

**STRENGTH OF GEOMATERIALS WITH
HIGH WATER CONTENT**

by

Ivan Lam (DOW)

**FOURTH-YEAR UNDERGRADUATE PROJECT
IN GROUP D, 2012/2013**



University of Cambridge

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

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Abstract

Bentonite grout, a type of Bingham fluid, is characterised by its shear yield stress and plastic viscosity. On top of possessing some useful mechanical properties, this type of grout can be manipulated to provide a large range of strength, making it suitable for a lot of applications in construction. However, the rheology of bentonite grout is not properly understood because laboratory equipment, such as rheometer, which is not always available on site, has to be used to obtain its material properties.

Several field tests exist for grout, such as the Marsh funnel test and slump flow test. The Marsh funnel test is used to measure the apparent viscosity of a material. However, the apparent viscosity cannot be used directly as the plastic viscosity. Also, there are no established link between the slump results of fluid grout and the material properties.

This project aims to establish a link between the field test data and the material characterisation test data. The availability of a quantitative correlation between the two allows construction work to speed up: material properties can be obtained by performing the field test. The current study tested a number of grout mixes, each with a different water-cement ratio and bentonite percentage. As the material properties are largely influenced by the water-cement ratio and bentonite percentage, changing these two parameters would produce a large range of yield stress and viscosity.

The second part of this project focused on numerical modelling of grout behaviours using material point methods (MPM). MPM is based on a finite elements method and is suitable for modelling large-scale deformations. Using MPM can enhance the quality of site-work and significantly reduce the need for expensive and time-consuming experiments. By simulating the slump test, the material properties may also be obtained via back analysis.

The results obtained provide a basic understanding of the effect of changing the water-cement ratio, bentonite percentage and time on the yield stress and plastic viscosity. From the Marsh funnel test results, the apparent viscosity and plastic viscosity seem to have a linear relationship, with the slope determined by the yield stress. The slump tests

results show that (1) the yield stress is linked to the final spread diameter and (2) the viscosity is linked to the grout flow time. Overall, because the feasibility of Marsh funnel test is dependent on the yield stress being known, the slump test is found to be more useful than the Marsh funnel test as a field test used on. The downside of it is that it is only applicable to a small range of mixes.

The MPM results show agreement with the final runoff of the slump test for most cases after applying a factor to convert the plain-strain results into axisymmetric result. However, further research is required to transform the code into 3D and to improve the accuracy by using real material properties. The results provide a basis for future work to enable the use of MPM to analyse the strength and viscosity of grout.

This project is successful in meeting the set objectives. The obtained results provide a groundwork for future research on testing and modelling of the strength of a broader range of geomaterials with high water content.

Table of Contents

1	INTRODUCTION	1
2	LITERATURE REVIEW	3
2.1	INTRODUCTION	3
2.2	GROUT RHEOLOGY	3
2.3	ADDITION OF BENTONITE	5
2.4	TESTING OF CEMENT-BASED GROUT IN LABORATORY	6
2.5	GROUT FIELD TESTING METHODS	7
2.5.1	<i>Marsh funnel cone test / Flow cone method</i>	7
2.5.2	<i>Slump Cone test</i>	9
2.5.3	<i>Criticism</i>	11
2.6	NUMERICAL MODELLING OF FLOW (MATERIAL POINT METHODS)	12
2.7	AN OVERVIEW	13
3	METHODOLOGY	15
3.1	DESIGN OF EXPERIMENT	15
3.2	BINGHAM FLUID ASSUMPTION	17
3.3	GROUT MATERIALS	17
3.4	APPARATUS AND EXPERIMENTAL TECHNIQUES	17
3.4.1	<i>Grout Mixing</i>	17
3.4.2	<i>Slump flow Test</i>	19
3.4.3	<i>Marsh Funnel Test</i>	20
3.4.4	<i>Rheometer Test</i>	21
4	RESULTS AND DISCUSSION	22
4.1	RHEOMETER RESULTS	22
4.1.1	<i>Time-dependency</i>	24
4.1.2	<i>Effect of w/c ratio and bentonite content</i>	28
4.1.3	<i>Bentonite Cement ratio</i>	30
4.2	SLUMP TEST RESULTS	31
4.2.1	<i>Effect of changing w/c ratio and bentonite %</i>	31
4.2.2	<i>Effect of Fast and Slow Pull-Up methods</i>	33
4.2.3	<i>Comparison with real material properties</i>	36
4.3	MARSH FUNNEL TEST	38
4.3.1	<i>General results</i>	38
4.3.2	<i>Comparison between apparent and plastic viscosity</i>	39
4.3.3	<i>Comparison of time effect on Marsh funnel and rheometer results</i>	41
4.3.4	<i>Applicability of Marsh funnel test</i>	42
4.4	MPM MODEL	43
5	CONCLUSION	46
5.1	ESTABLISHING LINK BETWEEN FIELD TEST AND MATERIAL CHARACTERISATION TEST	46
5.2	CHANGE OF BINGHAM YIELD STRESS AND VISCOSITY FOR DIFFERENT GROUT MIXES	46
5.3	USE OF MPM TO MODEL SLUMP TESTS	47
5.4	FUTURE WORK	47
5.4.1	<i>Range of experiment</i>	47
5.4.2	<i>MPM</i>	48
5.4.3	<i>Extending into a more complete cycle</i>	48
6	REFERENCE	49
7	APPENDIX	50
7.1	RISK ASSESSMENT EVALUATION	50

List of Tables

Table 1: Different tests carried out with varying w/c ratios and bentonite percentages	22
Table 2: Marsh funnel results	42
Table 3: Material parameters used for MPM model.....	43
Table 4: Estimated material parameters.....	Error! Bookmark not defined.
Table 5: Hazards associated with this project.....	50

List of Figures

Figure 1.1: Cement-based bentonite grout in mixing process (left) and modelling of large-scale landslides using MPM code (right).....	2
Figure 2.1: Newtonian and Binghamian behaviour in terms of shear stress and shear rate (Birch, 1997).....	4
Figure 2.2: Variation of heat evolved due to cement hydration at different time stages for neat grout mix (Gause & Bruce, 1997, p. 214)	5
Figure 2.3: Results from Bohlin and Brookfield (BF) rheometer for bentonite grout of different composition in terms of shear stress and shear rate (Eisa, 2008, p. 77)	6
Figure 2.4: Results from Bohlin and Brookfield (BF) rheometer for bentonite grout of different compositions in terms of viscosity and shear rate (Eisa, 2008, p. 78).....	7
Figure 2.5: ASTM C939 flow cone (left) and Marsh funnel (right) (Warner, 2004, p. 145)....	8
Figure 2.6: Marsh funnel viscosity for cement-based bentonite grout (Birch, 1997, p. 65) ...	9
Figure 2.7: Correlation between Marsh funnel viscosity and plastic viscosity for various grout mixes (Birch, 1997, p. 67).....	9
Figure 2.8: Measuring of slump height in a slump test (Warner, 2004, p. 148)	10
Figure 2.9 ASTM C1611 slump flow experiment (graceconstruction.com).....	11
Figure 2.10: Voids and tears produced by tempering of grout in the lower portion (Warner, 2004, p. 149).....	12
Figure 2.11: Flow evolution of granular column collapse simulations with different aspect ratios using MPM (Bandara, 2013, p. 104)	13
Figure 2.12: Scaled runout as a function of aspect ratio (Lajeunesse, Monnier, & Homsy, 2005)	13
Figure 3.1: Interaction diagram between field tests, material characterisation tests and MPM.....	16
Figure 3.2: Colloidal mill mixing principle (Eisa, 2008, p. 73).....	18
Figure 3.3: Set-up for slump test experiments for recording on high-speed camera.....	19
Figure 3.4: Special transparent acrylic slump cone made to allow high-speed camera to record grout flow and a standard metal slump cone	19
Figure 3.5: Testing of fresh concrete using slump test (civilqc.blogspot.com)	19
Figure 3.6: High-speed camera (left) and set up (right) used for recording the slump tests	20
Figure 3.7: Set-up for Marsh funnel flow experiments	21
Figure 3.8: Bohlin rheometer used for testing the shear stress and shear rate measurement (Eisa, 2008, p. 76).....	21
Figure 4.1: Shear stress and shear rate relationship for test 1.1, 2.1 and 3.1 at 5 minutes after mixing	23
Figure 4.2: Shear stress and shear rate relationship for test 2.1, 2.2 and 2.3 at 5 minutes after mixing	23

Figure 4.3: Time variation of Shear stress and shear rate relationship for test 1.1, 1.3, 3.1 and 3.3	24
Figure 4.4: Change of Bingham yield stress (left) and viscosity (right) with time	26
Figure 4.5: Variance of each curve-fitting equation for Bingham yield stress for each tests	27
Figure 4.6: Variance of each curve-fitting equation for viscosity for each tests	27
Figure 4.7: Change of Bingham yield stress with respect to change in w/c ratio for bentonite percentage of 2% (top), 4% (left) and 8% (right)	28
Figure 4.8: Change of Bingham yield stress with respect to change in bentonite percentage for w/c ratio of 0.5 (top), 1.0 (left) and 1.5 (right)	29
Figure 4.9: Fig. x Change of viscosity with respect to change in w/c ratio (left) and change in bentonite percentage (right)	30
Figure 4.10: Yield stress (left) and viscosity (right) against bentonite cement ratio	31
Figure 4.11: Final spread diameter for slump test for different w/c ratio and bentonite percentage	32
Figure 4.12: Final slump shape for mix with w/c 0.5 and bentonite percentage of 8% at 120 min after mixing	32
Figure 4.13: Final slump shape for mix with w/c 1.5 and bentonite percentage of 8% at 120 min after mixing	33
Figure 4.14: Final spread diameter for slump test for different w/c ratio and bentonite percentage	33
Figure 4.15: The effect on final slump shape due to fast and slow pull-up method, tested at 30 minutes after mixing	34
Figure 4.16: The effect on final slump shape due to fast and slow pull-up method, tested at 120 minutes after mixing	35
Figure 4.17: The flow of grout in slump test with fast pull-up method (top) and slow pull-up method (bottom)	36
Figure 4.18: Normalised spread diameter and height for slump test results using slow pull-up methods	36
Figure 4.19: Comparison of slump diameter with yield stress	37
Figure 4.20 Determination of the slump flow time	38
Figure 4.21: Comparison of flow time with viscosity	38
Figure 4.22: Change of average viscosity with bentonite cement ratio	39
Figure 4.23: Comparison of Marsh funnel viscosity and plastic viscosity	40
Figure 4.24: Comparison of apparent to plastic viscosity gradient and yield stress	40
Figure 4.25: Comparison of time dependency between Marsh funnel test and rheometer test results	41
Figure 4.26: Time range of Marsh funnel test (left) and contour of average apparent viscosity and suitable test range of Marsh funnel test (right)	43
Figure 4.27: Comparison of MPM simulation with slump test	44
Figure 4.28: Runoff from MPM simulations and actual results	45
Figure 4.29: Normalised spread diameter of MPM simulations	45

1 Introduction

Geomaterials with high water content, such as cementitious grout, are used in most constructions everyday. In particular, bentonite slurry is used frequently in a lot of geotechnical applications, such as in excavations for stabilising the soil and ground improvement. The high degree of workability, mobility and penetrability made possible by its wide range of strength and viscosity makes bentonite grout suitable for these applications.

However, the dynamic behaviour of these materials is not properly understood. In geometrically complex situations, a good understanding of the rheology would be useful to ensure that the materials can reach the desired position. In order to simulate the dynamic behaviour, numerical analysis would have to be employed which would require the input of material properties. The materials properties are mostly affected by its composition, i.e. the water-cement ratio (w/c ratio) and the percentage bentonite present (Gause & Bruce, 1997). Not only do they affect the rheology of the grout, they provide different mechanical properties such as permeability and wash-out resistance that are useful in certain grouting situations (Eisa, 2008).

Full testing for grout rheology requires laboratory equipment that is difficult to obtain on site. Certain field tests exist currently for grout; such as the Marsh funnel test (or flow cone test) and the slump test (Warner, 2004). The results of these tests however cannot be used alone. Therefore, there is a need to relate the field tests results to the real material properties and create a guideline in choosing the types of tests for this particular type of grout.

In order to provide accurate flow predictions, scaled experiments had been done over the past for different types of grout in different applications. However these experimental investigations are difficult to perform and require a lot of resources (Bandara, 2013). Numerical analysis is often used instead to predict grout flow, and they require input of the geometry of the problem and material properties only. Construction work would take much less time if the material properties collected from field tests can be applied directly in the modelling code, without going through laboratory tests or physical modelling. The Material Point Method (MPM) was developed primarily for granular soils in large-scale

deformations. It could be adapted to include Bingham fluids such as cementitious grout for predicting grout flows. However it is not been done yet and testing is required to verify the accuracy and applicability of the model.



Figure 1.1: Cement-based bentonite grout in mixing process (left) and modelling of large-scale landslides using MPM code (right)

2 Literature Review

2.1 Introduction

This section describes the grout rheology, testing with rheometer and other field methods and modelling using MPM. In particular, the review focused on cement-based bentonite type grout, which is idealised as a Bingham fluid; characterised by its yield strength and viscosity. The review highlighted the current field methods for testing grout and their criticisms. The findings set an important foundation for the current project work, as it shed light on the importance of linking the field method results to real material properties.

2.2 Grout Rheology

Grout is used in many geotechnical applications. Depending on the specific use, different compositions are used to achieve specific mechanical properties to suit different applications. For most applications, it is important to understand the rheology of the material. Conventionally, the consistency of a mix is an important parameter used for selecting grout for a given application, but the term ‘consistency’ is loosely defined and can be quite confusing (Warner, 2004, p. 51). For grout, it is more suitable to describe it in terms of cohesion, penetrability and mobility, or in other words shear stress and viscosity.

Grout is often described instead as paste-like or slurry. Most of them are subject to thixotropy, meaning that whilst it will exhibit viscous behaviour like a fluid, it requires the application of sufficient energy to initiate flow (Warner, 2004, p. 52). This type of flow is described as Binghamian, which is non-Newtonian. Figure 2.1 shows a comparison between Bingham flow and Newtonian flow. For Bingham fluids, they require a certain shear stress, sometimes referred to as the Bingham yield stress or cohesion, to become mobile. After that, the mobility is determined by the material’s viscosity, which is assumed to be constant in this simple model. For a more complex model, the viscosity may depend on the shear rate. Some cementitious grouts exhibit shear thinning, meaning that the resistance to flow will decrease when the shear rate increases. The rheology of a cementitious grout is heavily influenced by the water-cement ratio, composition of cement and the cement specific surface area (Gause & Bruce, 1997, p. 219).

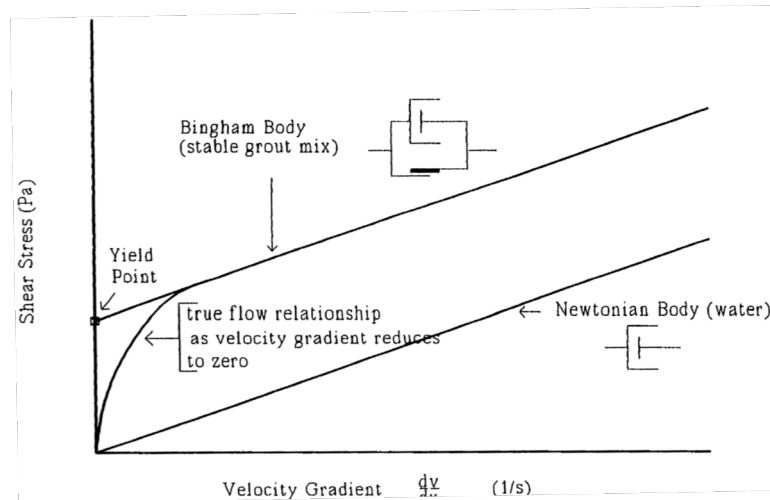


Figure 2.1: Newtonian and Binghamian behaviour in terms of shear stress and shear rate (Birch, 1997)

Time is also an important factor that can affect the rheology of grout. From freshly mixed to pouring on site, there may be certain time delay. These could have serious consequences if ignored since the material properties may be different from the initial strength and viscosity after mixing.

Grout or concrete hardens by a process called hydration. During this process, the tricalcium silicate (C_3H) which is the main ingredient of Portland cement will reach with water to form a rigid matrix of calcium silicate hydrate (CSH) gel in an exothermic reaction (Gause & Bruce, 1997). The gel would swell up to 2.4 times its original volume (Warner, 2004, p. 65). Figure 2.2 shows to normalised heat generation for different time stages during the process, which could go on for days or even weeks. Stage 1 refers to the period immediately after mixing; stage 2 is the dormant period, in which the neat grout will gradually cease to be workable; stage 3 usually occurs while the grout sets and gains most of its strength. The transition from stage 1 to 3 is an important period, where the grout will transform from Bingham fluids into a solid. Depending on the composition of the mix, the transition time may be different.

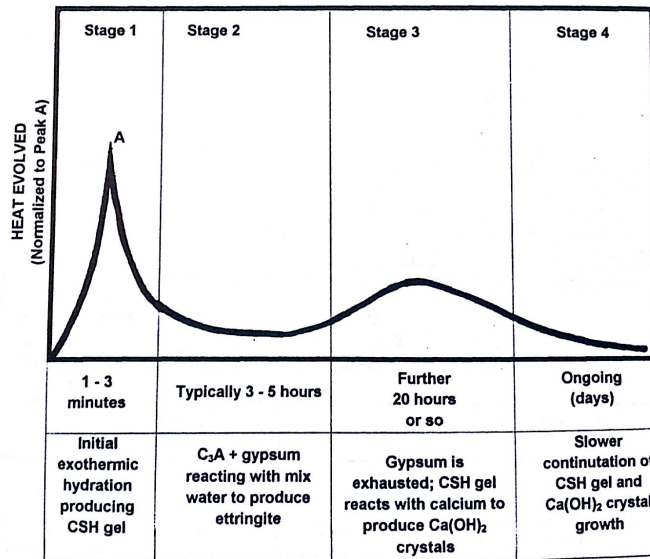


Figure 2.2: Variation of heat evolved due to cement hydration at different time stages for neat grout mix (Gause & Bruce, 1997, p. 214)

Typically, most cement-based grouts are classified as particulate grout. Particulate grouts usually exhibit Bingham fluid behaviours in stable conditions (Bruce, Littlejohn, & Naudts, 1997, p. 307). If the suspension is unstable, internal friction will occur in the mix, then the injection pressure will significantly affect the shear stress and shear rate (Gause & Bruce, 1997). As the amount of bleeding is affected by its composition, it is an important consideration factor when designing a particular grout for construction work.

