An Innovative Index to Assess Clogging Potential
by

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Abstract

Clogging frequently occurs during underground excavation using tunnel boring machines (TBMs) and can cause severe schedule delays and cost overruns on projects. However, an index to quantitatively describe clogging potential has not been standardized. This thesis presents a new index, W/A_c (the weight of soil stuck to the drill bit per unit area), to indicate clogging potential based on the results of a mixing test, and a sensitivity analysis has also been conducted to understand the effect of different types and weights of soil and different sizes of drill bit on the variability of the index.

To improve understanding of factors associated with clogging potential, a comprehensive review of previous clogging assessments approaches has been conducted. The advantages and disadvantages of previous clogging assessments have been compared and clogging classifications made by W/A_c (weight of soil stick to beater per unit area)was verified by data obtained from previous literature. Besides this, the mixing test results were also compared with previous mixing tests to ensure the accuracy of the results of this study.

The proposed index was also compared with the stickiness ratio based on standard deviation of the weight of soil stick to the drill bit over W/A_c and the stickiness ratio, respectively, to show the advantage of using the proposed index. The results show that although the mass of soil that sticks to the mixing tool varies, assessing clogging potential using the new index, W/A_c, can give more repeatable results, since it eliminates the impact of drill bit size and mass of soil. In addition, the clogging potential of different types of soil can be differentiated using W/A_c, and the average standard deviation of the test using different drill bit sizes and masses of soil is smaller using the index W/A_c compared to using the stickiness ratio. This work provides a reliable and

straightforward index to assess clogging potential easily and simply based on the results of a mixing test.

This work also investigates the sensitivity of beater shape on clogging potential by conducting mixing tests and Atterberg limit tests. The soil samples include five mixtures with varying bentonite and kaolin content. Two indices were employed to analyze the impact of beater shape in the mixing test: the weight of soil stuck to the drill bit per unit area (W/A_c) and the weight of soil stuck to the beater (G_B). In the mixing test, five samples with water contents distributed evenly between the plastic limit and liquid limit were used for each mixture. Three different shapes of beaters were employed in test. The original drill bit is the 20 qt beater for the Hobart mixer, and the metal bar was cut out to physically simulate different shapes of drill bits. Besides this, the ratio between the open area of the beater (A') and the entire surface area of a corresponding beater with no open area (A) was employed to quantify the impact of beater shape. The results show that W/A_c increases with increasing bentonite content, also increases with A'/A. The maximum W/A_c increases from 51.5 kg/m^2 to 123.4 kg/m^2 when A'/A increases from 0.52 to 0.7 for five clay mixtures, showing an increase in W/A_c by 140%. This indicates that a larger open area will cause a higher value of W/A_c. However, there is no clear trend that can be observed for different beater shapes in G_B. The variation of maximum G_B is within 0.5kg when A'/A increases from 0.52 to 0.7 for five clay mixtures, showing a difference of 12%. It is concluded that W/A_c is a good indicator to detect the impact of beater shape.

Preface

This thesis is an original work by Yang Zhou and paper based. The chapter 3 has been submitted to the Tunneling Underground Space Technology and is under review.

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Chapter 1: INTRODUCTION

1.1. Background

The tunnel boring machine (TBM) is one of the most commonly used machines to excavate tunnels. During excavation using a TBM, clogging problems are commonly occurred because cohesive clay tends to cling to the cutting head or the conveyor belt of the TBM (Alberto-Hernandez et al. 2017; Kang et al. 2019), leading to severe problems, such as schedule delay, and budget overrun (Hollmann and Thewes 2013; Spagnoli et al. 2014; Alberto-Hernandez et al. 2018). Drilling fluid is often used in underground excavation, to transport cuttings, cool down the drill bit, etc. Some chemical additives will be employed to decrease clogging potential.

Most clogging problems stem from the adhesion of soil to metal (Spagnoli et al. 2011). It is important to study the reasons behind clogging, since this is a very basic way to mitigate the clogging potential by addressing the source. However, clogging problems do not only depending on the soil type, but also other drilling parameters, such as penetration rate, applied torque, etc. (Feinendegen et al. 2010; Kang et al. 2018).

Cohesive soil becomes extremely sticky when encountering water, creating a mixture which easily sticks to the foreign metal due to adhesion. Soil clings to the surface of metal when the adhesion between the metal surface and the soil is larger than the applied shear stress (Kooistra et al 1998). Two scenarios need to be considered which might cause clogging. First, when the internal shear strength of the soil is larger than the applied stress, the bulk of the clay sticks to the metal. The second case involves shear failure within the soil sample, which occurs when the internal shear strength is less than the applied shear stress. In this case, while the bulk of the soil sample does not stick, some soil clings to the metal surface. Either of these two scenarios can cause clogging during excavation using a tunnel boring machine.

1.2. Research Objectives

The main objectives of this thesis are listed as following.

Objective 1: Conduct a literature review on previous clogging assessments and compare the advantages and disadvantages of each approach.

Objective 2: Provide repeatable mixing test results based on a new index, W/A_c (weight of soil stick to drill bit per unit area), and quantitatively assess the clogging potential of clay mixtures based on mixing test. Besides this, to assess clogging potential easily on site, a clogging classification has been introduced based on the new index, W/A_c. The accuracy of this approach has been verified using the universal diagram (Hollmann and Thewes 2013).

Objective 3: The third objective is to better understand the factors associated with clogging potential. A sensitivity analysis has been conducted for soil mass, size of drill bit and soil type to analyze how the new index, W/A_c, varies with those factors.

Objective 4: To study the effects of beater shape in clogging potential, different shapes of drill bits have been employed in mixing test. This allows a better understanding of the impact of the open area of drill bits on the results of the mixing test.

1.3. Methodology

A comprehensive literature review of previous clogging assessments has been conducted to gain better knowledge about advantages and disadvantages of each approach. The mixing test proposed by Zumsteg and Puzrin (2012) was employed in this thesis to assess clogging potential by applying a new index, W/A_c. Bentonite and kaolin were mixed according to certain percentages to obtain different mixtures. For each mixture, five samples with water contents distributed evenly between the plastic limit and liquid limit were used. A sensitivity analysis was conducted to compare W/A_c with the stickiness ratio. Besides, to provide a general assessment procedure, a clogging classification made using W/A_c has been proposed in this thesis.

The impact of beater shape was studied by employing three different shapes of drill bits in mixing test. Two indices, W/A_c and G_B (weight of soil stick to drill bit) were applied to analyze the impacts of shapes of drill bits. Additionally, the ratio (A'/A) between the open area of the drill bit (A') and the surface area of the whole drill bit with no open area (A) was employed to analyze the correlation between A'/A and the two indices.

1.4. Outline of Thesis

This thesis has the following structure:

Chapter 1: Introduction

A background of the research topic, the objectives and methodology, as well as the structure of the thesis were introduced.

Chapter 2: Literature review

This chapter introduces the history of tunnel boring machines and present different types of TBMs. Different clogging assessments, indices used in quantify clogging potential as well as clogging classifications have been introduced in this chapter.

Chapter 3: A new index to quantitatively assess clogging potential based on mixing test results

This chapter has been submitted to the Tunneling Underground Space Technology and is under review. A new index to quantitatively assess clogging potential has been proposed. The test results have been compared to data gathered from previous researchers. Mixtures with different bentonite and kaolin content were used in mixing test to represent different types of soil. A sensitivity analysis has been conducted to analyze the impacts of soil mass and size of drill bit, as well as soil type. Previous clogging assessments and different clogging classifications have been discussed from multiple aspects.

Chapter 4: The impacts of different beater shapes in mixing test

The impact of beater shape is discussed in this chapter. Three different beater shapes were employed in the mixing test. Test results based on measurements of W/A_c using the mixing test were compared with the universal diagram (Hollmann and Thewes, 2013). The impact of the open area of the beaters was analyzed using the indices W/A_c and G_{MT}. The mechanism of clogging is discussed. The open area was found to contribute to partial clogging.

Chapter 5: Summary and conclusions

This chapter presents the conclusions of this work and further research that needs to be done to study clogging potential.

Chapter 2: LITERATURE REVIEW

2.1. Introduction

2.1.1. History of Tunnel Boring Machines

Rapid development in transportation has increased the need for tunnels. The tunnel boring machine (TBM) is the most common equipment used in tunnel construction.

The first successful tunneling shield was developed by Marc Isambard Brunel in 1825. In this case, only a shield was employed in construction, while excavation work was still accomplished by manual labor. Although the shield concept worked, the project suffered flooding several times. The first boring machine is believed to have been designed in 1845, and consisted of over 100 cutters mounted in the front of the machine.

In the United States, the first machine was built in 1853, and could only excavate 10 feet of rock. In the 20^{th} century, Robbins built a machine that could excavate 160 feet in 24 hours (Zurich et al. 2009).

2.1.2. Different types of tunnel boring machine

2.1.2.1. Slurry machine

The slurry machine is a closed machine and used for excavating mixed soil with varying hardness. The slurry machine pumps slurry into the excavated material, which mixes with it to balance soil and water pressure on the tunnel face. Besides this, the excavated material will be transported outside the cutting area. This machine is most commonly used in sandy or gravely geotechnical conditions to stabilize the tunnel face (Zurich et al. 2009).

2.1.2.2. Earth pressure balance machine

The Earth Pressure Balance (EPB) machine is a typical type of TBM usually employed in soft ground and cohesive geotechnical conditions. EPB machines can turn the excavated soil into a soil paste which acts as support pressure to stabilize the tunnel face (Spagnoli et al. 2014). Therefore, clogging problems often occur in the cutter head or conveyor belt of earth pressure balance machines, because the excavated material is stickier and more cohesive. Both earth pressure balance machines and slurry machines employ closed shields, and are operated like single shield TBMs. For closed shield types of machine, frontal and lateral support are provided.

2.1.2.3. Rock machine

The rock machine is also known as main beam TBM, which is used to dig through hard rock. The machine employs a circular shield to protect workers inside the tunnel boring machine. When the machine moves forward, a rotating cutting head thrusts through the rock. Rock machines employ an open shield, which only provide lateral support (Zurich et al. 2009).

2.2. Clogging problems during excavation using TBM

Clogging is a common phenomenon that occurs during excavation using EPB machines, because EPB machines are often employed in cohesive geotechnical conditions. Sticky soil tends to cling to the cutting head and conveyor belt, leading to many problems, such as project schedule delays, and budget overrun (Hollmann and Thewes 2013; Alberto-Hernandez et al. 2017). When cohesive soil encounters a certain amount of water, it becomes sticky and tends to stick to the cutting head. The plasticity index of cohesive soil is normally large because of the high liquid limit. A higher plasticity index indicates a higher potential to cause clogging, according to the universal diagram (Hollmann and Thewes 2013).

Some researchers believe that clogging stems from adhesion. Adhesion is the attraction between soil and and a foreign metal object and includes tangential adhesion and normal adhesion.

2.3. Clogging assessment

2.3.1. Analytical approach

To date, there are many clogging assessments. Basically, three approaches are most often employed to assess clogging potential: analytical approach (Kooistra et al. (1998), semi-empirical approach (Hollmann and Thewes 2013) as well as physical simulation approach (Feinendegen et al. 2010; Zumsteg and Puzrin 2012; Peila et al. 2016; Kang et al. 2018).

In the analytical approach, the normal adhesion and cohesion of soil are compared with the applied shear stress. Normal adhesion is generally measured using the cone pull-out test (Feinendegen et al. (2010) and cohesion is measured by the vane shear test. According to Kooistra et al. (1998), there are two scenarios to consider when assessing clogging using a physical simulation approach. First, when the internal shear strength of the soil is larger than the applied stress, the bulk of the sample sticks to the metal. The second scenario involves shear failure within the soil sample, which occurs when the internal shear strength is less than the applied shear stress. In this case, while the bulk of the soil sample does not stick, some soil clings to the metal surface. Either of these two scenarios can cause clogging during excavation using a tunnel boring machine.

2.3.2. Semi-empirical approach

Hollmann and Thewes developed a universal diagram based on empirical observations (2013). This universal diagram (Hollmann and Thewes 2013) is based on simple soil properties, the plastic limit and liquid limit. It is known that when the water content of soil is closer to the liquid limit, the sample acts more like a liquid. When the water content of soil is closer to the plastic limit, the sample acts more like a solid.

The universal diagram (Hollmann and Thewes 2013) was divided into five different zones based on consistency index of soil: fines dispersing zone, little clogging zone, strong clogging zone, medium clogging zone and lumps zone. The five corresponding consistencies are liquid, very soft, medium, stiff and very stiff. The plasticity index is defined as the difference between the liquid limit and plastic limit. When the plasticity index increases, the line crossing though the clogging zone becomes wider according to the universal diagram (Hollmann and Thewes 2013), indicating there is higher chance of clogging (Hollmann and Thewes 2013).

Jancsecz et al. (1999) verified tunneling project data and stated that the clogging potential could be based on the plasticity index and plastic limit as well as liquid limit. Therefore, the semi-empirical approach is the most common method used to assess clogging potential. However, the universal diagram (Hollmann and Thewes 2013) is only based on soil properties, which does not involve any physical parameters, such as the shapes of drill bits, rotational velocity.

2.3.3. Physical simulation approach

Physical simulation approaches include indirect simulation and direct simulation. Indirect simulation approaches use a physical approach to assess clogging potential, but do not involve simulating the drilling process during the test. Direct simulation approaches involve simulating the physical drilling process.

2.3.3.1. Cone pull-out test

Feinendegen et al. (2010) proposed a cone pull-out test to measure normal adhesion. In this test, a cavity was made by a cone, and the sample material was then compacted using a Proctor compaction device. A steel cone was inserted into the pre-drilled cone with an applied load ranging from 2.3 kN/m^2 and 50 kN/m^2 for 10 minutes. The applied force then was then removed, and the cone was pulled out at rate of 5 mm/min. The required tensile force and displacements were recorded.

Feinendegen et al. (2010) used six different types of soil samples and five cones with different inclinations (10°, 31°, 45°, 58° and 72.6°). Additionally, Feinendegen et al. (2010) used adherence to quantify clogging potential, which referred to the amount of soil stuck to the cone. A classification scheme was developed by Feinendegen et al. (2010), with different clogging zones defined based on adherence. From the classification scheme, it is noted that the adherence increases with increasing consistency index, then decreases after reaching the peak, which agreed with the universal diagram (Hollmann and Thewes 2013). The clogging potential increases until reaching a peak, then decreases with increasing consistency.

However, the cone pull-out test measures the tensile force, which does not align with the practical drilling process. Therefore, using a cone pull-out test to assess clogging potential is not exactly precise.

2.3.3.2. Mixing test

Zumsteg and Puzrin (2012) proposed a mixing test to assess clogging potential based on a simple Hobart mixer. The schematic is shown in Figure 2.1. Four parts were included in the Hobart mixer, the motor, connector, beater and container. The motor converts electricity into the driving force. The connector connects the equipment with the beater. The beater is used to mix soil with a predetermined water content. The soil was added into the 20-L container, and the predetermined amount of water content was added into the soil sample. A beater is rotated in the sample for three minutes at 100 rpm using the mixer. After mixing for three minutes, the soil sample is assumed to be homogenous. The weight of soil stuck to the beater is recorded. The mixing test is one of the conventional geotechnical testing methods. The test procedure is time-saving and is easily performed. Oliveira et al. (2018) proposed a combined test, including mixing test and free fall test. The beater was dropped from a certain height after mixing test. The weight of soil stuck to the beater was recorded after the free fall. Also, Oliveira et al. (2018) pointed out that the combined approach might be limited for some mixed samples with low clay content.

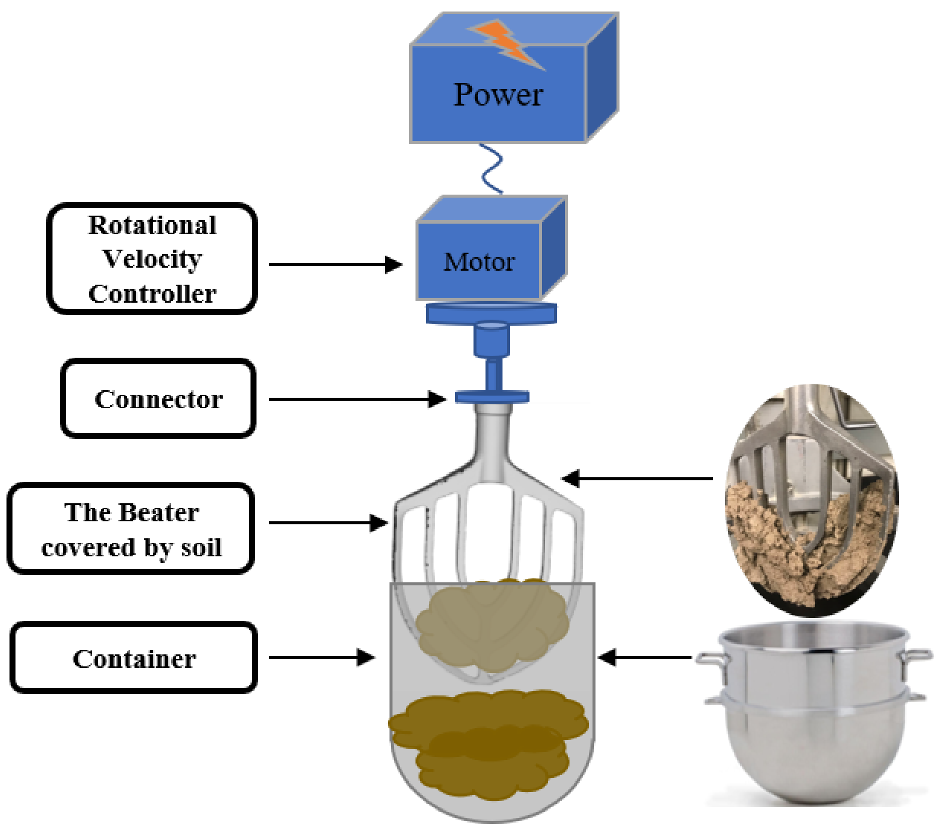

Figure 2.1. Schematic of mixing test equipment

Zumsteg and Puzrin (2012) introduced the stickiness ratio (λ) to quantify clogging potential. The stickiness ratio is defined as the ratio between weight of soil stuck to the beater (G_B) and weight of total soil used in the test (G_T). In addition, a clogging classification was made by Zumsteg and Puzrin (2012) (see Table 2.1). When the stickiness ratio is smaller than 0.2, this is defined as little clogging. When the stickiness ratio ranges from 0.2 to 0.4, thisis defined as medium clogging. When the stickiness ratio is larger than 0.4, this is defined as strong clogging.

