of similar value as common hydraulic lime mortar. For the grouts with hydraulic lime, cement and soil, they are about 50% lower than common cement mortar. Adding soil to the grout will reduce the elastic modulus of grout with hydraulic lime, cement and soil.

6.3.4 Rheological test

The aim of this test is to understand the rheological behaviour of the grout with varied percentage of sand and clay. Two speed profiles were chosen for the rheological test: The ramp test and the dwell test. The torque variation with time and the rheological parameters, viscosity coefficient (h) and flow resistance (g), were obtained.

6.3.4.1 Ramp test result

The Ramp test profile is as shown in Figure 33(a). This speed profile is to determine the immediate rheological parameters and to ascertain the grout is thixotropic. The grout can be proved thixotropic by the existence of hysteresis area. Thixotropic fluid means that the internal structure breaks down (decrease in viscosity) on shearing and slowly rebuild at decreasing shearing and rest. The rheological parameters can be determined by fitting the decreasing speed flow curve by the suitable mathematical model.

The flow curves as shown in Figure 41 are the response of the ramp profile. Grout group A and Grout 2B are proved thixotropic by the decrease in viscosity when subjected to a constant speed and the presence of hysteresis area. It can be concluded that grout with hydraulic lime and earth appears to be probably to form a thixotropic mixture. Changing the amount of clay did not affect this behaviour. Another observation is that Grout 1B and 3B are not evident to be thixotropic. The differences between Grout 1B, 2B and 3B are the W/B ratio, SP/B ratio and the clay content. If Grout 2B is taken as a reference, both Grout 1B and 3B consisted of higher amount of clay. However, Grout 1B consists of higher amount of SP/B ratio than Grout 2B and Grout 3B consisted of higher W/B ratio than Grout 2B. Therefore, it can be concluded that the amount of clay seems to be a factor which control the thixotropic properties of binder-based grout. However, providing adequate amount of SP and water may prevent the thixotropic behaviour.

Comparing the Group A and Group B, the initial torque is greater in Group B, this may due to the amount of SP and the W/B ratio in Group B is lesser than that in Group A, thus it requires a bigger force to break the structure to initiate the flow.

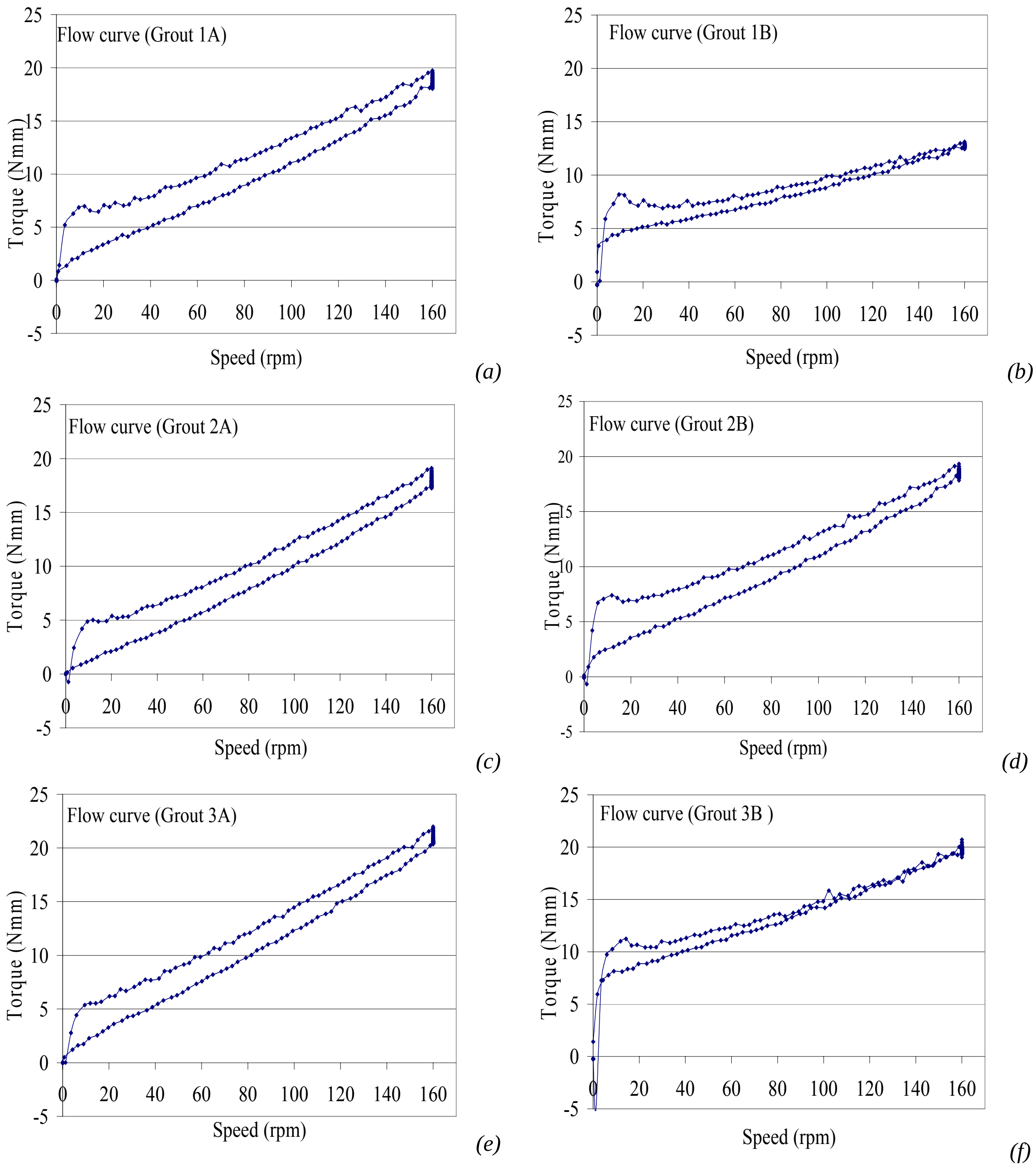


Figure 41: Flow curve (ramp profile) of (a) Grout 1A (b) Grout 1B (c) Grout 2A (d) Grout 2B (e) Grout 3A (f) Grout 3B

Immediate Rheological Parameters

The most common model used is Bingham model which can provide the yield stress and plastic viscosity coefficient. In this study, this model is used to all six grouts to fit the decreasing speed flow curve of the ramp test. The Bingham model fits very well in group B but not group A. For group A, the

Bingham model cannot fit the Grout 1A, 2A and 3A very well, especially for Grout 2A, it provides a negative value of the flow resistance. This indicates that the Grout group A behaves in such a non-linear that Bingham model cannot fit (Ferraris & Larrad, 1998). Thus, another two models, Herschel-Bulkley model and modified Bingham model, are used to fit the Grout 1A, 2A and 3A as shown in Figure 42. These two models are commonly applied to high flowable mix (Ferraris & Larrad, 1998). Therefore, Group A and Group B grout have different rheological behaviour. For group B, grout 1B, 2B and 3B can be fitted very well by Bingham model as shown in Figure 43. However, it

Table 23: Summary of rheological parameters of Bingham model and modified Bingham model

Model	Modified Bingham model			Bingham model		
Grout	1A	2A	3A	1B	2B	3B
Flow resistance g or g' (N mm)	0.690	0.063	0.360	3.560	1.006	6.532
Viscosity coefficient h or h' (N mm min)	0.1060	0.1026	0.1216	0.0552	0.1029	0.0804

The rheological parameters of Group A and Group B are listed in Table 23. For Group A, the flow resistance of Grout 1A is the highest followed by Grout 3A. It seems that the lower W/B ratio of Grout 1A leads to high flow resistance. However, the viscosity coefficient of Group A are very closed. In fact, as shown in Figure 41, the flow curve of Grout 1A, 2A and 3A are very similar that means changing the amount of soil did not affect the rheological behaviour too much. For Group B, the flow resistance of Grout 3B is the highest. This may be due to the lowest SP/B ratio and high percentage of clay. The viscosity coefficient of Group B are very closed and is in the range of 0.055 to 0.1Nmm min.

According to literature review, most of the rheological parameters are determined by using the Bingham model. The rheological parameters of Grout 1B, 2B and 3B can compare with the reference value. The viscosity coefficient of the binder paste is about 0.05 to 0.1 Nmm min (Seabra et al., 2008) and that of mortar is about 0.3 Nmm min (Sicker et al., 1997). The viscosity of the Group B grout in this study is more close to the binder paste. For the flow resistance of the binder paste is about 25 Nmm (Seabra et al., 2008) and that of mortar is about 60Nmm or higher (Sicker et al., 1997). Thus, in fact the torque of the grouts in this study are much lower that means it can start to flow easily.

