ASSESSMENT OF MECHANICAL AND HYDRAULIC PERFORMANCES OF RICE HUSK ASH-MIXED CEMENT FOR ROCK FRACTURES GROUTING

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A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Engineering in Civil, Transportation and Geo-resources Engineering

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การประเมินประสิทธิภาพเชิงกลศาสตร์และชลศาสตร์ของซีเมนต์ผสมเถ้าแกลบ เพื่ออุดรอยแตกในหิน

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วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรมหาบัณฑิต
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Suranaree University of Technology has approved this thesis submitted in partial fulfillment of the requirements for a Master's Degree.

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มธุรส นิลโขง : การประเมินประสิทธิภาพเชิงกลศาสตร์และชลศาสตร์ของซีเมนต์ผสมเถ้าแกลบเพื่ออุดรอยแตกในหิน (ASSESSMENT OF MECHANICAL AND HYDRAULIC PERFORMANCES OF RICE HUSK ASH-MIXED CEMENT FOR ROCK FRACTURES GROUTING) อาจารย์ที่ปรึกษา : ผู้ช่วยศาสตราจารย์ ดร.ปรัชญา เทพณรงค์, 99 หน้า.

วัตถุประสงค์ของการศึกษาเพื่อประเมินประสิทธิภาพเชิงกลศาสตร์และชลศาสตร์ของซีเมนต์ผสมเถ้าแกลบ (RHA) เพื่ออุดรอยแตกในรอยแตกมวลหิน ส่วนผสมวัสดุอุดเตรียมจากซีเมนต์ผสมเถ้าแกลบโดยมีอัตราส่วนของเถ้าแกลบต่อซีเมนต์ (RHA:C) เท่ากับ 1:10, 3:10, 5:10 และ 10:10โดยน้ำหนัก ด้วยปริมาณน้ำต่อซีเมนต์ (W:C) เท่ากับ 1:1 โดยน้ำหนัก ผลการทดสอบประสิทธิภาพของซีเมนต์ผสมเถ้าแกลบถูกเปรียบเทียบกับผลการทดสอบของซีเมนต์สำหรับอุดที่ไม่ได้ผสมเถ้าแกลบ (0:10) ผลการทดสอบพบว่าค่าความหนืดเฉลี่ยของซีเมนต์ผสมเถ้าแกลบมีแนวโน้มเพิ่มขึ้นตามสัดส่วนของเถ้าแกลบที่เพิ่มขึ้น ผลการทดสอบสมบัติทางกลศาสตร์พื้นฐานพบว่าเมื่อมีระยะเวลาบ่มตัวเพิ่มขึ้นทำให้ค่ากำลังรับแรงกดสูงสุดในแกนเดียว ค่าสัมประสิทธิ์ความยืดหยุ่น ค่ากำลังรับแรงดึงสูงสุดแบบบราซิล และค่ากำลังยึดติดสูงสุดของตัวอย่างแท่งซีเมนต์ผสมเถ้าแกลบสำหรับอุดสูงขึ้น ที่อัตราส่วนเถ้าแกลบต่อซีเมนต์เท่ากับ 5:10 เวลาบ่ม 28 วันให้ค่ากำลังรับแรงกดสูงสุดในแกนเดียว ค่าสัมประสิทธิ์ความยืดหยุ่นสูงสุด ค่ากำลังรับแรงดึงสูงสุดแบบบราซิล และค่ากำลังยึดติดสูงสุด เท่ากับ 16.11, 2,160, 1.70 และ 2.48 เมกะปาสคาลตามลำดับ นอกจากนี้ที่อัตราส่วนผสมนี้ยังให้ค่ากำลังรับแรงเฉือนระหว่างวัสดุอุดและรอยแตกของหินสูงสุดในการทดสอบค่ารับกำลังแรงเฉือนสูงสุดที่ระยะเวลาบ่ม 7 วัน และยังแสดงค่าความซึมผ่านและค่าความหนืดต่ำอีกด้วย ดังนั้นเป็นไปได้ว่าซีเมนต์ผสมเถ้าแกลบที่อัตราส่วน 5:10 มีศักยภาพที่เหมาะสมในการเป็นวัสดุอุดในรอยแตกได้

สาขาวิชา เทคโนโลยีธรณี

ปีการศึกษา 2562

ลายมือชื่อนักศึกษา ____________

ลายมือชื่ออาจารย์ที่ปรึกษา ____________

MATHUROT NINKHONG : ASSESSMENT OF MECHANICAL AND HYDRAULIC PERFORMANCES OF RICE HUSK ASH-MIXED CEMENT FOR ROCK FRACTURES GROUTING. THESIS ADVISOR : ASST. PROF. PRACHYA TEPNARONG, Ph.D., 99 PP

RICE HUSK ASH/GROUTING MATERIALS/ROCK FRACTURE.

The objective of this study is to assess the mechanical and hydraulic performances of rice husk ash (RHA)-mixed with the Portland cement for grouting in rock fractures. The mixtures of grouting materials are prepared from RHA-mixed cement. The RHA-cement ratios are 1:10, 3:10, 5:10 and 10:10 with water-cement ratio of 1:1 by weight. As a result performance of the RHA-cement mixtures are compared with grouting cement (0:10). The results indicate that the average viscosity of RHA-mixed cement tends to increase as the RHA-mixed cement ratio increases. The basic mechanical properties test results indicate that when the curing time increases the uniaxial compressive strength, elastic modulus, Brazilian tensile strength and bond strength of RHA-mixed cement grout increases. The specimens with RHA-cement ratio of 5:10 after 28 days curing time provide the highest compressive strength, elastic modulus, tensile strength and bond strength of 16.11, 2,160, 1.70 and 2.48 MPa, respectively. In addition, this mixtures ratio represents the highest shear strength between grouting material and rock fractures in direct shear test after 7 days curing time and gives the low permeability and slurry viscosity. Thus, the 5:10 ratio of RHA:C

probably has the good potential to be the suitable ratio that will be used as grouting materials.