Table 2. 1. Clogging classification made by stickiness ratio

	Stickiness ratio
Low clogging	0-0.2
Mid clogging	0.2-0.4
High clogging	>0.4

Later, Zhou (2020) collected data from different researchers who conducted mixing tests to verify this classification. The results showed the application of this clogging classification made by stickiness ratio is limited. Besides this, Zhou (2020) proposed a new index, W/A_c (the weight of soil stuck to the beater per unit area), to quantitively assess clogging potential. It was found that W/A_c is less sensitive to the total mass of soil and size of beaters compared with the stickiness ratio. Besides, the clogging potential of different types of soil is easier to distinguish using W/A_c.

2.3.3.3. Dynamic lateral adhesion test

The dynamic lateral adhesion test was proposed by Pelia et al. (2016). A flat metallic disc,120 mm in diameter and 10 mm thick, was employed to shear conditioned soil in a tank. Two jacks provide a contant presure to move the flat disc downard to shear conditioned soil samples with a rotation speed of 90 rpm. The torque required to rotate the disc is recorded. Pelia et al. (2016) also proposed a static lateral adhesion test to assess the stickiness of conditioned soil. The soil samples were compacted to a certain degree, then put on a inclined plate. The inclined angle was recorded once the sample slid down from the plate.

2.3.3.4. Drilling test

Kang et al. (2018) proposed a drilling test, shown in Figure 2.2. The test apparatus consist of a motor, ruler, and controller, as well as a drill bit. The diameter of the drill bit is 76.2 mm and its height is 24.2 mm. The ruler is used to control penetration depth and the controller manages the penetration rate. The mold is filled with the soil sample after being compacted three times and positioned underneath the drill bit. The rotational velocity of the drill bit is 30 rpm and the penetration rate is 1 mm/s. The drill bit was removed from apparatus after reaching a penetration depth of 1cm. The weight of soil stuck to the drill bit was measured and recorded as *W*. The ratio between *W* and the surface area of the drill bit was determined, defined as *WSDB* (weight of soil stick to the drill bit per unit area) by Kang et al. (2018). A sensitivity analysis then was conducted for rotational velocity, penetration depth, penetration speed and size of drill bit and mold. The drilling test proposed by Kang et al. (2018) is a relatively comprehensive test since many physical parameters are involved in it. According to Kang et al. (2018), *WSDB* is sensitive to penetration speed and rotational velocity. However, the test duration is relative long and the procedures are complex, involving a Proctor compaction test and clogging test. Besides this, the test apparatus is not portable, thus the test cannot be conducted on site.

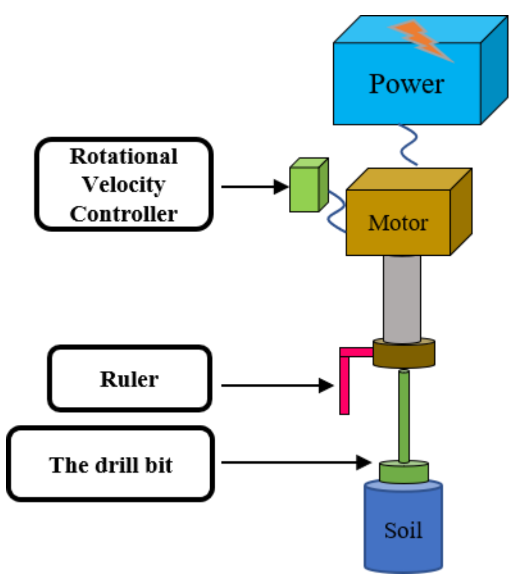

Figure 2.2. Schematic of drilling test apparatus. (adapted from Kang et al. 2018)

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Chapter 3: A NEW INDEX TO QUANTITATIVELY ASSESS CLOGGING POTENTIAL BASED ON MIXING TEST RESULTS[1]

3.1. Introduction

Earth pressure balance and slurry shield tunnel boring machines (TBMs) are frequently used in soft ground conditions. Typically, different machine types are chosen depending on the soil type, water pressure and inflow, as well as other factors (Langmaack 2002; Spagnoli et al. 2011). Clogging is the most common problem during excavation using a TBM, especially in the case of cohesive soils with a certain moisture content. In this case, fine-grain soil becomes extremely sticky and adheres to the cutter head and transportation belt, thus the project must be stopped, and tunneling operations can only be resumed after cleaning is complete (Kang et al. 2016; Alberto-Hernandez et al. 2017). Project costs rise rapidly as time is lost due to cleaning. Thus, it is extremely important to determine the clogging potential for tunneling projects (as well as other underground projects) so that corresponding mitigation measures can be taken to control potential clogging problems.

To date, there have been many methods presented in the literature to measure clogging potential. Researchers have classified clogging potential using different categories, each with their own method. The empirical universal diagram presented by Hollmann and Thewes (2013) categorizes clogging potential based on plastic limit and liquid limit. Feinendegen et al. (2010) developed a clogging classification based on the use of adherence to quantify the amount of soil stuck on the cone after a cone pull-out test. Zumsteg and Puzrin (2012), on the other hand, use the stickiness ratio to categorize clogging potential.

1 This chapter has been submitted to the Tunneling Underground Space Technology and is under review.

Three approaches often used to assess clogging potential: the analytical approach (Kooistra et al. 1998), the semi-empirical approach (Hollmann and Thewes 2013) and physical simulation (Feinendegen et al. 2010; Zumsteg and Puzrin 2012; Peila et al. 2016; Kang et al. 2018).

In analytical approaches, the clogging potential is assessed by comparing the cohesion within the soil and adhesion between the soil and an external object, with a shear stress applied on the soil (Kooistra et al. 1998). Cohesion can be obtained using the vane shear test and adhesion can be tested by a modified direct shear apparatus (Alberto-Hernandez et al. 2017).

In empirical approaches, clogging is assessed according a universal diagram proposed by Hollmann and Thewes (2013). The plastic limit and liquid limit, as well as water content of the soil, are used to determine the corresponding clogging potential. From the resulting diagram, it can be noted that the possibility of clogging is high for soils with a high plasticity index. Some researchers have also stated that higher clogging potential can occur with higher liquid limit and plasticity index due to the swelling potential. The empirical diagram (Hollmann and Thewes 2013) qualitatively shows the clogging potential.

In physical simulation approaches, clogging potential is assessed by simulating the physical drilling process. According to Kooistra et al., soil clings to the surface of metalwhen the adhesion between metal surface and the soil is larger than the applied shear stress (1998). There are two scenarios to consider when assessing clogging using a physical simulation approach. First, when the internal shear strength of the soil is larger than the applied stress, the bulk of the sample sticks to the metal. The second case involves shear failure within the soil sample, which occurs when the internal shear strength is less than the applied shear stress. In this case, while the bulk of the soil sample does not stick, some soil clings to the metal surface. Either of these two scenarios can cause clogging during excavation using a tunnel boring machine.

Physical simulation approaches can be broken down into direct drilling simulations and indirect simulations. The cone pull-out test is an indirect simulation approach, proposed by Feinendegen et al. (2010), who developed an apparatus to measure the tensile force between the soil and the metal surface using a cone. The tensile force is the normal adhesion between the soil sample and the cone. Various soil samples with different consistency indices have been used to evaluate the correlation between adherence and consistency index. Adherence refers to the amount of soil stuck on the cone. To determine adherence, a soil sample is mixed with water to achieve the desired water content, then stored for 48 hours to allow for the water to be distributed evenly. The sample is then compacted using a standard proctor device. A force of a magnitude dependant on the consistency index is applied so that the cone is inserted into the soil sample at a rate of 0.23 mm/min. The load is then removed, and another force is applied to pull the cone out at a rate of 5 mm/min. The force required to pull out the cone is recorded, and the amount of soil stuck on the cone after the cone has been pulled out of the sample completely is measured. The cone pull-out test measures the tensile force required to pull the cone out of the soil sample and the amount of soil stick to the cone. However, some researchers believed that clogging stems from tangential adhesion (Spagnoli et al. 2011) rather than normal adhesion; thus, it may not be accurate to measure clogging potential based on normal adhesion.

A mixing test to assess clogging was proposed by Zumsteg and Puzrin (2012). In order to quantitatively evaluate the clogging potential, Zumsteg and Puzrin (2012) introduced the stickiness ratio, λ, which is the ratio of the weight of soil stuck to the beater (G_B) and the total weight of soil (G_{TOT}). The soil is added to a 20-liter basin, and a beater is rotated in the sample for three minutes at 100 rpm using a Hobart mixer. After mixing for three minutes, the soil sample is assumed to be homogenous. The weight of soil stuck to the beater is recorded. The advantages of using a mixing test to determine clogging potential is that it is straightforward and time-saving. Furthermore, the apparatus is portable, which makes it possible to measure the clogging potential of soil samples onsite. However, the results of the mixing test are not repeatable; that is, the stickiness ratio determined using the test could vary for the same sample.

Peila et al. (2016) proposed two tests, a dynamic adhesion test and a static adhesion test. In the dynamic adhesion test, a metallic disc (120 mm in diameter and 10 mm thick) rotating at 90 rpm is positioned on top of a soil sample. The force applied to the rotating disc to cause it to move downward at a constant controlled rate is then measured. In the static adhesion test, a force of 10 N was applied to soil sample using the upper plane of a metallic wedge. The lower plane of the wedge is then tilted until the soil sample slides down the lower plane, and the angle at which the sample begins to slide is recorded. According to the author (Peila et al. 2016), the presence of water or an additive could effectively change the cohesive potential of the soil.

Kang et al. (2018) introduced a drilling apparatus to assess clogging, using the amount of soil stuck on a drill bit per unit area to quantify clogging potential. Since the drill bit used in the test is rotating, tangential adhesion is measured. The test apparatus is composed of four parts, a drill bit, a power supply, a motor and a penetration controller. The penetration controller is used to regulate the penetration rate, and a ruler is used to determine the penetration depth. In the procedure developed by Kang et al. (2018), a steel mold is filled with soil in three separate layers, with each layer compacted using 25 blows. Following compaction, the mold is placed underneath the drill bit, and the drill bit is used to shear the soil sample, moving downward at a rate of 1 mm/s. The drill bit is then removed and weighed to determine the total weight of the drill bit and soil stuck to it. After this, the weight of soil stuck on the drill bit per unit area (*WSDB*) is determined. A higher *WSDB* indicates a higher clogging potential. Kang et al. (2018) conducted a sensitivity analysis to determine the correlation between *WSDB*, penetration depth, penetration speed, size of drill bit, size of sample mould and rotational velocity. The results of the sensitivity analysis indicate that *WSDB* is sensitive to both rotational velocity and penetration speed. This drilling test for measurement of clogging potential developed by Kang et al. (2018) is more comprehensive than other tests, since it considers the movement of the drill bit to simulate the actual movement of the cutter head during drilling using a TBM.

A summary of the available tests for measuring clogging potential, along with their advantages and disadvantages, is given in Table 3.1.

Table 3. 1. Summary of literature test methods designed to measure clogging potential, along with proposed mixing text

Approach	Tests	Index Measured	Advantage	Disadvantage	References
Analytical approach	**Vane shear test, direct shear test**	Adhesion, cohesion, shear stress	Comprehensive repeatable	Complex, time consuming	Kooistra et al. (1998); Alberto-Hernandez et al. (2017)
Semi-empirical approach	**Atterberg limit test**	Plastic limit, liquid limit	Straightforward repeatable	Limited applications, time consuming	Hollmann and Thewes (2013)
Physical simulation	**Cone pull-out test (indirect simulation)**	Normal adhesion, adherence	Straightforward, comprehensive	Inaccurate	Feinendege et al. (2010)
	Drilling test	Weight of soil stuck on drill bit per unit area (*WSDB*)	Comprehensive, repeatable	Complex, time-consuming	Kang et al. (2018)
	Dynamic lateral adhesion test	Force required to rotate metal disc	Straightforward, comprehensive		Peila et al. (2016)

Previous mixing test	Stickiness ratio (λ)	Straightforward, timesaving	Not repeatable	Zumsteg and Puzrin (2012)
Current study	Weight of soil stuck on beater per unit contact area (W/A_c)	Straightforward, timesaving, repeatable		

Although many tests have been proposed by previous researchers to assess clogging potential, to date a standardized index to evaluate clogging potential does not exist. In this paper, a new index that can be used to assess clogging potential from a mixing test is introduced, based on the weight of soil stuck on a beater per unit contact area (W/A_c) after mixing, rather than the the stickiness ratio (λ). The clogging potential of different types of soil is assessed using the new index, W/A_c. In addition, clogging potential classifications using W/A_c and stickiness ratio have been compared with the universal diagram developed by Hollmann and Thewes (2013). Finally, a sensitivity analysis has been conducted for soil mass, sizes of beater, and type of soil. The difference between the new index and previous indices will also be investigated in this paper.

3.2. Methodology

3.2.1. Material

It is known that bentonite is an extremely sticky clay with a high plasticity index, while kaolin is a common clay with a low plasticity index, indicating low clogging potential (Liu et al. 2019). Bentonite and kaolin were thus chosen to be used for standardized samples in this research Bentonite (AQUAGEL GOLD SEAL®) and kaolin (EPK) were mixed in predetermined ratios in order to give samples with a range of plasticity, as measured by the plasticity index. Laboratory mixing tests were conducted on five clay mixtures with different contents of bentonite and kaolin, referred to in this work as M^{10}, M^{30}, M^{50}, M^{70}, and M^{90}, with the superscript used to indicate the percentage of bentonite content. Table 3.2 shows the liquid limits and plastic limits for pure bentonite (M^{100}) and kaolin (M^{0}), as well as other properties measured in laboratory, including the specific surface area (SSA), the methylene blue value (MBV), and the cation exchange capacity (CEC). The major mineralogical component of kaolin and bentonite is kaolinite and montmorillonite respectively. Besides the kaolinite and montmorillonite, small amounts of quartz and gypsum also exist in the kaolin and bentonite (Kang et al. 2019). The particle size of kaolinite is relatively small, around 0.2 µm, whereas the particle size of bentonite is approximately ten times greater, around 1.2 µm.

Table 3. 2. Properties and basic parameters of bentonite and kaolin measured in lab (adapted from Kang et al. (2019))

	M^{0}	M^{100}
Bentonite content (%)	0	100
Kaolin content (%)	100	0
Plastic limit (PL)	33%	44%
Liquid limit (LL)	56%	392%
Plasticity index (PI)	23%	348%
SSA (m^2/g)	82	988
MBV (g/100g)	3.4	40.4
CEC (meq/100g)	11	126

3.2.2. Atterberg Limit Test

An Atterberg limit test was conducted to determine the plastic limit (*PL*) and liquid limit (*LL*) of each sample. The consistency index, I_c, calculated as in Equation [1], in a given range corresponds to the clogging potential, which indicates the firmness of soil based on plastic limits and liquid limits, as well as water content. The Atterberg limits of the soil samples to be tested were determined according to ASTM D4318-17. Bentonite and kaolin powder were measured by weight, mixed, and then put in an oven at 150°C for 12 hours to ensure that the soil samples were completely dry. After drying, the soil samples were then processed by passing them through a 425-µm sieve (No. 40). The liquid limit was determined by the multipoint method. The soil was rolled into 3.2 mm diameter threads until it fell apart. The small pieces of soil were then collected and put back in the oven. After drying, the plastic limit was determined.

$$I_c=(LL-W_c)/(LL-PL) \quad [1]$$

3.2.3. Mixing test

After determining the Atterberg limits, the mixing test was conducted for each of the samples. Figure 3.1 indicates a schematic diagram of the equipment used for the mixing test. The apparatus has four key components: a motor, a rotational velocity controller, a beater and a container. The power provides mechanical force to the motor. The rotational velocity controller regulates the rate of rotation of the beater. The beater is removable and is used to shear the soil to simulate cutter head movement in a TBM. Different sizes of containers were employed to allow for different sizes of beaters to be used. A 3D-scan was performed on the beater to generate a 3D model for calculation of the surface area.

The soil samples were prepared for the mixing test as follows. Bentonite and kaolin powder were weighed and put into the mixing container. The dry powders were mixed using the beater for three minutes to ensure even mixing. A predetermined amount of distilled water was then added to the sample until a certain consistency was achieved in first 30 seconds while mixing (to avoid lump formation). Following the addition of the water, the soil was then mixed for another three minutes, according to the method described by Zumsteg et al. (2016).

The stickiness ratio proposed by Zumsteg and Puzrin (2012), as shown in Equation 2, will be compared with the new index, W/A_c, in this paper. The weight of the beater before and after mixing were recorded as W_1 and W_2, respectively. After mixing, a caliper was used to measure the distance that the soil extended up the beater from the top of the bit. This distance was entered in Autodesk Netfabb Premium 2019. Using Netfabb and a model developed from the 3D scan of the beater, the surface area of the part of the beater covered by soil was determined and recorded as A_c. The clogging potential was then quantified using A_c, the weight of soil stuck on the beater per unit area, and W_1 and W_2, as shown in Equation [3].

$$\lambda = G_B/G_{TOT} \quad [2]$$

$$W/A_c = (W_2 - W_1)/A_c \quad [3]$$

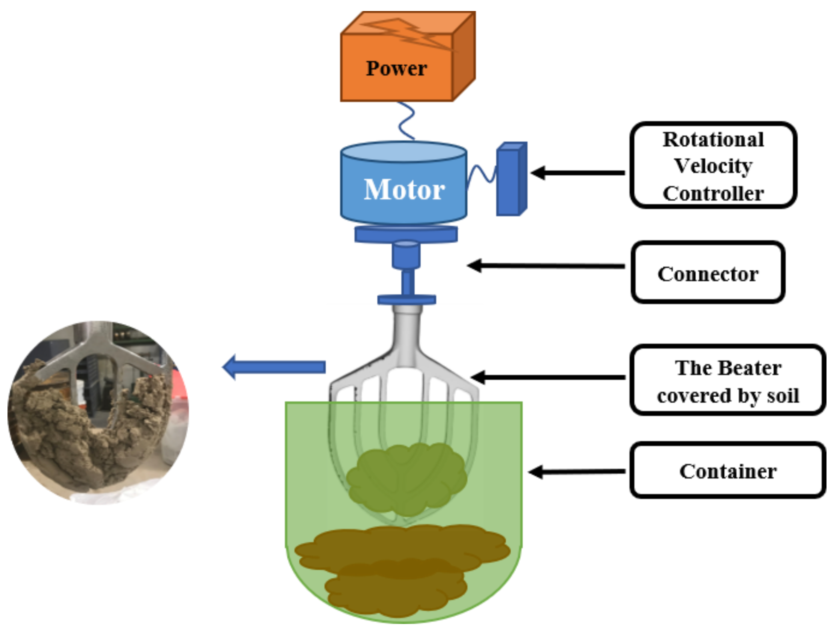


Figure 3. 1 Schematic of Hobart mixer used for mixing tests

The mixtures M^{10}, M^{50}, and M^{90} were chosen to evaluate how different types of soil affect the ratio W/A_c as determined from the mixing test. These soil mixes were chosen as they cover a range of clogging potential, from low to high clogging.