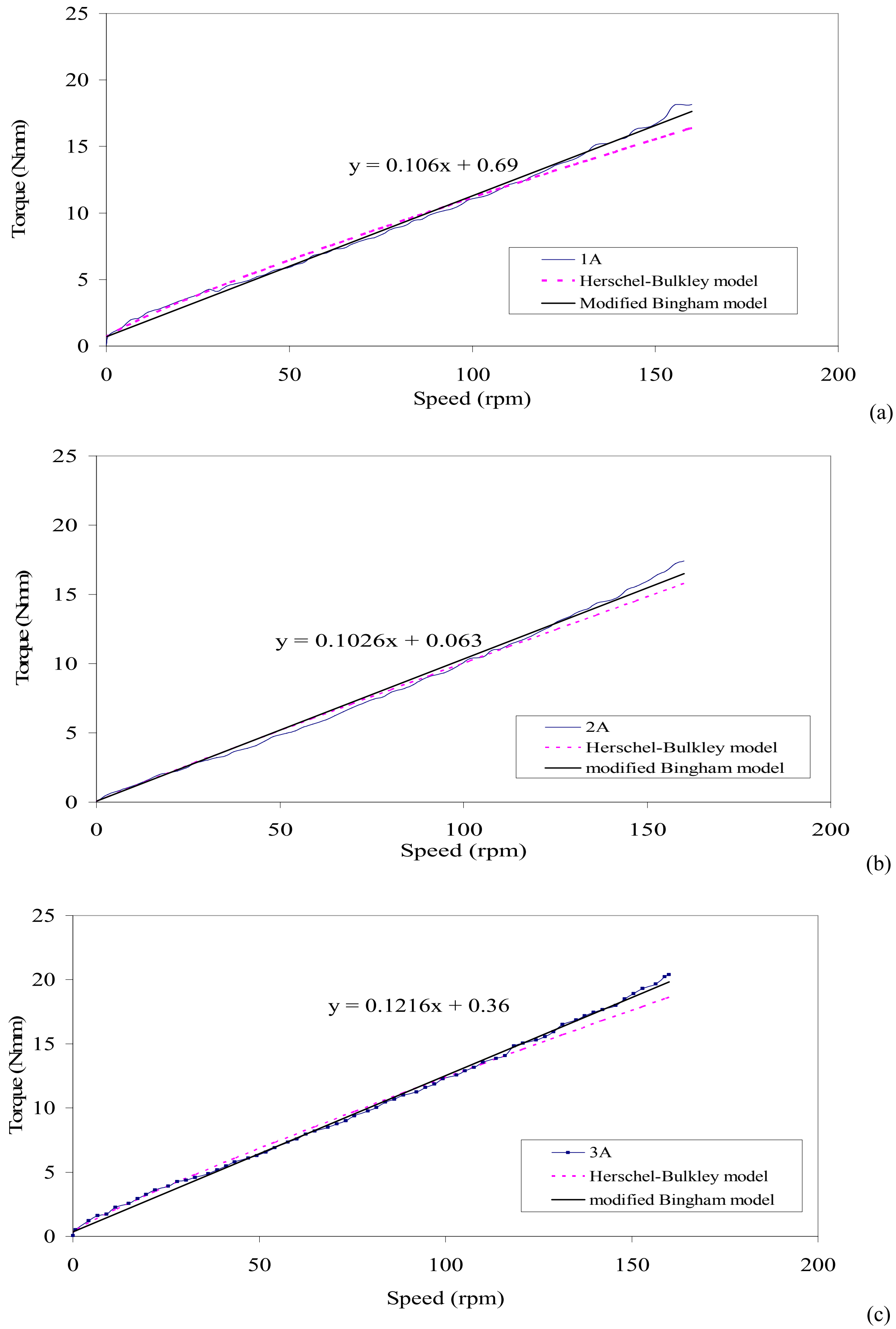
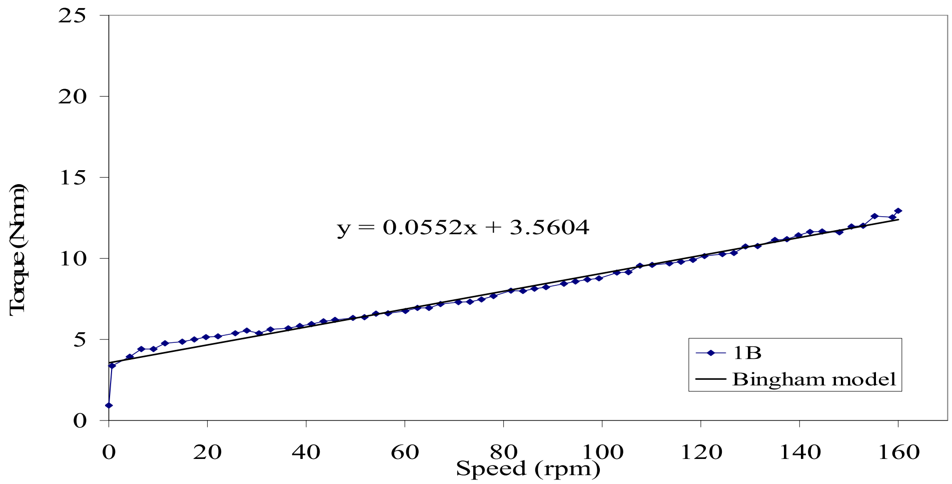
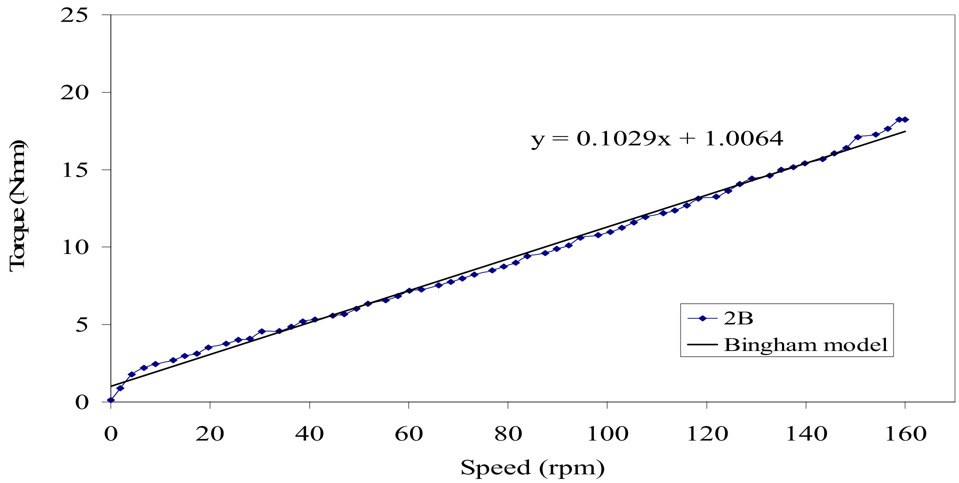


Figure 42: Flow curve (decreasing speed, ramp profile) based on modified Bingham and Herschel-Bulkley model (a) Grout 1A (b) Grout2A (c) Grout 3A



(a)



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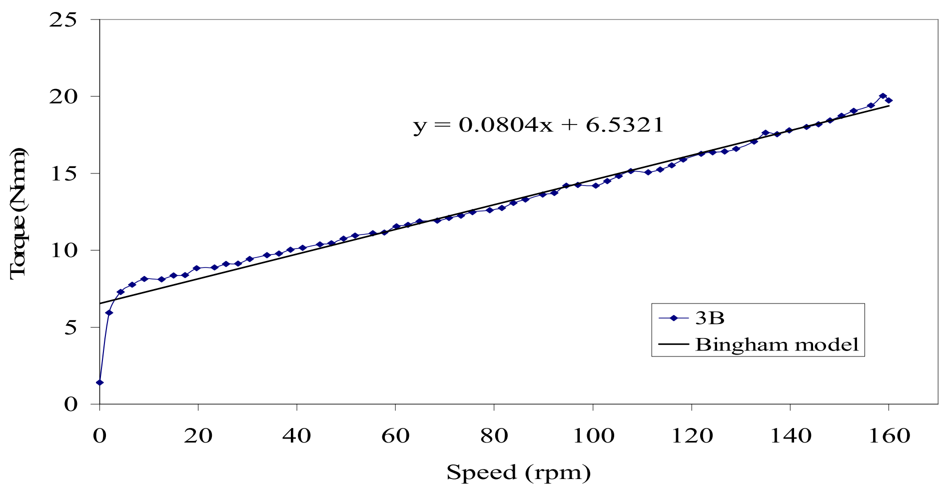


(c)

Figure 43: Flow curve (decreasing speed, ramp profile) with Bingham model (a) Grout 1B (b) Grout 2B (c) Grout 3B

6.3.4.2 Dwell Test Result

In order to study the variation of rheological parameters with time, the dwell speed profile is applied. The profile is as shown in Figure 33(b). In fact, the hysteresis area is a good indicator of the structural breakdown and reconstruction process of the grout (Labrincha, 2007). The flow curve of each period and the corresponding rheological parameters are determined.

Behaviour of grout with time

Using Figure 44 to Figure 48, the structural breakdown and reconstruction phenomenon of the grouts can be further studied. In Figure 44, all the grouts show a sudden increase in the torque at the beginning; it is because of the fast increase in speed up to 160rpm at the initial state. The drop of torque followed is due to the structural breakdown in the grout. However, this did not happen in Grout 3B, the main reason is that as mentioned above, the flow resistance of Grout 3B is the highest; the high amount of soil and low SP/B and W/B ratio result in higher friction in the grout. Thus, it behaves different from the other grout. For the first 15min, the slope of the all the grouts in Figure 44 are flat, this indicates the breakdown rate is very close to the reconstruction rate and means that the SP is still performing very well.