School of Geotechnology

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Student's Signature________________

Advisor's Signature________________

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Mathurot Ninkhong

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SYMBOLS AND ABBREVIATIONS

γ_w	=	Density of water
μ	=	Kinematic viscosity
σ	=	Normal stress
σ_B	=	Brazilian tensile strength
σ_c	=	Uniaxial compressive strength
τ	=	Shear strength
τ_{av}	=	Bond strength
ρ_{slurry}	=	Density of mixture slurry
ρ_w	=	Density of distilled water
ν	=	Kinematic viscosity
ϕ_p	=	Angle of internal friction
A	=	Cross-section area
C	=	Portland cement
c_p	=	Cohesion
D	=	Diameter of sample
F	=	Sheared force
i	=	Hydraulic gradient
K	=	Coefficient of permeability
k	=	Intrinsic permeability

SYMBOLS AND ABBREVIATIONS (Continued)

L	=	Length of sample
L/D	=	Length to diameter ratio
P	=	Applied load
P_f	=	Maximum load
Q	=	Volume flow rate
RHA:C	=	Rice husk ash – cement ratio
SG	=	Specific gravity
t	=	thickness of the sample
W:C	=	Water – cement ratio

CHAPTER I

INTRODUCTION

1.1 Background and rationale

Rice is an important agricultural product and it is also the main dish for more than half of our world's population. Thailand is one of the biggest rice exporters. Farmer harvest paddy then puts them through a process called milling process. Rice husk is a byproduct of the rice milling process. Each year, the quantity of the rick husk from rice process is about 8.1 million tons (Department of Alternative Energy Development and Efficiency, 2015). It is a major agriculture waste in Thailand. In the green technology field, the rice husk is used as fuel in electricity power plant. After the rice husk is burned, it gives heat of combustion at around 3,880 kcal/kg and produces ash as much as 17 percentages of the original volume called the Rice husk ash (RHA). (Kanjanawarawanich, 2013).

Pozzolanic material is often used as supplementary cementitious material in construction. Pozzolanic materials such as fly ash, rice husk, silica flume and sludge, are added in Portland cement mixture to reduce volume of the Portland cement. In addition, the pozzolanic material help in reducing the production of Portland cement, which can reduce the amount of carbon dioxide released to the atmosphere.

Many researchers confirmed that the RHA is a highly reactive pozzolanic material, and it has been successfully used to replace the Portland cement. The major composition of RHA is silica about 70-90% and the loss on ignition (LOI) was relatively high (5.81%) (Habeeb and Mahmud, 2010 and Korotkova et al., 2016). Moreover, the RHA is lightweight, high porosity, having a wide surface area, can be good absorber and a good insulator (Xu et al., 2012). At present, Portland cement is usually used as the grouting material because it can harden and cure underwater. However, an intention to replace the Portland cement by RHA is not only useful for economic viewpoint but also helps to eliminate agriculture waste and promote alternative choice for new technology. Only limited information is available on the mechanical performances of RHA for cement grout. So, it was led to the concept of this study is the mechanical and hydraulic performance of rice husk ash-mixed cement grouting in rock fractures for apply in field of Geological engineering.

1.2 Research objectives

The objective of this study is to assess the performance of rice husk ash mixed cement grouts in terms of the mechanical and hydraulic properties.

1.3 Research methodology

The research methodology show in Figure 1.1 comprises 5 steps; including literature review, sample collection and preparation, laboratory tests, discussions and conclusions and thesis writing.