The procedure outlined above was also conducted with different masses of dry soil mix (0.5 kg, 1 kg, 1.5 kg and 2 kg) of a mixture of 50% bentonite and 50% kaolin, M^{50}, to verify whether the mass of soil used for testing affects W/A_c. Different sizes of beaters were also used to evaluate the effect of size of the beater.

3.3. Results

3.3.1. Atterberg Limit Tests

Figure 3.2 shows the linear relationship for both liquid limit and plasticity index with increasing bentonite content. The liquid limit was found to increase from 94% to 445% as the bentonite content increased, whereas the plastic limit was observed to vary only slightly, within 5%. The plasticity index increases drastically with increasing bentonite content in the samples, indicating a higher possibility of clogging based on the universal diagram (Hollmann and Thewes, 2013).

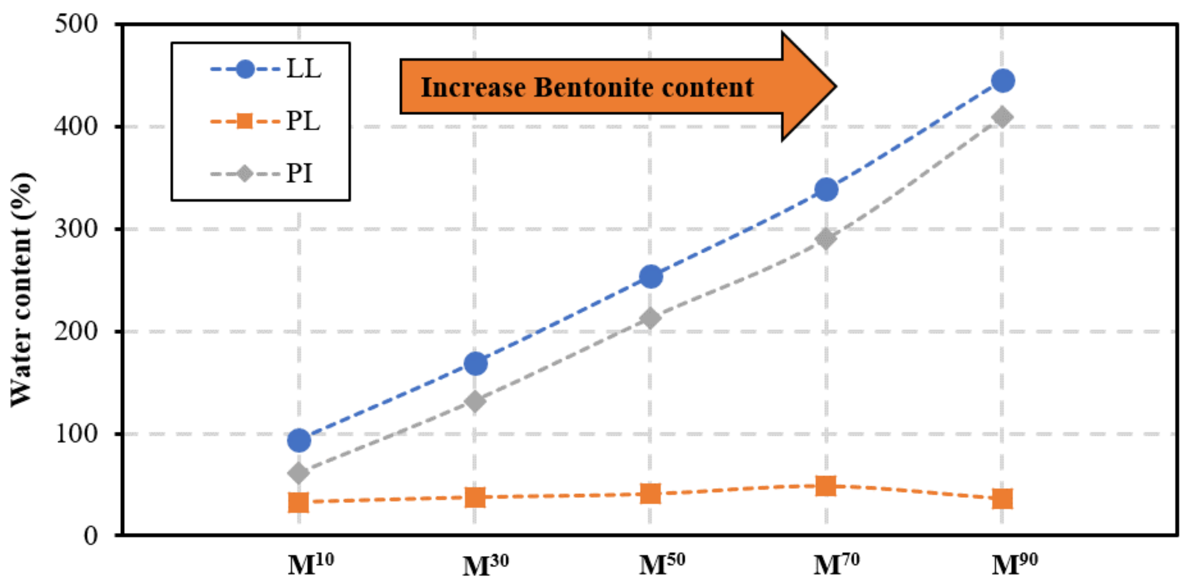


Figure 3. 2 Atterberg limit test results for mixtures with different bentonite contents (the superscript Mx indicates the percentage by weight of bentonite in the mixture).

3.3.2. Mixing test

Five samples with different water content distributed evenly between the *PL* and *LL* were used for each mixture. For each type of soil, the weight of soil stuck on the beater at first increases, then, after peaking, it decreases in accordance with the decrease of I_c. The same tendency can be found in the correlation between height of soil extended up the beater and I_c.

Figure 3.3 shows the correlation between the surface area covered by soil and the height of soil on the beater as measured from the bottom of the bit. After measuring the height of the beater covered by soil using a caliper, the surface area of beater covered by soil can be interpolated, as shown in Figure 3.3. Using this surface area, the parameter W/A_c can be determined for different types of soil samples.

Figure 3.4 shows the W/A_c of the mixtures M^{10}, M^{30}, M^{50}, M^{70}, M^{90} as determined by the mixing test. The weight of soil per unit area of beater, W/A_c, peaks at a consistency index, I_c, ranging from 0.5 to 0.6 for each type of soil that is defined as high clogging according to the universal diagram proposed by Hollmann and Thewes (2013). Besides this, the average W/A_c for each type of soil was calculated.

The area under each curve was integrated, and the average W/A_c can be obtained. It is noted that the average W/A_c increased with increasing bentonite content. W/A_c increased from 25.10 to 34.16 kg/m^2 when the bentonite content in the mixture increased from 10% to 90%. The standard deviation indicates the variation in W/A_c.

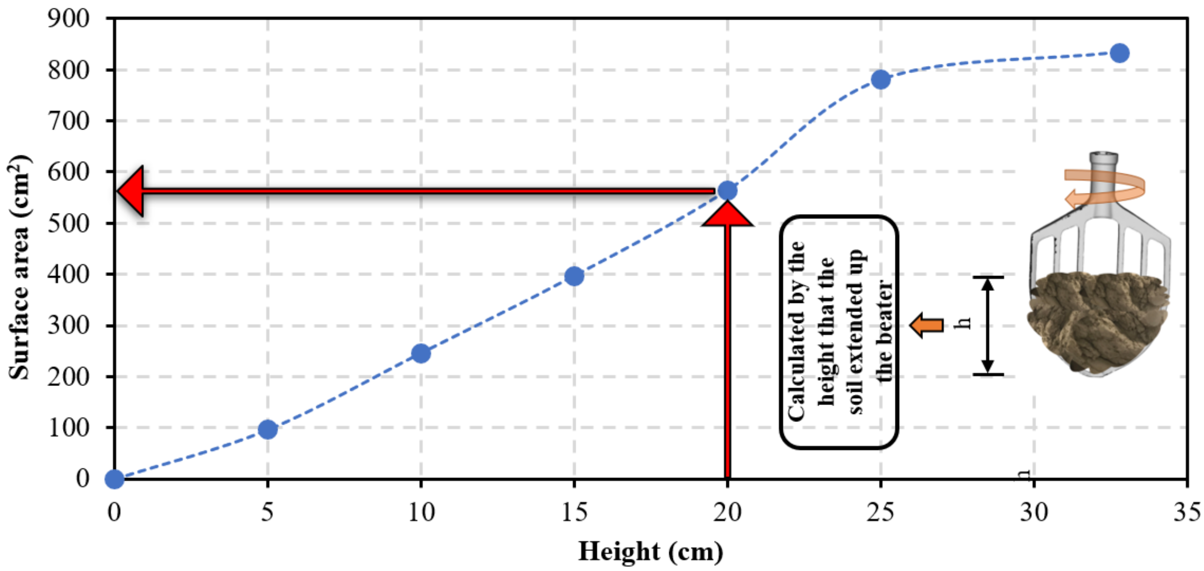


Figure 3. 3The correlation between surface area and height of beater from bottom of the beater to top of the soil

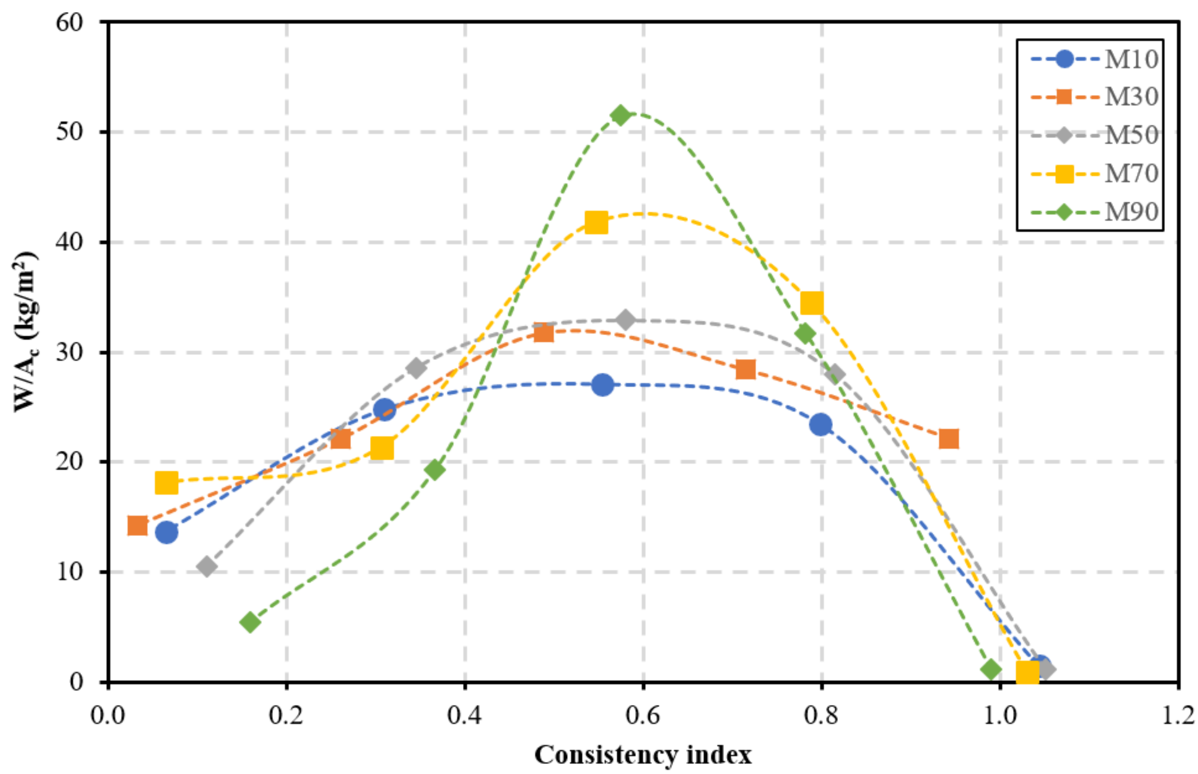


Figure 3. 4. Results for W/A_C determined based on mixing test

3.3.3. Verification of previous clogging categories using stickiness ratio

Table 3.3 shows the clogging potential categorized into three different zones (Zumsteg et al. 2013), high clogging ($\lambda > 0.4$), medium clogging ($0.2 < \lambda < 0.4$) and low clogging ($\lambda < 0.2$). The author did not mention the reason why the clogging potential was classified in this way. It is assumed that the clogging classification was based on empirical observations.

Data sets from Sebastiani (2016), Oliveira (2018) and Zumsteg (2012) were combined to verify the empirical clogging categories suggested by Zumsteg. Figure 3.5 shows the clogging classification classified by I_c based on the universal diagram (Holmann and Thewes 2013). Samples with I_c ranging from 0 to 0.5 are defined as having low clogging, from 0.5 to 0.75 as high clogging and larger than 0.75 as medium clogging. From the graph, it is seen that the clogging potential cannot be distinguished by the stickiness ratio due to the random distribution of the data. It is noted that the range of the stickiness ratio is large in the low, high or medium clogging categories. The stickiness ratio is expected to increase, then decrease after reaching a peak when I_c are in the range of 0 to 1. However, a correlation between stickiness ratio and I_c cannot be found in the data depicted in Figure 3.5. The data points from this study, which are marked in red in Figure 3.5, are classified as low clogging based on universal diagram (Hollmann and Thewes 2013). However, the stickiness ratio of these points ranges from 0.4 to 0.7, indicating that the clogging potential cannot be classified in terms of the stickiness ratio (Zumsteg and Puzrin (2012).)

Table 3. 3. Clogging categories proposed by Zumsteg and Puzrin (2012).

	Stickiness ratio
Low clogging	0-0.2
Mid clogging	0.2-0.4
High clogging	>0.4

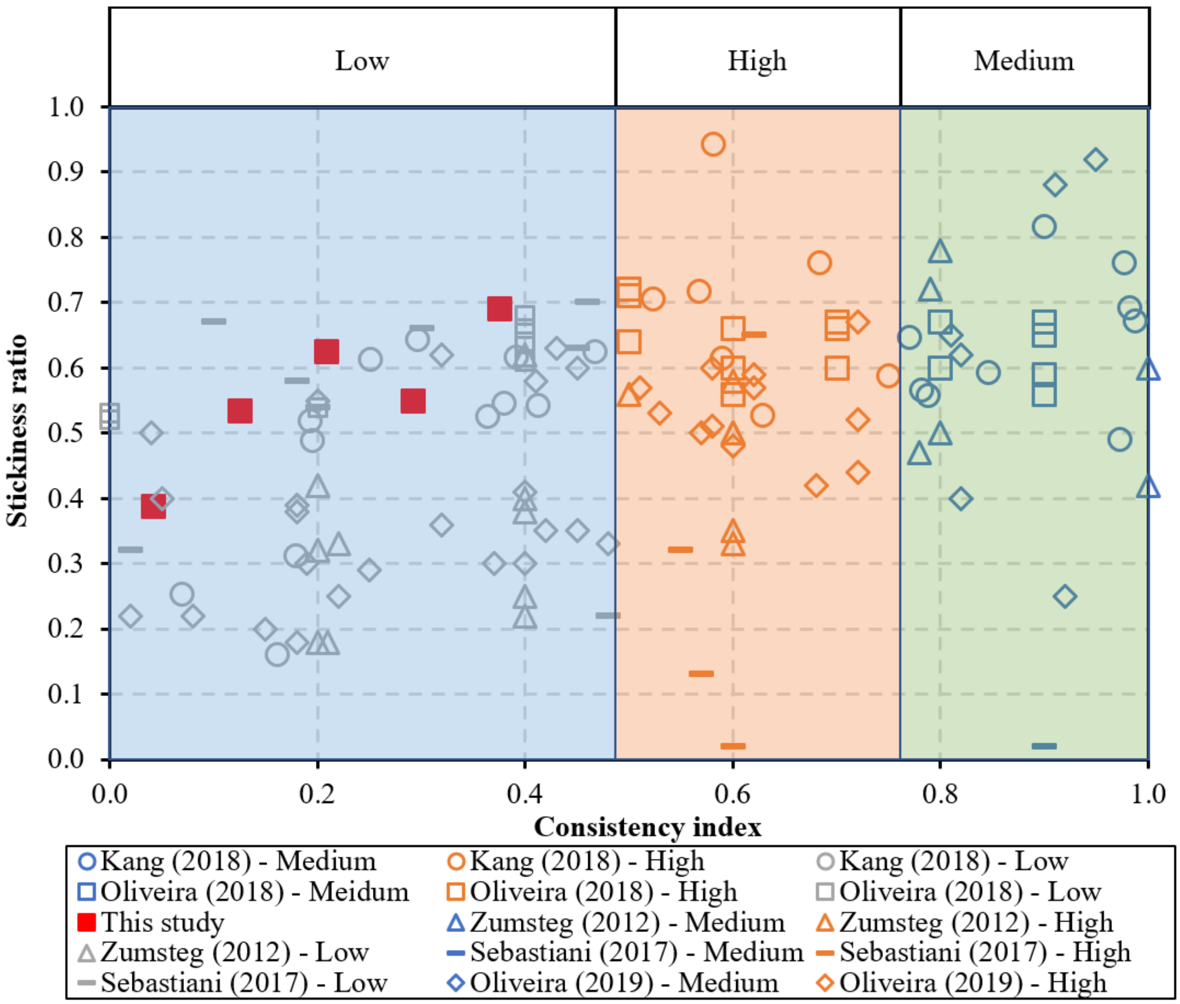


Figure 3. 5. Classification of stickiness ratio. The area shaded blue indicates low clogging potential, the area shaded orange indicates high clogging potential, and the area shaded green indicates medium clogging potential.

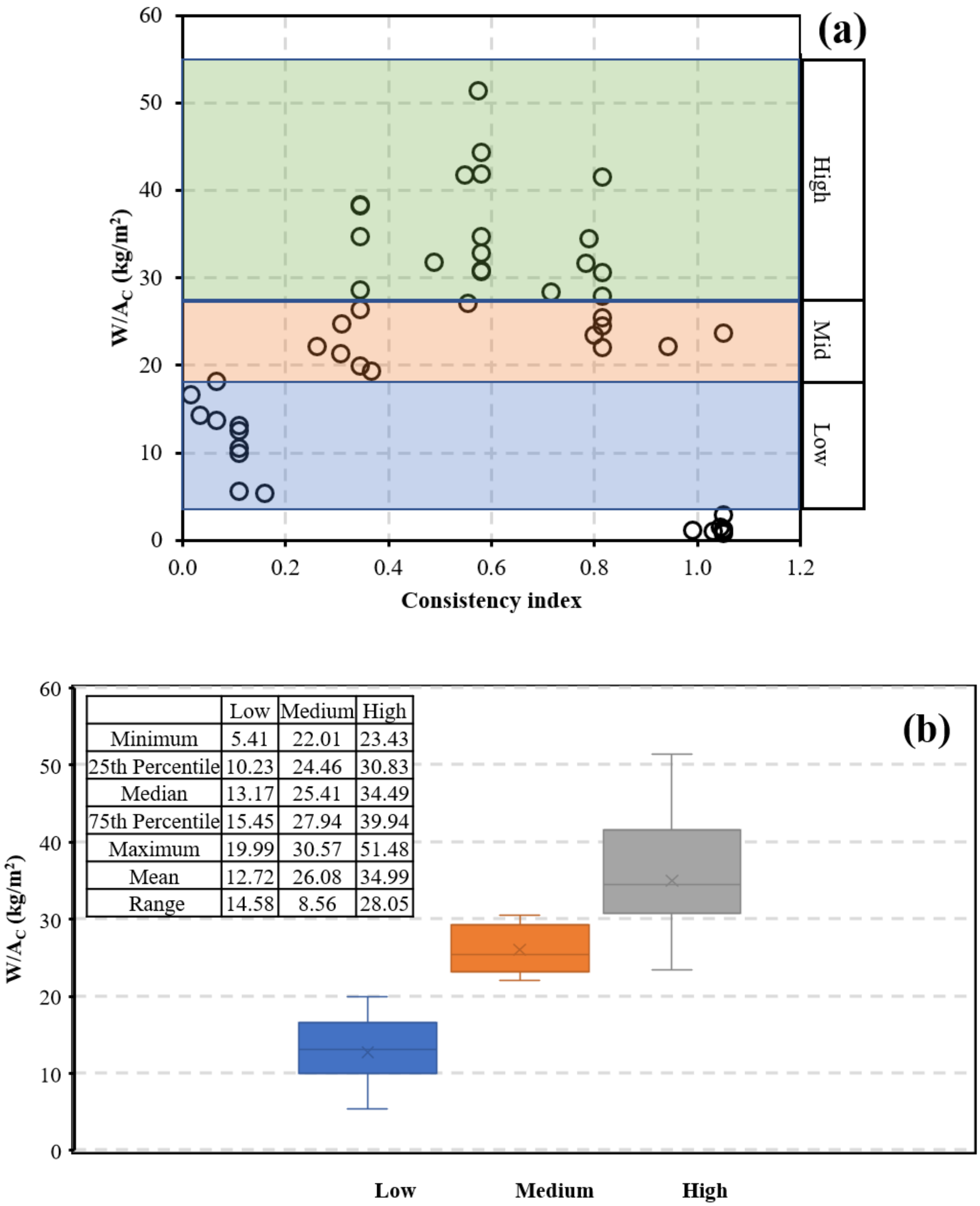
3.3.4. Clogging potential classification in W/A_c

Figure 3.6(a) shows a proposed clogging classification using W/A_c. The classification was made based on universal diagram (Hollmann and Thewes 2013) and the statistical distribution of W/A_c

shown in Figure 3.6(b). Mixtures with a value of W/A_c ranging from 3 to 20 are defined as having low clogging potential, and 20 to 30 as medium clogging. Any value of W/A_c greater than 30 indicates high clogging. If W/A_c is in the range 10 to 20, this is defined as low clogging, for 20 to 30, medium clogging, and greater than 40, high clogging.