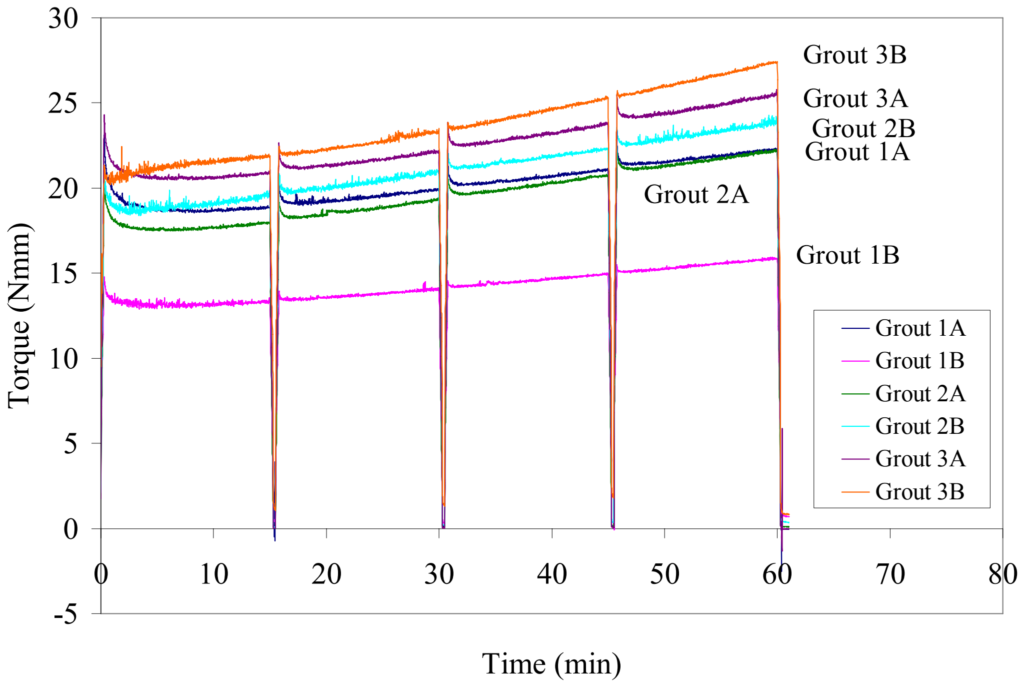
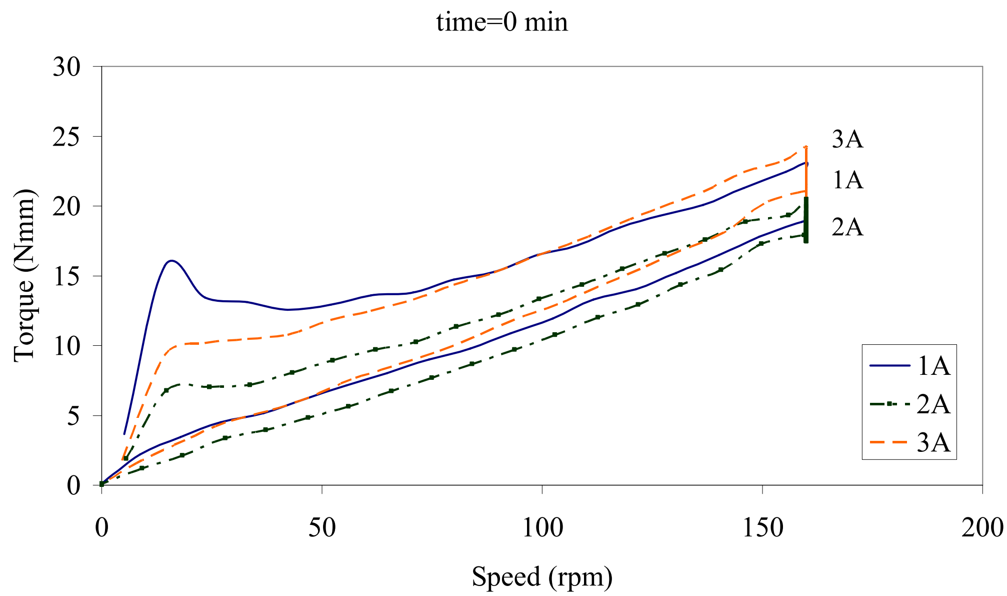


Figure 44: Torque versus time curve of all six grouts



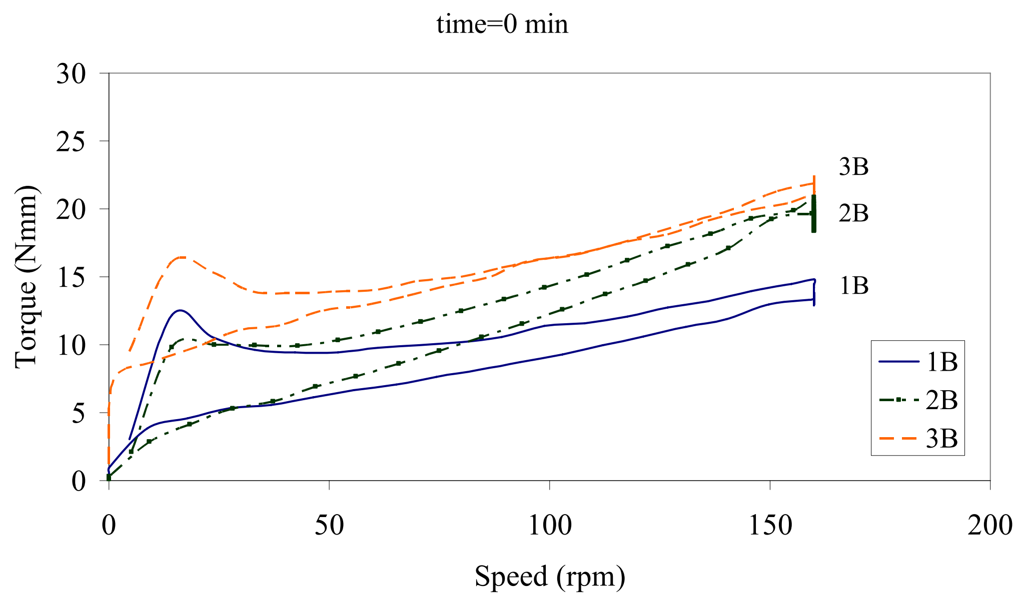


Figure 45: Flow curve (dwell profile) at time 0~15 min

Compare Figure 45 and Figure 46, the hysteresis area of Figure 45 is bigger than that of Figure 46. The small hysteresis area shows that the structural breakdown has completed and the SP is still working. However, in Figure 44, after the first 15 min, there is a slight increase in slope. There are steeper slopes of Grout 2A, 2B, 3A and 3B than that of Grout 1A and 1B. Therefore, it can be concluded that the structural breakdown of Grout 2A, 2B, 3A and 3B have been completed and the SP starts to loss its effect or the reconstruction process has started after the first 15min.