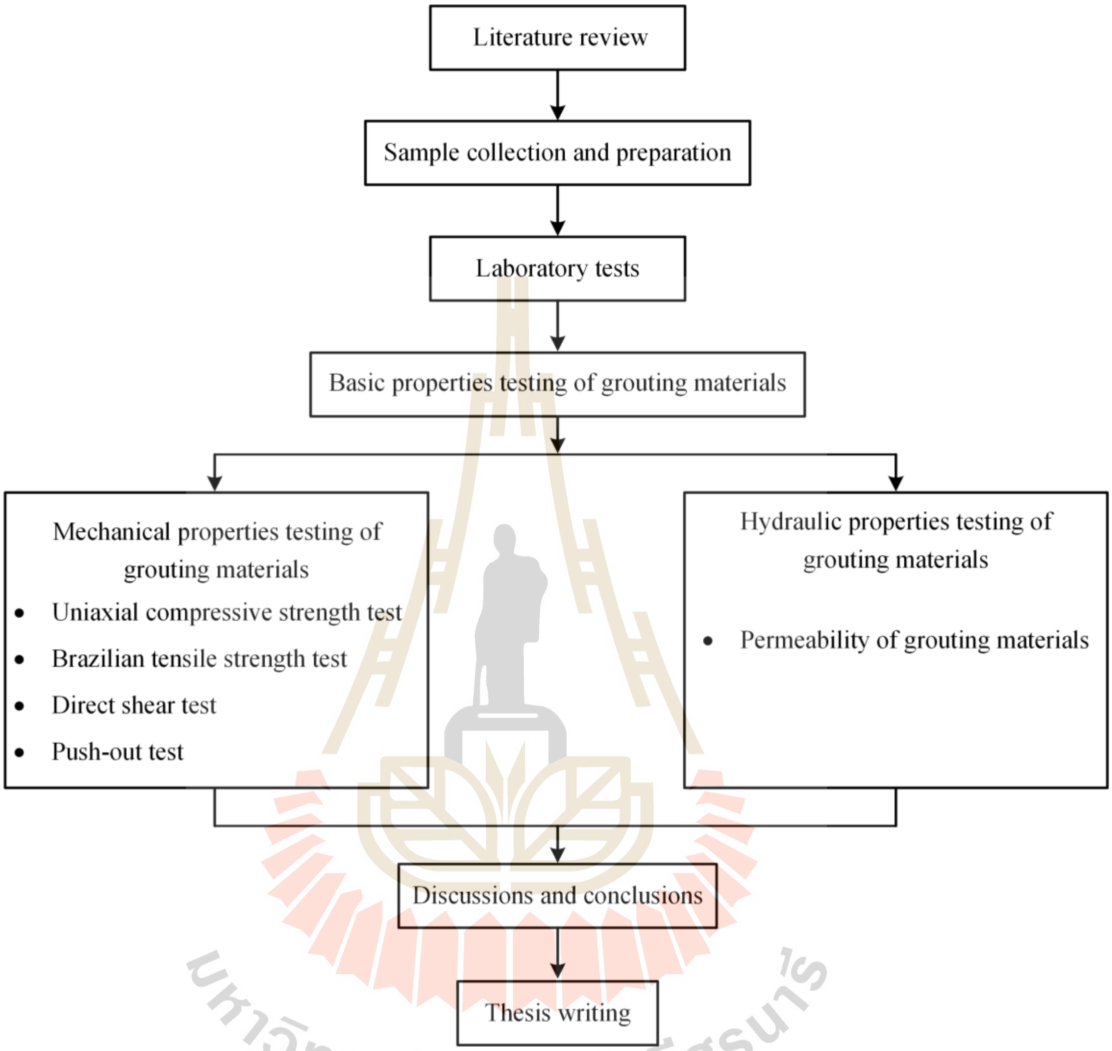


Figure 1.1 Research Methodology.

1.3.1 Literature review

Literature review is carried out to study researches about application of the RHA-mixed cement, grouting materials, permeability of rock fractures and bond strength of cement grouting in rock mass. The sources of information are from journals, technical reports and conference papers. A summary of the literature review is given in the thesis.

1.3.2 Sample collection and preparation

The grouting materials used in this study consist of the RHA with particle sizes less than 75 μm, ordinary Portland cement type I and sandstone block samples. The RHA is collected from biomass power plant of A.T. Biopower Co., Ltd. The mixture ratios of the RHA-mixed cement (RHA:C) are set to 1:10, 3:10, 5:10 and 10:10 with water-cement (W:C) ratio of 1:1 by weight. The pure cement is used for comparing with the RHA-mixed cement test result. The ratio of pure cement is 0:10 with W:C of 1:1 by weight. The sandstone block samples are collected from Pakchong district, Nakhon Ratchasima province. The rock belongs to Phra Wihan Formation of the Khorat Group. The sizes of block are 100×100×160 mm^3 for direct shear test and 110×110×130 mm^3 for push-out test. The sample preparation is carried out in the Geomechanics Research (GMR) Laboratory at Suranaree University of Technology.

1.3.3 Laboratory tests

1.3.3.1 Basic properties testing of grouting materials

The objective of basic properties test is to determine the physical properties of grouting materials as density and viscosity of RHA-mixed cement and cement slurry for selecting the optimum mixing content. Similarities and differences of the results will be compared. The optimum mixing content of grouting materials will be permeability testing.

1.3.3.2 Mechanical properties testing of grouting materials

1. Uniaxial compressive strength testing

The uniaxial compressive strength tests determine the uniaxial compressive strength and elastic modulus of grouting material specimens. The test procedure follows by the ASTM D7012 standard practice. RHA:C ratios vary from 1:10, 3:10, 5:10 and 10:10. The grouting material specimens are investigated after 3, 7, 14 and 28 days curing time.

2. Brazilian tensile strength test

The Brazilian tension test determines the indirect tensile strength of the grouting materials. The test procedure follows the ASTM D3967 standard practice. The samples are 54 mm diameters with L/D ratio as 0.5. The mixture proportions in this test are same with the compressive strength test.

3. Direct shear test

The objective of the direct sheared tests is determined the shear strength of grouting material in rock fractures. Grouting materials are RHA and cement. The test method and calculation follow as much as practical the ASTM D5607 standard practice. The direct shear tests are performed with the normal stresses of 0.5, 1.0 and 1.5 MPa. The mixture proportions in this test are same with the compressive strength test. The test is carried out at the ages of 7 days curing.

4. Push – out test

The objective of this test is to determine the bond strength of cement plug in sandstone specimen through push-out test. The cement plug is prepared from the grouting materials in the same ratio as the compressive strength test. The size of rock specimens is 110 × 110 × 130 mm and all specimens are drilled as perpendicular to the bottom sample surfaces. The curing period for all push-out tests is 3, 7, 14 and 28 days.

1.3.3.3 Hydraulic properties testing of grouting materials

1. Permeability of grouting materials

The objective of the grout permeability tests is to determine the water permeability of grouting material specimen using constant head flow tests. The permeability of grouting material is the factor to be used to determinate the most suitable mixing ratios for grouting in rock. Proportions of RHA:C mixtures are 1:10, 3:10, 5:10 and 10:10 with W:C ratio of 1:1 by weight. Results of both mixtures are compared. These tests are conducted at 3, 7, 14, 28 and 60 days of curing.

1.3.4 Discussions and conclusions

Discussions of the results are described to determine the reliability and accuracy of the measurement. Performances of RHA-mixed cement as grouting material are discussed base on the test results. Similarities and discrepancies of the grouting material in terms of the mechanical and hydraulic properties are discussed. The research results are concluded.

1.3.5 Thesis writing

All research activities, methods and results are documented and complied in the thesis. The research or findings will be published in the conference proceedings.

1.4 Scope and limitations

The scope and limitations of the research include as follows.