The new index W/A_c at first increases (as does I_c), then declines after reaching a peak. Compared to the classification proposed by Zumsteg and Puzrin (2012), the newly proposed category corresponds more closely to the universal diagram (Hollmann and Thewes, 2013). Furthermore, more repeatable test results can be obtained using W/A_c.

Considering the points discussed above, the index W/A_c is a more reliable means to quantify clogging potential. It also has the advantage that it can be used on site, since the mixing test apparatus is portable. In addition, the test process proposed in this work is straightforward and requires little time. Compared to the universal diagram (Hollmann and Thewes 2013), the measurement of W/A_c is much easier than determination of the Atterberg limit and water content of a soil mixture.



	Low	Medium	High
Minimum	5.41	22.01	23.43
25th Percentile	10.23	24.46	30.83
Median	13.17	25.41	34.49
75th Percentile	15.45	27.94	39.94
Maximum	19.99	30.57	51.48
Mean	12.72	26.08	34.99
Range	14.58	8.56	28.05

Figure 3. 6 (a) Classification of clogging potential made on the basis of determination of W/A_c: The blue shaded area indicates low clogging, the orange shaded area indicates medium clogging, and the green area indicates high clogging. (b) Classification of clogging potential using a box chart.

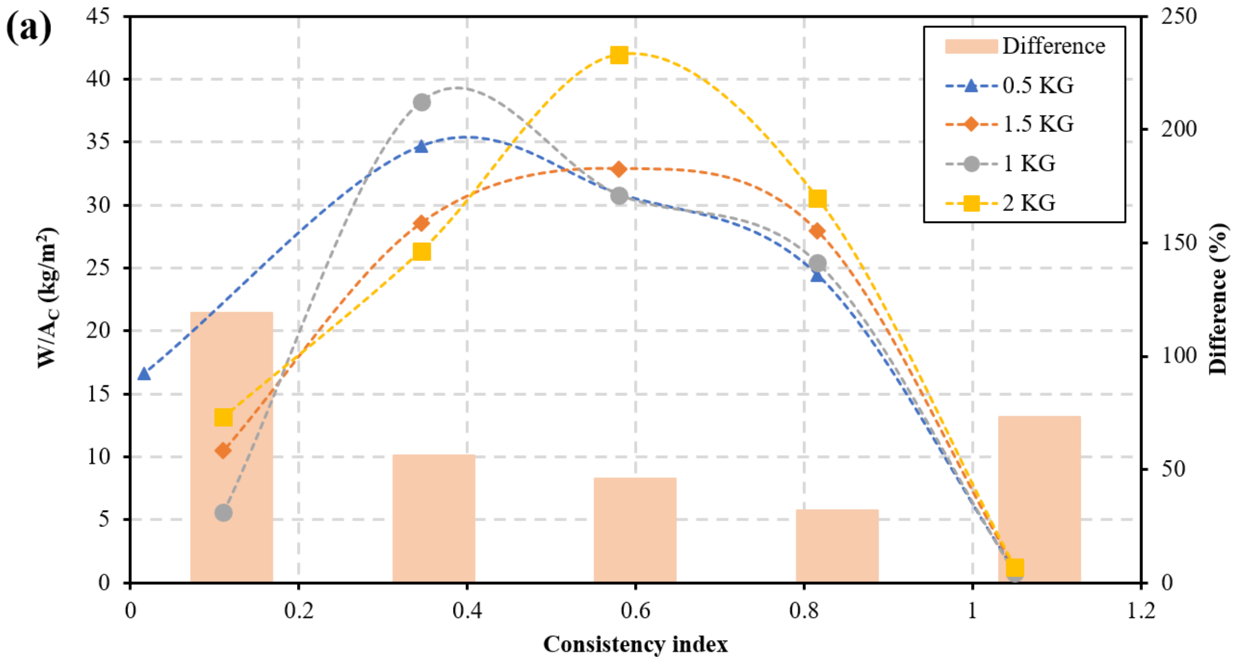
3.4. Sensitivity analysis

The new index W/A_c has been proposed to assess clogging potential of different types of soil. Undoubtedly, however, there will be some other factors that influence the test results, such as total mass of soil used in the test, or the size of beater used, among others. It must be demonstrated that W/A_c is independent of mass of soil or size of beater to show that there is no impact of mass of soil or size of beater on W/A_c. To evaluate how W/A_c changes with mass of soil or size of beater used in the test, a sensitivity analysis was conducted.

3.4.1. Soil mass

A mixture of 50% bentonite and 50% kaolin (M^{50}) by weight was used to conduct a sensitivity analysis on the effect of the mass of sample in the mixing test. Tests on each of four different masses (0.5 kg, 1 kg, 1.5 kg and 2 kg) of the M^{50} mixture were conducted with five different water contents, corresponding to an I_c range from 0 to 1. It was found that the test conducted with 0.5 kg of the M^{50} mixture resulted in one third of the beater being covered by soil, while the test conducted with 2 kg of the M^{50} mixture resulted in the beater being completely covered with soil.

The average W/A_c was calculated for each consistency, and then the absolute value of the difference between W/A_c for the four soil masses and average W/A_c was calculated. The absolute value of the difference in percentage was then determined. The average difference then was calculated (shown as bar charts on secondary axis in Figure 3.7) indicating the average variation of W/A_c these four different masses. The difference of W/A_c is smaller than the difference of stickiness ratio, indicating that the index (W/A_c or stickiness ratio) is less sensitive than stickiness ratio to the variation of mass. From Figure 3.7, it can be seen that, as expected, the index *W/Ac* is not sensitive to the mass of soil used in the test.



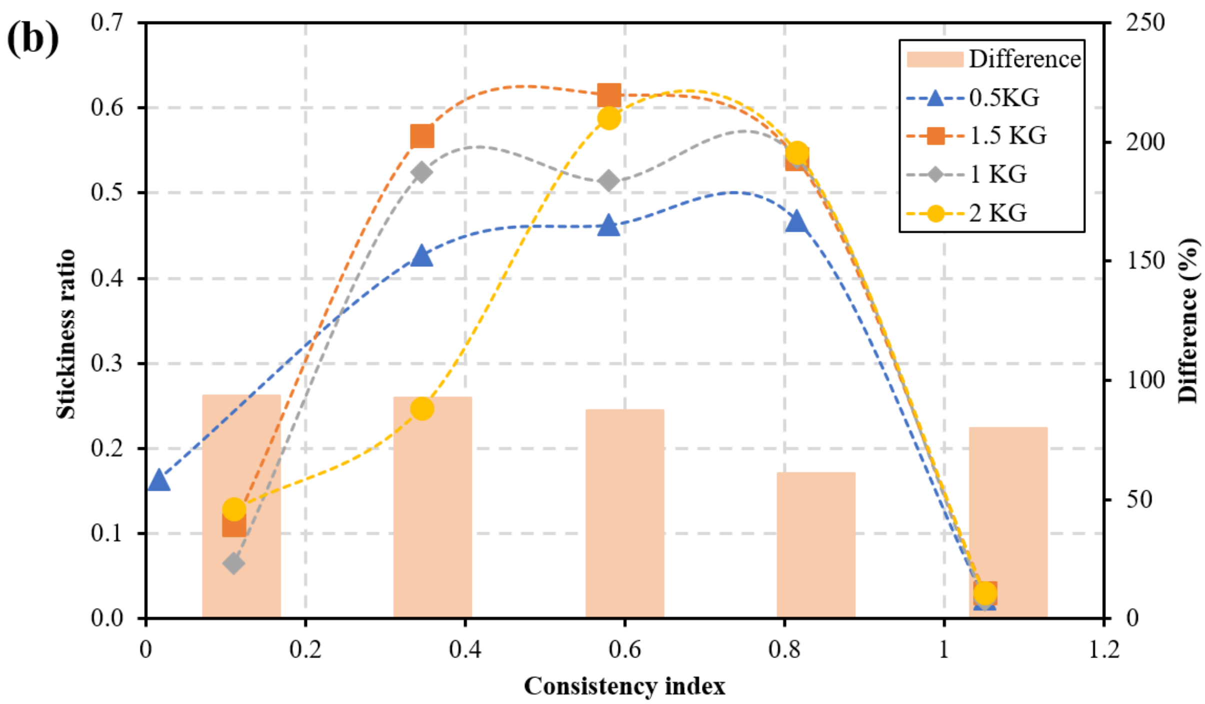


Figure 3. 7 Mixing test results in (a) W/A_c vs. I_C and (b) stickiness ratio vs. I_C, along with % difference.

3.4.2. Size of beater

Two different sizes of beaters were employed in testing. The dimensions of both beaters are shown in Figure 3.8, and these bits were used to verify whether W/A_c is sensitive to the size of the beater. The surface areas of the beaters are 834.5 cm^2 and 274.9 cm^2, repectively. For each test, 500 grams of a 50% mixture of bentonite and kaolin (M^{50}) was used. Results are shown in Figure 3.9, with a secondary axis added to the graphs to show the difference in results for tests conducted with the 20-liter beater and the 5-liter beater. The difference is defined as absolute value of the difference between W/A_c for the 20-liter beater and 5-liter beater, divided by W/A_c for the 20-liter beater. Figures 3.9 (a) and (b) show less difference between results for two different beaters is observed for W/A_c compared to the consistency index. A smaller difference in W/A_c indicates that the index (W/A_c or stickiness ratio) is less sensitive to the size of beater.

However, it should be noted that since only two different beaters were tested, using beaters that had different capacities, these results do not provide a solid conclusion that W/A_c is independent of the size of the beater at this point. It is necessary to conduct more tests using different beaters (ideally with the same beater) to verify this point.

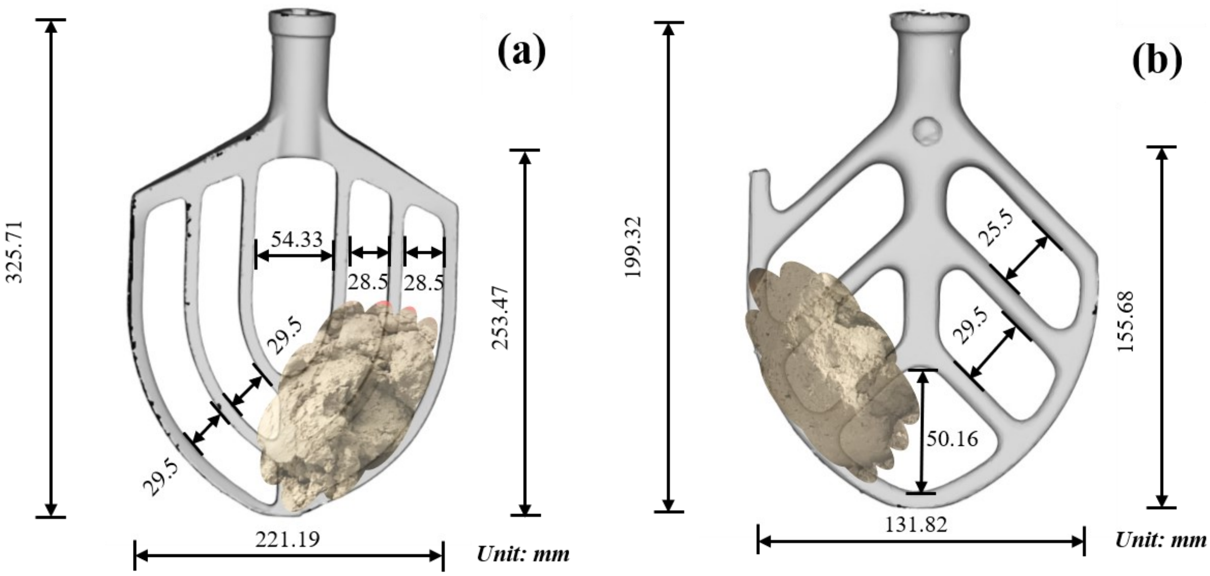
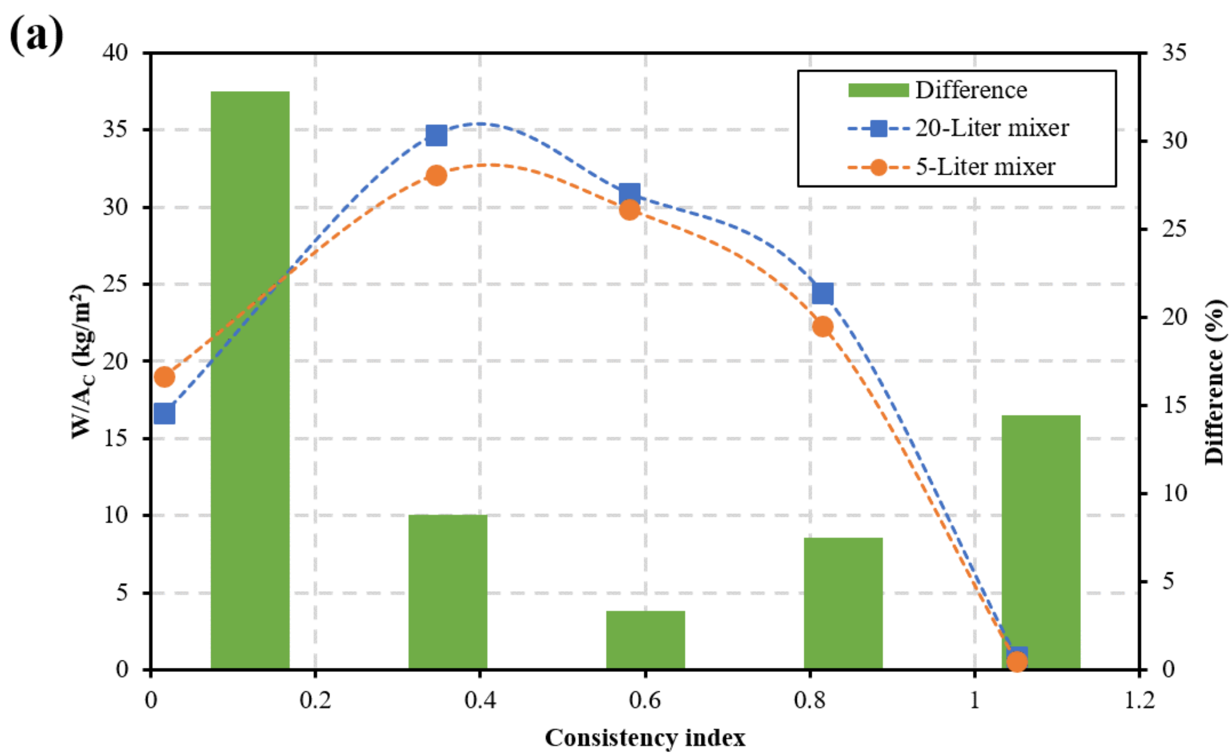


Figure 3. 8 Dimensions and shape of (a) the beater used in the 20-liter beater and (b) the beater used in the 5-liter beater



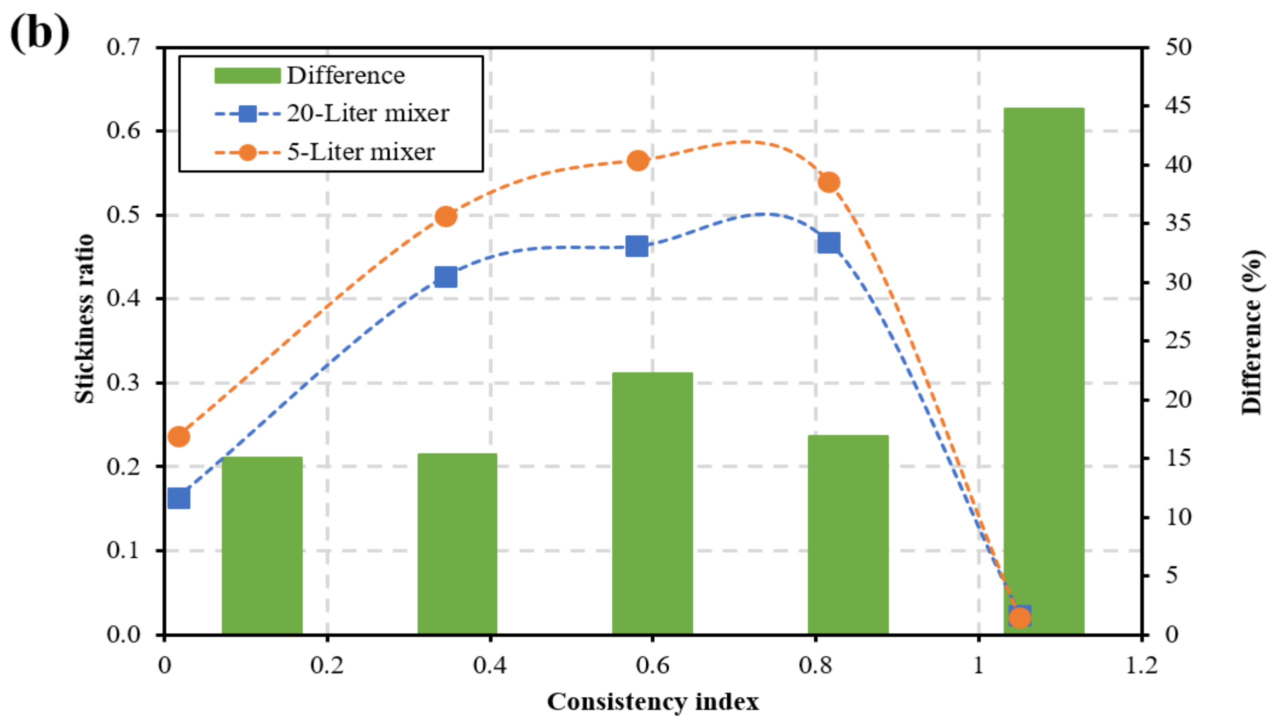


Figure 3. 9 Graph of (a) W/A_c vs. I_c for 20-liter beater and 5-liter beater, along with % difference between tests conducted using the two beaters and (b) stickiness ratio vs. I_c for 20-liter beater and 5-liter beater, along with % difference.