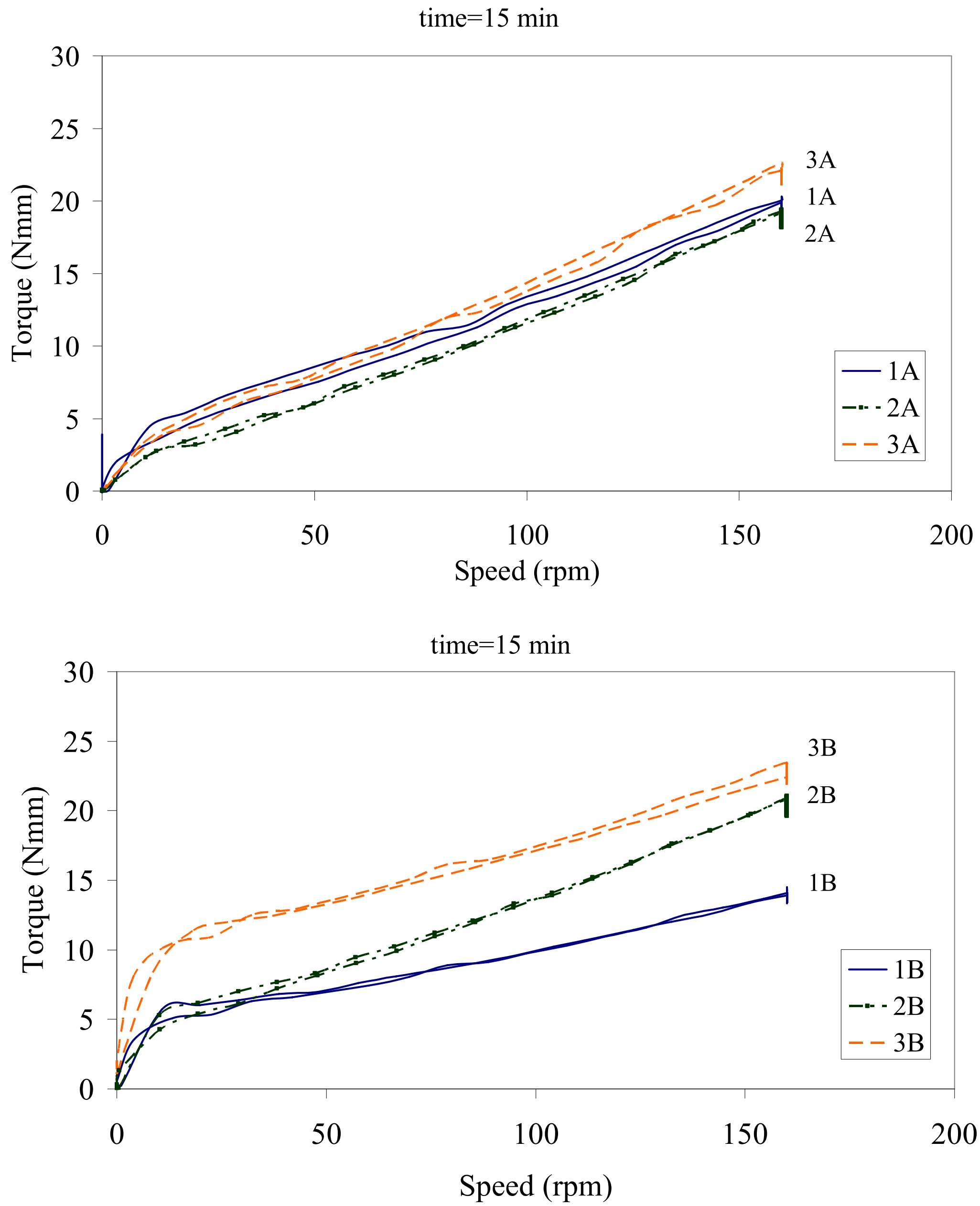
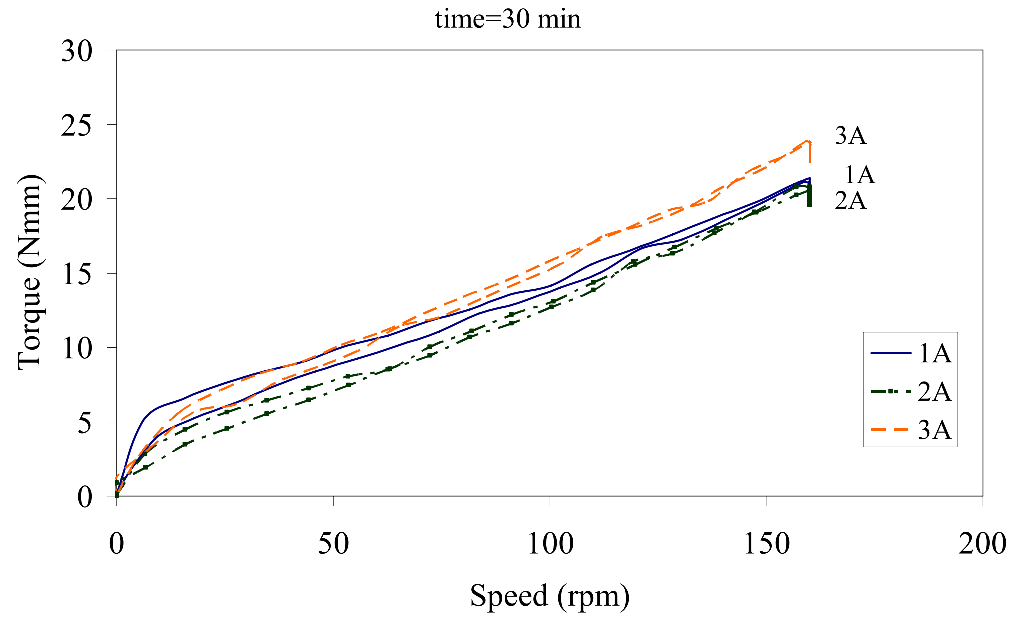


Figure 46: Flow curve (dwell profile) at time 16~30 min

Compare Figure 46 and Figure 47, the hysteresis area of Grout 1A, 2A, 2B and 3B have increased which shows that the reconstruction rate is increasing. The torque versus time curve of Grout 3A and 3B consist of the steepest slope after 30min; follow by Grout 2A and 2B. The Grout 1A and 1B consisted of the flattest slope. Thus, Grout 3A and 3B have the highest reconstruction rate. This probably cause by the highest amount of clay in Grout 3A and Grout 3B.



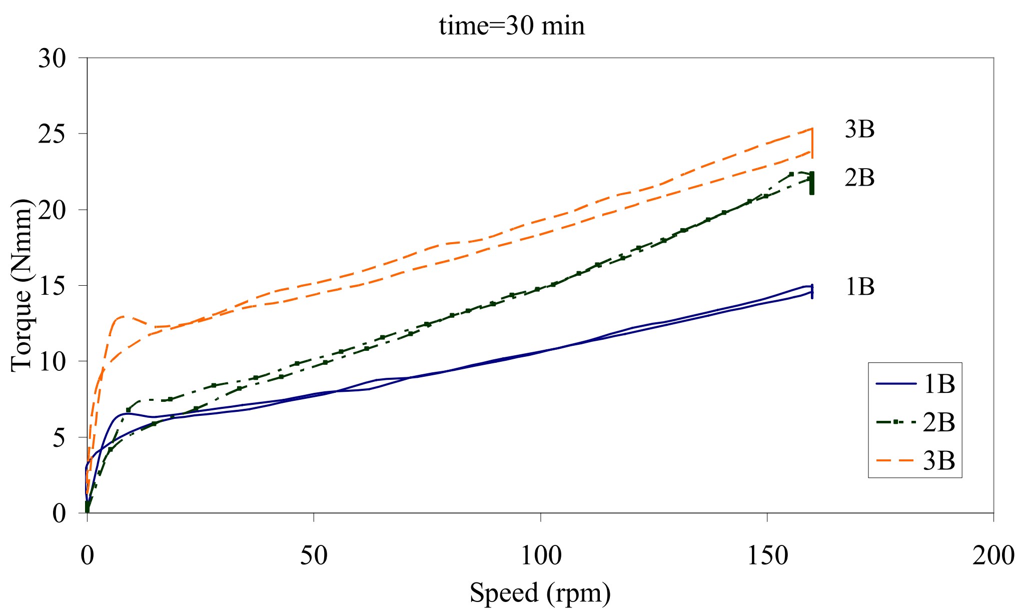
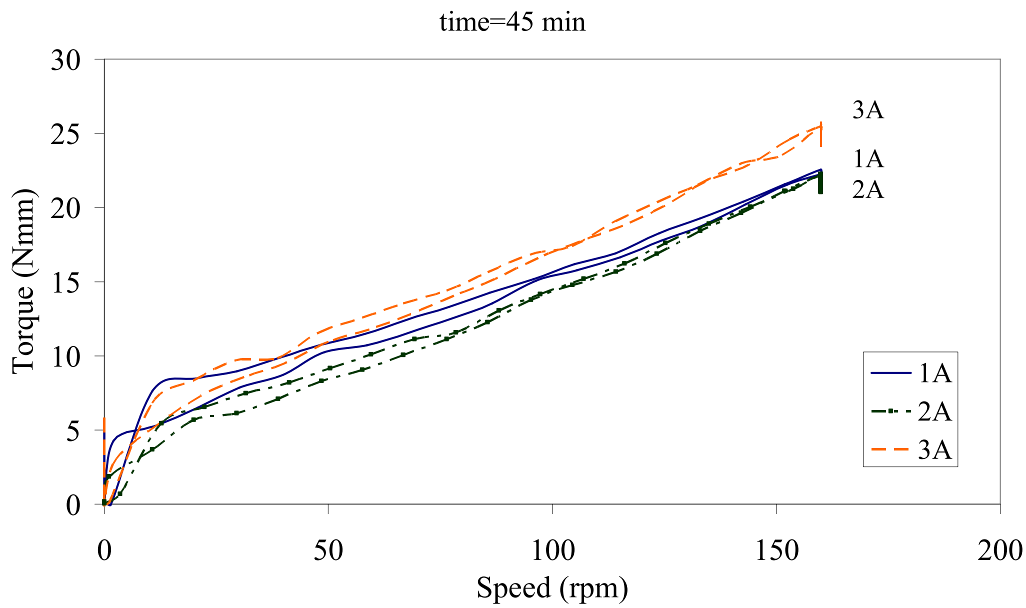


Figure 47: Flow curve (dwell profile) at time 31~45 min

Compare Figure 47 and Figure 48, the hysteresis area of all the grouts is increasing. All the grouts start the reconstruction process and are losing the workability gradually.

Therefore, grouts with higher amount of clay appears to consist of higher reconstruction rate.



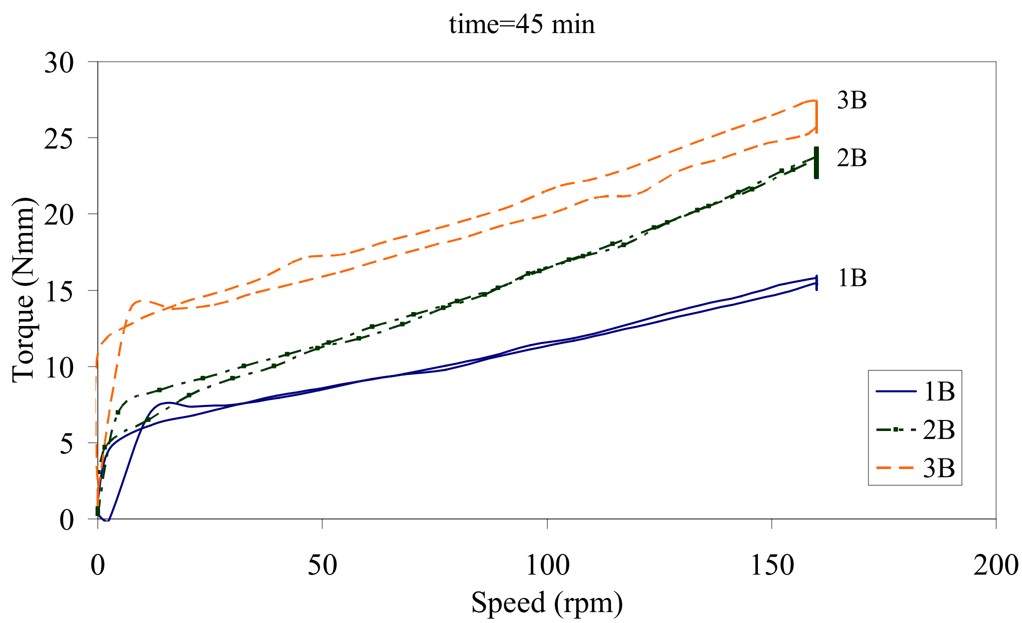


Figure 48: Flow curve (dwell profile) at time 46~60 min

Variation of Rheological Parameters with Time

The rheological parameters of each decreasing speed flow curve were determined as that in Ramp test result. Grout 1A, 2A and 3A are fitted by modified Bingham model and Grout 1B, 2B and 3B are fitted by Bingham model.