2.3 Addition of Bentonite

Cement-based grouts are the most commonly used material for waterproofing and ground strengthening due to their basic characteristics and economy. Clay/Bentonite-cement grout is one example of that. The bentonite is added mainly to improve the hydration time and penetrability and reduce the permeability and the amount of bleeding and to provide a wider range of viscosities, comparing to the limited use of 'neat' mix (pure water and cement mixes). 'Neat' grout tends to be quite unstable in suspension except at low water-cement ratios (0.4), meaning that the particles no longer remain in suspension within the slurry. The addition of bentonite can significantly improve this situation and allow the water-cement ratio to go as far as 5. Portland cement is most commonly used, with CEM-1 type being the most popular. As for bentonite, the sodium

bentonite unique to Wyoming gives the best performances (Bruce, Littlejohn, & Naudts, Grouting materials for ground treatment: a practitioner's guide, p. 310). A typical composition of grout may contain bentonite up to 10% by weight. The method of mixing is also importance as it does affect the rheology of the mixes. For cementitious grouts, high shear mixing is often required to thoroughly disperse the grains within the slurry (Warner, 2004, p. 59). Colloidal shear mixers are widely used to produce the high shear rate required.

2.4 Testing of Cement-based Grout in laboratory

To fully test the grout rheology, laboratory equipment had to be used. There are several commonly used viscometers for research purposes, such as the Bohlin rheometer, Fann viscometer and Brookfield viscometer. Previous research, using CEM 1 cement, has showed that cement-bentonite mixes in fact behave more like a pseudo-plastic non-Newtonian fluid in low shear rates (Eisa, 2008). Figure 2.3 shows that the mixes are mostly shear thinning, which means that the viscosity decreases with the increase in shear rate in a shear-rate controlled rheometer test. Results also proved that the strength is characterised by the Bingham yield stress but may be difficult to determine in some cases, due to lack of accuracy at low shear rates. There is an observable trend that decreasing the water-cement ratio in the mix will increase the yield stress. These mixes tend to be more Bingham-fluid-like in the sense that the yield stress is more apparent.

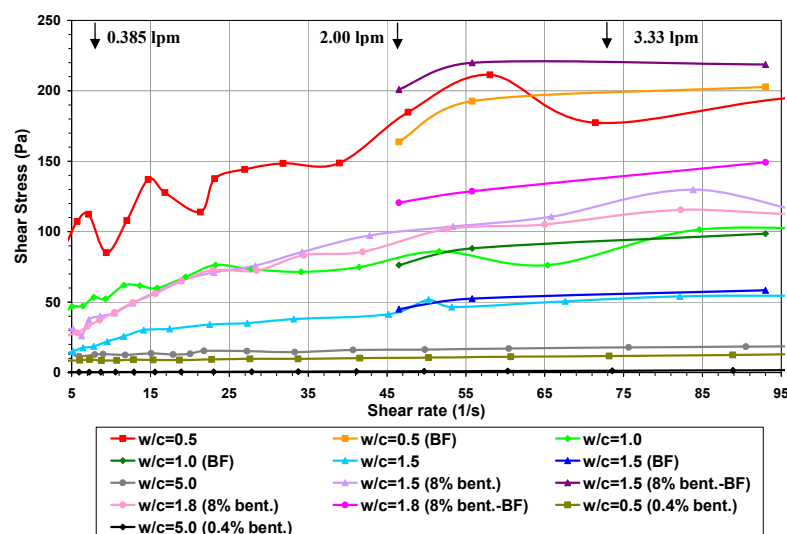


Figure 2.3: Results from Bohlin and Brookfield (BF) rheometer for bentonite grout of different composition in terms of shear stress and shear rate (Eisa, 2008, p. 77)

Eisa (2008) also plotted the instantaneous viscosity measured at a shear rate range of 5 to 95 per second in figure 2.4. For all mixes, the viscosity initially is high but converges to a smaller value as the shear rate increases. However there is still a tendency for the viscosity to decrease as the shear rate increases. For a given shear rate, the viscosity is found to increase with the decrease in w/c ratio or the increase in the percentage of bentonite (Eisa, 2008, p. 77).

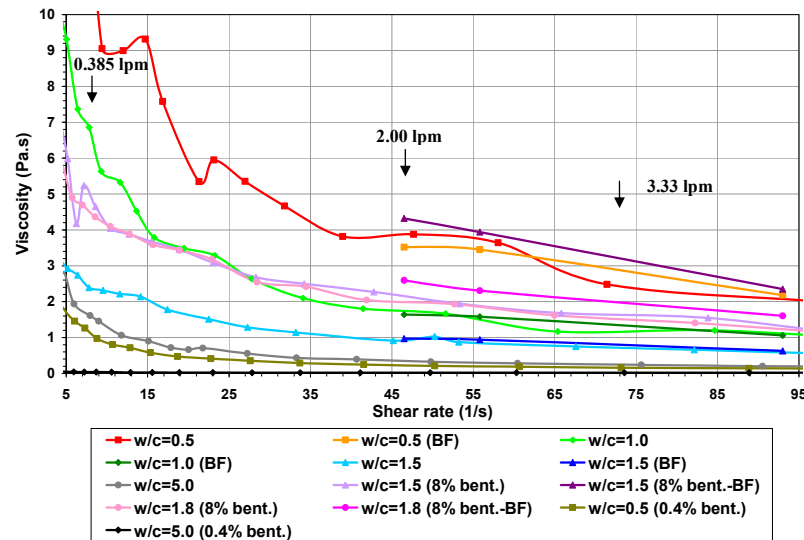


Figure 2.4: Results from Bohlin and Brookfield (BF) rheometer for bentonite grout of different compositions in terms of viscosity and shear rate (Eisa, 2008, p. 78)

2.5 Grout Field Testing Methods

Field tests are done to measure and ensure that the properties and quality of a grout are adequate for a certain application. In the absence of sophisticated laboratory equipment, some simple tests had been developed and adapted over the past to give some indication of the strength and viscosity of the grout. Some of these tests were not originally designed specifically for grout, and thus they may only be suitable for a certain range of grout. Even with the available test, very few can be performed on very thin or very thick grouts (Warner, 2004) and therefore there is a need to select suitable field test for a wide range of grout.

2.5.1 Marsh funnel cone test / Flow cone method

The flow cone was originally developed in the 1940s by the U.S. Army Corps of Engineers, and adopted later on by the American Standard Testing Materials (ASTM)

under the designation C939, “Standard Test Methods for Flow of Grout for Preplaced-Aggregate Concrete (Flow Cone Method),” in 1988 (Warner, 2004, p. 144). To use it, the flow cone is first set in position, making sure that it is vertical. It is rinsed with water one minute before filling the grout up to the proper level. A finger is held over the orifice to stop the grout from flowing out. A stopwatch is then used to record the time required from the release of the finger to the point where a first break in the continuous flow of grout is noted. The time is then converted to viscosity measurement using a simple formula (ASTM International).

The Marsh funnel operates under the same principles. It is widely used, especially in the oil industry, for providing repeatable tests for evaluating the flow properties of drilling mud. Instead of a cast aluminium cone specified by ASTM, the Marsh funnel cone is made of a single continuous piece of moulded plastic. An important difference is that the time records for only 946 ml of the material to drain as oppose to the time for it to drain completely. The typical time is between 26 to 60 seconds, with 26 seconds being the lower bound since it is the efflux time for water. Grouts that have flow time greater than 75 seconds are not recommended for this test (Warner, 2004, p. 145). The Marsh funnel is known to produce variable results, especially for mixes that have efflux time of more than 60 seconds (Bruce, 2013).

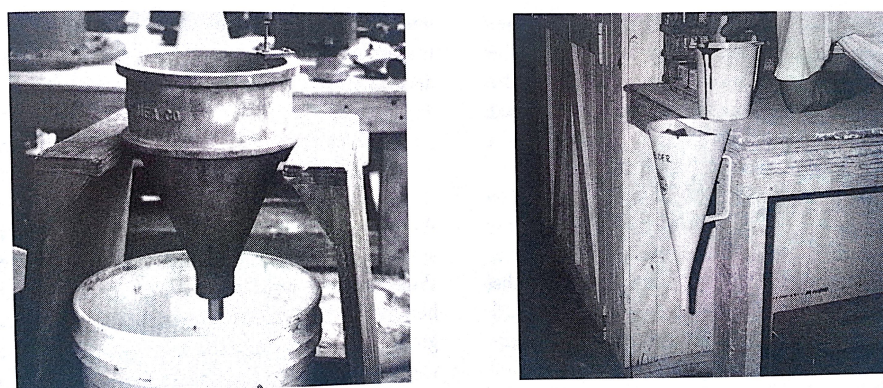


Figure 2.5: ASTM C939 flow cone (left) and Marsh funnel (right) (Warner, 2004, p. 145)

Figure 2.6 shows previous research done on cement-based bentonite grout. The Marsh funnel viscosity is also compared with the plastic viscosity obtained from a rotational viscometer. Deere (1982) suggested that the apparent viscosity measured from Marsh funnel is a function of the plastic viscosity (cited in (Birch, 1997, p. 49)). Figure 2.7

shows the viscosity measured using a Brazilian funnel and transformed into Marsh funnel viscosity through correlation tables. Deere (1982) observed a reasonable good fit between the two for grout with Marsh funnel viscosity up to 50 second.

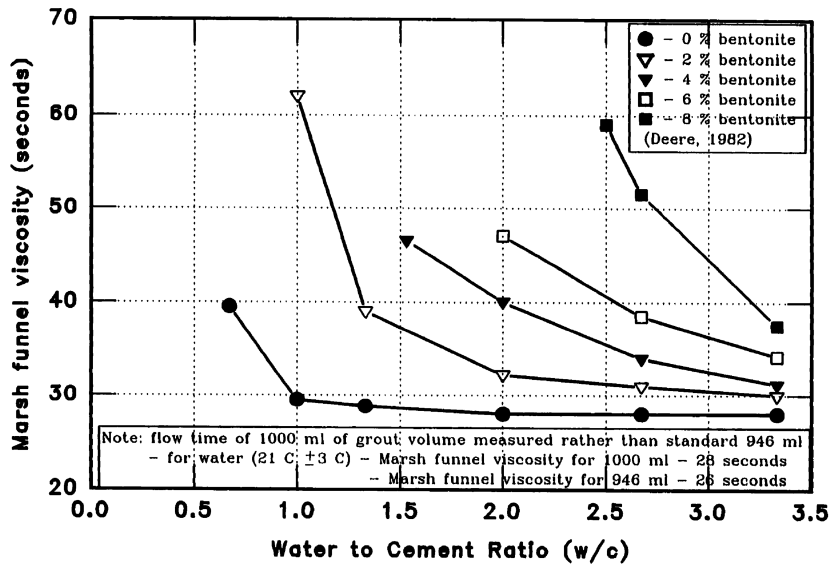


Figure 2.6: Marsh funnel viscosity for cement-based bentonite grout (Birch, 1997, p. 65)

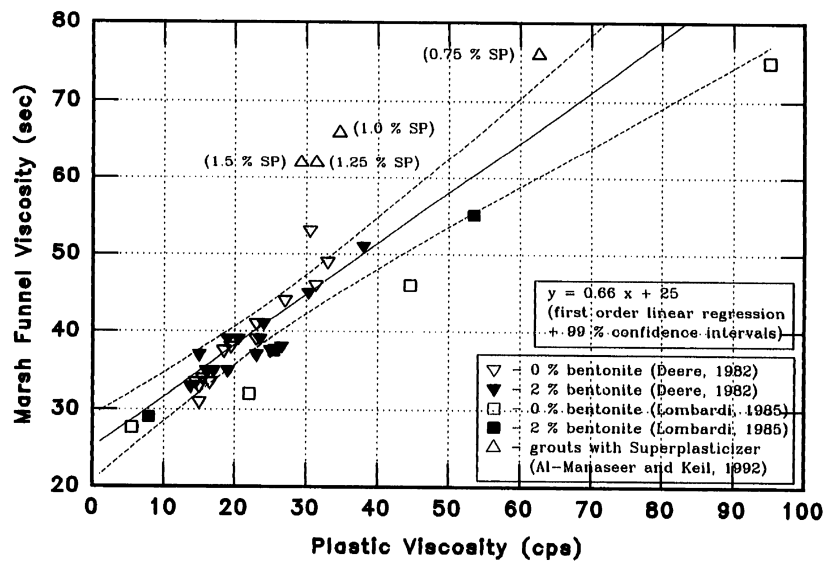


Figure 2.7: Correlation between Marsh funnel viscosity and plastic viscosity for various grout mixes (Birch, 1997, p. 67)

2.5.2 Slump Cone test

Another test that is usually performed is the slump test. While originally developed to measure the consistency of concrete mixes, some engineers have adopted this test for some highly cohesive cementitious grouts. The test involves filling a truncated cone

with 10 cm diameter at the top and 20 cm diameter at the bottom with concrete. The concrete is usually tempered and compacted with a stick for each filling of about one-third of the overall volume to ensure that there are no voids inside. The cone would then be pulled up and the unrestrained material is allowed to flow in radial direction under gravity. As the material deforms, the height of the mix will subside, as shown in figure 2.8. The slump height is then measured relative to the original height of 30 cm (top of the slump cone) and is used to characterise the consistency. In UK, this test was originally specified in the British Standards BS 1881-102 but is now replaced by the European Code BS EN 12350-2. A variation of this test is the half slump test, which uses a smaller cone. Although it might be more appropriate for grout, it is less commonly accepted. Generally the slump is found to increase proportionally with the w/c ratio.

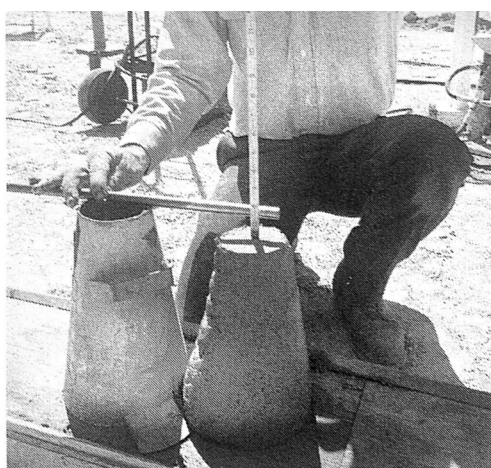


Figure 2.8: Measuring of slump height in a slump test (Warner, 2004, p. 148)

While the USA standard ASTM C143/C143M provided test for conventional concrete mixes, ASTM C1611 is more appropriately used for testing self-consolidating concrete (SCC) mixes and certain types of grout that are self-consolidating (ASTM International). The difference of the C1611 test to the C143 is that instead of measuring slump, the time for the grout to reach a certain spread is measured instead. A circle of 500 mm in diameter is marked at the centre of a 1 m square non-absorbent rigid plate (figure 2.9). The recommended time for raising the slump cone to a specified height from the slump is 3 ± 1 second. The spread of the slump is also measured, averaged over the greatest diameter and the diameter perpendicular to this direction. If large disparities are observed between the two then the results must be discarded. Different practitioners use

different orientations of slump cone, which can be inverted. A single person can more easily perform the experiment in the inverted orientation, as it requires less force to hold down the cone. There were concerns about the different friction between the cone and the material due to the inverted orientation, however these effects are small and often ignored. For normal SCC uses, this test also provided visual test for surface bleed, mortar halo and aggregate distribution.

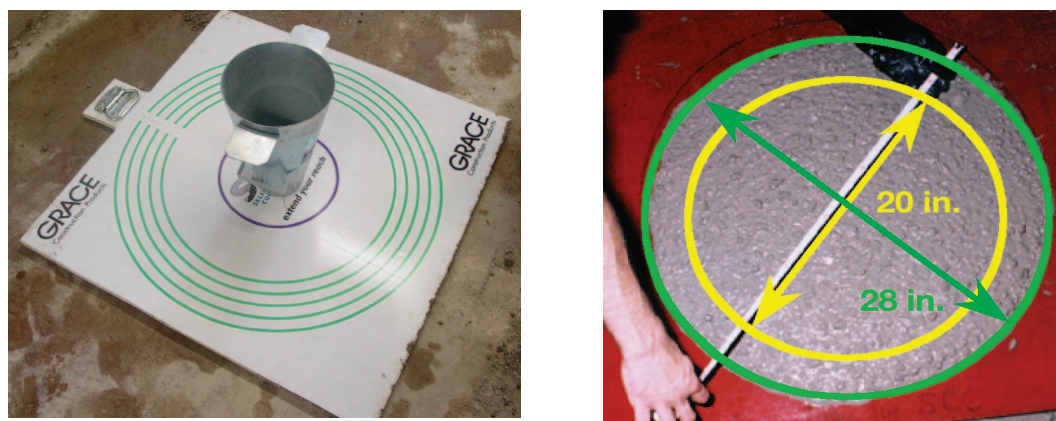


Figure 2.9 ASTM C1611 slump flow experiment (graceconstruction.com)

2.5.3 Criticism

For the Marsh funnel test, the quality of the results is very dependent on the competence of the personnel performing the test. It could produce errors of up to 2 seconds, which will have significant impact on the calculated apparent viscosity (ASTM International). Also the apparent viscosity cannot be applied directly for Bingham model as it is a function of the plastic viscosity, which is may be different for each material. For fast setting grouts, the rate of gelation could affect the bulk density, which would distort the hydrostatic head within the cone (Ata & Vipulanandan, 1997). This could affect the time for the material to pass through and hence the accuracy of the results.