3.4.3. Soil Types

The mixing test was performed for different bentonite and kaolin contents to determine whether W/A_c can be used to differentiate the clogging potential of different types of clay. The mixing test was repeated for 2 kg of M^{10}, M^{50} and M^{90}, with results shown in Figure 3.10. Figure 3.10(a) shows that W/A_c is highest for M^{90}, peaking at 44.42 kg/m^2 when I_c is around 0.58. The values of W/A_c determined for M^{10} are obviously smaller than for M^{50} and M^{90}, indicating that M^{10} (which contains 10% bentonite) is the mixture with the least clogging potential. On top of that, Figure 3.10(a) shows the same trend as in the universal diagram (Hollmann and Thewes, 2013). It is also known that the clogging potential increases as bentonite content increases. As can be seen in Figure 3.10(b), there is no obvious trend that can be found based on the stickiness ratio of different soil types, therefore the stickiness ratio fails to differentiate which bentonite/kaolin mix exhibits more clogging than other mixtures.

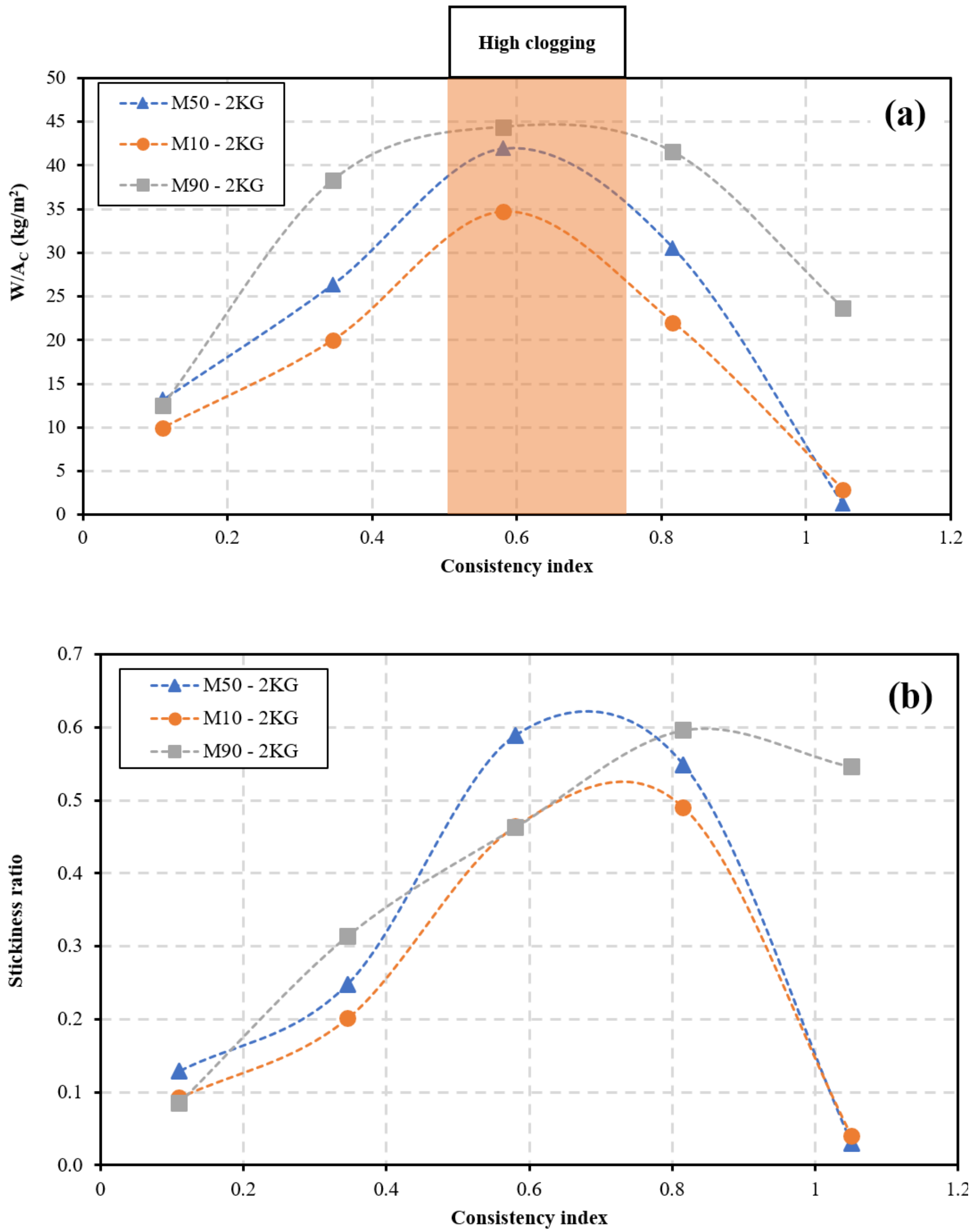


Figure 3. 1 Graph of (a) W/A_C vs. I_C for M^{10}, M^{50} and M^{90} and (b) stickiness ratio vs. I_C for M^{10}, M^{50} and M^{90}

3.5. Discussion

3.5.1. Comparison between clogging classification made in W/A_c and stickiness ratio

Figures 3.5 and 3.6(a) show the different clogging classification made according to stickiness ratio and W/A_c, respectively. For both categories, the clogging potential is determined based on I_c in universal diagram (Hollmann and Thewes, 2013). However, according to the results shown in Figure 3.5, the stickiness ratio fails to assess clogging potential. This is because when different masses of soil and sizes of beater were applied, the results vary dramatically, indicating that the stickiness ratio is very sensitive to the mass of soil used for testing and the size of the beater used in the tests. In terms of Figure 3.6, different clogging potentials can be found based on W/A_c. The weight of soil stuck to the beater after the mixing test depends on the contact area between the soil and beater for any shape of beater. The contact area will increase with the increase of total amount of soil, until the beater is fully covered by soil. At this point, the amount of soil stuck on the beater and the contact area will stay constant regardless of an increase in the total amount of soil. However, the stickiness ratio will decrease with an increase in the total amount of soil after the beater is fully covered.

3.5.2. Comparison of previous approaches to assess clogging potential

Empirical approaches assess clogging potential using the consistency of soil (I_c), which is mainly based on soil properties (plastic limit and liquid limit). It is possible to estimate the clogging potential based on the firmness of soil sample, because the firmness of a sample corresponds to the consistency. Therefore, an empirical approach can be used to estimate the clogging potential as a qualitative method.

Physical simulation methods can quantitatively assess clogging potential. The cone pull-out test evaluates the clogging potential from two perspectives: energy (the amount of tensile force required) and adherence (the amount of soil stuck on the cone per unit area). Feinendegen et al. (2010) used different cones with different inclinations (10°, 31°, 45°, 58°, and 72.6°). In this test, the clogging potential is determined by the types of soil and inclinations of cones. In real excavation using a TBM, the clogging potential is not only determined by soil properties, but many other factors, such as shape or size of cutter head, penetration rate, rotational velocity, etc.

The physical drilling test proposed by Kang et al. (2018) is more advanced and comprehensive. It simulates more complex mechanism that occur during the drilling process. Among the various physical methods to assess clogging potential, the drilling test comes closest to simulating clogging during drilling. This is because it takes into account the rate of penetration, rotational velocity, and penetration depth.

This paper assesses clogging potential using a new index, W/A_c, based on the mixing test proposed by Zumsteg and Puzrin (2012). From the sensitivity analysis, soil with different plasticity indices can be classified in terms of clogging potential using the parameter W/A_c. Furthermore, unlike the previous tests, the impact of the mass of soil tested and the size of beater can be mitigated by using W/A_c.

3.5.3. Sensitivity analysis

Figure 3.7 shows the variation in W/A_c for different masses of a mixture of 50% bentonite/50% kaolin. The value of W/A_c determined using a 2 kg sample peaks at 42 kg/m^2 when I_c is 0.57, and is also 11 kg/m^2 higher than W/A_c determined for a 1 kg soil sample. At this point, the bridging effect occurred, because the soil sample becomes extremely sticky with increasing water content;

thus, when the total amount of soil increases, a whole bunch of soil is stuck in the open part of the beater when the beater moves.

It can be noted that W/A_c is very sensitive to I_c. W/A_c increases at first and reaches a peak, then decreases dramatically when I_c increases from 0 to 1, indicating that the clogging potential was determined by water content and plasticity index of the sample. Too much or little water content can cause a soil samples to act like a solid or liquid. Therefore, strategies to decrease clogging potential may be to either keep adding water to the sample or increase the temperature to dry the soil samples.

Figure 3.10(a) shows that different types of soil can be clearly distinguished by W/A_c clearly. Meanwhile, it is difficult to observe any change in clogging potential using the stickiness ratio to distinguish different types of soil, as shown in Figure 3.10(b). Thus, W/A_c is a good indicator for assessing the clogging potential of different types of soil.

3.6. Conclusions

This paper introduces a new index, W/A_c, to quantify clogging potential based on a simple mixing test. Two different clogging classifications have been made using W/A_c and the stickiness ratio, and it was found that different clogging potentials can be categorized clearly using W/A_c. This is because the index W/A_c is more comprehensive and takes into account the contact area between soil the and beater. The weight of soil stuck on the beater changes with contact area, giving more repeatable results for W/A_c determined using the mixing test described in this work.

According to a sensitivity analysis, the standard deviation of W/A_c for different sample masses and size of beater are smaller for the index W/A_c, indicating that more repeatable results could be obtained using W/A_c regardless of size of beater or mass of soil. In addition, the clogging potential of different types of soil can be differentiated using W/A_c. On this basis, W/A_c is a good indicator to quantitively assess clogging potential. It is worth noting that different shapes of beaters will affect the weight of soil that sticks to the beater. Also, different mechanisms (i.e. bridging) might come into play based on different shapes of beaters. Future work needs to be done on the influence of different shapes of beater on W/A_c.

The mixing test apparatus used to determine W/A_c is portable, and this test is easily conducted in a minimal amount of time. Using the improved index W/A_c based on mixing test, the clogging potential can be assessed quantitatively with more repeatable results than stickiness ratio. Using this method, the clogging potential of soil samples can be quickly assessed on site, giving information to inform decisions on the use of additives to prevent clogging, which brings benefits from both an environmental and economic standpoint.

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Chapter 4: THE IMPACTS OF DIFFERENT BEATER SHAPES IN MIXING TEST

4.1. Introduction

Problems with clogging have been encountered since the introduction of tunnel boring machine (TBM) excavation (Alberto-Hernandez et al. 2017, Kang et al. 2019). This is because cohesive soil tends to cling to metal surfaces, such as the surfaces at the cutter head, screw conveyor or conveyor belt. The impacts of clogging on TBM projects, including schedule delays and budget overruns, are concern for engineers. (Langmaack 2002; Spagnoli et al. 2011). Clogging problems do not only depend on the soil type, but also other physical parameters associated with the drilling process, such as penetration rate, rotational velocity, and applied torque, etc. (Feinendegen et al. 2010; Kang et al. 2018). Additionally, the effect of cutter shapes on clogging potential can also not be ignored (Rostami and Chang 2017). It is assumed that different cutter head geometries might result in differences in clogging potential.

To date, many researchers have proposed different approaches to evaluate clogging potential. However, the effect of different beater shapes on tests to determine clogging potential has not been well studied. The most commonly used methods to evaluate clogging potential are summarized in Table 4.1. The analytical approach (Kooistra et al. 1998) and semi-empirical approach (Hollmann and Thewes 2013) are based on analyzing soil properties, thus the effect of cutterhead shape cannot be assessed using these two approaches. However, the effect of different cutterhead shapes can be evaluated in physical simulation approaches, such as the cone pull-out test (Feinendegen et al. 2010), the mixing test (Zumsteg and Puzrin, 2012), the plate shear test (Peila et al. 2016) and the drilling test (Kang et al. 2018).

In the analytical approach, the clogging potential is assessed by comparing cohesion and adhesion with applied shear stress (Kooistra et al. 1998). In the empirical approach, clogging potential is evaluated using the universal diagram proposed by Hollmann and Thewes (2013). Using this diagram, the clogging potential can be determined based on the plastic limit, liquid limit and water content of soil samples. From the diagram, it is observed that clogging potential increase with increasing plasticity index. However, the clogging potential is assessed based solely on the properties of soil samples in both the analytical and empirical approaches. The effect of cutterhead shape or beater shape cannot be determined using either of these approaches.

Physical simulation approaches include direct simulation and indirect simulation. A cone pull-out test has been proposed by Feinendegen et al. (2010) to determine tensile force and displacement while pulling a cone out of soil samples. This is an example of an indirect simulation approach, since it does not simulate the drilling process. Various clays with different consistencies and mineralogies were tested, with tests done using three cones with different inclinations. The results indicate that the displacement of the steep cone is larger than for the flat cone using the same applied load, and the tensile force required to pull out the steep cone is less than for the flat cone. (Feinendegen et al. 2010). The results somehow reflect that the shapes of cone might bring difference.

In direct physical simulation approaches, clogging potential is evaluated based on physical simulation of the drilling process. Examples include the mixing test proposed by Zumsteg and Puzrin (2012), a dynamic lateral adhesion test (Peila et al. 2016) and the drilling test developed by Kang et al. (2018). In the last case, a beater was employed to simulate the cutterhead motion in a direct physical simulation approach.

Zumsteg and Puzrin (2012) proposed a mixing test using a Hobart mixer and beater. The mixing test involved using the beater to mix soil with a predetermined water content, followed by weighing the beater with the soil stuck to it. Zumsteg and Puzrin (2012) proposed the use of the stickiness ratio (λ) to quantify the clogging potential. The stickiness ratio is defined as the ratio between the weight of soil stuck to the beater and the total weight of soil used. Oliveira et al. (2018) proposed an improved test, combining the mixing test and free fall test. The beater was dropped from a certain height after the mixing test. The weight of soil stuck to the beater was recorded after the free fall. Oliveira et al. (2018) pointed out that the combined approach might be limited for some mixed samples with low clay content. Zhou (2020) proposed a new index, W/A_c (the weight of soil stuck to the beater per unit area) to quantitively assess clogging potential. It was found that W/A_c is less sensitive to the total mass of soil and beater size compared to the stickiness raito. It was also determined that the clogging potential of different soil types can more easily be distinguished using W/A_c.

A dynamic lateral adhesion test was proposed by Pelia et al. (2016) to assess clogging potential. In this test, a flat metallic disc (120 mm in diameter and 10 mm thick) was employed to shear conditioned soil in a filled tank. Two jacks were used to provide a contant presure, moving the flat disc downard to shear conditioned soil samples at a rotation speed of 90 rpm. The torque required to rotate the disc was recorded. Pelia et al. (2016) also proposed a static lateral adhesion test to assess the stickiness of conditioned soil. In this test, soil samples were compacted by 10N force for 60 seconds, then put on a inclined plate. The inclination angle was recorded once the sample slid down the plate.

Kang et al. (2018) proposed a drilling test with a test apparatus consisting of a motor with a controller, a ruler, and a beater. The dimensions of the beater used in the test were 76.2 mm wide and 24.2 mm high. The ruler was used to determine penetration depth and the controller was used to control penetration rate. To conduct the test, the mold, filled with a soil sample that was compacted three times, was positioned underneath the beater. The rotational velocity of the beater was 30 rpm, and a penetration rate of 1 mm/s was used. The beater was removed from the test apparatus after a penetration depth of 1 cm was reached. The weight of soil stuck to the beater, *W*, was then measured and recorded. The ratio between *W* and the cross-sectional area of the beater was determined, referred to as *WSDB* (weight of soil stuck to drirll bit per unit area) by Kang et al. (2018). A sensitivity analysis was conducted on the rotational velocity, penetration depth, penetration speed and size of drill bit and mould. The drilling test proposed by Kang et al. (2018) is relatively comprehensive test, since many physical parameters are involved. According to Kang et al. (2018), the parameter *WSDB* is sensitive to penetration speed and rotational velocity. However, the drawbacks of this test are that its duration is relatively long and the test procedures are complex, involving both a Proctor compaction test and clogging test. Besides this, the test apparatus is not portable, thus the drilling test cannot be conducted onsite.

Although there have been many physical simulation approaches proposed by researchers (Feinendegen et al. 2010; Zumsteg and Puzrin 2012; Peila et al. 2016; Kang et al. 2018) to assess clogging potential, the effects of beater shape on clogging potential has not been well-studied. Therefore, this paper focus on researching the effects of beater shapes.

In this paper, a mixing test was conducted to assess clogging potential since the mixing test since is a conventional geotechnical testing method. The equipment used for the test is readily available. Besides this, the apparatus for the mixing test is portable, so the test can be conducted at the site. The most common clays, such as kaolin and bentonite, were mixed in different percentages to represent a range of different types of soil, which can be repeated by other researchers. Additionally, three different shapes of beaters were employed in a test to study the effects of shapes of beater on clogging potential. A new index, W/A_c , proposed by Zhou (2020) was also employed in this paper. The current paper uses the average and maximum W/A_c and G_B to analyze the results of the mixing test, also employs A'/A to study the impact of beater shape.

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Table 4. 1. Summary of approaches to assess clogging potential

<table>
<tr><th></th><th colspan="2">Beater shape not considered</th><th colspan="5">Beater shape considered</th></tr>
<tr><th>Approaches</th><th>Analytical approach</th><th>Semi-empirical approach</th><th colspan="5">Physical simulation approach</th></tr>
<tr><th rowspan="2">Tests</th><th rowspan="2">Vane shear test,
direct shear test</th><th rowspan="2">Atterberg limit tests</th><th>Indirect simulation</th><th colspan="4">Direct simulation</th></tr>
<tr><th>Cone pull-out test</th><th>Drilling test</th><th>Dynamic lateral adhesion test</th><th>Previous mixing test</th><th>This study</th></tr>
<tr><td>Indice Measured</td><td>Adhesion, cohesion, shear stress</td><td>Plastic limit, liquid limit</td><td>Normal adhesion, adherence</td><td>Weight of soil stick to drill bit per unit area (WSDB)</td><td>The required force to rotate the disc</td><td>Stickiness ratio (λ)</td><td>Weight of soil stick to beater per unit contact area (W/A_c)</td></tr>
<tr><td>References</td><td>Kooistra et al. (1998); Alberto-Hernandez et al. (2017)</td><td>Hollmann and Thewes (2013)</td><td>Feinendege et al. (2010)</td><td>Kang et al. (2018)</td><td>Peila et al. (2016)</td><td>Zumsteg and Puzrin (2012)</td><td>Zhou (2020)</td></tr>
</table>

4.2. Methodology

4.2.1. Material

Mixtures of bentonite (AQUAGEL GOLD SEAL) and kaolinite (EPK) were employed for the mixing test. It is known that bentonite is strongly cohesive while kaolin is weakly cohesive; thus, soil samples with different cohesive properties can be obtained by mixing different bentonite and kaolin content.