As shown in Figure 49, the flow resistance (g') of Grout 1A, 2A and 3A are increasing with time. Grout 1A consists of the highest flow resistance after one hour. All three grouts show a great increase in flow resistance after 30 min. However, Grout 3A shows a gentle increase after 45min. There is a slower increase in flow resistance in grout with higher amount of clay.

The viscosity coefficient of the three grouts are very closed, range from 0.113 to 0.147 Nmm min. The viscosity coefficient of Grout 3A is the highest. It can be found that the viscosity coefficient of Grout 2A and 3A start to increase after 45 min. Therefore, the viscosity of this three grouts does not change a lot but the viscosity of grout with more clay increase faster with time.

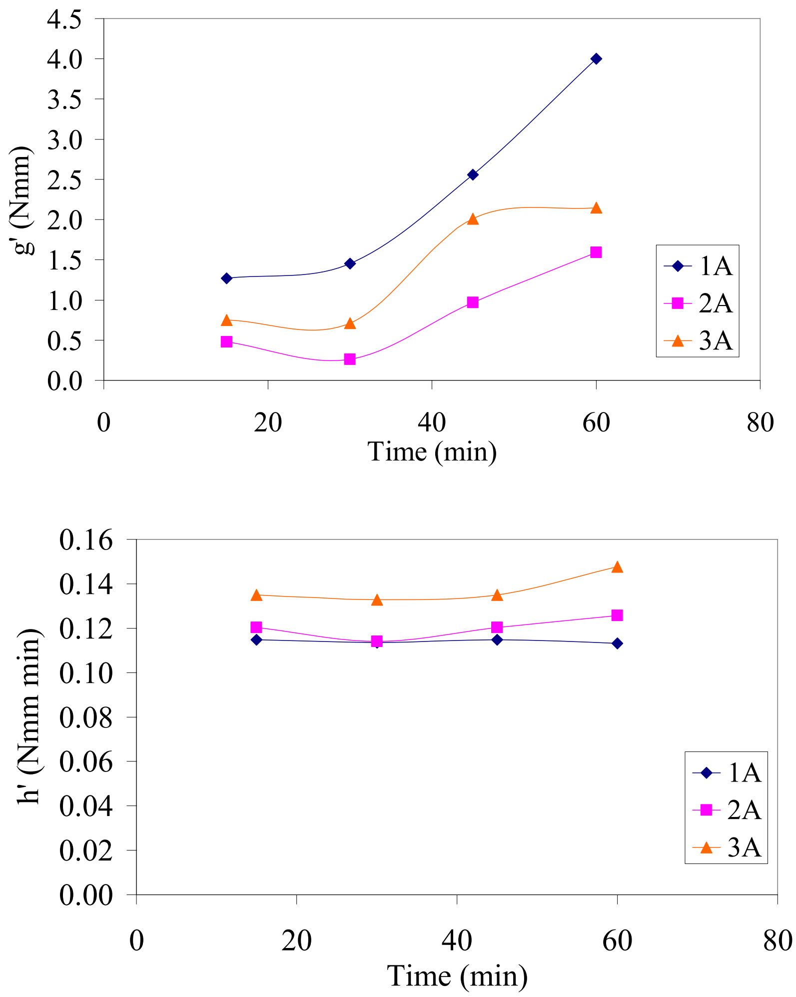


Figure 49: Flow resistance (g')and viscosity coefficient (h') of modified Bingham model

The rheological parameters of Grout 1B, 2B and 3B were determined by applying the Bingham model. The variations of the values with time are shown in Figure 50, the flow resistance (g) of Grout 1B, 2B and 3B are increasing with time. Grouts with cement and without cement behave differently. The flow resistance of Grout 3B is highest. Furthermore, flow resistance of grouts with more clay show a greater increase after 60min.

The viscosity coefficient of the three grouts is ranged from 0.06 to 0.113 Nmm min. The viscosity coefficient of Grout 2B is the highest. It can be found that the viscosity coefficient curve of Grout 1B and 2B are flat but that of 3B shows a slight increase after 30 min. Therefore, the viscosity of this three grouts does not change a lot within 60min but the viscosity of grout with more clay increase faster.

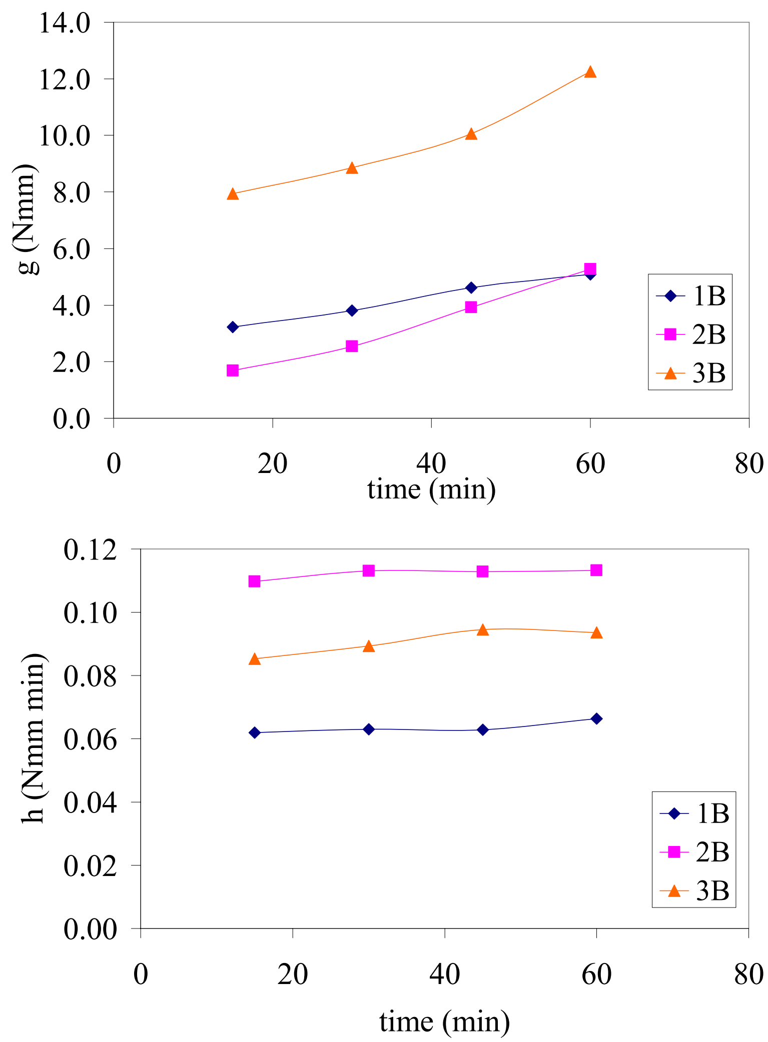


Figure 50: Flow resistance (g) and viscosity coefficent (h) of Group B grout (Bingham model)

According to literature review, the flow resistance of grout with hydraulic lime and aggregate or that with air lime, aggregate and metakaolin is about 2.5~4.5 Nmm (Martins et al., 2008). The viscosity coefficient is about 0.09~0.12Nmm min. For group A, the viscosity coefficient is about 0.12~0.15 Nmm min which is higher than the reference value. For group B, the viscosity coefficient of the result are very similar to those grouts. For the flow resistance, group A has flow resistance below 4.0 Nmm which is very similar to the reference value. For group B, the flow resistance of grout 3B is almost 50% higher than the reference value. This may due to the lowest SP/W ratio.

6.3.4.3 Comparison of Fluidity test result and Rheological test Result

The result from the fluidity test and that of rheological test are both related to the flow mechanism of grout. In Table 24, the viscosity coefficient of the ramp test and the flow time of the fluidity test are listed. It was found that the viscosity coefficient is changing in the same way as the flow time. In Group A, the most fluid grout is Grout 2A, which consists both lowest viscosity coefficient and flow time. In Group B, the most fluid grout is Grout 1B which consist both the lowest viscosity coefficient and flow time. Therefore, we can conclude that the rheological test and fluidity test are related. The viscosity coefficient and the flow time show the same trend.

Table 24: Comparison data of viscosity coefficient and Fluidity test result

Model	Modified Bingham model			Bingham model		
Grout	1A	2A	3A	1B	2B	3B
Viscosity coefficient h or h’ (N mm min)	0.1060	0.1026	0.1216	0.0552	0.1029	0.0804
Fluidity Test Result Flow time (1L) (s)	15.51s	13.98s	15.62s	11.48s	14.93s	12.73s

6.4 General Remark

After carrying out all the experiment, the grouts provided some unexpected but interesting result. The presence of high proportion of soil and the addition of saturated clay make the grouts have a different physical, mechanical and rheological response from the traditional grout. Adding clay to grout mixture is a new concept, there is no definite standard. In this section, an overall review of all the test will be presented.