The use of slump test for every types of grout has not been generally accepted yet. As stated in the ASTM Special Publication 169 C, the slump test is not appropriate for ‘very dry’ or ‘very wet’ mixes. Most grout would contain high water content that would make them too wet for slump tests. Furthermore, cementitious grouts are cohesive and thixotropic. In some cases, the hydrostatic force alone is not sufficient to initiate movement, thus giving misleadingly low slump. Another limitation is that for thick

mixes, the compaction required might be difficult to achieve in accordance with ASTM C143/C143M requirements. The UK code also specified that a steel rod to be used to temper the grout for every one-third fillings. In highly cohesive mixes, it tends to leave a lot of voids in the grout as the rod is pulled out (Warner, 2004, p. 149). An example of this is shown in figure 2.10. For these mixes, pumping the grout directly into the cone or tapping the mould might help provide complete filling. The alternative is using the ASTM C1611 test, but it is limited to self-consolidating grouts only. Currently there are no guidelines or previous studies on using the slump test for cement-based bentonite grout.



Figure 2.10: Voids and tears produced by tempering of grout in the lower portion (Warner, 2004, p. 149)

2.6 Numerical Modelling of Flow (Material Point Methods)

Finite elements methods (FEM) are traditionally used for static problems. For granular soils problems, which often include large deformations, the classical mesh based methods such as FEM is not suitable due to severe mesh distortions. Materials Point Method (MPM) was developed as a special numerical method to deal with such large deformation problems, using Lagrangian particles moving in an Eulerian grid based on a continuum approach (Bandara, 2013, p. 28). The model is based primarily on granular soils, which are assumed as discontinuum in nature. The use of MPM is justified when considering a large-scale problem in which the granular flow will become a continuum (see figure 2.11 as example). Since grout is already a continuum such problems do not exist. Currently the code can only model classical Mohr-Coulomb situations, but can be modified to include Bingham fluid models. Besides the geometry of the mesh and particle sizes and position, the code only requires the input of true material properties

(i.e. Bingham yield stress, viscosity), which is to be determined from experiments. However it can only provide plain-strain solutions. For column collapse type problems, the plain-strain results can be converted to axisymmetric results using figure 2.12 (Lajeunesse, Monnier, & Homsy, 2005).

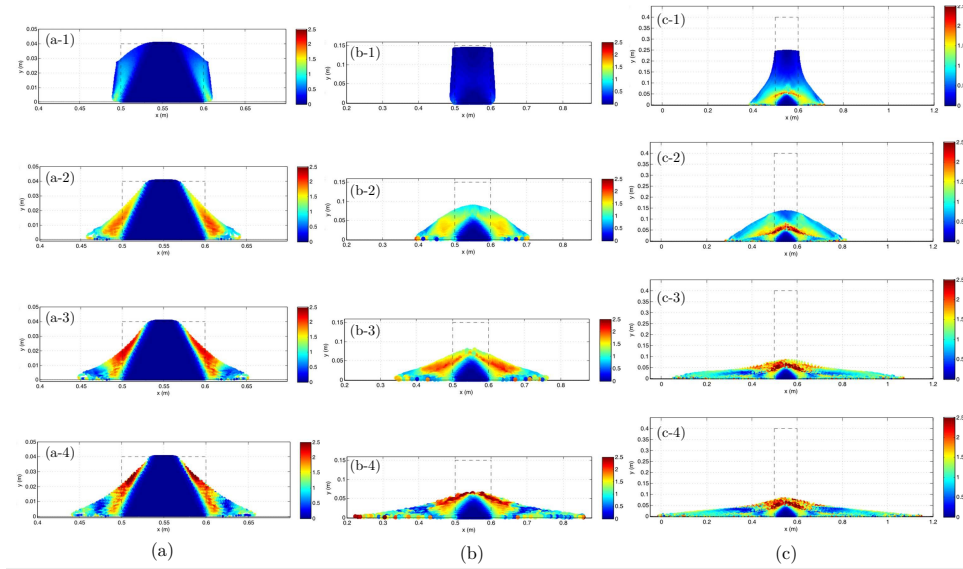


Figure 2.11: Flow evolution of granular column collapse simulations with different aspect ratios using MPM (Bandara, 2013, p. 104)

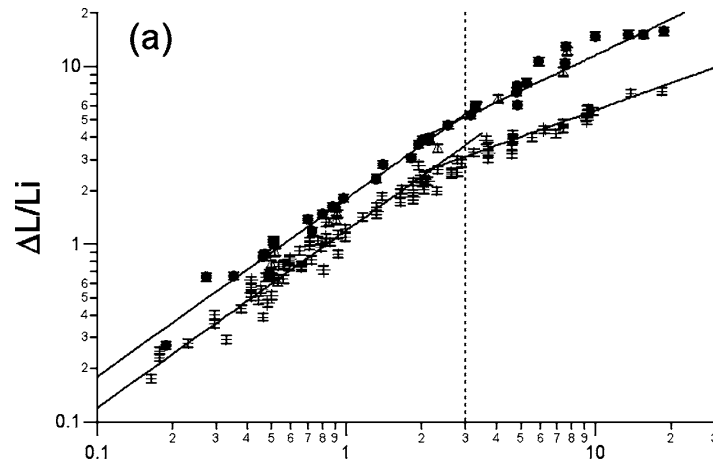


Figure 2.12: Scaled runout as a function of aspect ratio (Lajeunesse, Monnier, & Homsy, 2005)

2.7 An Overview

For many geomaterials, the understanding of the rheology is very important. In particular, grout is interesting to study because most applications of grout require precise controlling of the mobility and penetrability. In absence of sophisticated equipment, simple field tests are often performed to give an indication of the consistency of the

grout. The available literature proposed several field tests available for grout testing. However, these methods are often criticised for their appropriateness and inaccuracies. There is a strong need to provide a quantitative and qualitative link between the field test results and the real material properties.

Review of the available literature about application of cement-based bentonite grout in compensation grouting shows the importance of the grout composition. Eisa (2008) conducted experiments using CEM 1 cement and tested the rheology of several mixes. However, the range of materials tested is limited and the effect of changing the w/c ratio and bentonite content on the rheology of grout is not properly researched. There is a need to extend the work into including time dependency effects and testing other materials such as CEM 2 cement.

The proposed project work would investigate the appropriateness of the field tests currently used to characterise grout, using different grout compositions. Furthermore, MPM code would be used to model the flow of grout, based on measured material properties from experiments, which would lead on to modelling of complex real-life situations on site using data from field tests in the future.

3 Methodology

3.1 Design of experiment

The proposed project work focuses on establishing links between conventional field tests, such as Marsh funnel test and test, real material properties obtained from characterisation tests and computer models. By providing qualitative and quantitative comparisons, the amount of time spent for site work when using these geomaterials, such as grout, can be reduced.

Rheology of cement-based bentonite grout is affected by primarily the water-cement ratio and bentonite content. Previous research was conducted on a small range of mixes using CEM 1 cement (Eisa, 2008). The proposed project work will extend the research into CEM 2 cement and include time dependency effect.

MPM modelling would be used to model the flow of grout. In particular, the slump test is chosen for modelling. By comparing the predicted results with the real experiment, the use of MPM could be extended to speed up material characterisation and create a base for more complex designs in future construction work.

Field Tests to Real Material Properties:

Using a Bohlin rheometer, the Bingham yield stress and the viscosity of grout can be measured directly. This is to be compared with the apparent viscosity measured by Marsh funnel tests. The spread diameter from slump tests or slump flow tests would also be compared with the strength of the grout to provide quantitative relationships.

Real Material Properties to MPM:

Results from the Bohlin rheometer tests can be entered into the MPM code directly, by modifying the available MPM code to include Bingham fluid model. This will create a basis for future work, where the MPM could be used to obtain the real material properties without performing material characterisation tests in the laboratory via back analysis.

MPM to Field Tests:

The MPM code would utilise the material properties measured in the material characterisation tests for each individual mix to create a plain-strain simulation of the slump test. Then, by using figure 2.12, the simulation results can be converted in axisymmetric results, which would then be compared with the actual measured runoff in the slump flow test. This would provide the basis for further research that which would allow MPM model to generate the material properties directly just by matching the simulations to the slump results via a back analysis approach.

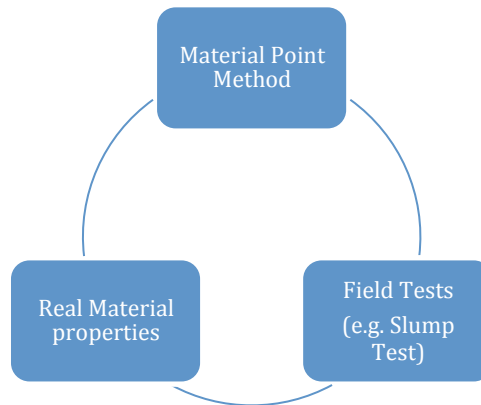


Figure 3.1: Interaction diagram between field tests, material characterisation tests and MPM

The aims of this project are:

- Establishing a link between conventional field tests for grout and the true material properties determined from material characterisation tests, and comment on the suitability of these field tests on various mixes of grout,
- Investigating how the strength and viscosity of grout can be affected by the water-cement ratio, bentonite content and time and comment on any general trends,
- Using computer programme (MPM) to model the behaviour of slump tests from the measured material properties, and
- Comparing the simulations of the model with the slump tests and comment on discrepancies.

3.2 Bingham fluid assumption

Grout can be modelled as a Bingham plastic. Bingham fluid behaves like a rigid body until a certain shear yield stress is reached. At yield, the shear stress increases proportionally with shear rate. For some cementitious grout mixes, the material may be shear thinning, meaning the viscosity will decrease as the shear rate increases. These two parameters: shear yield stress and viscosity, will generally determine the rheology of grout in terms of mobility and penetrability. The main factors that control the material parameters are w/c ratio, bentonite percentage and time after mixing. Like concrete, grout will begin to set as soon as mixing finishes. The test time for grout is limited to within 2 hours, which is the usual time limit that concrete has to be poured after mixing for site work.

3.3 Grout Materials

Throughout the project, Ordinary Portland cement (OPC) was used in all experiments. The brand used was Rugby cement, produced by Cemex, which conformed to BS EN 197-2 CEM II.

The GWB Wyoming sodium bentonite used was produced by Steetley Bentonite & Absorbents. Before testing, the bentonite was hydrated at least 24 hours beforehand to ensure the no lumps existed in the mix. Bentonite provides important physical properties such as permeability and improving the penetrability and has significant effect on the rheology of grout. The amount of bentonite added is usually expressed as a percentage of the weight of the water added.

The mixing water came from water tap at testing site that is potable for human consumption, which is usually adequate for grout (Warner, 2004, p. 69).

3.4 Apparatus and experimental techniques

3.4.1 Grout Mixing

The method of mixing is important for grout, as different mixing techniques can yield different material properties. For fairness, the mixing time and procedure was kept constant for every mix.

Before mixing, the bentonite had to be fully hydrated with the exact amount of water required for a mix with a particular w/c ratio. The recommended hydrating time is 24 hours, but slightly shorter time was used if the amount of bentonite used is very small. The bentonite container was covered and kept in a cool room to avoid as much evaporation as possible. At the start of mixing, Ordinary Portland cement was added to the hydrated bentonite and constantly stirred using a steel rod for 3 to 4 minutes, depending on how much cement was added. After that, the mix was pouring into a colloidal mill mixer, where the grout was further mixed for another 3 to 4 minutes, depending on the volume.

The machine used is a R14 Roller mixer, produced by the Colcrete Eurodrill Company. The mixer runs at 2100 rpm, which produces a shear rate of 8346 s^{-1} . The high shear rate and small gap size ensures that the grout is fully mixed and no lumps exists in the mix. Since the amount required for slump tests is quite large compared to the capacity of the machine, hand mixing ensures that the mix is fluid enough so that the machine will not overload.

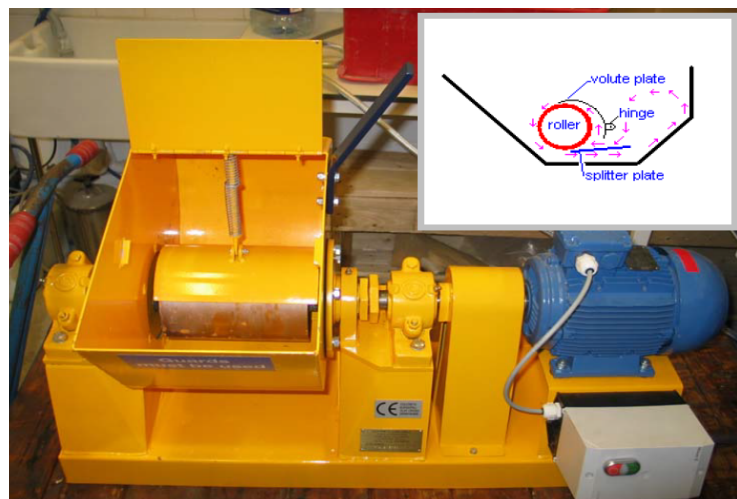


Figure 3.2: Colloidal mill mixing principle (Eisa, 2008, p. 73)

For the rheometer tests and Marsh Funnel test, only a small amount of grout was needed. The volume was too small to be mixed inside the machine so hand-mixing technique was adopted instead. The mixes were given enough time to mix to ensure that the texture of the grout was the same as those mixed using the colloidal mill.

3.4.2 Slump flow Test

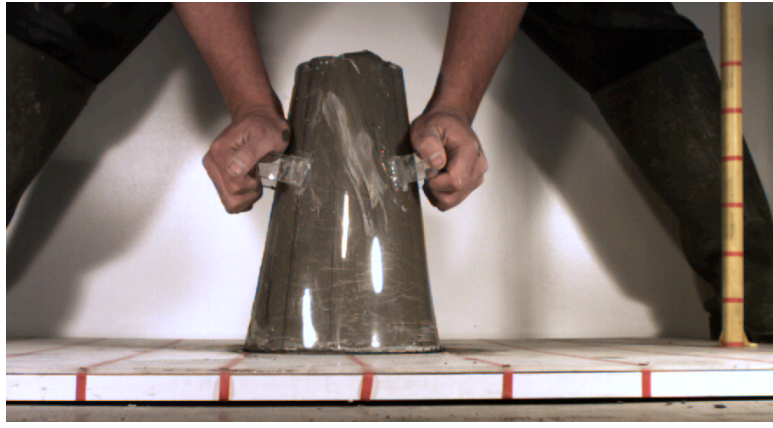


Figure 3.3: Set-up for slump test experiments for recording on high-speed camera

The slump flow tests were performed on a plastic board, which is supported by a rigid white wooden base plate. The board is marked with red tape spaced at every 20 cm, so that it gives a rough measurement of the spread of the slump. A yellow pole also marked with red tape spaced at every 5 cm was used to measure the height. A special transparent slump cone was made, with its specifications made exactly as described in the ISO standards (ISO 4109-1980).



Figure 3.4: Special transparent acrylic slump cone made to allow high-speed camera to record grout flow and a standard metal slump cone

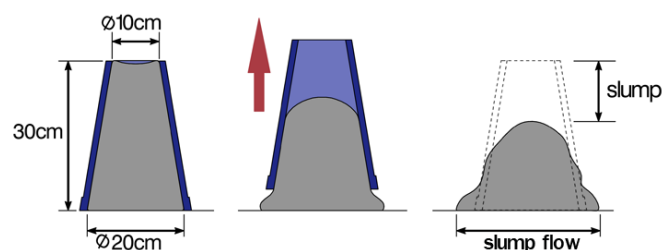


Figure 3.5: Testing of fresh concrete using slump test (civilqc.blogspot.com)

At the start of the test, the slump cone would be lifted up vertically to allow the grout to flow outwards due to gravity (figure 3.5). For fairness, a consistent pull-up time for the slump cone was used. A high-speed camera was used to capture the slump process at 500 frames per second (figure 3.6). 3 spotlights were used to improve the lighting so that the outline of the grout is more visible.



Figure 3.6: High-speed camera (left) and set up (right) used for recording the slump tests

3.4.3 Marsh Funnel Test

The Marsh Funnel is a standardised tool for ground engineers to characterise geomaterial with high water content, such as drilling mud, and is regularly used on site to measure the apparent viscosity. The advantage of this test is that it is very simple to perform. Only a marsh funnel cone, a collecting bucket and a timer are needed. The slurry is poured into the Marsh funnel, and the time need for the slurry to fill a volume of 946 ml after released is measured. The time of flow duration through the specially shaped funnel is related to the apparent viscosity of the slurry by the following equation.

$$\mu = \rho(t - 25)$$

where t is the mentioned flow time in seconds, ρ is the density of grout and μ is measured in Pas. While it does not give the actual viscosity of non-Newtonian fluids, empirical equations may be used to convert it into the plastic viscosity for Bingham fluids.



Figure 3.7: Set-up for Marsh funnel flow experiments

3.4.4 Rheometer Test

To measure the shear stress and shear rate relationship of the grout, a Bohlin CVO 120 High Resolution rheometer was used. A small amount of sample was placed within the serrated parallel plates and sheared in controlled shear stress steps, with the shear rate measured. The time for each test was limited to 5 minutes, which would give a snapshot of the material's properties at a particular time. A temperature of 20°C was used throughout all tests, kept constant by temperature-controlled air flowing underneath the parallel plates. The shear yield stress and plastic viscosity can be measured directly from the shear rate versus shear stress graphs.



Figure 3.8: Bohlin rheometer used for testing the shear stress and shear rate measurement (Eisa, 2008, p. 76)

4 Results and Discussion

4.1 Rheometer Results

For the rheometer tests, a typical range of w/c ratios and bentonite percentages used in most grout applications were chosen. w/c ratios of 0.5, 1.0 and 1.5 and bentonite content of 2%, 4% and 8% were used. In total there were 9 different mixes being tested. All tests were done in controlled shear stress increases, which is more appropriate for Bingham fluids from than controlled shear rate tests according to preliminary tests.

The grout mixes can be roughly classified as either ‘soft’ or ‘hard’. Hard mixes tend to be more paste-like and have higher cohesion and hence a more obvious Bingham yield stress, whilst soft mixes on the other hand tends to be more fluid-like with a lower viscosity and much less obvious Bing yield stress. Low w/c ratio combined with high bentonite percentage seemed to generate ‘hard’ mixes, and the opposite for ‘soft’ mixes. To test the time dependency, each mix is tested at 5 minutes, 30 minutes, 75 minutes and 120 minutes after mixing. Each test is repeated 3 times to ensure accurate results. Theoretically, the yield stress and viscosity are time dependant since grout will harden with time.