The clay particles passing through a 425 µm sieve were collected to conduct Atterberg limit test. Bentonite and kaolin were mixed by weight to obtain mixed dry samples of 1.5 kg. Five clay mixtures containing different bentonite content were employed: M^{10}, M^{30}, M^{50}, M^{70}, and M^{90}, with the superscript indicating the percentage of bentonite in the mixture. An Atterberg limit test was carried out according to ASTM D4318-17 to determine liquid limit (*LL*), plastic limit (*PL*) and plasticity index (*PI*) of soil samples.

4.2.2. Test apparatus and procedures

The apparatus used in the mixing test is a Hobart mixer, composed of four parts: a power supply, a rotational velocity controller, a beater, and a container. A schematic of the apparatus is shown in Figure 4.1. The power supply provides electricity to motor, which is converted by the motor to mechanical force. The rotational velocity controller gives 100 rpm according to Zumsteg and Puzrin (2016). The beater used is removable, allowing other beater shapes to be used in testing.

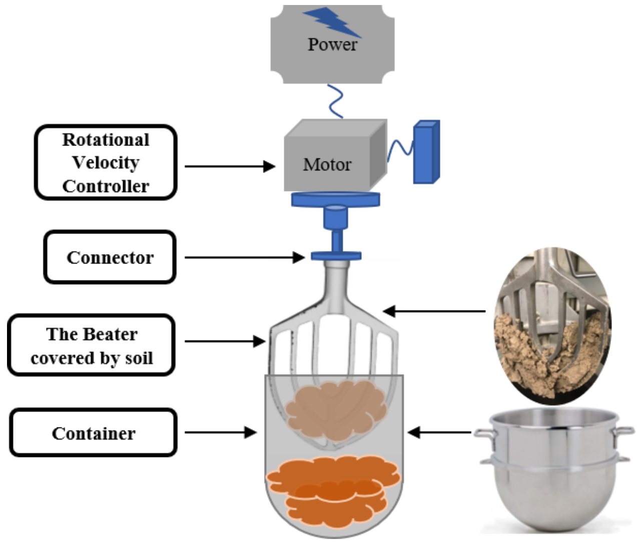

Figure 4. 1. Schematic of mixing test apparatus

Three different shapes beaters were employed in the mixing test, as shown in Figure 4.2. The original beater (Beater 1) is the standard beater from the Hobart mixer, shown as Figure 4.2a. The second beater (Beater 2) was obtained by removing the side bars of the original (standard) beater, as shown in Figure 4.2b. The side bar and bottom bar are removed to give the third beater (Beater 3), as shown in Figure 4.2c. The surface area of beater 1, beater 2 and beater 3 are 842 cm^2, 694 cm^2 and 665 cm^2 respectively.

A theoretical beater – a model of the standard beater geometry with no openings – was used as reference to calculate the open area for each of the beater configurations (Beaters 1-3) (Figure 4.2d).

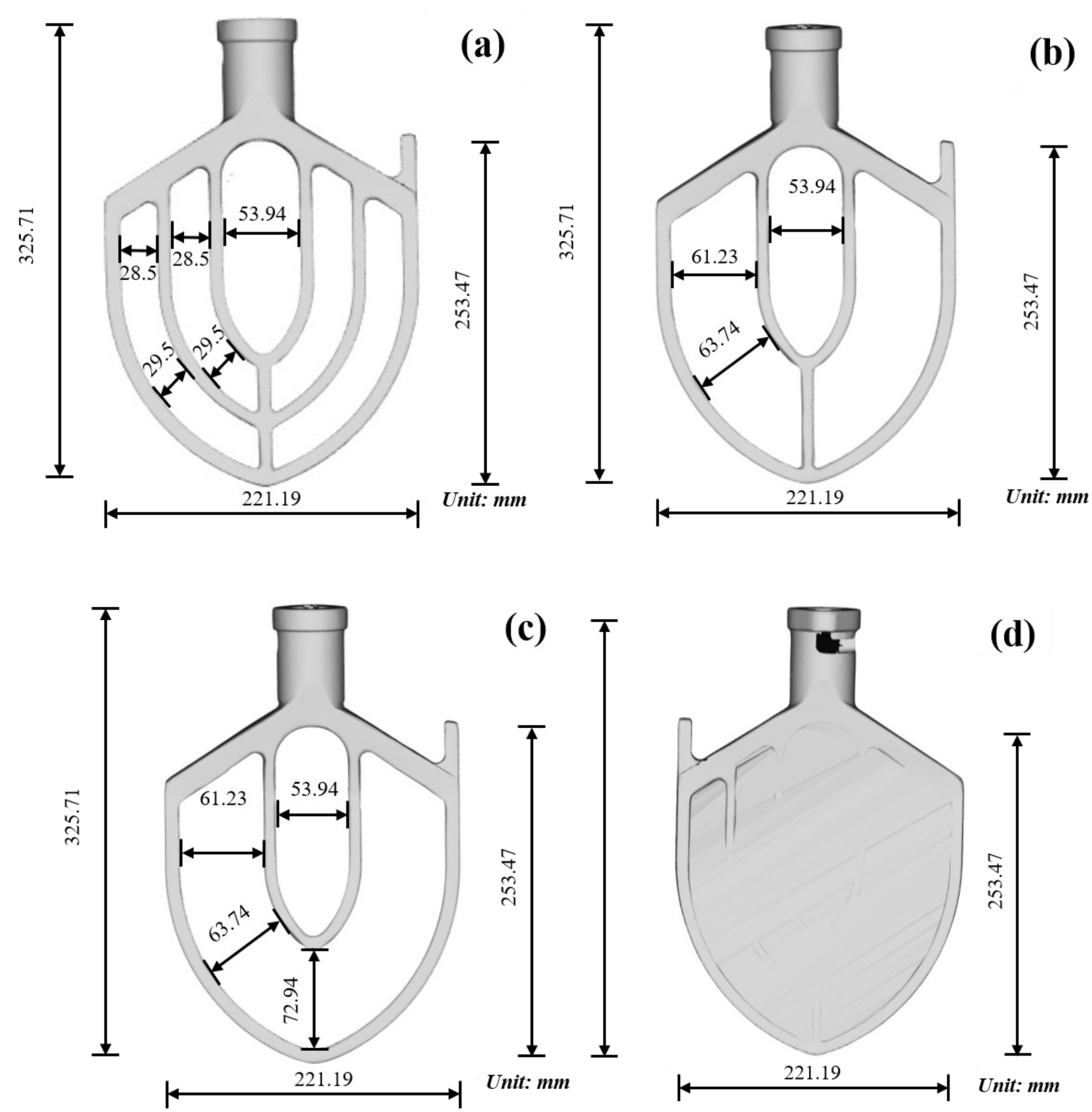

Figure 4. 2. 3D model of three beaters: (a) Original beater; (b) The beater after first cut; (c) The beater after second cut; (d) Theoretical beater

The surface area of three beaters has been plotted with respect to the height of the beater covered by the sample in Figure 4.3. Heights of 20 cm and 25 cm have been marked on a schematic of each beater in the Figure 4.3. For each of the three beater configurations, five soil mixtures (M^{10},

M^{30}, M^{50}, M^{70}, and M^{90}) with five samples containing water contents distributed evenly between the plastic limit and liquid limit were tested using the mixing test.

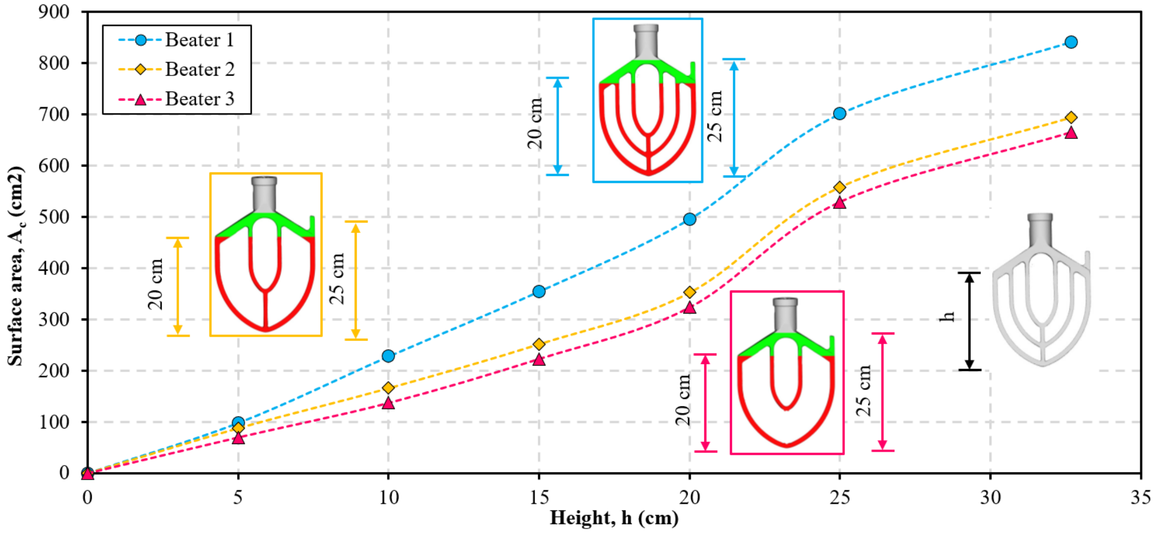

Figure 4. 3. The surface area with the variation of height of three beaters.

To conduct the mixing tests, the dry mixed soil sample was put in the container, and the Hobart mixer was switched on. Dry mixtures were mixed for one minute using a pre-weighed beater to ensure that the mixtures were mixed thoroughly. Soil mixtures with corresponding predetermined moisture content were mixed for three minutes, according to the procedure described by Zumsteg and Puzrin (2016). The amount of soil stuck to the beater tends to remain constant after three minutes mixing. After mixing, the beater was removed from the apparatus and reweighed. The weight of soil stuck to the beater (G_B) was measured and recorded. The height that soil extended up the beater (from the beater tip) was measured using a caliper, and recorded as h. Using Figure 4.3, the surface area (A_c) of the beaters used in this work can be interpolated using the measured height. It is noted that the surface area of the beater was determined by the sum of the areas of all faces on a 3D model in Autodesk Netfabb Premium 2019.

4.2.3. Index to assess clogging potential

Test results were analyzed based on two indices, G_B (weight of soil stuck to the beater) and W/A_c (weight of soil stuck to the beater per unit area). Zumsteg and Purzin (2012) introduced the stickiness ratio (λ) as given in Equation 1, \ defined as the ratio between G_B and G_T. In this equation, G_B is the amount of soil stuck to the beater and G_T is the total weight of soil. However, according to Zhou thesis (2020), the stickiness ratio is relatively sensitive to the variation of the weight of total soil used in the test compared to the index W/A_c (weight of soil stuck to the beater per unit area).

$$\lambda = G_B/G_T \qquad [1]$$

Another index, W/A_c, is expending on the idea of *WSDB* (Kang et al. 2018), both of them stands for weight of soil stick to beater per unit area. The clogging potential is assessed using the ratio between the weight of soil stick to beater (G_B) and the surface area of beater covered by soil (A_c). According to Zhou (2020), the clogging potential of different types of soil can be more easily distinguished by W/A_c, compared to the stickiness ratio (Zumsteg and Purzin, 2012).

To compare the results using W/A_c, the plastic and liquid limits were measured and plotted in the universal diagram (Hollmann and Thewes, 2013). the x-axis is the difference between the plastic limit and water content, and the y-axis is the difference between liquid limit and water content. Six different clogging zones were defined, based on liquid limit, plastic limit and water content.

4.3. Results

4.3.1. Atterberg Limit Test

Table 4.2 shows the plastic and liquid limits obtained using the Atterberg limit test. It is noted that the plasticity index increases dramatically with increasing bentonite content. For each mixture, samples with five different water contents ranging from the liquid to the plastic limit were determined to obtain five consistency indices distributed evenly from 0 to 1 (Table 4.3).

Table 4. 2. Liquid limit, plastic limit and plasticity index of soil samples (Kang et al. 2019).

	M^{10}	M^{30}	M^{50}	M^{70}	M^{90}
LL	94.0%	169.4%	253.5%	338.8%	445.1%
PL	32.7%	37.5%	40.7%	48.8%	36.0%
PI	61.3%	131.9%	212.7%	290.0%	409.1%

Table 4. 3. Water content and consistency index for each type of sample

Sample tested	#1		#2		#3		#4		#5	
	w(%)	I_c	*w(%)*	I_c	*w(%)*	I_c	*w(%)*	I_c	*w(%)*	I_c
M^{10}	30	1.04	45	0.80	60	0.55	75	0.31	90	0.06
M^{30}	45	0.94	75	0.72	105	0.49	135	0.26	165	0.03
M^{50}	30	1.05	80	0.82	130	0.58	180	0.35	230	0.11
M^{70}	40	1.03	110	0.79	180	0.55	250	0.31	320	0.06
M^{90}	40	0.99	125	0.78	210	0.57	295	0.37	380	0.16

Figure 4.4 demonstrates the clogging potential of the five soil mixtures, (M^{10}, M^{30}, M^{50}, M^{70}, and M^{90}) with the corresponding consistencies plotted on the universal diagram (Hollmann and Thewes, 2013). It is noted that the soil samples with low bentonite content are more sensitive to the water content since the plasticity index is relatively small. In this case, the plastic limit or liquid limit of the samples could be reached with only a slight variation in water content. Besides, the clogging potential is associated with plasticity index. From Figure 4.4, the area that

the I_p line crosses becomes larger with increasing plasticity index, indicating higher clogging potential.

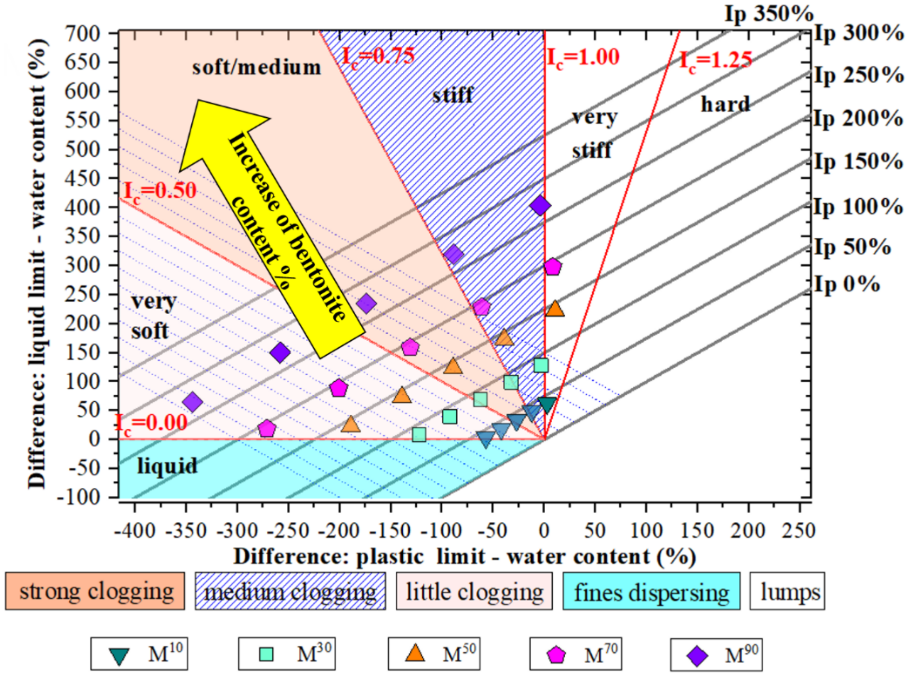

Figure 4. 4. Five soil samples with corresponding consistency indices were plotted in universal diagram (Hollmann and Thewes 2013).

4.3.2. Mixing test

4.3.2.1. Weight of soil stick to the beater per unit area (W/A_c)

Figures 4.5 shows the W/A_c for three beaters with different shapes in five soil samples, M^{10}, M^{30}, M^{50}, M^{70}, and M^{90}. Table 4.5 presents the descriptive statistics of each box chart for measurements of W/A_c. Figure 4.5a shows that the W/A_c of the three beaters reaches a peak when the consistency index, I_c, is 0.55, which follows the trend in the universal diagram (Hollmann and Thewes, 2013). The area defined as “strong clogging” applies when I_c is in the range of 0.5 to 0.75 (Figure 4.3). Figure 4.5b demonstrates that the value of W/A_c for Beater 3 peaks at 78.99 kg/m^2 when I_c is 0.26, which is defined as “little clogging” according to universal diagram

(Hollmann and Thewes, 2013). Figures 4.5c to e illustrate that the value of W/A_c for both Beater 2 and Beater 3 peaks when I_c is in the "little clogging" zone. Figure 4.6 shows the statistical distribution of W/A_c for all three beaters. It is noted that the parameter W/A_c is very sensitive to the increase of bentonite content. The values of W/A_c determined using Beater 2 and Beater 3 are much larger than for Beater 1, and the W/A_c of Beater 2 and Beater 3 are relatively close, since the difference in surface area of both bits is small, approximately 29 cm^2. The opening size increases by 177 cm^2 from Beater 1 to Beater 3, leading to a doubling in W/A_c. The height of soil extending up the beater decreases with an increase in the open area, since the soil tends to bridge over the open area of beater. The contact area of the beater covered by soil then decreases correspondingly. Therefore, W/A_c increase dramatically with an increase of opening area.

Table 4. 4. The maximum of W/Ac and corresponding consistency index (Ic) of five samples used in the three beaters.