Composition definition

Through the calibration process, a basic idea of the effect of increasing the percentage of soil and saturated clay was obtained. This served as a guide to design the percentage of sand and clay in the future study. It is observed that with the presence of cement, the grout will require less superplasticizer and water content to achieve the workability and the sample results in higher compressive and flexural strength. Another observation is that grouts with earth will reduce the fluidity and require more superplasticizer and water to achieve the workability. However, increases in the sand content can improve the compressive strength and flexural strength but higher clay content seems will speed up the loss of fluidity. Through the experiment phase, it was found that an increase in the percentage of earth to 75% is not suitable. The grout will become too thick, causing the segregation and bleeding problem. Adding superplasticizer is one option to improve the fluidity but this is not economical. Furthermore, grout with clay dominant is more difficult to achieve the suitable amount of W/B and SP/B ratio. The grout is either too fluid or losses workability rapidly.

Physical Test Result

Fluidity Test

This test is used to define the composition definition and to understand the fluidity of the grout. Through this test, it is recognized that with the presence of cement, hydraulic lime and soil, less superplasticizer and water content are needed to achieve the workability than grout with hydraulic lime and soil. With the presence of soil, grout will require higher W/B and SP/B ratio with higher amount of sand and clay. In addition, it is observed that grout loses workability without mixing.

Segregation/Bleeding Test

Since the grout have a high percentage of earth, it is necessary to understand the stability of the grout. It is found that the grout shows no sign of segregation and bleeding when there is up to 60% of soil.

Electrical Resistivity

Porosity, moisture and temperature are the factors which affect the electrical resistivity. Through this test, it was found that the presence of cement and earth will show different response. When there is presence of cement, it seems that it will slow down the rate of increase in electrical resistivity. When there is presence of sand and clay, the electrical resistivity will be higher.

Porosity test

The aim of this test is to understand how the presence of earth affect the porosity. It is known that hydraulic lime and sand can improve the porosity. However, the presence of saturated clay appears to affect the result. It is observed that the presence of cement will reduce the porosity which may be due to its fine particle size. Furthermore, grouts with saturated clay seems will lead to an increase in porosity because its viscous properties trap the air bubbles during the mixing process. Comparing the result with reference value, it is found that the grout with hydraulic lime and soil will have porosity better than hydraulic lime mortar and the grout with hydraulic lime, cement and soil will have porosity better than cement mortar.

Capillary Absorption

Through this test, it is possible to understand the capillary absorption of grout with presence of saturated clay. Grouts with cement will have lower capillary absorption. Another observation is that the porosity and the capillary absorption result behave differently. This may due to the presence of sand and clay. The saturated clay increases the porosity but not capillary absorption because of the viscous properties of saturated clay.

Retraction mechanism

This test shows the retraction mechanism of the grout when there is presence of cement and soil. It is noticed that with the presence of cement reduces retraction mechanism. Besides, of cement, higher percentage of sand seems will reduce the retraction mechanism.

Mechanical Test result

Flexural Strength

This test shows how the presence of earth affect the flexural strength. Through the test, the flexural strength will be higher when there is cement. Furthermore, for grout with hydraulic lime and soil, the percentage of soil seems not the main factor affecting the flexural strength. For grout with hydraulic lime, cement and soil, the amount of sand appears to have a slight effect on the flexural strength. As mentioned in previous section, since the saturated clay will affect the porosity thus it will also reduce the flexural strength.

When compare the result value with the reference value, grout with hydraulic lime and soil results in higher flexural strength than common hydraulic lime mortar. For grout with hydraulic lime, cement and soil have similar flexural strength as common cement mortar.

Compressive Strength

This test shows how the presence of earth affects the compressive strength. When there is presence of cement, the compressive strength will be higher also there is a faster rate of increase in strength. For grout with hydraulic lime and soil, it seems that the percentage of soil is not the main factor affecting the strength. For grout with hydraulic lime, cement and soil, the amount of sand will improve the compressive strength. Similar to flexural strength, saturated clay appears to be a factor of compressive strength because it affects the porosity.

When compare the result with reference value, grout with hydraulic lime and soil results in lower compressive strength than common hydraulic lime mortar but more close to that of the adobe block and rammed earth unit. Furthermore, grout with hydraulic lime, cement and soil have lower compressive strength than the common cement mortar.

Elastic Modulus

This test shows how the presence of earth affects the elastic modulus. When there is presence of cement the sample will result in higher elastic modulus. However, it is found that the presence of earth does not show a great effect on the elastic modulus for grout with hydraulic lime and soil. Nevertheless, the lower percentage of clay seems will improve the elastic modulus because of reducing the porosity. When compare the result with the reference value, grout with hydraulic lime and soil results in similar value as common hydraulic lime mortar. Grout with hydraulic lime, cement and soil have lower elastic modulus than the common cement mortar.

Rheological Test

This test clarifies how the presence of saturated clay affects the fluidity with time. It is found that with the presence of clay does not ascertain the grout will be thixotropic since changing the amount of SP/B and W/B will affect this properties. However, grout with hydraulic lime and earth seems more certain to be thixotropic. Through the test, it is observed that the flow resistance is control by the SP/B, W/B and the amount of clay. Grouts with higher percentage of clay consist of higher reconstruction rate and SP will lose power faster. The rheological test and fluidity test are related. The viscosity coefficient and the flow time show the same trend.

7. CONCLUSION AND FUTURE STUDIES

7.1 Conclusion

It is necessary to develop a new generation of grout for applying on earth construction. In this study, it was found that adding earth to traditional grout is feasible. Grout with earth can maintain the property of traditional grout but at the same time consists of similar characteristic as the earth construction. The percentage of earth needs careful calibration since high earth content will reduce the fluidity and will lead to segregation, coagulation and bleeding problem. High earth content will lead to the demanding amount of superplasticizer and lead to an increase in production cost.

Physical Properties

The physical properties of the earth-based grout being studied included: fluidity, segregation, electrical resistivity, porosity, capillary absorption and retraction. In this study, the grout mixture is stable with no sign of segregation. This type of grout can be workable even the earth content is dominant. Referring to the rheological test, this type of grout is mostly thixotropic except when there is a high amount of superplasticizer or water content. In fact, the presence of clay will reduce the effective time of the superplasticizer. Therefore, it is needed to calibrate a suitable amount of superplasticizer such that to provide a fluid grout with adequate thixotropic properties and with longer workable time. The presence of earth also leads to an increase in electrical resistivity. Furthermore, the saturated clay appears to affect the porosity and capillary absorption. It seems that it can improve the porosity without changing much capillary absorption.

Mechanical Test result

Grout used for injection in earth construction should be of low shrinkage and possesses compatible strength. In this study, the earth-based grout is found to consist of certain standard of retraction problem; especially for those without cement will lead to higher percentage of retraction. However, it was observed that the presence of sand could reduce the retraction mechanism efficiently. Although, grout with only hydraulic lime and earth will lead to higher shrinkage, it provides a more suitable flexural and compressive strength which is similar to the earth construction unit. Furthermore, the presence of earth does not affect significantly the elastic modulus.

7.2 Future studies

The future studies should be related to chemical properties of the grout and various composition parameters to understand the effect of proportions. It is suggested to carry out scanning electron microscopy to understand better the chemical bonding of the materials. This can also provide further information to explain how the saturated clay affects the porosity, permeability and the rheological behaviour. Furthermore, different combination of grout can be tried especially with different proportion of cement and hydraulic lime. It is also suggested to attempt different types of superplasticizer such that to prolong the workability of the grout and to obtain one which is most suitable for clay.

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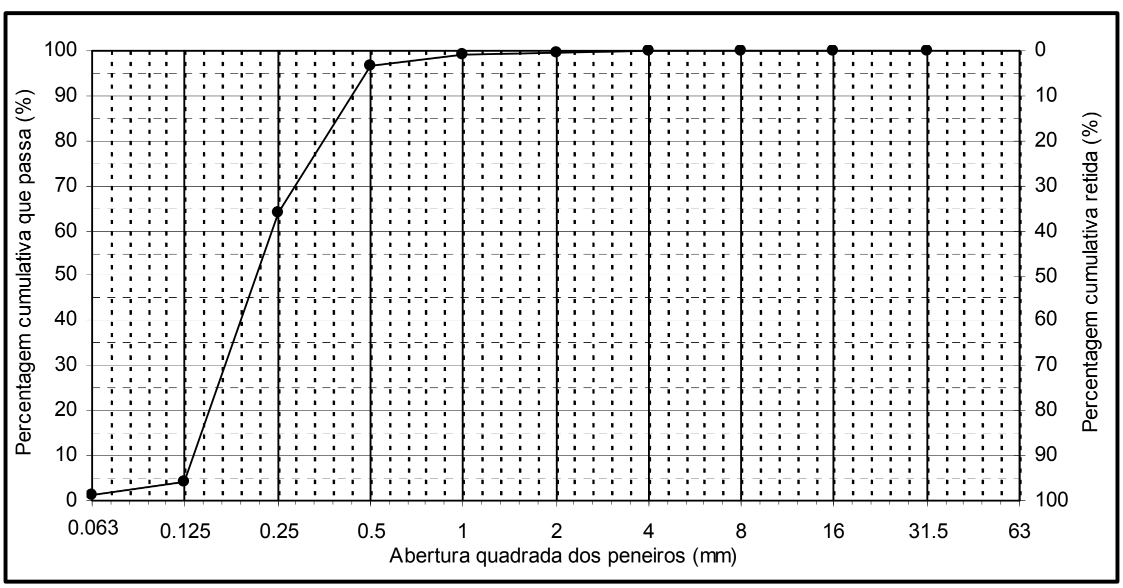
APPENDIX: RAW DATA RESULT