Contrary to the result of Eisa (2008), the results shows that most mixes exhibit almost perfect Bingham fluid behaviours. Some test results are plotted in figure 4.1 and 4.2. For most cases the viscosity seems to be constant and that there is no shear thinning effects.

	Bentonite %	2	4	8
w/c ratio	0.5	Test 1.1	Test 1.2	Test 1.3
	1.0	Test 2.1	Test 2.2	Test 2.3
	1.5	Test 3.1	Test 3.2	Test 3.3

Table 1: Different tests carried out with varying w/c ratios and bentonite percentages

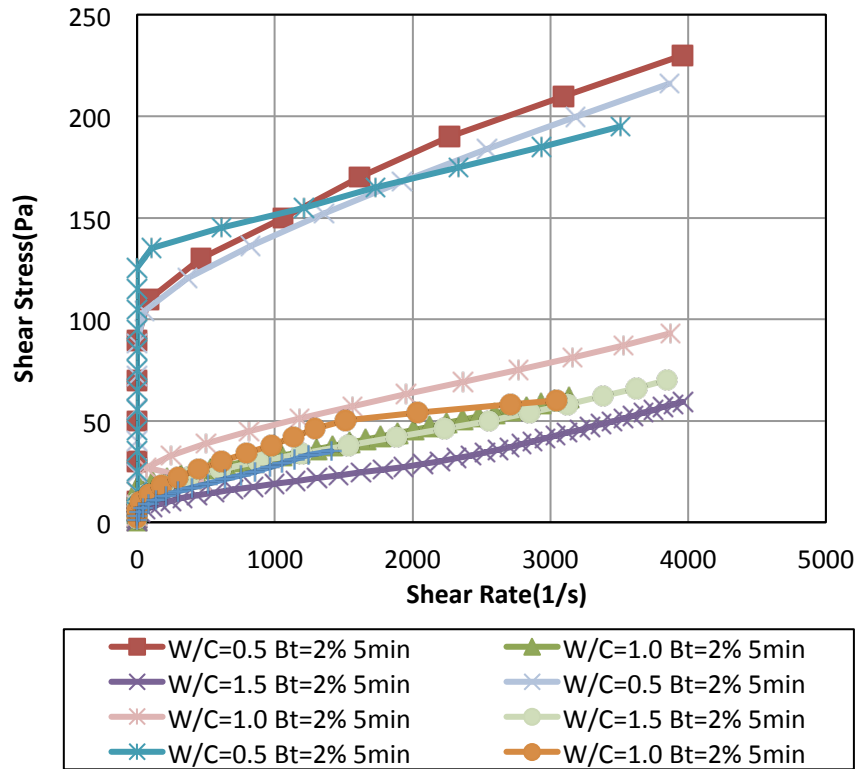


Figure 4.1: Shear stress and shear rate relationship for test 1.1, 2.1 and 3.1 at 5 minutes after mixing

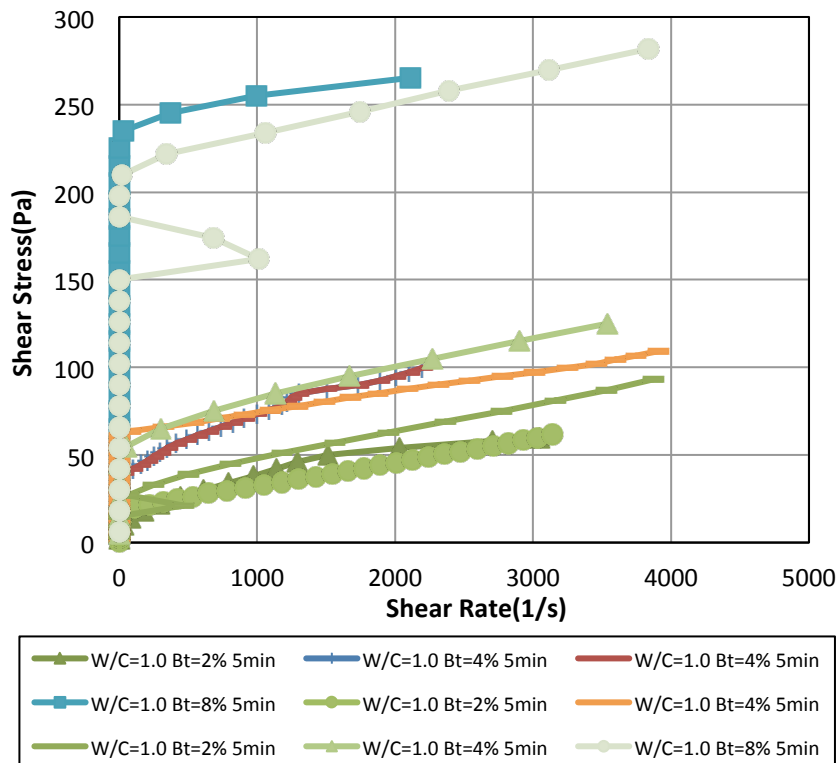


Figure 4.2: Shear stress and shear rate relationship for test 2.1, 2.2 and 2.3 at 5 minutes after mixing

From the results data, a specific shear rate range was selected for each test to determine the yield stress and viscosity. A common phenomenon during testing was that the grout tends to splash outside of the plates due to the centrifugal force as the shear rate increases. When splash out occurs, the shear rate will suddenly drop to a certain value and remain constant even if the shear stress increases. This is particularly common for ‘hard’ mixes, which include those with low w/c ratio and high bentonite percentage, due to larger stress steps. At the point of yielding, there is usually a smooth transition of shear rate between before and after yield as oppose to a rigid yield characterised in an idealised Bingham fluid model. Discretion was applied in selecting the minimum and maximum shear rate that is to be used for curve-fitting purposes

4.1.1 Time-dependency

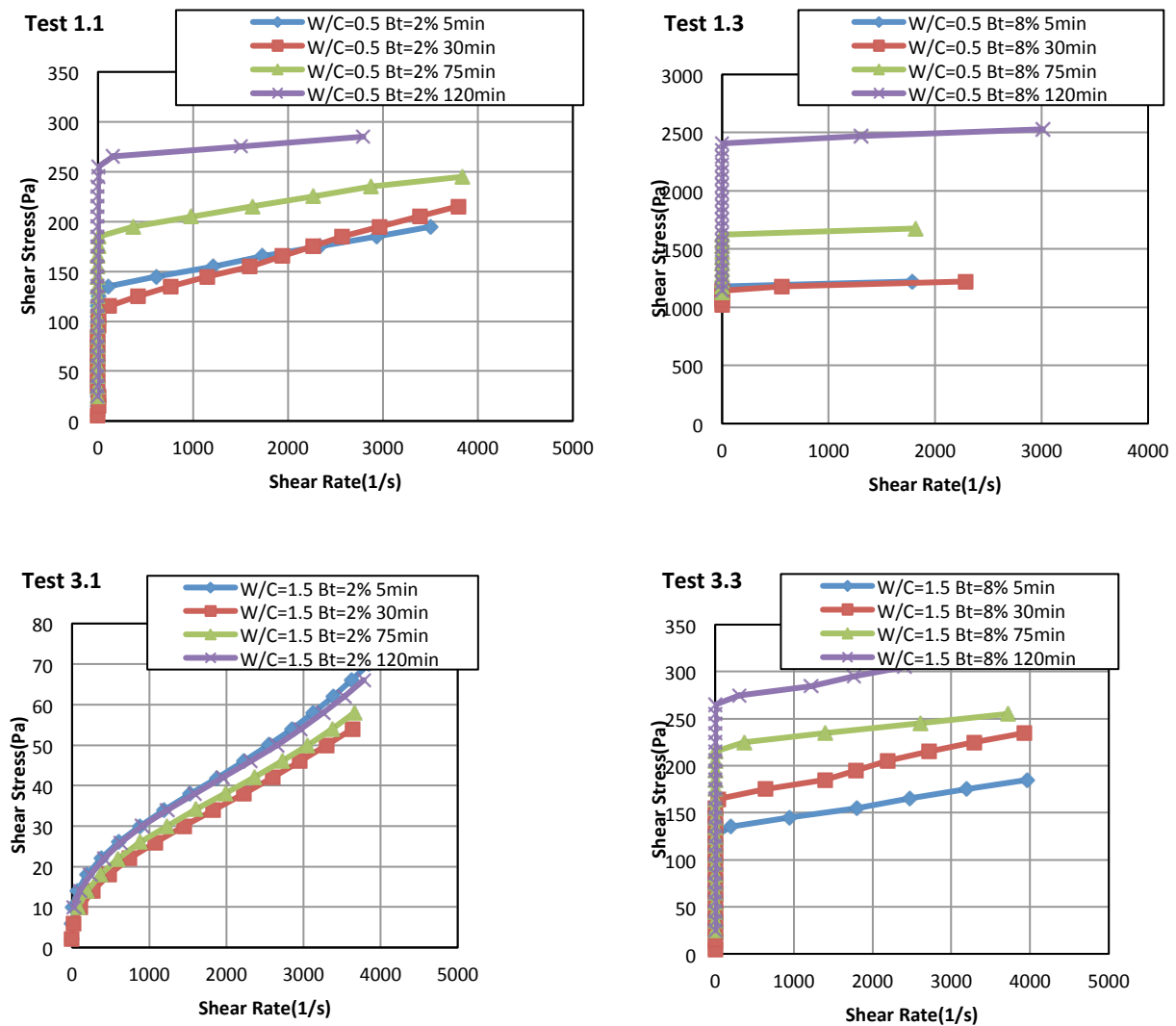


Figure 4.3: Time variation of Shear stress and shear rate relationship for test 1.1, 1.3, 3.1 and 3.3

As expected, the grout hardens as time progresses after mixing, which is shown in the increase of yield stress with time in figure 4.3. The effect of hardening occurs across all mixes, but the effect is particularly noticeable for low w/c ratio and high bentonite percentage mixes. This is supported by comparing results from test 1.1 with test 1.3 and test 1.3 with test 3.3. Hydration of cement powder does not happen all at once, but rather spreads out for an extended period of time as the water contacts each individual cement grain gradually (Warner, 2004, p. 64). Increasing the proportion of cement within the mix will thus increase the time to complete hydration. Since the hydration process is the driving factor for strength increase, the time effect is therefore more significant for low w/c ratio mixes. Bentonite on the other hand also provides some extra delay in hydration times by blocking the access of cement grains to water.

The values of Bingham yield stress (y-axis intercept) and viscosity (gradient) were determined using linear approximations. The strength and viscosity were then plotted with respect to time (figure 4.4). Four types of equations were used to model the time effect: linear, power exponential and logarithmic, and the variance for each were compared in figure 4.5 for all tests. Both exponential and linear approximations seem equally suitable to model the time dependency of yield stress. For simplicity, the relationship between yield stress and time is assumed to be linear for the MPM codes.

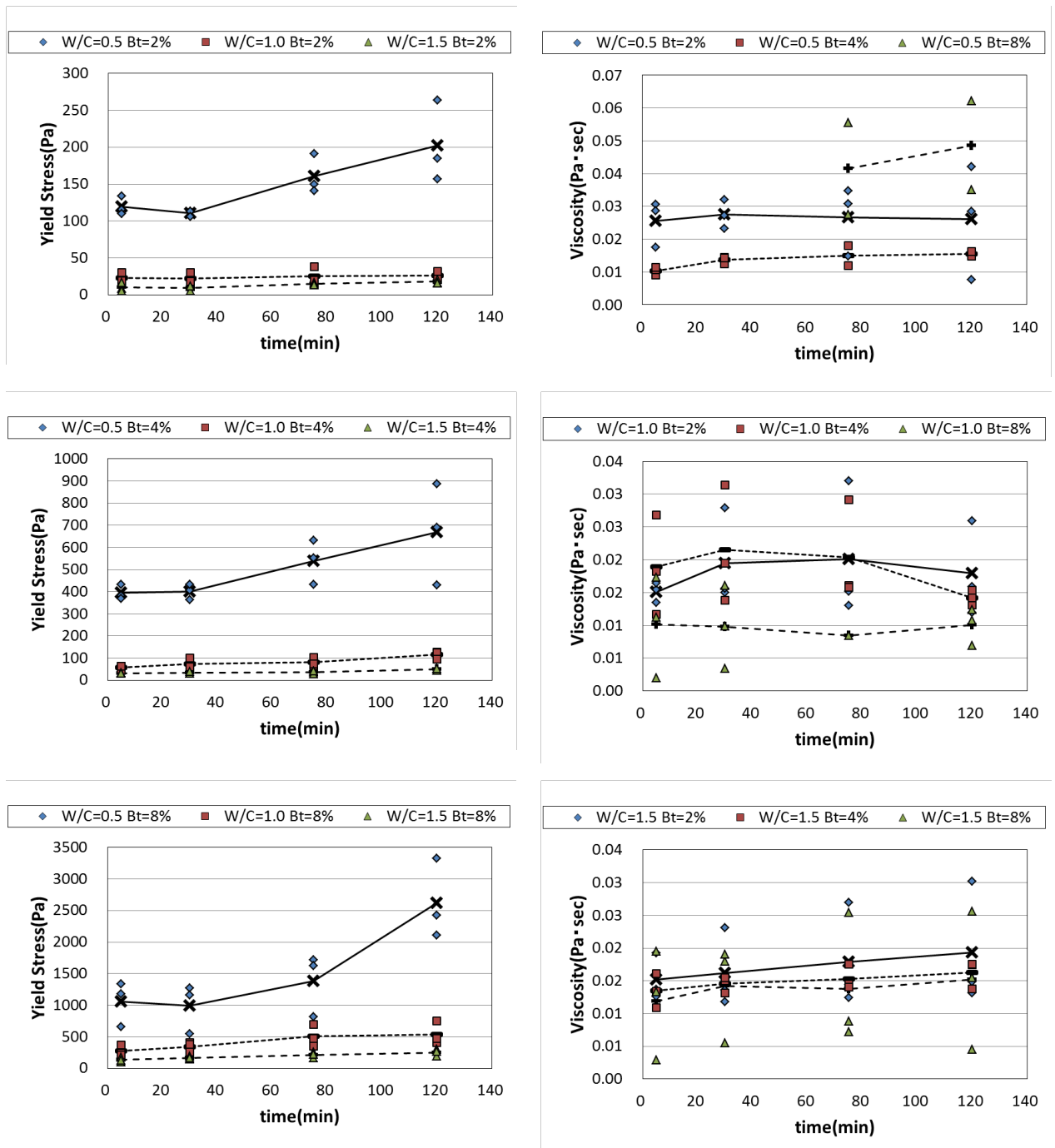


Figure 4.4: Change of Bingham yield stress (left) and viscosity (right) with time

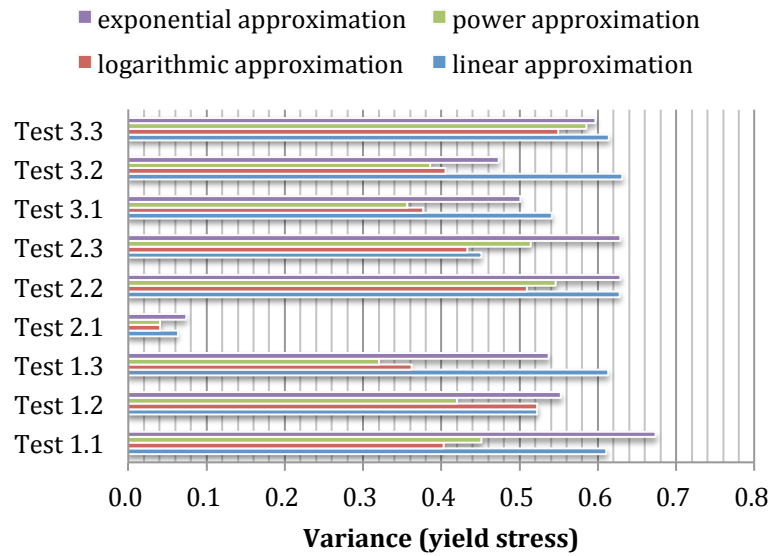


Figure 4.5: Variance of each curve-fitting equation for Bingham yield stress for each tests

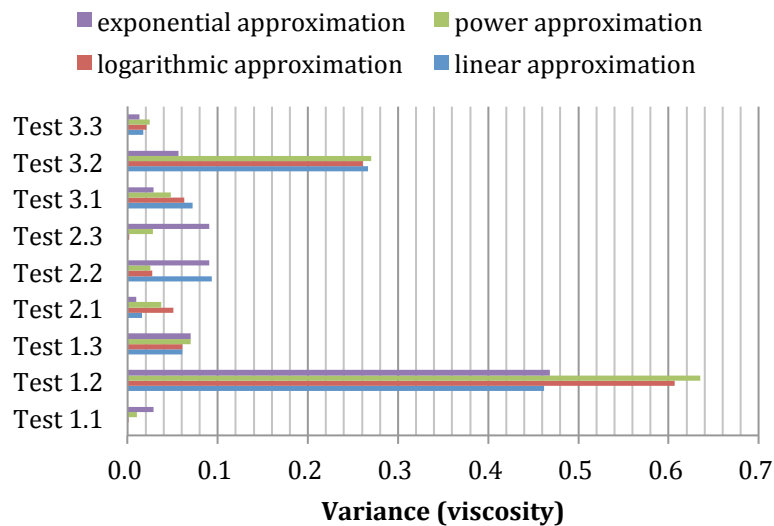


Figure 4.6: Variance of each curve-fitting equation for viscosity for each tests

For the viscosity, the results are inconclusive. Figure 4.6 shows that the variance is too low to draw any meaningful conclusions in almost all mixes. For the ‘hard’ mixes, due to large time steps, the mixes tend to splash out much quicker. This means there were less data collected from the intermediate shear rate range, which makes the determination of the viscosity very difficult. There is some tendency for the viscosity to increase with time in some cases but it is not obvious.