Beater #	M^{10}		M^{30}		M^{50}		M^{70}		M^{90}	
	W/A_c (max) (kg/m^2)	I_c	W/A_c (max) (kg/m^2)	I_c	W/A_c (max) (kg/m^2)	I_c	W/A_c (max) (kg/m^2)	I_c	W/A_c (max) (kg/m^2)	I_c
Beater 1	27.08	0.55	31.75	0.49	32.88	0.58	41.85	0.55	51.48	0.57
Beater 2	54.32	0.55	72.75	0.49	83.35	0.35	92.39	0.31	95.08	0.37
Beater 3	52.84	0.55	78.99	0.26	89.66	0.35	104.73	0.31	123.4	0.37

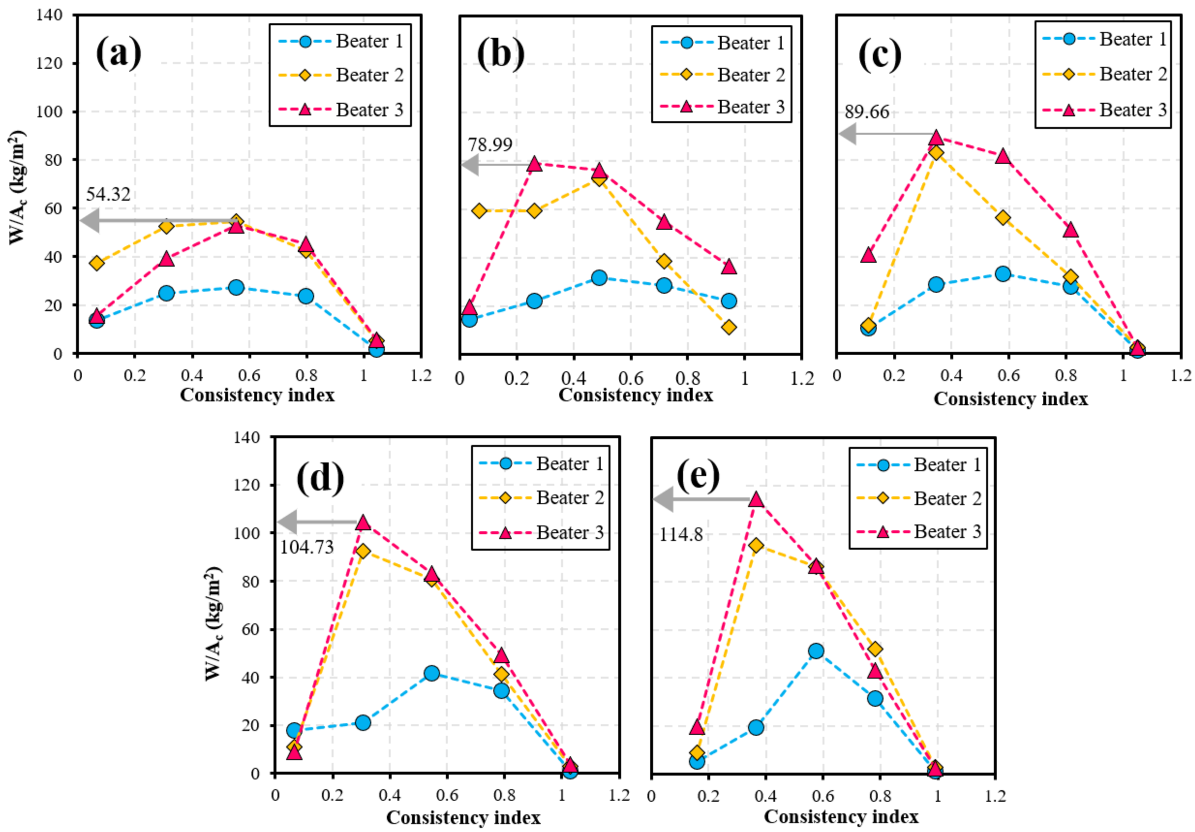

Figure 4. 5. W/A_c in beater 1, beater 2 and beater 3 of (a) M^{10}; (b) M^{30}; (c) M^{50}; (d) M^{70}; (e) M^{90}

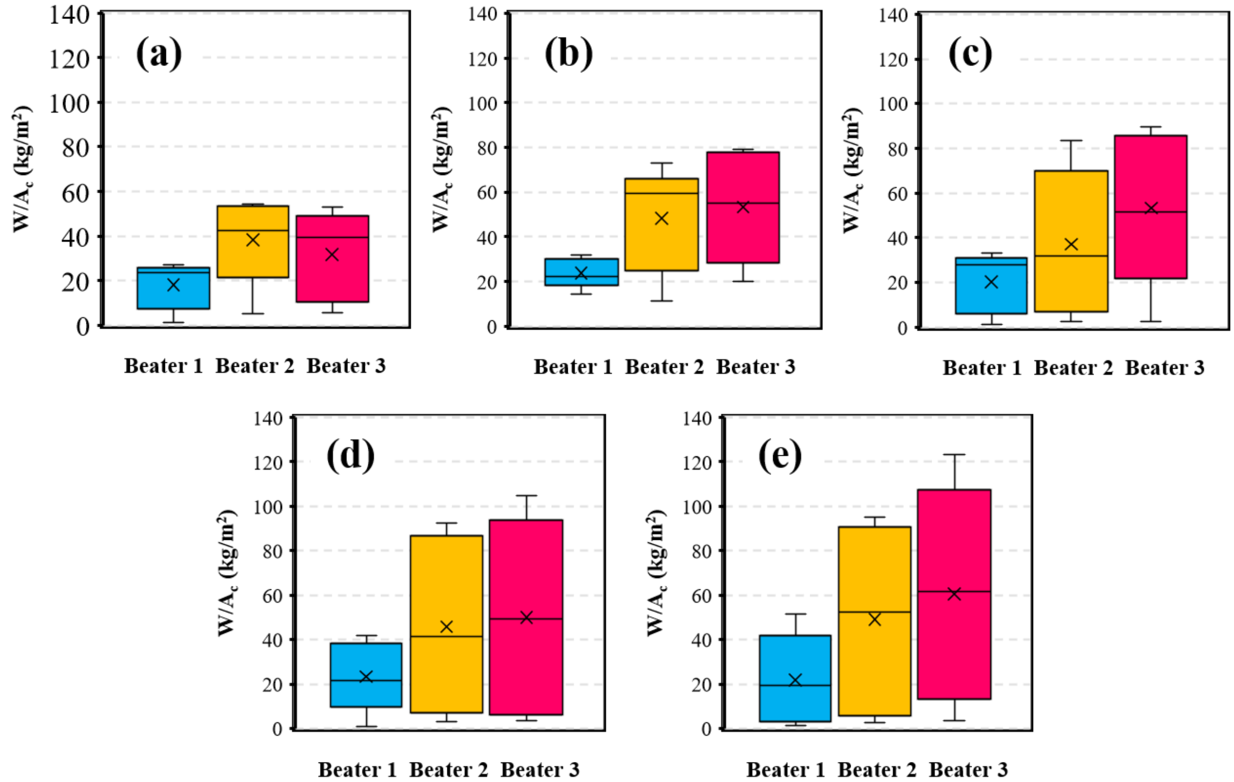

Figure 4. 6 Statistical distribution of W/A_c for beater 1, beater 2 and beater 3: (a) M^{10}; (b) M^{30}; (c) M^{50}; (d) M^{70}; (e) M^{90}

Table 4. 5. The descriptive statistics of W/A_c

	M¹⁰			**M³⁰**			**M⁵⁰**			**M⁷⁰**			**M⁹⁰**		
	B-1	**B-2**	**B-3**	**B-1**	**B-2**	**B-3**	**B-1**	**B-2**	**B-3**	**B-1**	**B-2**	**B-3**	**B-1**	**B-2**	**B-3**
Minimum	1.4	5.2	5.7	14.3	11.1	19.8	1.1	2.4	2.5	1.0	3.1	3.7	1.1	2.8	3.6
Q1	13.7	37.5	15.6	22.1	38.6	36.5	10.5	11.6	41.1	18.1	10.9	8.9	5.4	9.0	22.6
Median	23.4	42.3	39.4	22.2	59.2	54.9	27.9	31.7	51.3	21.3	41.4	49.4	19.3	52.2	61.8
Q3	24.8	52.7	45.4	28.4	59.4	76.2	28.6	56.5	81.9	34.5	80.8	83.2	31.7	86.3	91.5
Maximum	27.1	27.1	52.8	31.7	72.7	79.0	32.9	83.3	89.7	41.8	92.4	104.7	51.5	95.1	123.4
Mean	18.1	38.4	31.8	23.7	48.2	53.3	20.2	37.1	53.3	23.4	45.7	50.0	21.8	49.1	60.6
Range	25.6	21.9	47.1	17.5	61.7	59.2	31.7	80.9	87.2	40.9	89.2	101.0	50.4	92.3	119.9

Note: In this table, B-1 represents Beater 1, B-2 represents Beater 2 and B-3 represents Beater 3.

4.3.2.2. Weight of soil stick to the beater (G_B)

Figure 4.7 shows the correlation between consistency index and G_B and Figure 4.8 shows the statistical distribution of G_B for all three beaters in a box chart. Table 4.6 presents the descriptive statistics of each box chart in G_B. It is noted that the average weight of soil stuck to the beater

(G_B) increase with increasing bentonite content, indicating that mixtures with a higher plasticity index might result in a higher clogging potential. The same conclusion can be made from the universal diagram (Hollmann and Thewes, 2013). Besides, the range of G_B increased with increasing bentonite content, indicating that G_B is sensitive to the plasticity index.

Figures 4.8a to d indicate that the average G_B measured using Beater 1 is the largest, and the average G_B for Beater 3 is the smallest among the three beater geometries. However, the contact area between the beater and the soil mixtures decreases with an increase in the open area of the beater. The bentonite/kaolin mixtures with moisture contents in a certain range tends to cling to the metal due to adhesion, which is in agreement with results observed by previous researchers. (Spagnoli et al. 2011; Alberto-Hernandez et al. 2017).

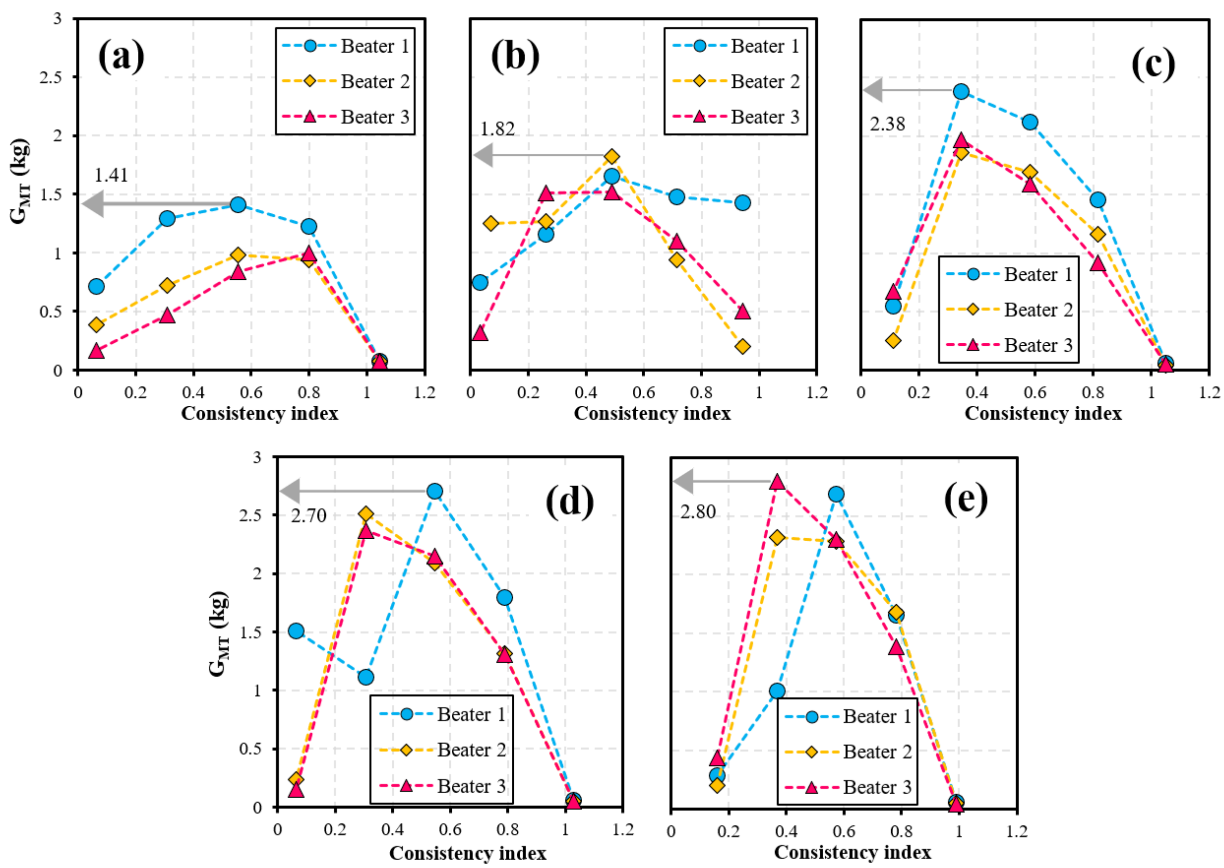

Figure 4. 7. G_B in beater 1, beater 2 and beater 3 of (a) M^{10}; (b) M^{30}; (c) M^{50}; (d) M^{70}; (e) M^{90}

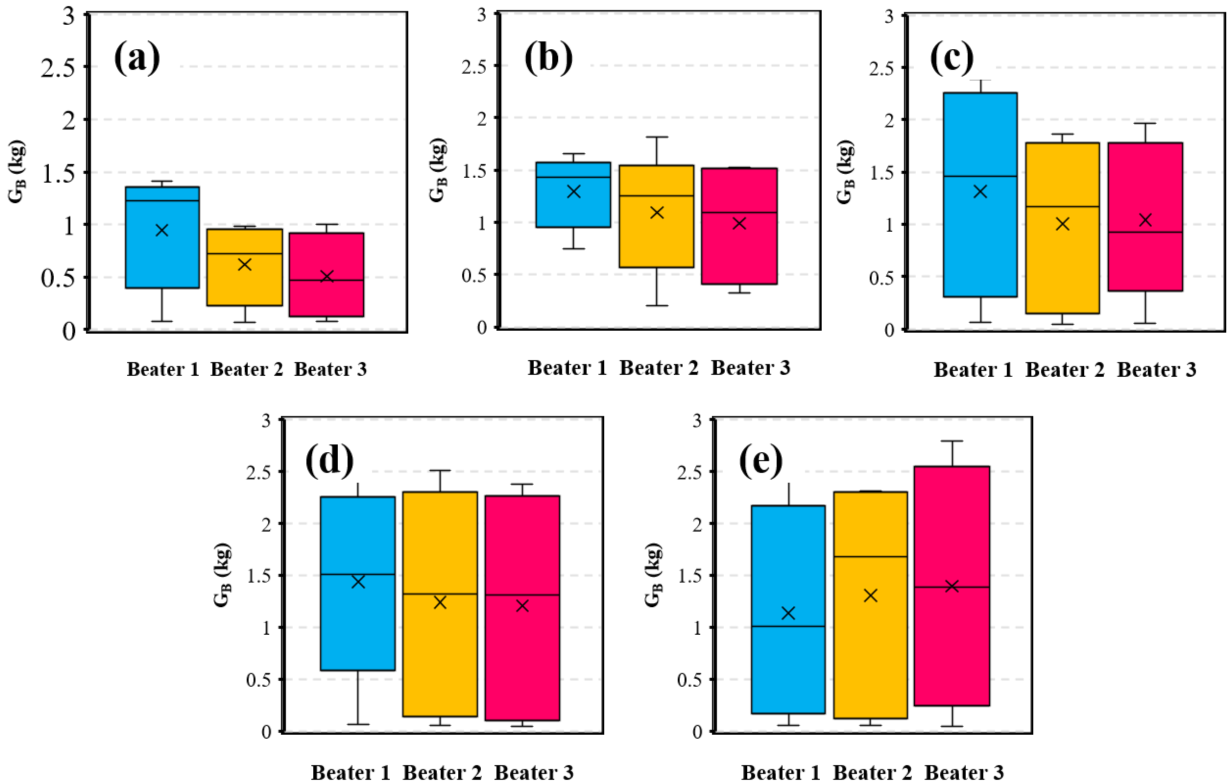

Figure 4. 8. Statistical distribution of weight of soil stick to beater 1, beater 2 and beater 3: (a) M^{10}; (b) M^{30}; (c) M^{50}; (d) M^{70}; (e) M^{90}

Table 4. 6. The descriptive statistics of G_B

	M^{10}			M^{30}			M^{50}			M^{70}			M^{90}		
	B-1	**B-2**	**B-3**	**B-1**	**B-2**	**B-3**	**B-1**	**B-2**	**B-3**	**B-1**	**B-2**	**B-3**	**B-1**	**B-2**	**B-3**
Minimum	0.1	0.1	0.1	0.7	0.2	0.3	0.1	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.0
Q1	0.7	0.4	0.2	1.2	0.9	0.5	0.5	0.2	0.7	1.1	0.2	0.2	0.3	0.2	0.4
Median	1.2	0.7	0.5	1.4	1.3	1.1	1.5	1.2	0.9	1.5	1.3	1.3	1.0	1.7	1.4
Q3	1.3	0.9	0.8	1.5	1.3	1.5	2.1	1.7	1.6	1.8	2.1	2.1	1.7	2.3	2.3
Maximum	1.4	1.0	1.0	1.7	1.8	1.5	2.4	1.9	2.0	2.7	2.5	2.4	2.7	2.3	2.8
Mean	0.9	0.6	0.5	1.3	1.1	1.0	1.3	1.0	1.0	1.4	1.2	1.2	1.1	1.3	1.4
Range	1.3	0.9	0.9	0.9	1.6	1.2	2.3	1.8	1.9	2.6	2.5	2.3	2.6	2.3	2.7

Note: In this table, B-1 represents Beater 1, B-2 represents Beater 2 and B-3 represents Beater 3.

4.4. Discussion

4.4.1. Laboratory test

The mixing test was conducted following the procedure presented by Zumsteg and Purzin (2012). Each set of tests was repeated three times to ensure the accuracy of the results, and it should be noted that the standard deviation of weight of soil stuck to the beater (G_B) for a given soil sample with a corresponding moisture content is within 3%.

To validate whether the test results were in a reasonable range, G_B retrieved for the mixtures M^{10}, M^{30}, M^{50}, M^{70}, and M^{90} were compared with G_B for M^{20}, M^{40}, M^{60}, M^{80} and M^{100} (Kang et al. 2018) since Kang et al. (2018) conducted the mixing test for the mixtures M^{20}, M^{40}, M^{60}, M^{80} and M^{100} using G_B. According to Hollman and Thewes (2013), clogging potential increases with increasing of consistency index, then decreases after reaches peaks. Therefore, three polynomial trendlines between G_B and the consistency index were made to verify this point. The blue, orange and red curve are best-fit lines of data from Kang's results (2018), the data from this rest results, and the overall data, respectively.

It can be noted that R^2 between the blue trendline and Kang's results (2018) is 0.48, and R^2 between the orange trendline and this study result is 0.61. Additionally, R^2 between the red trendline and the overall result is 0.51, indicating three trendlines are good fit for those data. Three trendlines are all agreed with universal diagram (Hollmann and Thewes, 2013).

The blue curve is above orange curve, indicating that the average G_B for M^{20}, M^{40}, M^{60}, M^{80} and M^{100} is larger than that of M^{10}, M^{30}, M^{50}, M^{70}, and M^{90}. This result indicates that increasing bentonite content results in more soil stuck to the beater, which is in agreement with the universal diagram (Hollmann and Thewes 2013). It is known that the plasticity index increases with increasing bentonite content. From Figure 4.4, the area that the I_p line crosses through each clogging zone becomes wider with increasing plasticity index, indicating higher clogging potential.