1. This research emphasizes on studying the mechanical and hydraulic properties of RHA-mixed ordinary Portland cement for grouting rock fractures.
2. Portland cement type I is used (ASTM C150 standard practice).
3. The RHA-mixed cement ratios (RHA:C) are 1:10, 3:10, 5:10 and 10:10 with water-cement (W:C) ratio of 1:1 by weight. The ratios of mixtures are the additional ratio.
4. Mixing, curing and testing of the cement and mixtures follows, as much as, the ASTM standards practical.
5. Laboratory testing will be conducted on specimens from Phra Wihan sandstone.
6. All tested fractures will be artificially made in the laboratory.
7. The laboratory tests of permeability of RHA-mixed cement include constant head flow test.
8. Comparing the engineering properties of RHA ingredients with standardized cementitious components to assess the potential of grouting materials.
9. The permeability of grouting materials is determined in term of intrinsic permeability.

1.5 Thesis contents

Chapter I describes the background and rationale, the objectives, the methodology and scope and limitations of the research. Chapter II summarizes results of the literature review. Chapter III describes the sample preparation. Chapter IV to VI describes the laboratory testing and test results. Chapter VII discusses and concludes the research results and provides recommendations for future research studies.

CHAPTER II

LITERATURE REVIEW

2.1 Introduction

This chapter provides the results of literature review carried out to improve an understanding of application of the RHA-mixed cement, grouting materials, experimental researches on the strength of cement grout and permeability of cement grout.

2.2 Application of the RHA-mixed cement

In Thailand, the annual production of RHA has been approximated at 1.6 million (Wansom et al., 2010). Rice husk ash (RHA) is a by-product of electricity generation in biomass power plants. After the rice husk is burned, it gives heat of combustion at around 3,880 kcal/kg and produces ash as much as 17 percentages of the original volume (Kanjanawarawanich, 2013).

The researchers found the major composition of RHA is silica about 70-90% and the loss on ignition (LOI) was relatively high that show in Table 2.1. The chemical compositions of RHA are difference depend on the type of paddy, crop year, climate and geographical conditions of paddy field.

Table 2.1 The chemical compositions of rice husk ash that collected from the several researches (Habeeb and Mahmud, 2010; Antiohos et al., 2014 and Korotkova et al., 2016).

Chemical compositions	Weight % of the chemical compositions of rice husk ash from		
	Habeeb and Mahmud (2010)	Antiohos et al. (2014)	Korotkova et al. (2016)
SiO_2	88.32	93.15	93.40
K_2O	2.91	1.63	1.40
Na_2O	0.12	160.00 (ppm)	0.10
CaO	0.67	0.89	0.31
MgO	0.44	0.40	0.35
Fe_2O	0.67	0.18 (ppm)	0.06
P_2O_5	-	0.51	0.80
SO_3	-	0.10	-
CI	-	410.00 (ppm)	-
Al_2O_3	0.46	0.13	0.05
LOI	5.81	5.61	-

Many researchers confirmed that the RHA is a highly reactive pozzolanic material, and it has been successfully used to replace the Portland cement. Mehta (1987) reported that RHA is a highly reactive pozzolan and consists of a high amount of amorphous silica that could contribute to a higher compressive strength than a Portland cement control.

Zhang and Malhotra (1996) found that rice husk ash has reacted pozzolanic reactivity. It could be used as a supplementary cementing material to produce high - performance concrete. These results reported that the compressive strength increased by more than 80 MPa as compared to high strength concrete when replacing 10% of the Portland cement with RHA.

Dabai et al. (2009) studied on compressive strength, setting time, and chemical analysis of cement mixed with RHA. The chemical analysis of RHA result shows that RHA has high amount of silica (68.12%). For setting time testing, the increasing in setting time of paste having RHA shows low level of hydration for RHA concrete. This is resulted from the reaction between cement and water which liberate calcium hydroxide ($Ca\ (OH)_2$). Compressive strength test show that the best compressive strength result was obtained from cement samples which were replaced by 10% RHA and it was decreased as the percentage of RHA was increased (Table 2.2). The compressive strength of specimens also increases with the setting time increasing as the highest compressive strength encountered at 28 days. This may be due to the retention of water with the structural framework of the mixture there by allowing

Table 2.2 Compressive strength test of cement mixed with RHA (Dabai et al., 2009).

Amount of Cement (%)	Amount of RHA (%)	Design Strength (N/mm^2)				
		1 Day	3 Days	7 Days	14 Day	28 Days
100	0	16.00	25.70	28.00	32.30	41.00
90	10	12.60	14.20	22.10	28.50	36.30
80	20	6.70	10.40	18.60	24.30	30.20
70	30	4.20	8.60	16.30	22.40	24.00
60	40	2.00	6.20	14.40	18.20	20.30
50	50	0.90	4.10	9.20	11.50	14.00

Habeeb and Mahmud (2010) studied on properties of RHA and its use as cement replacement material. The research was presented the properties of RHA produced by using a ferro-cement furnace. Furthermore, the effect of grinding on the particle size and the surface area was first investigated, then the XRD analysis was conducted to verify the presence of amorphous silica in the ash the effect of RHA average particle size and percentage on concrete workability, fresh density, superplasticizer (SP) content and the compressive strength were also investigated. Although grinding RHA would reduce its average particle size (APS), it was not the main factor controlling the surface area and it is thus resulted from RHA's multilayered, angular and microporous surface. Incorporation of RHA in concrete increased water demand. RHA concrete gave excellent improvement in strength for 10% replacement (30.8% increment compared to the control mix), and up to 20% of cement could be valuably replaced with RHA without adversely affecting the strength. Increasing RHA fineness enhanced the strength of blended concrete compared to coarser RHA and control ordinary Portland cement (OPC) mixtures.