4.1.2 Effect of w/c ratio and bentonite content

The changes with shear yield stress with change of w/c ratio and bentonite percentage are plotted on figure 4.7 and 4.8 respectively. The results were obtained using linear approximation and extrapolating the shear stress back to 0 min (i.e. immediately after mixing). From figure 4.7, it is apparent that the yield stress increases with decrease in w/c ratio. The increase in strength is sensitive to the bentonite percentage and the rate of increase is high when the bentonite content is also high. It also shows that for high w/c ratio and low bentonite content the grout has almost negligible yield stress.

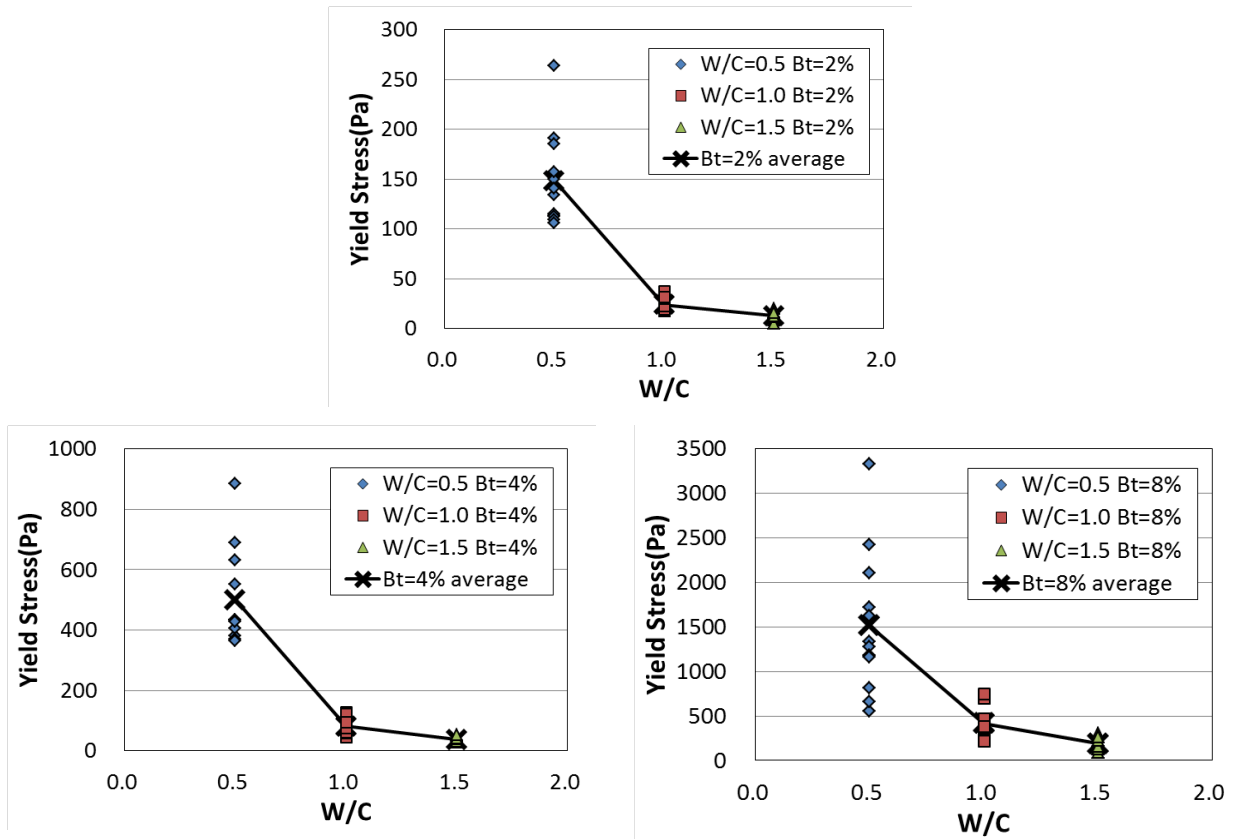


Figure 4.7: Change of Bingham yield stress with respect to change in w/c ratio for bentonite percentage of 2% (top), 4% (left) and 8% (right)

Increasing the bentonite content also has a positive effect on the yield stress. It is shown that in figure 4.8: the higher the w/c ratio, the more sensitive the mix is to the increment of bentonite. An increase of bentonite percentage from 2% to 8% can cause 7-15 times the yield stress. This shows that the strength is very strongly correlated to the combination effect of both w/c ratio and bentonite.

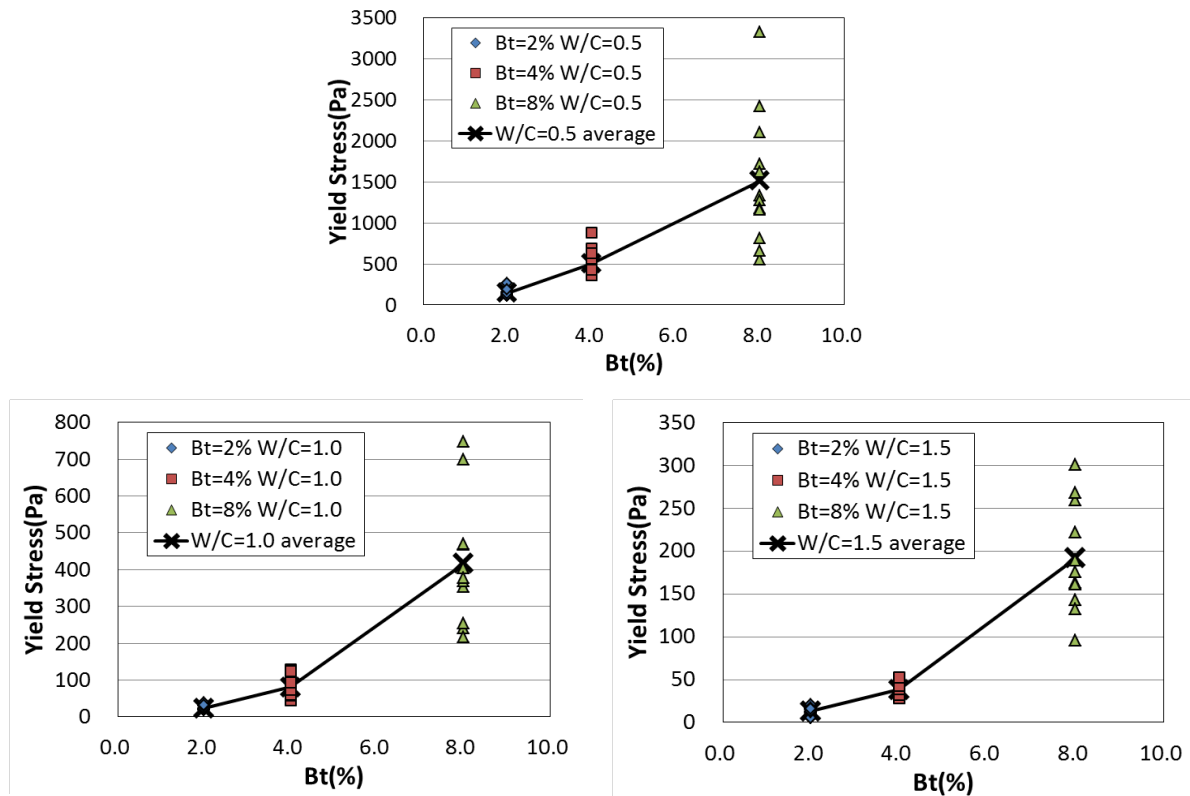
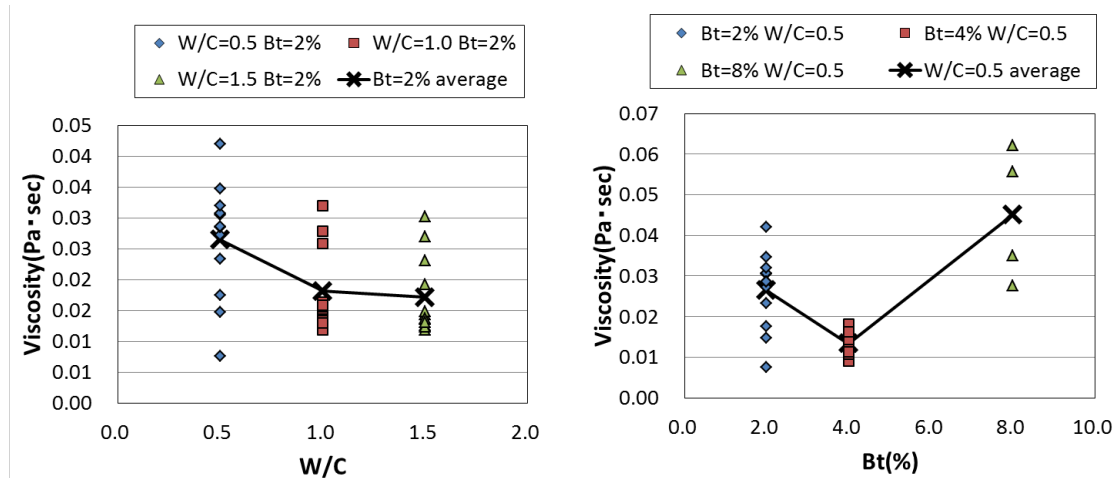


Figure 4.8: Change of Bingham yield stress with respect to change in bentonite percentage for w/c ratio of 0.5 (top), 1.0 (left) and 1.5 (right)

The changes in viscosity due to change in w/c ratio and bentonite percentage are shown in figure 4.9. In terms of effect of w/c ratio, the viscosity seems to increase when the low w/c ratio is used. On the other hand, the addition of bentonite would slightly reduce the viscosity. However the correlation is not strong for both. As mentioned in section 4.1.1, the difficulty in measuring the viscosity for ‘hard’ mixes makes the data quite unreliable.



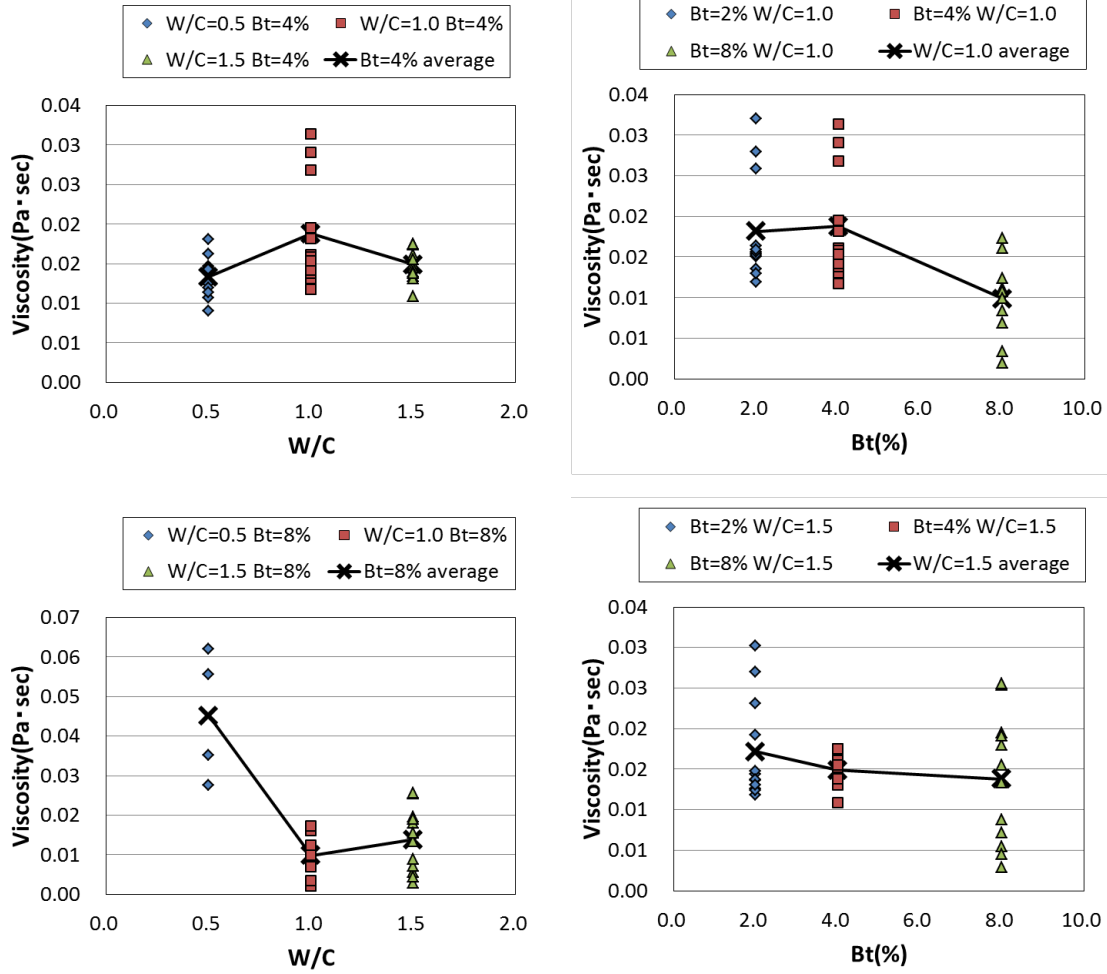


Figure 4.9: Fig. x Change of viscosity with respect to change in w/c ratio (left) and change in bentonite percentage (right)

4.1.3 Bentonite Cement ratio

The results from section 4.1.2 suggest that there is a coupling effect between bentonite percentage and w/c ratio. The yield stress and viscosity are plotted against the bentonite cement ratio in figure 4.10. The bentonite cement ratio is calculated by dividing the bentonite percentage by the w/c ratio. For the yield stress, the data suggests that there is a strong positive relationship between yield stress and bentonite cement ratio. It shows clearly that the yield stress is high for high bentonite cement ratio mixes, which are characterised by high bentonite percentage or low w/c ratio. On the other hand the viscosity results do not show the same correlation. As expected, the high level of difficulty associated the viscosity measurement, especially for high bentonite cement ratio, produced a lot of scatter in the data.

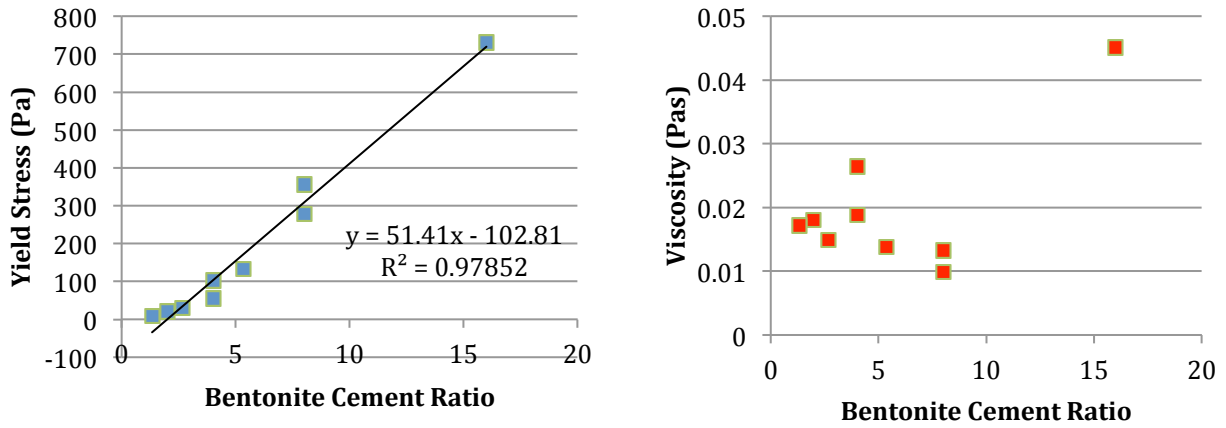


Figure 4.10: Yield stress (left) and viscosity (right) against bentonite cement ratio

4.2 Slump Test Results

4.2.1 Effect of changing w/c ratio and bentonite %

Preliminary slump tests were performed for all 9 mixes. However, 4 of those mixes were too 'soft' and watery that the final slump flowed outside the measuring area (which is 1m x 1m). Also, due to the time required to set up each test, the number of tests were reduced to only 2 times per each batch. The tests were performed at 30 min and 120 min respectively. Out of the 9 mixes, only the mixes for test 1.1, 1.2, 1.3, 2.3 and 3.3 were tested. Overall the 5 tests combine to give a general indication of the effect of w/c ratio and bentonite content.

	Bentonite %	2	4	8
w/c ratio	0.5	Test 1.1	Test 1.2	Test 1.3
	1.0	×	×	Test 2.3
	1.5	×	×	Test 3.3

Table 2: Slump tests carried out

Figure 4.11 plotted the measured diameter of the final slump for each mix. The greatest diameter and the diameter perpendicular to that direction are measured and averaged to give the final spread diameter. There is a sharp change between w/c ratio of 0.5 and 1.0. For the most extreme one, which is with w/c ratio of 0.5 and 8% bentonite, the final slump shape still retains the shape of the slump cone, with the base expanding only by one or two cm only (figure 4.12). However, there are some obvious voids in the lower

portion of the slump, which is impossible to remove even with the use of a steel rod to temper the grout before testing. For w/c 1.0 and 1.5, the mixes behaved more like a fluid. Figure 4.13 shows that the grout is too soft to hold a slump cone shape. As soon as the restraint of the slump cone was removed, the mix spread out quickly into a circular pool of slurry. The addition of bentonite also reduces the final spread. Even at low w/c ratio, mixes with low bentonite percentages are still classified as ‘soft’. Also, the spread is reduced with time as the grout hardens.