Particle Size Distribution Result

Table 25: The raw data of the particle size distribution test

Total Mass M_1 (kg)			253.500
Mass after washing M_2 (kg)			250.800
Mass of sample loss after wash M_2 (kg)			2.700
1ª Análise granulométrica			
Dimension (mm)	Mass (kg)	% Remain	% Cumulative of passing
63	0.000	0	100.00
31.5	0.000	0	100.00
16	0.000	0	100.00
8	0.000	0	100.00
4	0.2	0	99.92
2	0.6	0	99.68
1	0.8	0	99.37
0.5	7.3	3	96.49
0.25	82	32	64.14
0.125	152.2	60	4.10
0.063	7.3	3	1.22
P	0.3	-	-
% Finos	-	1.2	-
Total	250.700	100	-



Porosity

Table 26: Raw data of porosity test

Sample	Age (days)	Dry Mass (g)	Width (cm)	Length (cm)	Height (cm)	Saturated Mass (g)	Immersed Mass (g)	Porosity (%)
1A	42	385.2	3.9	15.9	3.8	466.2	228.4	34.062
1B	43	412.6	4	15.9	3.85	469.4	226.7	23.403
2A	41	406.2	3.9	15.8	3.8	478.7	239	30.246
2B	43	443.5	3.95	15.9	3.9	489.3	245	18.747
3A	44	427	3.95	15.8	3.9	497.9	252.1	28.845
3B	47	434.7	3.9	15.9	3.9	499.7	251.4	26.178

Capillary absorption rate

Table 27: Raw data of capillary absorption test

Sample	Age (days)	Dry sample mass (g)	Mass after (g)				Absorption rate (g/cm^2)			
			3hrs	6hrs	24 hrs	72hrs	3hrs	6hrs	24hrs	72hrs
1A	40	392.52	402.95	406	414.58	420.89	0.6519	0.8425	1.3788	1.7731
1B	41	423.23	430.43	432.58	439.1	443.84	0.4500	0.5844	0.9919	1.2881
2A	39	407.53	418.16	421.32	431.77	437.59	0.6644	0.8619	1.5150	1.8788
2B	41	447.76	452.96	454.43	459.08	462.55	0.3250	0.4169	0.7075	0.9244
3A	42	412.75	422	424.66	432.34	437.21	0.5781	0.7444	1.2244	1.5288
3B	45	440.54	450.15	452.93	462.31	468.43	0.6006	0.7744	1.3606	1.7431

Electrical Resistivity

Table 28: The raw data of electrical resistivity test

	Electrical Resistivity (kΩ cm)					
Age	1A	1B	2A	2B	3A	3B
4			2.023			
5	2.083					
6		3.403	2.413	4.61		
7	2.477				3.268	
8		3.675	2.858	4.908		
9	2.835				4.185	
10		3.728		4.998		7.012
11			3.565		4.638	
12	3.497					7.212
13		3.865		5.555		
14	4.047				5.835	7.038
15		4.538	4.895			
16	4.663					
17		4.577		6.16		7.45
18			5.552		7.63	
19	5.493					
20		4.9		6.443		

21					8.235	7.835
22						
23						
24						8.023
25			6.793			
26	6.602					
27		5.25		7.197		
28	7.03	5.347	7.56	7.173	10.69	8.072

Retraction result

Table 29: The raw data of retraction test

Age	Percentage of retraction		
Days	1A(1)	1A(2)	1A(3)
6	0.0000	0.0000	0.0000
16	-0.8334	-0.4971	-0.6404
19	-0.9212	-0.5578	-0.6993
26	-1.0089	-0.6565	-0.6146

Age	Percentage of retraction		
Days	1B(1)	1B(2)	1B(3)
8	0.0000	0.0000	0.0000
18	0.0400	-0.0078	-0.0313
21	0.0400	-0.0078	-0.0352
28	0.0400	-0.0078	-0.0430

Age	Percentage of retraction		
Days	2A(1)	2A(2)	2A(3)
5	0	0	0
15	-0.6752	-0.5586	-0.2659
18	-0.7012	-0.5849	-0.3260
25	-0.7730	-0.6276	-0.3817

Age	Percentage of retraction		
Days	2B(1)	2B(2)	2B(3)
7	0	0	0
17	-0.3239	0.13782	0.0967
20	-0.3530	0.1263	0.0967
27	-0.3639	0.1378	0.1168

Age	Percentage of retraction		
Days	3A(1)	3A(2)	3A(3)
8	0	0	0
19	-0.0624	-0.4126	-0.4976
22	-0.0990	-0.4638	-0.5554
29	-0.2274	-0.5246	-0.6003

Age	Percentage of retraction		
Days	3B(1)	3B(2)	3B(3)
10	0	0	0
20	0.0177	0.0377	0.0421
23	0.01198	0.0440	0.0360
30	0.01497	0.0471	0.0361

Flexural Strength Result

Table 30: The raw data of 7-Day Felxural strength of trial grout

Grout	Day	Sample	Mass (g)	Flexural Load (N)	Flexural Strength (MPa)	Average flexural strength (MPa)
HH1A	8	A	413.8	73.24	0.17	0.26
		B	417.7	93.84	0.22	
		C	416.2	164.79	0.39	
FS1B	8	A	443.7	--		0.87
		B	452.4	350.19	0.82	
		C	435.8	389.10	0.91	
HH1B	8	A	453.4	769.04	1.80	1.69
		B	449.7	679.78	1.59	
		C	444.1	711.82	1.67	
TS1B	7	A	421.6	272.37	0.64	0.67
		B	428.4	302.12	0.71	
		C	422.9	281.52	0.66	
HH3B	7	A	447.2	617.98	1.45	1.63
		B	453.6	672.91	1.58	
		C	452.9	789.64	1.85	
HH3A	7	A	417.7	139.62	0.33	0.28
		B	408.7	109.86	0.26	
		C	418.0	103.00	0.24	
FS2A	7	A	428.5	141.91	0.33	0.28
		B	430.4	89.26	0.21	
		C	427.0	125.89	0.30	
FS3B	7	A	451.5	551.61	1.29	1.36
		B	449.5	595.09	1.39	
		C	449.8	588.23	1.38	

FS2B	7	A	445.7	592.80	1.39	1.31
		B	439.5	521.85	1.22	
		C	449.2	558.47	1.31	
HH2A	6	A	422.1	203.70	0.48	0.45
		B	419.8	173.95	0.41	
		C	419.1	203.70	0.48	
HH2B	6	A	429.7	634.00	1.49	1.44
		B	441.6	656.89	1.54	
		C	441.3	551.61	1.29	

Table 31: The raw data of Flexural strength test

Grout	Day	Sample	Mass (g)	Flexural load (N)	Length (cm)	width (cm)	height (cm)	Flexural strength (Mpa)	Average Flexural Strength (Mpa)
1A	14	A	476.8	968.17	15.90	3.90	4.00	2.27	2.20
		B	474.8	890.35	15.80	3.90	4.00	2.09	
		C	468.9	961.30	15.80	3.90	4.00	2.25	
1A	28	A	465.2	1043.70	15.80	4.00	3.80	2.45	2.94
		B	478.7	1171.88	15.70	3.90	4.00	2.75	
		C	466.7	1551.82	15.80	3.90	3.90	3.64	
1B	14	A	478.7	1853.94	15.90	3.90	4.00	4.35	4.56
		B	470.9	1982.12	15.80	3.90	3.90	4.65	
		C	471.4	2002.72	15.80	4.00	4.00	4.69	
1B	28	A	474.4	2114.87	16.00	3.90	4.00	4.96	5.03
		B	481.0	2204.13	16.00	3.90	4.00	5.17	
		C	481.5	2124.02	16.00	3.90	4.00	4.98	
2A	14	A	471.9	940.70	15.80	3.90	4.00	2.20	2.24
		B	482.2	924.68	15.80	3.90	4.00	2.17	
		C	478.5	1007.08	15.80	3.90	4.00	2.36	

2A	28	A	477.3	1016.24	15.90	3.90	4.00	2.38	2.56
		B	467.1	1222.23	15.90	3.90	4.00	2.86	
		C	466.4	1043.70	15.90	3.90	4.00	2.45	
2B	14	A	500.7	1918.03	15.80	4.00	3.90	4.50	4.43
		B	491.2	1821.90	15.90	3.90	3.90	4.27	
		C	504.3	1924.90	15.80	4.00	4.00	4.51	
2B	28	A	503.4	2796.94	16.00	4.00	3.90	6.56	5.85
		B	495.1	2416.99	16.00	4.00	3.90	5.66	
		C	501.7	2279.66	16.00	4.00	4.00	5.34	
3A	14	A	482.8	924.68	15.80	3.90	4.00	2.17	2.02
		B	486.0	675.20	15.80	4.00	3.90	1.58	
		C	482.0	986.48	15.70	3.80	3.90	2.31	
3A	28	A	490.7	1087.19	15.80	3.90	4.00	2.55	2.66
		B	485.8	1082.61	15.90	3.90	4.00	2.54	
		C	481.3	1238.25	15.80	3.90	4.00	2.90	
3B	14	A	488.9	1602.17	15.80	3.90	4.00	3.76	3.57
		B	492.3	1295.47	15.90	4.00	4.00	3.04	
		C	488.8	1668.55	15.90	3.90	4.00	3.91	
3B	28	A	477.8	1531.22	16.00	3.90	4.00	3.59	3.77
		B	470.6	1599.88	15.90	3.80	4.00	3.75	
		C	478.4	1691.44	16.00	3.90	4.00	3.96	