Rashid et al. (2010) studied the durability of cement mortar that mixed of RHA. The durability results are different follow as level of replacement ordinary Portland cement by RHA. The results show the samples that level of replacement ordinary Portland cement by RHA as 20% at 90 days are high strength (3,860 psi). In durability test, all samples passed for 20 cycles except 25% and 30% replacement level.

Chatveera and Kongsab (2011) studied the durability of concrete containing black rice husk ash (BRHA) from the rice mill. They found that BRHA can be classified as a pozzolanic material of type N. For 20% BRHA concrete, the dry shrinkage was increased more than 40%. The autogenous shrinkage and weight loss due to acid solutions of BRHA concrete were less than the normal concrete.

Hwang et al. (2011) studied the effect of rice husk ash on the strength and durability characteristics of concrete. The properties of the concrete were investigated, including compressive strength, concrete electrical resistivity, and ultrasonic pulse velocity. For the compressive strength test, they compared the compressive strength between non-RHA and ground RHA cylindrical concrete. The results of the study indicate the comparison of the data for 56 and 91 days of curing ages shows the compressive strength of concretes with up to 20% ground RHA attain values equivalent to that control concrete. With water-to-binder ratio from 0.23 to 0.47, compressive strength at 28 days. After 91 days of curing, the electrical resistance of all RHA concrete becomes higher than 20 kΩ-cm. Similarly, for all RHA concrete samples, the UPV are all higher 3660 m/s after 91 days of curing. The strength efficiency of cement in ground RHA concrete is much higher than that of the control concrete. RHA concrete in the 47–66 MPa range is obtained in this investigation.

Alex et al. (2016) studies the experimental investigation on rice husk ash as cement replacement on concrete production. The objective of this study is to optimize the grinding conditions (15 and 60 min) and the amount of RHA replacement (10, 15 and 20 wt%) required for various types of RHA used as a supplementary cementitious material. The results indicate that the average particle size decreased with increasing grinding time whereas, the specific surface area increased with increasing grinding time for all types of RHA samples. The bulk density also followed similar trend of the average particle size and RHA of type A subjected to 60 min of grinding, being the finest sample showed higher bulk density of the all the samples. In case of compressive strength development, the partial replacement of RHA ground samples at 20 wt% could be regarded suitable and for unground RHA 15 wt% might be considered satisfactory. Although, 10 wt% cement replacement showed a remarkable percentage of strength gain (7.8%) as compared to normal concrete but 20 wt% replaced concrete also performed better than the normal concrete, thereby contenting to be the optimal replacement level. For tensile strength development, 20 wt% replacement was considered to be optimal.

2.3 Grouting material

Grouting has a wide application in the modern civil engineering world. It is a special technique involves procedure that injection into voids, fissures, and cavities in soil or rock formation in order to improve their properties, specifically to reduce permeability, to increase strength and durability or to lessen deformability of the formations. Various materials are used for grouting depending on the purpose of the grouting and the properties of the grouted rock or soil. The conventional method currently used to improve the mechanical properties of rock mass is the grouting with ordinary Portland cement (OPC). The ordinary Portland cement (OPC) in the forms of cement-water, cement-water-sand, cement-water additive, or cement-water-sand-additive combinations is usually used. Characteristics of the grouts are influenced by many variables. The important ones include water-cement ratio (W/C), chemical compositions, fineness of the cement, additives to the grout, speed of mixing, mixing time, efficiency of mixing, and temperature (Anagnostopoulos, 2006).

The cement grouting is the most popular and economical way to improve the properties of the rock masses. Essentially the cement grout, or slurry, is a mixture of cement and water. It is a well-established rule in the concrete technology to define the ratio W/C by weight (e.g. W/C=0.5: means 0.5 kg water added to 1.0 kg cement), thus considering the cement as the base of the mix. Strange enough, in the field of grouting the habits are quite unstable. They refer to this ratio, but also to its inverse, from time to time they use the weight but also the volume of the components. It is felt that a conformity with the concrete technology should be enforced by any mean to avoid additional confusions and that only the W/C ratio by weight should be used, as shown in Figure 2.1. In the following only said water/cement ratio will apply (Deere, 1982).

Warner (2004) stated that Portland cement is one of grouting material, consists of a mixture of calcareous materials such as limestone, chalk, or shells and argillaceous materials such as clay or shale. Appropriate proportions of these raw materials are combined, crushed, pulverized and burned in a rotary kiln at temperatures of 2,600°F-3,000°F (1,430°C-1,650°C). The resulting material, known as clinker, is pulverized upon cooling. Ordinary Portland cement is very active, in that a chemical reaction develops immediately upon its coming in contact with water. This re-action, which is known as hydration, is exothermic; that is, it produces heat and is responsible for the rate of hardening of the cementitious composition.