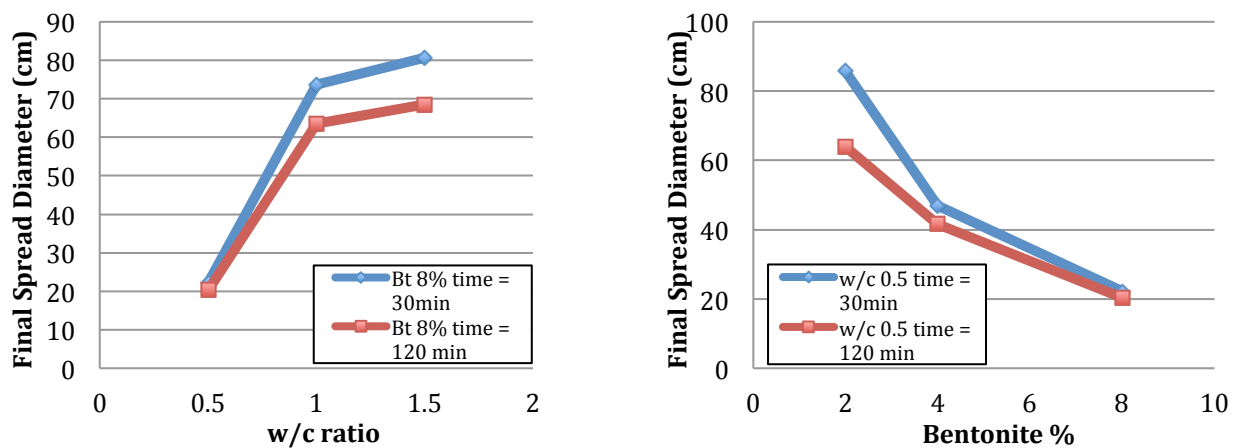


Figure 4.11: Final spread diameter for slump test for different w/c ratio and bentonite percentage

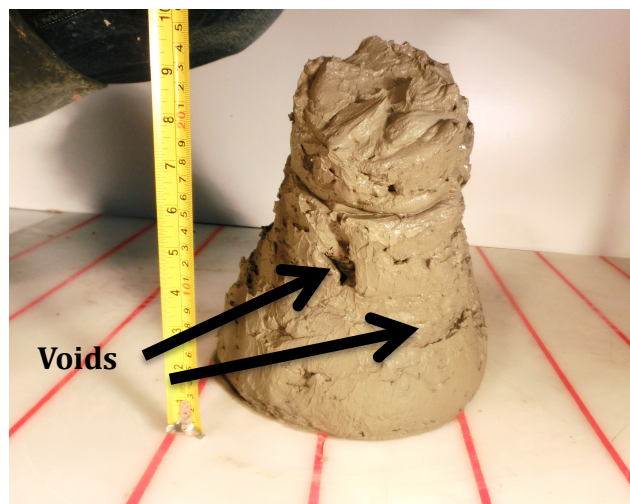


Figure 4.12: Final slump shape for mix with w/c 0.5 and bentonite percentage of 8% at 120 min after mixing

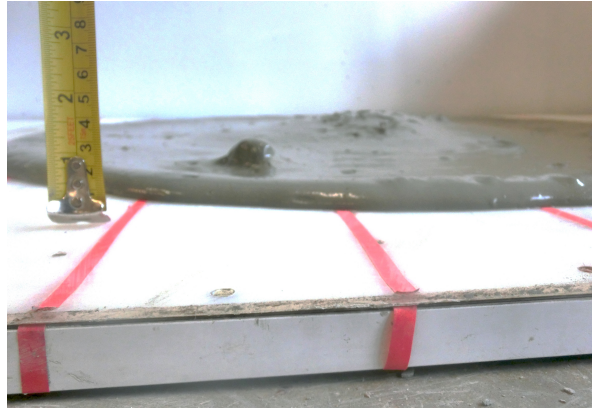


Figure 4.13: Final slump shape for mix with w/c 1.5 and bentonite percentage of 8% at 120 min after mixing

Likewise, in terms of slump height, the ‘harder’ mixes tend to have a smaller slump. This is shown in figure 4.14. The height is very difficult to measure accurately for the ‘soft’ mixes due to large errors and the fact that the height is not uniform.

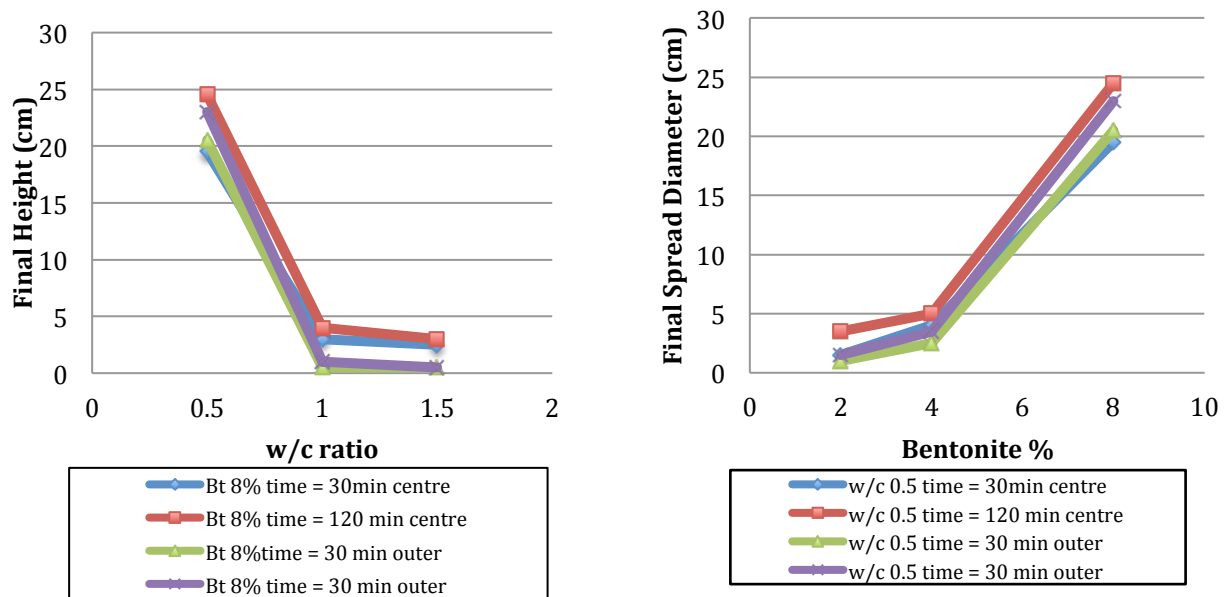


Figure 4.14: Final spread diameter for slump test for different w/c ratio and bentonite percentage

4.2.2 Effect of Fast and Slow Pull-Up methods

The ISO (ISO 4109-1980) standards have specified that for concrete slump tests, a 5-10 seconds of pull-up time is recommended. This recommendation exists because the speed of pulling up the slump cone does affect the slump height. The effect is reported in JIS (Japan Industrial Standards), where the JIS recommended a pull-up time of 2-3 seconds

(JIS A 1101-1975). The ASTM C1611 slump flow test also specified a 3 seconds pull-up time, with one-second tolerance. The resulting slump had been reported in the document to have about 10% difference with that following the ISO standards. For this project, a 0.5 second of pull-up time is used to simplify the numerical analysis model.

Figure 4.15 and 4.16 show photos of the final slump shapes, where ‘fast’ denotes 0.5 second pull-up time and ‘slow’ denotes 5-10 seconds pull-up time. The photos show that the slower pull-up method consistently produces a final slump with smaller diameter and a smaller slump. The difference between 3 seconds to 5 seconds pull-up time is negligible. However, the slow pull-up method may distort the final slump shape, as shown in the case for test 1.2.

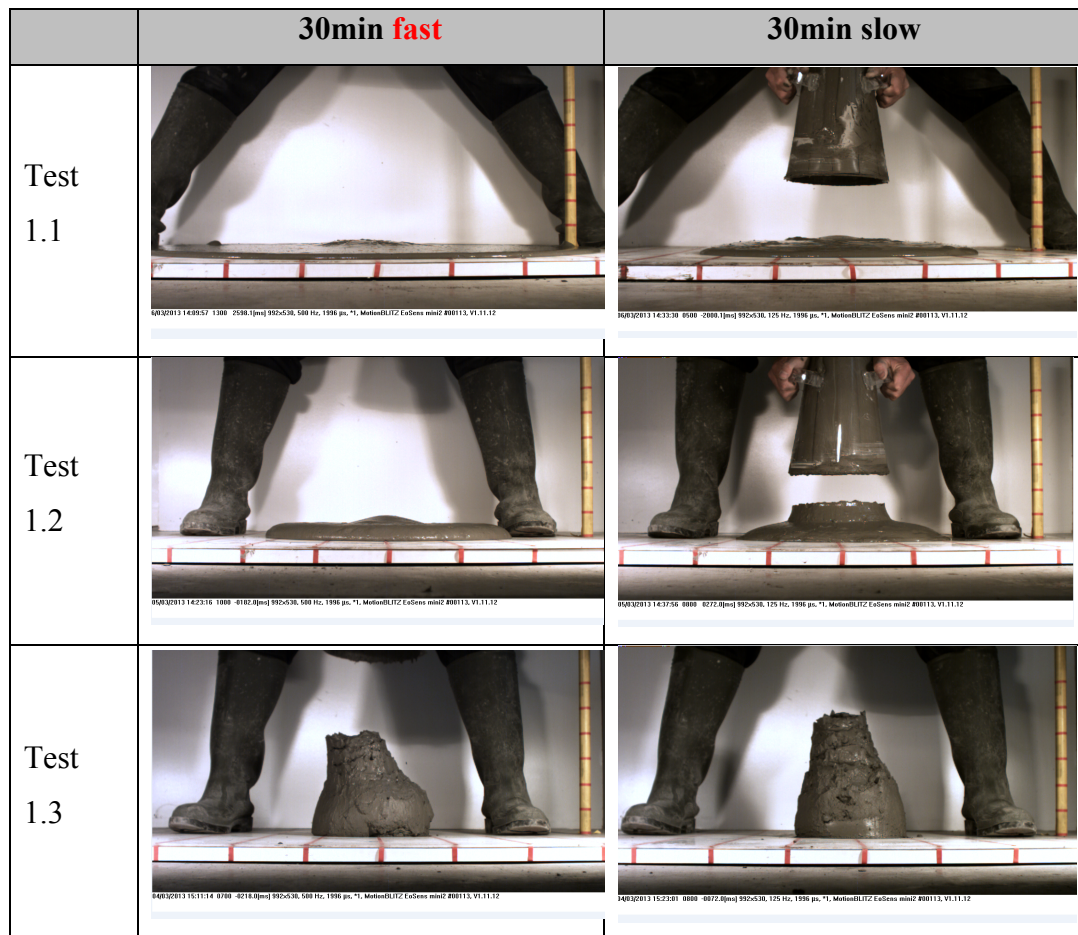


Figure 4.15: The effect on final slump shape due to fast and slow pull-up method, tested at 30 minutes after mixing

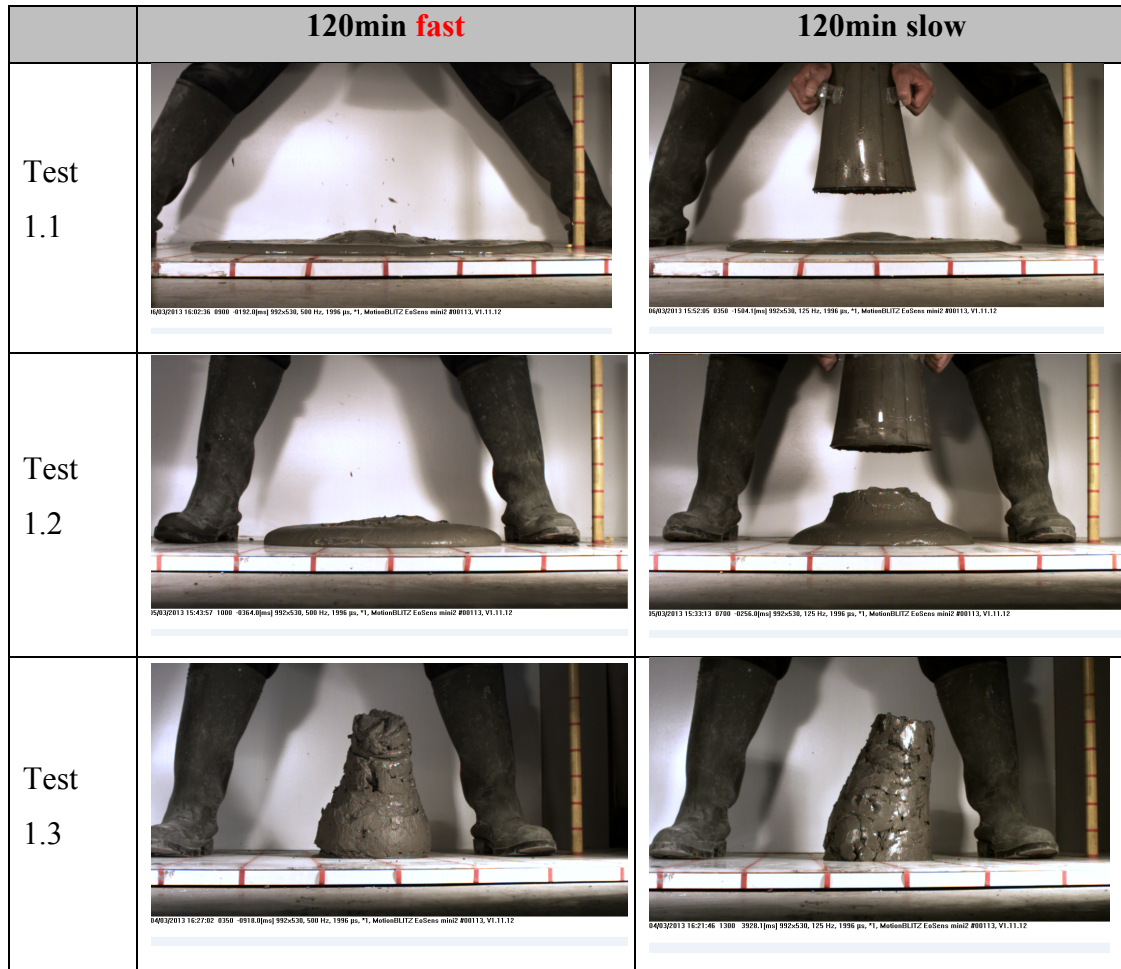


Figure 4.16: The effect on final slump shape due to fast and slow pull-up method, tested at 120 minutes after mixing

For the faster method, the slump cone was removed almost instantly. The slump was then allowed to freely deform under the effects of gravity. For the slower method, as the cone was removed slowly, the cone restricted the grout to flow away from underneath. As the grout piled up on the outside, the pressure of the grout outside is equal to the hydrostatic pressure on the inside, thus inhibiting further flows of grout. Therefore in the end, more grout was piled up in the centre then spread out to the sides. This is much harder to simulate in MPM so the faster method is chosen.

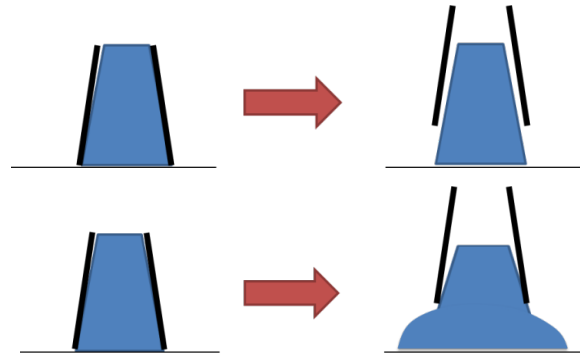


Figure 4.17: The flow of grout in slump test with fast pull-up method (top) and slow pull-up method (bottom)

The normalised difference in slump height and spread diameter for test 1.1, 1.2 and 1.3 are summarised in figure 4.18. It shows that the slump tests results for ‘hard’ mixes are most significantly affected by the speed of pull-up. Hardening of grout would reduce this effect, but the error due to pull-up speed is still significant.

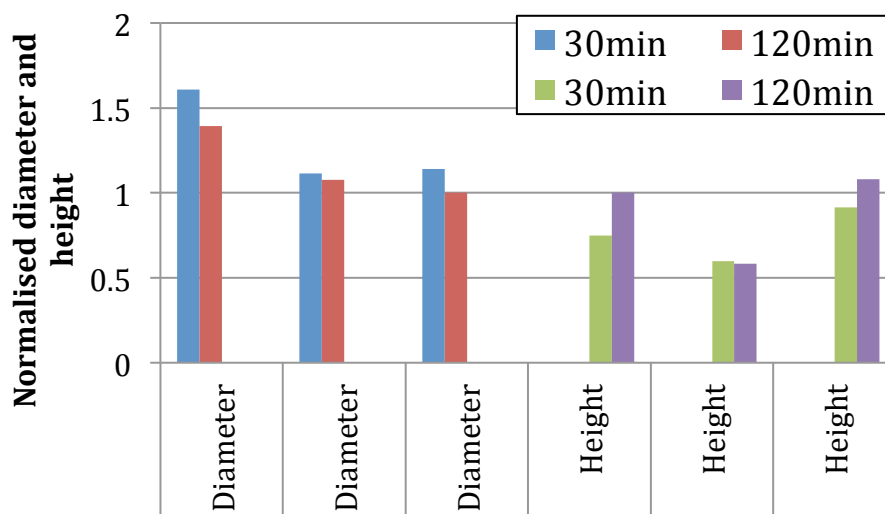


Figure 4.18: Normalised spread diameter and height for slump test results using slow pull-up methods

4.2.3 Comparison with real material properties

The measured spread diameter is plotted against yield stress, which is measured from the rheometer, in figure 4.19. The best-fit line from linear regression shows a reasonably good fit between the spread diameter and yield stress. For higher yield stress, a larger force is required to initiate flow. As the grout flows further away, the hydrostatic force acting on the grout due to gravity will decrease due to decrease in height, flow will

terminate when the force can no longer meet the required shear force for it to have non-zero shear rate. Hence for the final slump spread is smaller for grout with higher yield stress. This is supported by the results, which shows a negative slope between the yield stress and spread diameter.