Compressive Strength Result

Table 32: The raw data of 7-day compressive strength of trial grout

Grout	Day		Compressive Load (kN)	Compressive Strength (MPa)	Average Compressive Strength (MPa)
HH1A	8	A0	1.38	0.86	0.80
		A1	1.34	0.84	
		B0	1.13	0.71	
		B1	1.40	0.88	

		C0	1.17	0.73	
		C1	1.25	0.78	
FS1B	8	A0	6.44	4.03	3.92
		A1	5.58	3.49	
		B0	5.62	3.51	
		B1	7.53	4.71	
		C0	6.25	3.91	
		C1	6.21	3.88	
HH1B	8	A0	8.11	5.07	5.86
		A1	9.08	5.68	
		B0	9.78	6.11	
		B1	10.35	6.47	
		C0	9.43	5.89	
		C1	9.49	5.93	
TS1B	7	A0	2.57	1.61	1.48
		A1	2.24	1.40	
		B0	1.61	1.01	
		B1	2.73	1.71	
		C0	2.59	1.62	
		C1	2.45	1.53	
HH3B	7	A0	8.41	5.26	6.36
		A1	10.60	6.63	
		B0	9.97	6.23	
		B1	10.37	6.48	
		C0	10.28	6.43	
		C1	11.46	7.16	
HH3A	7	A0	1.62	1.01	1.03
		A1	1.63	1.02	
		B0	1.67	1.04	
		B1	1.63	1.02	
		C0	1.59	0.99	
		C1	1.77	1.11	
FS2A	7	A0	1.07	0.67	0.68
		A1	1.10	0.69	
		B0	1.05	0.66	
		B1	1.11	0.69	
		C0	1.05	0.66	
		C1	1.15	0.72	
FS3B	7	A0	6.89	4.31	4.37
		A1	7.11	4.44	
		B0	7.01	4.38	
		B1	6.95	4.34	
		C0	6.85	4.28	
		C1	7.11	4.44	
FS2B	7	A0	6.17	3.86	4.41
		A1	7.15	4.47	
		B0	7.72	4.83	
		B1	6.67	4.17	
		C0	7.59	4.74	
		C1	7.02	4.39	
HH2A	6	A0	0.96	0.60	0.57
		A1	0.85	0.53	
		B0	0.81	0.51	
		B1	0.82	0.51	
		C0	1.00	0.63	

		C1	0.99	0.62	
HH2B	6	A0	6.62	4.14	4.18
		A1	6.42	4.01	
		B0	6.98	4.36	
		B1	6.52	4.08	
		C0	6.57	4.11	
		C1	7.06	4.41	

Table 33: The raw data of compressive strength test result

Grout	Day	Sample	Mass (g)	Flexural load (N)	Length (cm)	width (cm)	height (cm)		Comp. load (kN)	Comp. Strength (Mpa)	Average Comp. strength (Mpa)
1A	14	A	476.8	968.17	15.90	3.90	4.00	A0	5.34	3.34	3.26
								A1	5.35	3.34	
		B	474.8	890.35	15.80	3.90	4.00	B0	5.30	3.31	
								B1	4.93	3.08	
		C	468.9	961.30	15.80	3.90	4.00	C0	5.09	3.18	
								C1	5.25	3.28	
1A	28	A	465.2	1043.70	15.80	4.00	3.80	A0	9.20	5.75	5.85
								A1	9.17	5.73	
		B	478.7	1171.88	15.70	3.90	4.00	B0	9.86	6.16	
								B1	8.98	5.61	
		C	466.7	1551.82	15.80	3.90	3.90	C0	9.14	5.71	
								C1	9.82	6.14	
1B	14	A	478.7	1853.94	15.90	3.90	4.00	A0	19.67	12.29	13.04
								A1	19.83	12.39	
		B	470.9	1982.12	15.80	3.90	3.90	B0	21.35	13.34	
								B1	20.50	12.81	
		C	471.4	2002.72	15.80	4.00	4.00	C0	21.40	13.38	
								C1	22.46	14.04	
1B	28	A	474.4	2114.87	16.00	3.90	4.00	A0	26.43	16.52	15.66
								A1	24.93	15.58	
		B	481.0	2204.13	16.00	3.90	4.00	B0	26.20	16.38	
								B1	22.29	13.93	
		C	481.5	2124.02	16.00	3.90	4.00	C0	25.55	15.97	
								C1	24.92	15.58	
2A	14	A	471.9	940.70	15.80	3.90	4.00	A0	6.29	3.93	3.94
								A1	6.23	3.89	
		B	482.2	924.68	15.80	3.90	4.00	B0	6.49	4.06	
								B1	6.48	4.05	
		C	478.5	1007.08	15.80	3.90	4.00	C0	6.15	3.84	
								C1	6.20	3.88	
2A	28	A	477.3	1016.24	15.90	3.90	4.00	A0	8.78	5.49	5.64
								A1	8.65	5.41	
		B	467.1	1222.23	15.90	3.90	4.00	B0	9.01	5.63	
								B1	9.25	5.78	
		C	466.4	1043.70	15.90	3.90	4.00	C0	8.99	5.62	
								C1	9.43	5.89	
2B	14	A	500.7	1918.03	15.80	4.00	3.90	A0	28.41	17.76	17.86
								A1	29.67	18.54	
		B	491.2	1821.90	15.90	3.90	3.90	B0	27.52	17.20	
								B1	28.03	17.52	
		C	504.3	1924.90	15.80	4.00	4.00	C0	29.02	18.14	

								C1	28.79	17.99	
2B	28	A	503.4	2796.94	16.00	4.00	3.90	A0	30.04	18.78	19.41
								A1	31.01	19.38	
		B	495.1	2416.99	16.00	4.00	3.90	B0	30.03	18.77	
								B1	32.07	20.04	
		C	501.7	2279.66	16.00	4.00	4.00	C0	31.91	19.94	
								C1	31.25	19.53	
3A	14	A	482.8	924.68	15.80	3.90	4.00	A0	4.71	2.94	3.16
								A1	4.74	2.96	
		B	486.0	675.20	15.80	4.00	3.90	B0	4.96	3.10	
								B1	4.91	3.07	
		C	482.0	986.48	15.70	3.80	3.90	C0	5.51	3.44	
								C1	5.53	3.46	
3A	28	A	490.7	1087.19	15.80	3.90	4.00	A0	8.49	5.31	5.27
								A1	8.39	5.24	
		B	485.8	1082.61	15.90	3.90	4.00	B0	8.04	5.03	
								B1	8.50	5.31	
		C	481.3	1238.25	15.80	3.90	4.00	C0	8.32	5.20	
								C1	8.87	5.54	
3B	14	A	488.9	1602.17	15.80	3.90	4.00	A0	16.17	10.11	10.57
								A1	15.61	9.76	
		B	492.3	1295.47	15.90	4.00	4.00	B0	16.84	10.53	
								B1	17.96	11.23	
		C	488.8	1668.55	15.90	3.90	4.00	C0	16.94	10.59	
								C1	17.92	11.20	
3B	28	A	477.8	1531.22	16.00	3.90	4.00	A0	20.19	12.62	12.45
								A1	20.84	13.03	
		B	470.6	1599.88	15.90	3.80	4.00	B0	20.42	12.76	
								B1	19.36	12.10	
		C	478.4	1691.44	16.00	3.90	4.00	C0	19.39	12.12	
								C1	19.30	12.06	

Elastic Modulus Result

Table 34: Raw data of Elastic modulus

Grout	Sample	Age (days)	Elastic Modulus (GPa)
1A	1	44	4.56
	2	44	7.01
2A	1	46	6.52
	2	46	6.42
3A	1	49	7.47
	2	49	6.55
1B	1	49	12.83
	2	49	7.95
2B	1	50	21.96
	2	44	14.36
3B	1	52	10.34
	2	52	10.59

Rheological parameters

Table 35: Raw data of rhelogical parameters (Dwell test)

Rheological parameters	Time (min)	Modified Bingham model			Bingham model		
		1A	2A	3A	1B	2B	3B
Flow resistance g or g' (N mm)	15	1.270	0.480	0.750	3.229	1.678	7.944
	30	1.450	0.260	0.710	3.808	2.537	8.862
	45	2.560	0.970	2.010	4.618	3.925	10.065
	60	4.000	1.590	2.150	5.090	5.278	12.260
Viscosity coefficient h or h' (N mm min)	15	0.115	0.120	0.135	0.062	0.110	0.085
	30	0.114	0.114	0.133	0.063	0.113	0.089
	45	0.115	0.120	0.135	0.063	0.113	0.095
	60	0.113	0.126	0.148	0.066	0.113	0.094