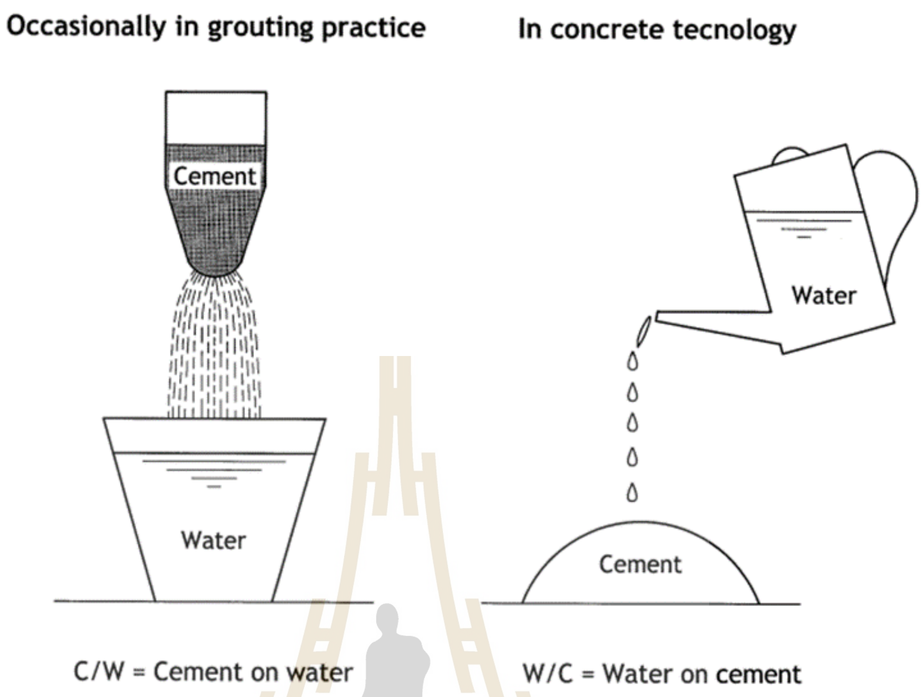


Figure 2.1 Definition of the water to cement ratio (W/C) (Deere, 1982).

The composition of Portland cement is delineated in ASTM C 150, "Standard Specification for Portland Cement" wherein it is defined as a hydraulic cement produced by pulverizing clinker consisting essentially of hydraulic calcium silicates, usually containing one or more of the forms of calcium sulfate as an inter-ground addition. The term hydraulic in the definition signifies that the product will set and harden under water as a result of a chemical reaction. Five different types of cement are enumerated in ASTM C 150

Type I-For use when the special properties specified for any other type are not required

Type II-For general use, more especially when moderate sulfate resistance or moderate heat of hydration is desired

Type III-For use when high early strength desired

Type IV-For use when a low heat of hydration is desired.

Type V- For use when high sulfate resistance is desired.

When using a normal Portland cement a total water-cement ratio of the order of 0.6 to 0.7 is a practical minimum but also a quite adequate value in a great majority of cases. See Table 2.3 For micro-fine cement however a higher W/C ratio is required, e.g. up to 1.0 or 1.2 (Bremen, 1997).

Rahmani (2004) stated that grouting had been used over the past two centuries to increase the strength, decrease the deformation and reduce the permeability of soils or fractured rocks. Numerical models could simulate a distribution of grout inside fractures by which the effectiveness of grout could be estimated. Few numerical studies had been carried out to model grout penetration in fractured rocks. Due to complexities of modeling grout and fracture most of these studies had either used simplifying assumptions or been bound to small sizes of fractures, both resulting in unrealistic simulations. Then the current work is aimed to eliminate some of the simplifying assumptions and to develop a model that could improve the reliability of the results. In reality, grouts were believed to behave as a Bingham fluid, but many models did not consider a full Bingham fluid flow solution due to its complexity. Real fractures had rough surfaces with randomly varying apertures. However, some models considered fractures as planes with two parallel sides and a constant aperture. In this work the

Bingham fluid flow equations were solved numerically over a stochastically varying aperture fracture. To simplify the equations and decrease the computational time the current model substituted two-dimensional elements by one-dimensional pipes with equivalent properties. The model was capable of simulating the time penetration of grout in a mesh of fracture over a rather long period of time. The results of the model could be used to predict the grout penetration for different conditions of fractures or grout.

Table 2.3 Examples of unique thick mixes used in a number of important dams and tunnels (Bremen, 1997).

Dams and tunnels	W/C	Fluidifier
Paute (Ecuador) upper part	0.6	Intraplast 1.4%
Alicura (Argentina)	0.67	Intraplast 1.2%
El Cajon (Honduras)	0.7	Bentonite 0.2%
Clyde dam (New Zealand) 2nd part	0.6	Intraplast 1.0%
El Chocon (Argentina) repairs	1.0	Bentonite 0.5%
Sir (Turkey)	0.7or 1.0%	Puzolanic cement, Mistra 1.0% Bentonite 1.2%
Katze (Lesotho)	0.59	Cement + ash. Conplast 1.5%
Pichi Picum Leufu (Argentina)	0.7	Various
Potrerillos (Argentina)	0.7	Rheobuild/Viscocrete 0.7 – 0.8%
Ait Hamou (Morocco)	1.0	Bentonite 2.0%
Casecnan lower tunnel (Philippines)	0.63	Intraplast 1.0%

Samaiklang and Fuenkajorn (2013) studied the mechanical and hydraulic performance of commercial grade cement grouts in rock fracture. The results are compared in terms of compressive strength, tensile strength, bond strength and push-out strength for against rock fracture. All grouts are prepared by mixing at the water-cement ratio of 0.60. The compressive strength after 28 day curing times is 25.77±2.54 MPa and the average tensile strength is 2.80±0.27 MPa. The bond strength test and push-out test results indicate that the bond strength between the cured grout and Phu Kradung sandstone fractures is varying from 1.03 to 2.53 MPa, and the push-out strength varying from 4.06 to 5.55 MPa.

Wetchasat (2013) assessed the performance of sludge mixed with the commercial grade Portland cement type I for reducing permeability of fractures in sandstone. This study aims at determining the minimum slurry viscosity and appropriate strength of the grouting materials. The results indicate that the suitable mixing ratios for sludge: cement (S: C) are 1:10, 3:10 and 5:10 with water-cement ratio (W: C) of 1:1 by weight. These proportions yield the lowest slurry viscosity of 5 Pa·s. For S: C = 3:10, the compressive strength and elastic modulus are 1.22 MPa and 224 MPa which are similar to those of bentonite mixed with cement. The shear strength of grouted fractures varies from 0.22 to 0.90 MPa under normal stresses ranging from 0.25 to 1.25 MPa. Permeability of grouting materials is from 10^{-17} to 10^{-15} m^2 and decreases with curing time. The S:C ratio of 5:10 gives the lowest permeability. Permeability of grouted fractures with apertures of 2, 10 and 20 mm range from 10^{-16} to 10^{-14} m^2.