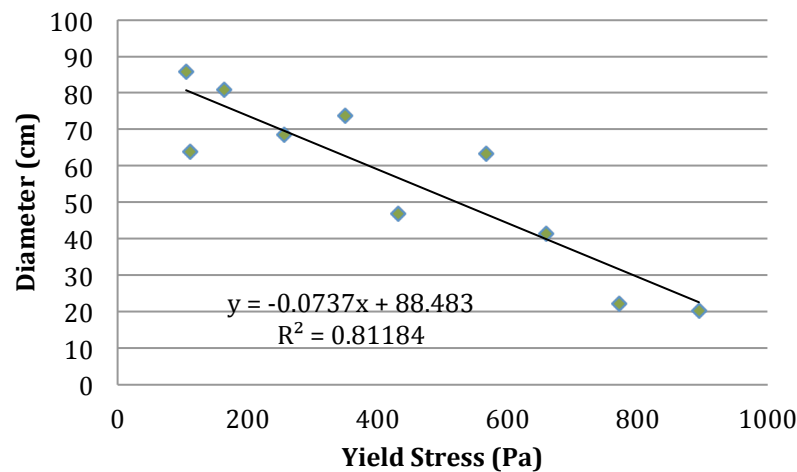


Figure 4.19: Comparison of slump diameter with yield stress

On the other hand, the viscosity of grout is more likely to govern the flow speed of grout. In order to measure the flow speed, the time from the start of the lifting up of the slump cone to the time the grout reached a 40 mm diameter is measured. This is done by referring to the photos took at a rate of 500 frames per second by using the high-speed camera. For test 1.3, which is highly cohesive, the slump did not reach the 40mm diameter line and is therefore excluded. The time measured is plotted against viscosity on figure 4.21.

From the data, it seems to suggest a correlation there is a positive relationship between flow time and viscosity, if the results of test 1.2 is excluded. Test 1.2 is excluded due to the difficulty in measuring its viscosity from the rheometer results, which makes the data unreliable (see section 4.1.1). However this is only speculation, more research is required to proof that the relationship exists. For future research, a different diameter can be set to increase the time difference so that it is easier to measure on site.

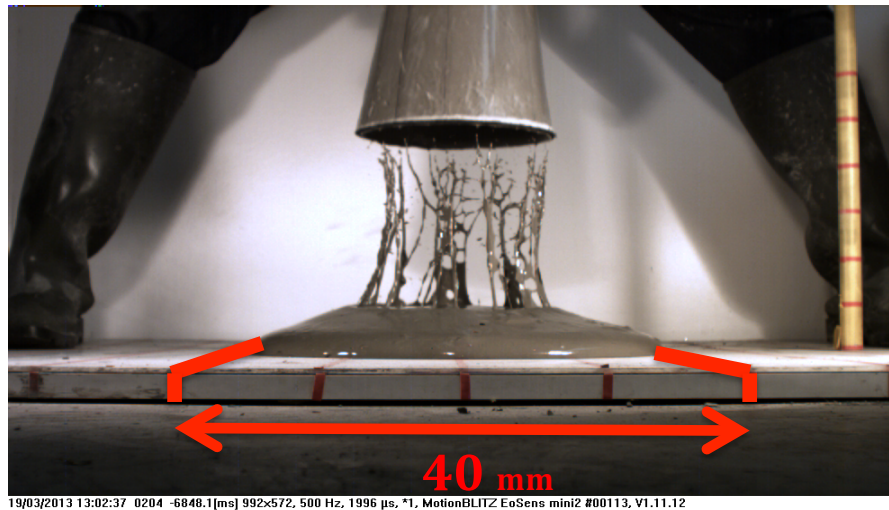


Figure 4.20 Determination of the slump flow time

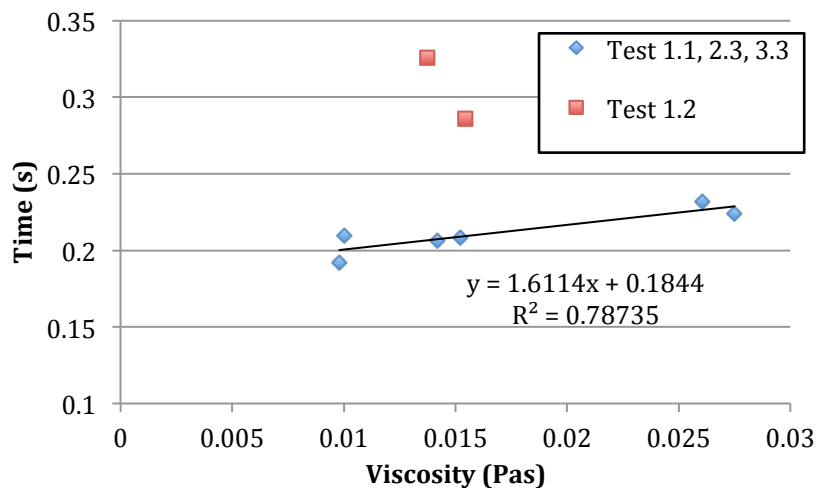


Figure 4.21: Comparison of flow time with viscosity

4.3 Marsh funnel Test

4.3.1 General results

Marsh funnel test were carried out in accordance with the ASTM guideline. The acceptable time for each measurement should be within 26 to 75 seconds (Warner, 2004, p. 145). From preliminary tests, the mixes that took more than 60 seconds of flow time were often quite difficult to measure since the flow was unsteady. These mixes were considered to be unsuitable for Marsh funnel tests. This applies to high bentonite percentage and low w/c ratio mixes, including test 1.1, 1.2 1.3, 2.2, 2.3 and 3.3. The tests were performed at 5, 30, 75 and 120 min after mixing and the results were

compared with the rheometer test results. Figure 4.22 plotted the apparent viscosity with change in bentonite cement ratio. It shows an increase in initial apparent viscosity with increases in bentonite cement ratio, in contrast with the previous plot of plastic viscosity against bentonite cement ratio, which shows a lack of correlation (figure 4.10).

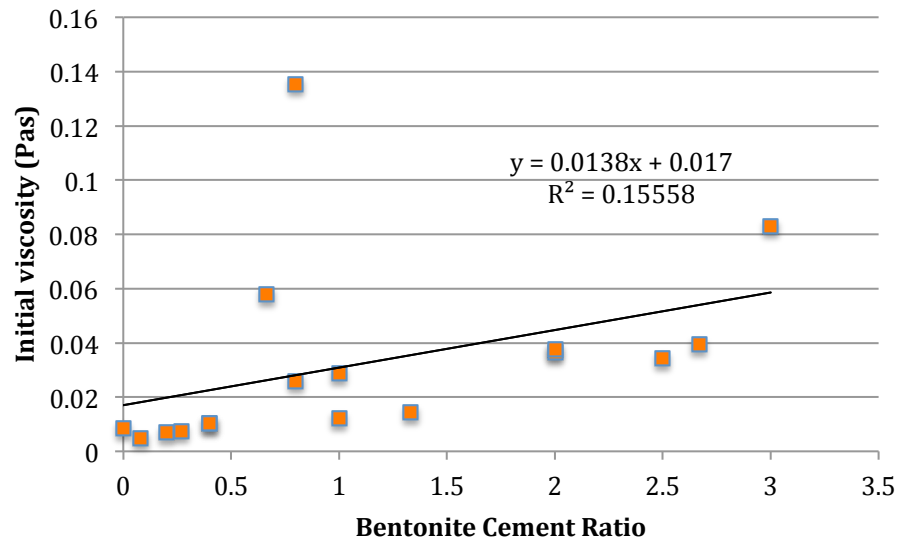


Figure 4.22: Change of average viscosity with bentonite cement ratio

4.3.2 Comparison between apparent and plastic viscosity

The results are plotted against the plastic viscosity, which is measured from matching rheometer tests and plotted on figure 4.23 (see section 4.1). Linear regression is used to relate the apparent and plastic viscosities. Test 3.1 shows very good fit, while test 2.1 and 3.1 has less linear correlation. The difference between the apparent and plastic viscometer arises from the assumption for Marsh funnel test that the material is Newtonian, or at least pseudo-Newtonian. For Bingham fluids, the shear stress acting on the grout within the funnel will be affected by the shear yield stress. This observation is supported by the fact that all three equations that link the apparent to plastic viscosity are distinctly different from each other. This suggests that for different mixes, there is a different relationship between the apparent and plastic viscosity. Figure 4.24 shows a positive relationship between the gradient of apparent to plastic viscosity and the yield stress of each mix. The results seem to suggest that for higher yield stress, the more the Marsh funnel viscosity deviates from the plastic viscosity. However, given the limited amount of results, there is a need for further research to confirm this conclusion.

Overall, this makes the Marsh funnel test quite unsuitable for site work, because the use of it to achieve the measurement of plastic viscosity would rely on established relationship between the apparent and plastic viscosity. To do so would require testing the plastic viscosity using rheometer, which defeated the purpose of performing the Marsh funnel test as a quick field test. Otherwise, the equations would have to be established beforehand for each and every single types of mix, which is not practical.

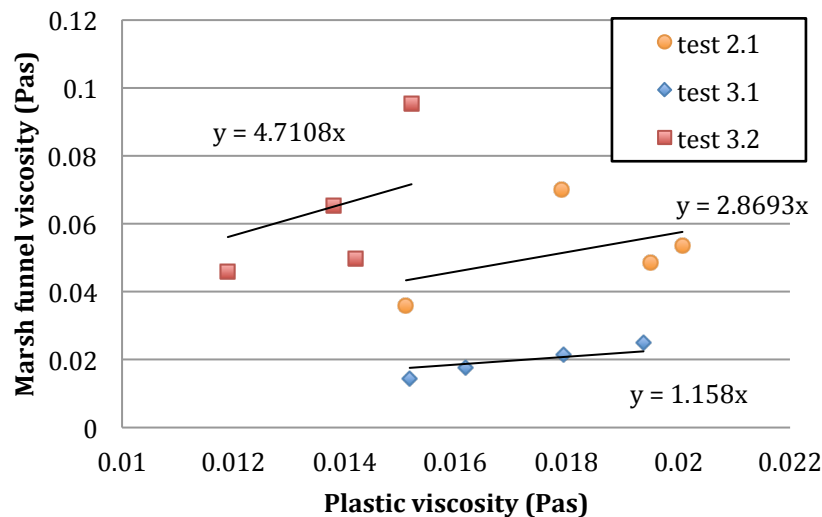


Figure 4.23: Comparison of Marsh funnel viscosity and plastic viscosity

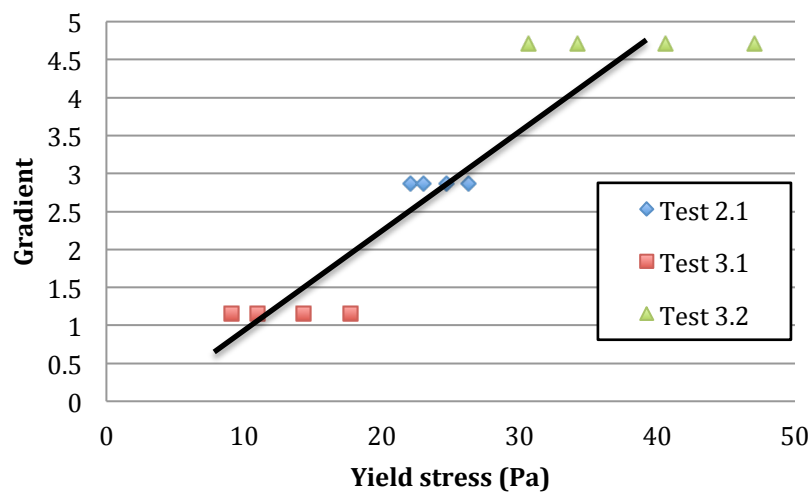


Figure 4.24: Comparison of apparent to plastic viscosity gradient and yield stress

4.3.3 Comparison of time effect on Marsh funnel and rheometer results

From figure 4.25, the Marsh funnel results show a much stronger linear correlation with time compared to the rheometer. In certain cases, the gradient of the linear approximation are very small, some are even negative, which indicates almost no change of viscosity over time. The results are shown in table 3.

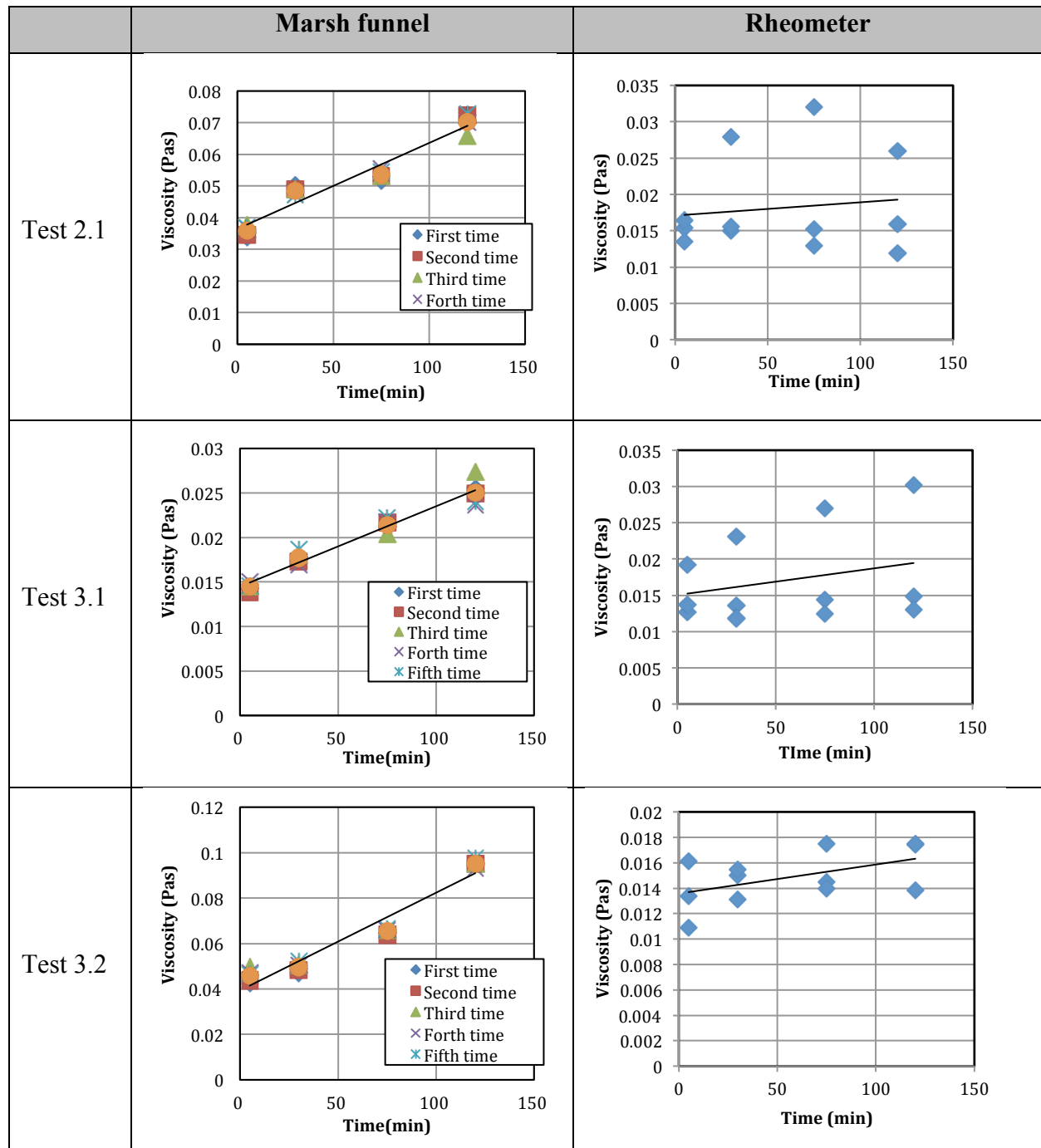


Figure 4.25: Comparison of time dependency between Marsh funnel test and rheometer test results

Test	W/C	Bt(%)	Slope (Pa · sec · min ⁻¹)	Initial Viscosity (Pa · sec)
1.1	0.5	0	0.0012	0.1143
1.2	0.5	0.4	0.0008	0.1354
2.1	0.6	0	0.00006	0.0392
2.2	0.6	0.4	0.0001	0.0578
3.1	1	0	0.00001	0.0085
3.2	1	0.4	0.00002	0.0104
3.3	1	2	0.0003	0.0364
3.4	1	3	-0.0004	0.083
4.1	1.5	0	0.00002	0.0053
4.2	1.5	0.4	-0.000003	0.0076
4.3	1.5	2	0.00009	0.0145
4.4	1.5	4	0.0004	0.0393
5.1	2	0	-0.000002	0.005
5.2	2	0.4	0.000002	0.0068
5.3	2	2	0.0004	0.0123
5.4	2	4	0.0002	0.0378
5.5	2	5	0.0018	0.0343
6.1	5	0	0.00001	0.003
6.2	5	0.4	-0.0000004	0.0049
6.3	5	2	-0.000005	0.0103
6.4	5	4	-0.0000005	0.026
6.5	5	5	0.0003	0.0287

Table 3: Marsh funnel results

4.3.4 Applicability of Marsh funnel test

In order to test the applicability of Marsh funnel test for a full range of grout mixes, the tests were extended to include w/c ratios of up to 5. In total, tests were conducted on 25 mixes. The contours of time range and average viscosity are plotted in figure 4.26.