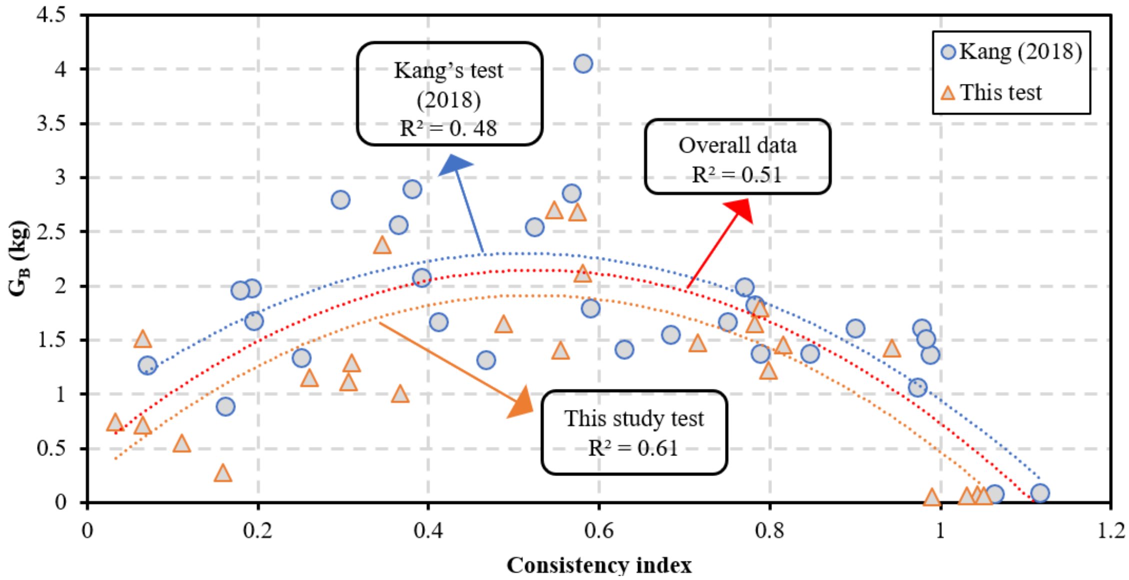

Figure 4. 9. Polynomial trendline of G_B in Kang (2018) results (blue line), this test results (Orange line) and combined data (Red line).

The shape of the cutterhead is an important factor to be considered during excavation using a tunnel boring machine (TBM). Previously, it was demonstrated that a flat cutterhead is more efficient and easier to maintain compared to cone and dome shapes (Rostami and Chang 2017). Cutters with different cutter spacing or different tilt angles need to be considered, according to different project requirements. To mitigate the possibility of clogging during excavation using a TBM, the effect of the shape of cutterhead should be well studied. In this paper, a simple mixing test is conducted to study the effect of the beater geometry on clogging potential, and three different shapes of beaters are used to simulate a scaled-down cutterhead in TBM. This approach has several advantages, since the apparatus for the mixing test is portable and the test is repeatable. Besides, the mixing test could simulate rotation process of cutterhead. However, it is not possible to directly mimic the shape of a cutterhead on a TBM using different beater geometries.

4.4.2. The impacts of shapes of beater

According to Hajime, the soil strength decreases dramatically with an increase in moisture content (1968). Soil samples with low moisture content retain high shear strength and have low adhesion to metal. In this case, the soil sample barely clings to the beater due to the low adhesion of soil to the metal. Adhesion increases with increasing moisture content, leading to a condition where the internal cohesive force between water molecules in the soil particles increases. Therefore, the soil particles tend to cling to each other. However, the shear strength of soil decreases with increasing moisture content, thus the internal cohesive force will be offset by the shear stress of the rotating beater. Eventually, failure of the sample occurs due to low shear strength.

From Figure 4.2, it can be seen that for Beater 1, the open area of the beater is smallest among the three beaters used in the tests. A huge amount of soil sample clings to the beater because of adhesion of the soil to metal surface. According to Kooistra et al. (1998), when the internal shear strength of soil is larger than applied shear stress, a whole piece of soil will cling to the metal surface without internal failure. Shear failure occurs when the internal shear strength is smaller than the applied shear stress. Therefore, the remaining portion of the soil will be stuck to the metal surface. Both of these scenarios may cause clogging issues. When beaters with a relatively small opening size are employed in the mixing test, the clogging observed mainly stems from adhesion.

For Beater 2, it is evident that the values of W/A_c for M^{50}, M^{70} and M^{90} reach a maximum at a higher moisture content, when the values of I_c are 0.35, 0.31 and 0.37, respectively. Comparing Beater 2 with Beater 1, the metal surface area is smaller since a segment of steel was removed from the beater. It is known that adhesion is the attraction between cohesive soil and a foreign metal surface. Adhesion is expected to decrease with a decrease in the surface area of the metal, because there is less contact area between soil and metal. In this case, clogging mainly stems from the cohesive properties of the soil mixture. Shear failure occurs because shear strength of the soil samples decreases with increasing moisture content when the applied shear stress remains constant. Thus, the bulk of the soil sample is sheared into small pieces, and these small pieces tend to form a large ball with the movement of the beaters because of the strongly cohesive tendencies within the soil mixture. A large ball of soil tends to press through the open area of Beater 2 with the rotation of beater, while the open area is not large enough to allow the ball of soil to pass through. This is known as the bridging effect (Thewes 1999). Therefore, a large ball of soil cling to the beater 2, and the W/A_c of M^{50}, M^{70} and M^{90} reach the maximum when I_c are in the range of 0.31 to 0.37.

Comparing the results of the mixing test obtained with Beater 3 with the results obtained using Beater 2, the W/A_c for the mixture M^{30} reaches a maximum when I_c is 0.26, located in the "little clogging" zone according to the universal diagram (Hollmann and Thewes 2013). The metal surface area of Beater 3 is smaller compared with the surface area of Beater 2, and clogging is more dependent on the soil cohesive properties rather than adhesion of soil to metal surface. It is noted that the parameter W/A_c is very sensitive to the opening size. The maximum value of W/A_c might occur for samples with different moisture content rather than in the "strong clogging" zone defined in the universal diagram (Hollmann and Thewes 2013) with the variation in beater shape.

This is because the universal diagram (Hollmann and Thewes 2013) is based on empirical observations and is only based on soil properties.

Figures 4.7 and 4.8 show a slight variation in the average weight of soil stuck to the three beaters, indicating that G_B is not sensitive to the opening size of the beater for each type of soil. Although there is little difference in the average G_B for the three different shapes of beaters for the various samlpes, the value of the parameter W/A_c for each of the three beaters varies a lot with increasing bentonite content. A huge difference in W/A_c can be observed between Beater 1 and Beater 3, as shown in Figures 4.5 and 4.6. This is because when the open area of the beater increases, this leads to cohesive soils, such as M^{70} or M^{90}, clinging to the open bottom part instead of covering the beater evenly. Then, partial clogging can be observed using a beater with a large opening. Therefore, the surface area of the beater covered by soil decreases dramatically. This explains why W/A_c varies a lot when a beater with a large open area was used in the test. The beater shape can result in a large difference in the clogging potential. Thus, by extension, it is also essential to consider cutter spacing based on different geotechnical conditions for TBM excavation in the design phase.

4.4.3. The impacts of opening area in beater

Figures 4.5 and 4.6 indicate that the parameter W/A_c varies a lot for different beater shapes. The main difference among the three beaters is the open area. It is essential to study the impact of the open area on the test results. Therefore, the parameter A'/A was introduced to quantify opening area of each beater. The parameter A' indicates the area of the open part of the beater, wherease A is used to indicate the theoretical surface area for a corresponding beater geometry with no open area.

Figures 4.10 show the maximum values of G_B and W/A_c for five soil mixtures with five consistencies for each mixture. Figure 4.10a indicates that there is a slight variation of G_B with an increase in A'/A. The theoretical mass is the maximum mass of soil stick to the theoretical beater (with zero open area), which peaks at 4.7 kg. To determine whether G_B increases with a decrease in the open area requires verification by future testing. In this case, G_B is not a good indicator to show the impact of beater shape.

Figure 4.10b shows that the maximum of W/A_c increases with an increase in A'/A. The maximum value of W/A_c for a beater with no open area is approximately 40 kg/m^2. A trendline was included in Figure 4.10b, indicating that W/A_c increases dramatically with an increase in the open area. The average value of W/A_c increases from 27 kg/m^2 to 78 kg/m^2 for the four beaters (three actual and one theoretical).

The theoretical mass of sample stuck to the beater (G_B) is largest for the beater with no open area according to Figure 4.10a, while the value of W/A_c for the theoretical beater is the lowest, according to Figure 4.10b. To mitigate clogging potential, both G_B and W/A_c need to be maintained in a low range. In terms of implications for the design of cutting heads for TBMs, it is important to take into account cutter spacing to decrease clogging potential.

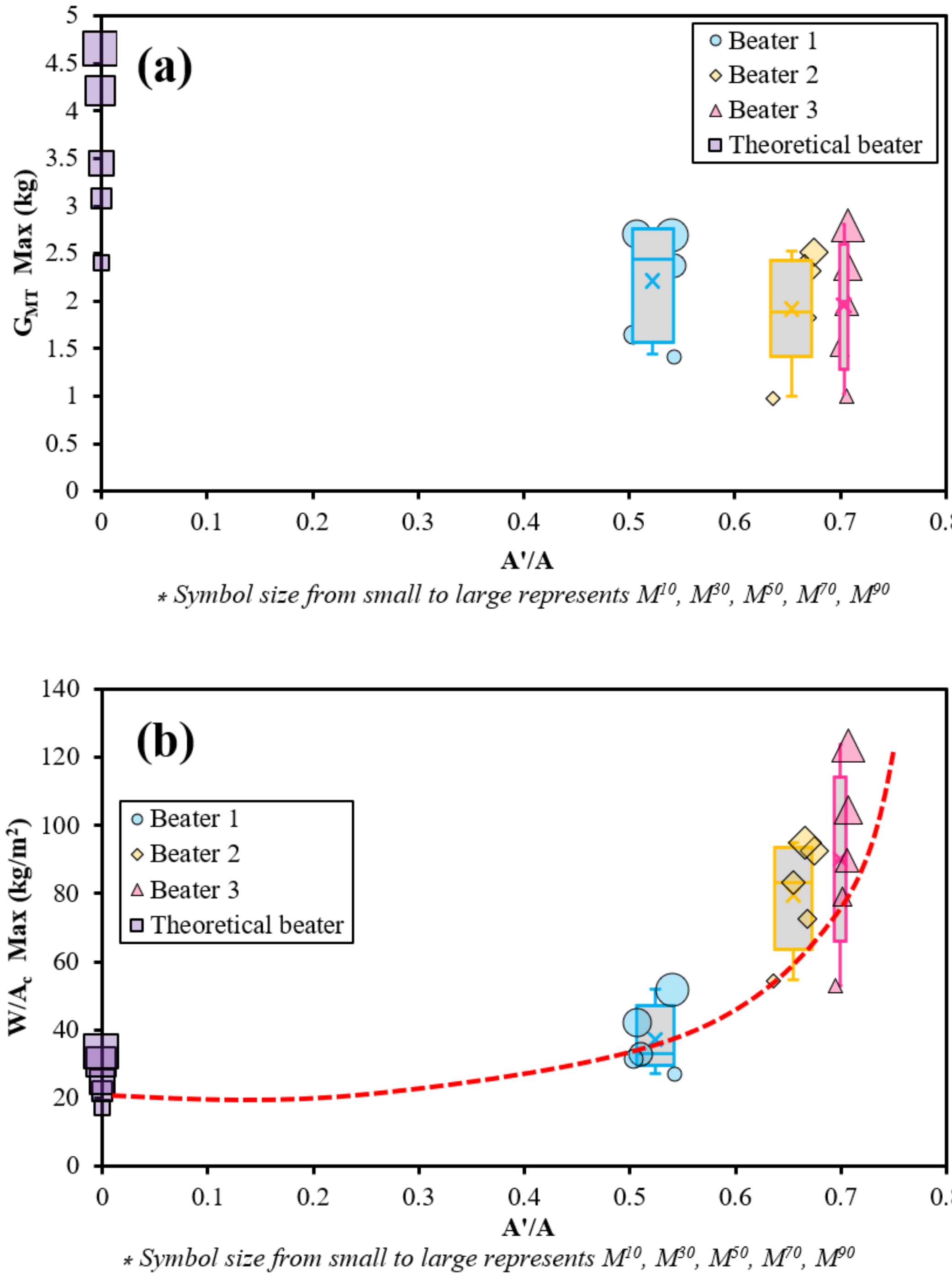

Figure 4. 10. The correlation between A'/A and: (a) maximum G_B; (b) maximum W/A_c

4.5. Conclusion

This paper presents the effect of beater shape in tests to determine clogging potential by comparing the index W/A_c with G_B obtained from the mixing test. Five soil mixtures contain different percentages of bentonite and kaolin corresponding to different consistency indices (I_c) were tested, and three beaters with the same frame but different open areas were employed to assess the effect of beater shape. The results for W/A_c were also compared with the statistical distribution of G_B and the universal diagram **(**Hollmann and Thewes 2013). It is found that the results for mixing tests conducted using different beater shapes were not completely in agreement with the universal diagram (Hollmann and Thewes, 2013). Undoubtedly, the impacts of beater geometry cannot be ignored. Therefore, it is necessary to take into account cutter spacing to mitigate clogging potential in the design of the cutterhead for TBM excavations.

In the Atterberg limit test, the plasticity index increases with the increasing bentonite content, leading to a higher W/A_c in the mixing test, which is in accordance with the universal diagram **(**Hollmann and Thewes 2013). In the mixing test, cohesive soil with a high moisture content tends to cling to the open area of beater, which is known as the bridging effect. In this work, the parameter A'/A was used to represent the open area for each beater, where A'/A stands for the ratio of the open area of beater over the entire area of a beater with the same outer shape but no open area. The values of A'/A for Beater 1, Beater 2 and Beater 3 were determined to be in the range of 0.5 to 0.54, 0.63 to 0.67 and 0.69 to 0.71, respectively. From Beater 1 to Beater 3, the average W/A_c increases by 53 kg/m^2. This is because whole bulk of soil tends to stick to the open area of the beater instead of sticking to the whole surface area of the beater, leading to a decrease in the contact area between soil and beater. Therefore, the value of W/A_c will increase dramatically with an increase in A'/A.

It was also found that G_B (weight of soil stick to beater) is not sensitive to the open area of the beater. An increase in the open area leads to a slight variation in G_B. The average G_B is within 0.2 kg for the three beaters with different shapes. In this case, G_B stays constant, while the contact area between the soil and beater varies a lot. For small contact areas with the same G_B, partial clogging is inevitable. To mitigate this phenomenon, the spacing of cutters and the surface area of the cutters on the cutterhead needs to be studied in further research simulating excavation using a TBM

Compared with analytical and empirical approaches, the use of physical approaches such as the mixing test, along with the index W/A_c can be used to quantitatively assess the effect of beater shape when determining clogging potential. Compared with other physical simulation approaches, the mixing test is simple to conduct, and the test results are more repeatable. Furthermore, the test apparatus is portable, which means that it could be used on site to measure clogging potential for different geotechnical conditions during tunneling operations.

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Chapter 5: SUMMARY AND CONCLUSIONS

Chapter 2 introduces the history of tunnel boring machines, also includes the different types of tunnel boring machine as well as the advantages of each. Besides this, the topic of clogging problems during excavation and how they occur was introduced. Finally, previous clogging assessments were introduced, as well as the different indices used to evaluate clogging potential and different clogging classifications.

In Chapter 3, a new index, W/A_c (weight of soil stick to the beater per unit area) was introduced to assess clogging potential. Five different types of mixtures composed of bentonite and kaolin were employed. Five samples, with water content distributed evenly between the plastic limit and liquid limit, were tested for each bentonite/kaolin mixture. For each sample, a mixing test and Atterberg limit test were conducted. A comparison was made between this new index, W/A_c, and the stickiness ratio. The classifications made using the stickiness ratio were verified by using combined data collected from previous researchers. In addition, a clogging classification made using W/A_c was introduced to provide a straightforward way to assess clogging potential on site.

A sensitivity analysis was also conducted to compare the new index, W/A_c, and the stickiness ratio. It was found that the index W/A_c is more repeatable and less sensitive to the mass of soil, and size of drill bit used. Moreover, the clogging potential of different types of soil can be differentiated more clearly by using W/A_c.

In Chapter 4, the impact of beater shape was studied by conducting mixing tests. Three different shapes of beater, with different open areas, were employed in the mixing test. The ratio A'/A (the ratio between the open area of the beater and the entire area of a beater with no opening) was employed to quantify the variation of the open area. Besides this, two indices were used to analyze the impact of the open area on mixing test results, W/A_c and G_B (weight of soil stuck to the beater). It was found that both indices increase with increasing bentonite content. However, G_B does not reflect the variation in the open area, while W/A_c (the weight of soil stuck to the beater per unit area) increases with an increase in the open area of the beater.

The key conclusions of this work are highlighted below.

(1) A mixing test was conducted to assess clogging potential, with five soil mixtures containing different percentages of bentonite and kaolin corresponding to different consistency indices (I_c) tested. A sensitivity analysis was conducted to study the impact of soil mass, size of drill bit, and soil type, as well as the impact of beater shape on clogging potential.

(2) Test results based on the parameter W/A_c are more repeatable compared to the stickiness ratio, since the standard deviation of W/A_c for different soil mass and size of drill bit is smaller for W/A_c. Moreover, the clogging potential of different types of soil can be differentiated more clearly using W/A_c.

(3) The mixing test apparatus used to determine clogging potential is portable, and the test is conducted easily and saves time. Therefore, the test could be conducted on site to assess clogging potential.

(4) The effect of different beater shape on determination of clogging potential was analyzed by comparing W/A_c with G_{MT} from the mixing test. Three beaters with the same frame (outer shape) but different opening sizes were employed to assess the effect of beater shape. The parameter A'/A was used to represent the open area of each drill bit, where A'/A is the ratio of the open area of the beater over the entire area of the beater with no open area. The value of A'/A for Beater 1, Beater 2 and Beater 3 are in the range of 0.5 to 0.54, 0.63 to 0.67 and 0.69 to 0.71, respectively.

From Beater 1 to Beater 3, the average value of W/A_c increases by 53 kg/m^2. This is because the large piece of soil tends to stick to the open area of the beater instead of sticking to the whole beater surface, leading to a decrease in the contact area between the soil and beater. Therefore, the parameter W/A_c increases dramatically with an increase in A'/A.

(5) G_{MT} is not sensitive to the open area of the beater. An increase in the open area leads to a slight variation in G_{MT}. The average G_{MT} is within 0.2 kg for the three beaters studied. In this case, G_{MT} stays constant, while the contact area between soil and beater varies a lot. For a small contact area with the same G_{MT}, partial clogging is inevitable. During excavation using a TBM, to mitigate this phenomenon, the spacing of cutters and the surface area of the cutters on the cutterhead needs to be studied in further research.

(6) Compared with analytical and empirical approaches to assess clogging potential, the mixing test, along with the index W/A_c, can be used to quantitatively assess the effect of beater shape. Compared with other physical simulation approaches, the mixing test can be conducted easily and test results are more repeatable. The test apparatus is portable, which means that it could be used on site to measure the clogging potential for different geotechnical conditions while tunneling.

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