Kaeso and Wannakamol (2017) studied the using of rice husk ash (RHA) as an additive for cement in petroleum well drilling. They found that the compressive strength of set cement specimens was increased with the amount of RHA and curing time increasing. The chemical analysis of the rice husk ash revealed high amount of silica oxide (96.72%). High amount of silica which is responsible for the strength. The results indicated that RHA can be used as cement substitute at 10%, 20% of replacement cause of setting time stop decrease after 10%wt.

Chiangmai and Tepnarong (2016) studied the performance of fly ash-mixed cement grouts for sealing boreholes in sandstone. The results lead to the selection of the most suitable ratio of fly ash-mixed cement for grouting in rock fracture. They indicate that the viscosity of grout slurry tends to increase as the fly ash-mixed cement ratio increases and when the curing time increases the intrinsic permeability (k) of cement grout decreases. The compressive strength after 28 days curing times is 10.45 ± 1.48 MPa. The highest compressive strength is from the fly ash-mixed cement ratio of 5:10. When the curing increases. For 3 days of curing time, the average bond strength of the fly ash-mixed cement ratio as 5:10 is 2.58±0.15 MPa. The permeability of grouting materials decreases when the curing time increases. The 5:10 ratio of fly ash mixed cement has the lowest permeability value. The fly ash-mixed cement mixtures have the mechanical and hydraulic properties equivalent to those of the commercial grade Portland cement mixtures which indicates that the fly ash can be used as a substituted material to mix with cement for sandstone sealing purpose.

2.4 Experimental researches on the strength of cement grout

Akgun (1996) conducted a research on bond strength of cement grout seals in rock. The objective of the research was to study the relationship between the strength of cement grout and the length-to-radius ratio of cement specimen. The strength values were obtained from the push-out tests of the cement grout borehole plugs with various diameter and length placed in welded tuff cylinders. The results showed that the three strength measures decreased with increasing plug radius and with decreasing plug length. The specimen with plug the length-to-radius ratio of eight had the highest axial strength. The result of the test indicated that in order to gain enough mechanical stability in permanently sealing of borehole with cement, length-to-radius ratio of cement grout should equal or greater than eight.

Shannag (2002) studied cement base grouts containing 0, 5, 10, and 15% replacement with metakaolin and with a water/cementitious materials ratio of 0.38 have been investigated. The rheological and mechanical properties of the proposed grouts are interesting, since, from a practical point of view, they exhibit no bleeding or segregation and reach high compressive strength and flowability. Metakaolin additions enhanced the strength, somewhat prolonged the setting times, reduced the flowability, improved sulfate resistance, and caused some increase in drying shrinkage. The results showed that Metakaolin could be added up to 15 % by weight of cement without reducing the 28-day strength. At 15 % admixing level, strength of the grout at the age of 28 days was increased by about 10 %. Based on the test results the use of Metakaolin for producing high-strength cementitious grouts is recommended. Considering the relative importance of compressive strength in cement and concrete technology, the compressive strength of the grouts was measured on 75 mm × 150 mm cylinders that were cast and cured in steel molds. Strength measurements for grouts cured in water were conducted at ages of 7 and 28 days. The compressive strength of the grout is a property that relates to the structure of the cement paste and provides an indicator of its quality. As expected, the hardened grouts developed high-early compressive strength. After 28 days, it was around 55.5 MPa. The highest compressive strengths were observed for the grout containing 15 % MK (Matakaolinite) as shown in Table 2.4. It is observed that adding up to 15 % MK caused about 10 % increase in 28 days strength. The increase in strength of the grouts containing MK is probably the result of a combined filler and pozzolanic effect. The filler effect leads to reduction in porosity of the transition zone and provides a dense microstructure and thus increases the strength of the grout. The pozzolanic effect helps in the formation of bonds between the densely packed particles in the transition zone through the pozzolanic reaction with the calcium hydroxide liberated during the hydration of Portland cement to form extra binding calcium silicates hydrates, which leads to further increase in strength.

Table 2.4 Compressive strength of the grouts proposed (Shannag, 2002).

Metakaolin Content (%)	Uniaxial Compressive Strength, σ_c (MPa)	
	7 days	28 days
0 (OPC)	45.30	50.30
5	44.40	52.10
10	46.20	52.40
15	49.50	55.50

Pattani and Tepnarong (2015) studied time dependent bond strength of cement sealing in rock salt for determine the mechanical and hydraulic performance of cement sealing in rock salt as a function of time. The results of constant head flow test indicate that when the curing time increases the coefficient of permeability (K) and the intrinsic permeability (k) of cement grout decreases. The short-term direct shear tests results indicate the frictional resistance at cement-salt interface with the friction angle of 44 degrees and cohesion of 2.12 MPa. The long-term push-out tests are performed on cement plugs with a series of relatively long curing time with the constant shear stress. Base on the visco-elastic shear creep behavior results, the relation between shear displacement and time are obtained with a various constant shear stress levels with 30 days. The Hookean-Kelvin model is chosen to determine the visco-elastic shear creep behavior. The fitting parameters of elastic shear modulus, visco-elastic shear modulus and viscous coefficient are determined as function of the applied constant shear ratio of borehole cement plug. The predicted curve is agreed well with the experiment data, which shows the reasonability of nonlinear visco-elastic shear creep model.