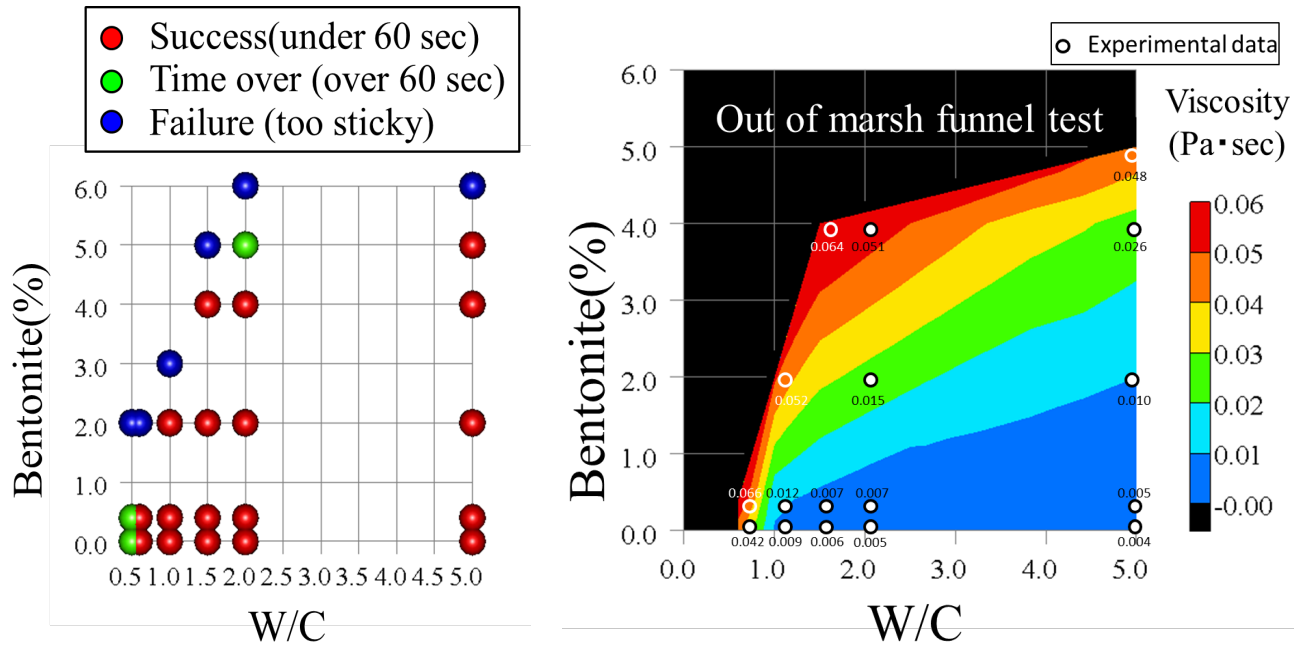


Figure 4.26: Time range of Marsh funnel test (left) and contour of average apparent viscosity and suitable test range of Marsh funnel test (right)

4.4 MPM Model

Test	W/C	Bt(%)	Average Viscosity (Pas)	Gradient of Yield Stress (Pa.min ⁻¹)	Yield Stress (Pa)
1-1	0.5	2%	0.0264	0.079	103
1-2	0.5	4%	0.0133	2.52	356
1-3	0.5	8%	0.0451	13.6	731
2-1	1.0	2%	0.0181	0.0367	21.9
2-2	1.0	4%	0.0188	0.0472	54.1
2-3	1.0	8%	0.00984	2.41	278
3-1	1.5	2%	0.0172	0.0745	8.74
3-2	1.5	4%	0.0149	0.143	29.9
3-3	1.5	8%	0.0138	1.04	132

Table 4: Material parameters used for MPM model

$$\tau = \tau_y + \mu \frac{du}{dx}$$

where τ_y is the yield stress, μ is the viscosity and $\frac{du}{dx}$ is the velocity gradient for a 2D flow.

Numerical simulations of the slump test were done using MPM, with the material parameters estimated from the rheometer experiments shown in table 4 and the above equation. The MPM code was based on Bingham fluids, but currently it is only available for plain strain problems. The model also assumed a surface friction of 0.509, density from 2000-2400 g/cm³, Poisson’s ratio of 0.2-0.3 and Young’s modulus of 1-10 MPa. These were estimated based on conventional values.

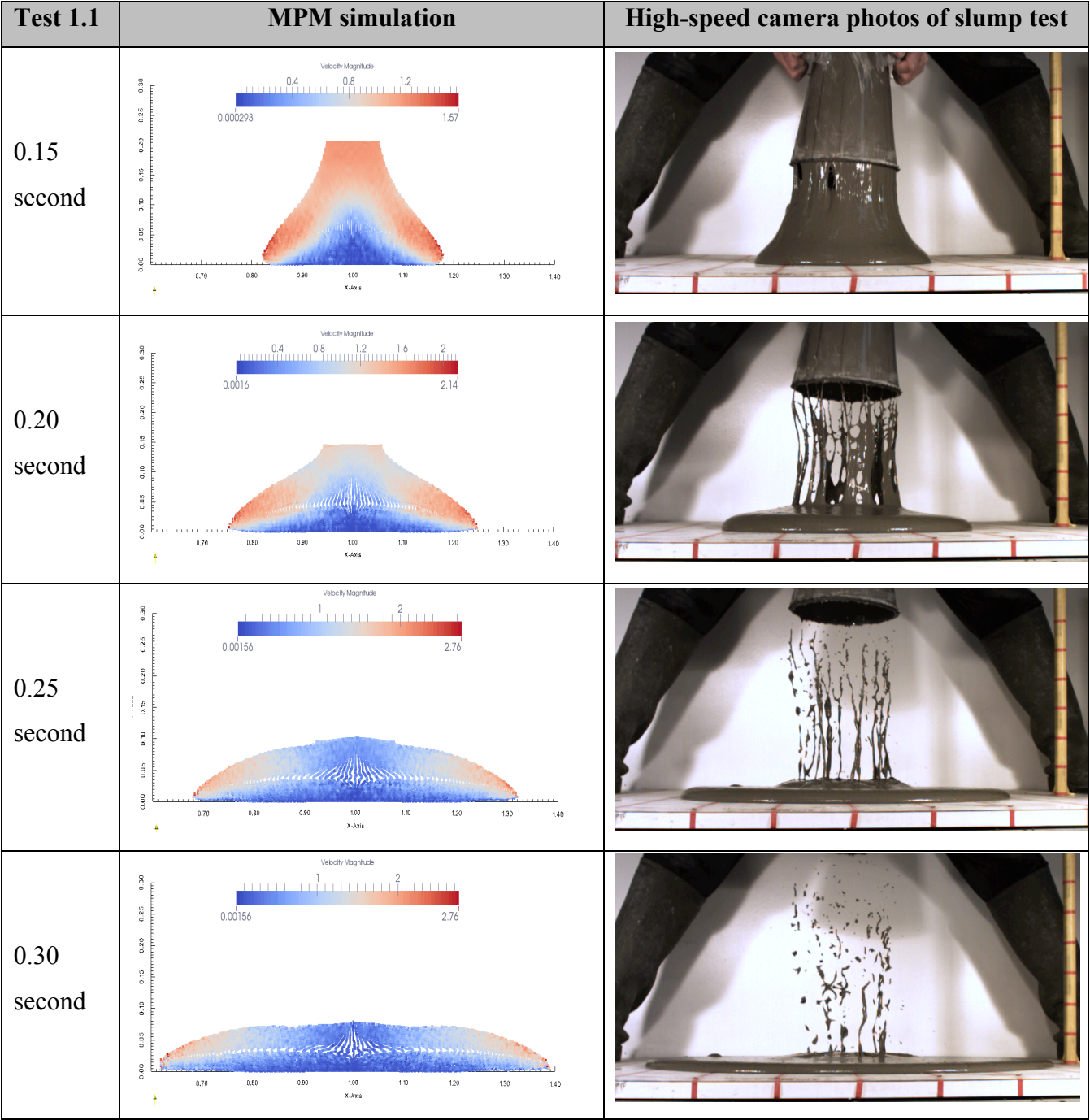


Figure 4.27: Comparison of MPM simulation with slump test

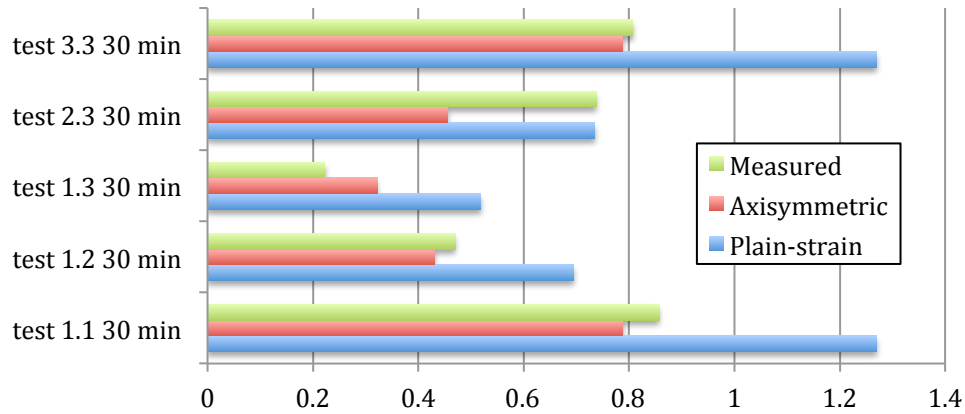


Figure 4.28: Runoff from MPM simulations and actual results

The runoff of the simulations, which uses a plain-strain model, can be converted to axisymmetric results. From figure 2.12, the scaled runoff of plain-strain and axisymmetric problem for $a=1.5$ (average aspect ratio of slump cone is 1.5) are 2.9 and 1.8 respectively. Using these factors to scale the final spread diameter, the results of the final slump spread from the simulation normalised with the measured diameter is plotted in figure 4.29. It shows that for most cases, with the exception of test 1.3, the model slightly underestimated the final spread, which suggests maybe the surface friction used is higher than the actual case. Simulations for test 1.1, 1.2 and 1.3 showed very good fit with the actual data, with errors within 10% of the measured spread. However, the material parameters used were not from actual measurement. Due to time constraint, the density, Poisson's ratio and Young's modulus used were estimated using typical range of values and applying an engineering judgement. The simulations for test 1.3 show large discrepancy with the high-speed camera photos, which suggested maybe there are other factors that affect the slump. For future work these values need to be measured experimentally for a higher accuracy.

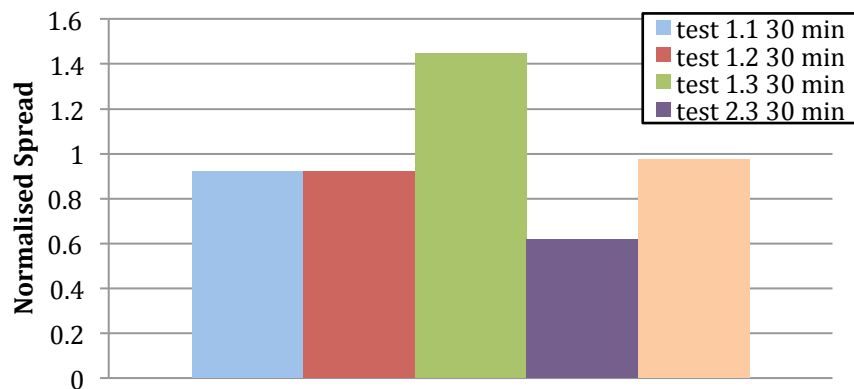


Figure 4.29: Normalised spread diameter of MPM simulations

5 Conclusion

5.1 Establishing Link between Field Test and Material characterisation test

For the slump test, there is a clear relationship between the slump spread and the yield stress of grout. When the yield stress increases, the final spread decreases. However, the slump height is not a useful measurement for comparison, except for some extremely cohesive cases, due the difficulty of measuring. The viscosity on the other hand is linked to the slump flow speed. Excluding outliers that arises due to difficult in calculating the viscosity, the results seem to suggest a positive relationship between the time for the grout to flow to a 40 mm diameter mark and the viscosity. However, the time difference may be too small for accurate measurements on site without high-speed camera. Changing the reference diameter could fix this, but it might exclude some mixes that are not fluid enough to meet the mark. Overall, the slump test is a useful tool to measure the material parameters on site. The downside is that the test is not suitable for ‘soft’ mixes, which means high w/c ratio and low bentonite mixes. Also, the speed of removing the slump cone is proven to be a significant factor that affects the final shape of the grout, which is more significant for high cohesion mixes.

For the Marsh funnel test, the apparent viscosities were compared with the plastic viscosities. The results showed that there is a linear relationship between the two, and the gradient is affected by the yield stress of the mix. This arises due to the extra shear stress acting on grout from the funnel wall, assuming that grout obeys Bingham flow. The Marsh funnel results also showed a better linear fit of viscosity versus time, which contradicts the scatter of data observed in rheometer tests. However, the Marsh funnel test is only appropriate for a limited range of materials. Overall, the Marsh funnel test is not suitable for a field test to measure the real material properties since the viscosity measurement is distorted by the yield stress and therefore cannot be applied directly.

5.2 Change of Bingham yield stress and viscosity for different grout mixes

From the rheometer and Marsh funnel results, it is clear that bentonite grout exhibits Bingham fluid behaviour. The Bingham yield stress and viscosity are heavily influenced by the bentonite percentage and w/c ratio. ‘Hard’ mixes, which contain low w/c ratio and high bentonite percentages, have higher yield stress and viscosity. The opposite is

true for ‘soft’ mixes. The results suggest that there is a coupling effect between bentonite percentage and w/c ratio. By plotting the bentonite cement ratio against yield stress, there is a clear linear relationship between the two. However, due to difficulties with viscosity measurements, no conclusions can be drawn.

In terms of time dependencies, low w/c ratio has higher amount of cement inside the mixes, which means it will take more time for the cement grains to be hydrated. As the hydration process provides the gain in strength for grout, these mixes tend to have higher time dependencies. Likewise, increasing the bentonite content will also delay the hydration process and hence increases the time dependency effect. The viscosity shows little to no change within 2 hours from the rheometer measurements.

5.3 Use of MPM to model slump tests

Using the yield stress and viscosity measured from the rheometer test, the MPM simulations results showed good fit with the slump data for most cases. However, the spread is slightly underestimated which suggests that maybe the base friction is higher than the actual case. Simulations of test 1.3 and 2.3 showed large discrepancies with the measured data. This shows that estimated material parameter used might not be appropriate for these cases. Experiments may be required to obtain the actual values to improve the accuracy of the model.

5.4 Future Work

5.4.1 Range of experiment

Due to time limitations, only a limited number of tests were performed using the rheometer. Unfortunately, the only a portion of the range of the Marsh funnel tests coincide with the range of rheometer tests, therefore only a few results were presented. More results are required to proof the apparent viscosity and plastic viscosity relationships. For the slump flow test, more tests performed in the intermediate range are also required to give a more reliable relationship between the slump results and the material properties. In order to achieve full understand of bentonite grout, future experiments should include other types of cement, including CEM type 1 and different types of bentonite.

5.4.2 MPM

For this project a plain-strain model is used, which does not reflect the physical situation accurately. For future work, developing axisymmetric code would enable simulations of much more complex problems, like flow of concrete around dense rebar in deep trenches. Also the using the actual material parameters for density, Poisson's ratio and Young's modulus should improve the accuracy of the model.

5.4.3 Extending into a more complete cycle

With a working MPM codes that can accurately model slump flow, the material properties can be extracted directly from back analysis. Engineers can use modify the material parameters until the model is exactly the same as the slump results. This could eliminate the need for laboratory testing and save time for construction work.

6 Reference

- Bruce, D. A., Littlejohn, G. S., & Naudts, A. M. (1997). Grouting materials for ground treatment: a practitioner's guide. In C. Vipulanandan (Ed.), *Grouting: compaction, remediation and testing* (Vol. 66, pp. 306-334). New York: American Society of Civil Engineers.
- Ata, A., & Vipulanandan, C. (1997). Silica fume in cement and silicate grouts and grouted sands. In C. Vipulanandan (Ed.), *Grouting: compaction, remediation and testing* (Vol. 66, pp. 242-257). New York: American Society of Civil Engineers.
- Warner, J. (2004). *Practical handbook of grouting: soil, rock, and structures*. New Jersey: John Wiley & Sons.
- Gause, C., & Bruce, D. A. (1997). Control of fluid properties of particulate grouts: part 1 - general concepts. In C. Vipulanandan (Ed.), *Grouting: compaction, remediation and testing* (Vol. 66, pp. 212-229). New York: American Society of Civil Engineers.
- Perret, S., Ballivy, G., Khayat, K., & Mnif, T. (1997). Injectability of fine sand with cement-based grout. In C. Vipulanandan (Ed.), *Grouting: compaction, remediation and testing* (Vol. 66, pp. 289-304). New York: American Society of Civil Engineers.
- Eisa, K. (2008). *Compensation grouting in sand*. University of Cambridge, Department of Engineering.
- Bandara, S. S. (2013). *Material point method to simulate large deformation problems in fluid-saturated granular medium*. University of Cambridge, Department of Engineering.
- ASTM International. *Standard test method for flow of grout for preplaced-aggregate concrete (flow cone method)*. ASTM International.
- ASTM International. (n.d.). C 476, Standard specification for grout masonry; C 1019, Standard method of sampling and testing grout. 04.05.
- ASTM International. (n.d.). C 143, C 939, C 942, C 1611. *Annual Book of ASTM Standards*, 04.02.
- Bruce, D. A. (Ed.). (2013). *Specialty construction techniques for dam and levee remediation*. USA: CRC Press.
- Birch, J. K. (1997). *An investigation into increasing the interface strength of concrete dams on rock foundations by grouting*. University of Cambridge, Department of Civil Engineering.
- Lajeunesse, E., Monnier, J., & Homsy, G. (2005). Granular slumping on a horizontal surface. *Physics of fluids*, 17, 103302.

7 Appendix

7.1 Risk Assessment Evaluation

Hazard: Skin irritation when handling bentonite and hydrated cement Persons at risk: Person(s) performing experiment, technicians involved Control: All disposal and handling of all chemicals will be carried out as recommended in the MSDS sheets of each chemical. (Please see the COSHH form) Likelihood: 1 Severity: 1 Risk rating: 1 (Low Risk) Hazard: Inhaling bentonite dust when using the high-shear roller machine Persons at risk: Person(s) performing experiment, technicians involved, other persons in nearby area Control: Wearing suitable eye protection near the machine, and using a dust extractor Likelihood: 3 Severity: 1 Risk rating: 3 (Low Risk) Hazard: Dangers associated with operating high-shear roller machine Persons at risk: Person(s) performing experiment, technicians involved Control: Make sure that the machine is operated under the guidelines of the machine's manual. (R14 Roller mixer by Colcrete Eurodrill Company) Likelihood: 1 Severity: 2 Risk rating: 2 (Low Risk)

Table 5: Hazards associated with this project

1. Gloves wear worn when handling hydrated cement. There was some unavoidable contact with skin however but the skin irritation is mild. The dry bentonite powder has almost no adverse effects on skin.
2. Instead of using dust extractor, the mixing operation was performed outside. Safety helmets with face shield and air ventilation system were worn by all persons performing the experiment, which successfully reduced the inhalation of any dust particles during mixing and handling of the materials (especially cement powder).
3. No accidents incurred during the operation of the machine. Care was taken to remove the powder cables when filling and cleaning the machine. After each use, the machine was thoroughly cleaned to avoid any build up of grout inside. Lubricant was applied regularly to ensure smooth operations.

Overall the hazards within this project were of minor consequences and were mostly unlikely to occur. The procedures taken to reduce risk were adequate.