2.5 Permeability of cement grout

Permeability is one of the basic characteristics of the fluid that to flow through porous and creaking material. In rock mass that has crystalline texture, the fluid can flow through rock layer less than cracking one because number of connected porous and its size in hard rock is not a lot. (Gale, 1975; Iwai, 1976 and Raven and Gale, 1985) Permeability values effect rock mechanics behavior and to increase or decrease the stability of the engineering structure in rock mass. Fluid in rock sample can flow through rock texture and connected pore or both. Permeability level can be separate into 3 category which are 1) Permeability through into rock texture 2) Permeability through its cracking and 3) Permeability through both rock texture and cracking. The main factor that control fluid flow and permeability in crack is surface roughness, apertures, orientation of fractures, normal and shear stresses, and unloading behavior. (Indraratna and Ranjith, 2001)

Christensen et al. (1996) the experimental and calculated permeability of hardened cement pastes were compared. Experimental data for water permeability was obtained from the work of Nyame and Illston in 1980 on neat pastes with water to cement ratios (w/c) between 0.23 and 1.0. Mercury intrusion porosimetry (MIP) and impedance spectroscopy (IS) measurements were performed on equivalently prepared specimens. Then the Katz-Thompson relation was used to calculate permeability. Calculated results track well with experimental data as a location of time, with the experimental value of permeability slightly higher at most times. The correlation between experimental and calculated permeability, at all times, are within 1.5 orders of magnitude. The largest differences occurred at late times for the samples with low W/C ratio. This calculated permeability is quick, relatively simple and appears to give reasonable results when compared to conventional water intrusion methods.

Valenza and Thomas (2012) the permeability and elastic modulus of mature cement paste cured at temperatures between 8 °C and 60 °C were measured using a previously described beam bending method. The permeability increases by two orders of magnitude over this range, with most of the increase occurring when the curing temperature increases from 40 °C to 60 °C. The elastic modulus varies much less, decreasing by about 20% as the curing temperature increases from 20 °C to 60 °C. All specimens had very low permeability, kb 0.1 nm^2, despite having relatively high porosity, ϕ ~40%. Concomitant investigations of the microstructure using small angle neutron scattering and thermoporometry indicate that the porosity is characterized by nanometric pores, and that the characteristic size of pores controlling transport increases with curing temperature. The variation of the microstructure with curing temperature is attributed to changes in the pore structure of the calcium–silicate–hydrate reaction product. Both the empirical Carmen–Kozeny and modified Carmen–Kozeny permeability models suggest that the tortuosity is very high regardless of curing temperature.

Wong et al. (2012) a method to estimate permeability of cement-based materials using pore areas and perimeters from SEM images is presented. The pore structure is idealized as a cubic lattice having pores of arbitrary size. The hydraulic conductance of each pore is calculated using the hydraulic radius approximation, and a stereological factor is applied to account for the random orientation of the image plane. A ‘constriction factor’ is applied to account for variations in pore radius along the pore axis. Kirkpatrick's effective medium equation is then used to obtain an effective pore conductance, from which the macroscopic permeability is derived. The method was tested on forty-six pastes and mortars with different w/c ratio, cement, age and sand content. The permeability ranged from 3.0×10^{-18} to 5.8×10^{-16} m^2 It was found that 76% of the permeability was predicted to within a factor of ±2 and 98% within a factor of ±5 from measured values.

Setwong (2016) studied pozzolanic material as additives of the oil well API Class G cement to improve the compressive strength and permeability property of the mixed cement. The selected pozzolanic material consists of fly ash, palm oil fuel ash and sugarcane bagasse ash as was replaced cement at 10, 15, 20 and 30% by weight.

The cement specimens were cured at 7, 28 and 50 days curing time and 80°C of room temperature. The density and fluid loss volume of pozzolan cement slurry were reversely proportional to the amount of selected pozzolanic materials. The results indicated that the compressive strength of pozzolan cement specimens was directly proportional to the amount of mixed pozzolanic material and curing time due to the effect of pozzolanic reaction. The cement slurry mixed with more than 20% of each pozzolanic materials and the curing time of 50 days at 80°C its compressive strength decreased because the quantity of calcium hydroxide to pozzolanic reaction reduced. The permeability of pozzolan cement decreased with increasing quantity of pozzolanic materials and curing time. The percentage of replacement at a range between 15-20% by weight are suitable for additives of oil well API class G cement. This has the filtrate loss volume and viscosity are not much different from those of the cement without pozzolanic material while the density is lowered. These selected pozzolanic materials can increase the compressive strength and can also reduce the permeability of cement specimens effectively.

CHAPTER III

SAMPLE PREPARATION

3.1 Introduction

This chapter describes basic characteristics of materials test. Materials uses in this experiment are rice husk ash, Portland cement and sandstone rock samples.

3.2 Rice husk ash preparation

The rice husk ash samples used in this study are the byproduct from combustion processes of biomass power plant of A.T. Biopower Co., Ltd. (Figure 3.1). The chemical compositions of the RHA is determined based on X-ray fluorescence (XRF) spectrometer (reported from Nation Metal and Materials Technology Center, National Science and Technology Development Agency database) as shown in Table 3.1. The chemical compositions of fly ash (Chiangmai, 2016), sludge, bentonite (Wetchasat, 2013) and Portland cement type1 are summarized for comparing with the chemical compositions of RHA. The chemical compositions and particle size distribution of Portland cement type 1 obtained from Siam City Cement Public Company Limited (SCCC). One of the basic properties of the RHA is the distribution of the grain size particle. The particle size analysis provides the particle size distribution of material ranging from 0.00064 to 0.85 mm. Sieve analysis is determined the distribution of coarser particle and hydrometer method is used to determine the distribution of finer particle. The test procedures follow the ASTM D6913 and D7928 standard practice. The particle size distribution curves are shown in Figure 3.2. The results are comparable to Chiangmai (2016) and Wetchasat (2013) that studied the fly ash, sludge and bentonite. The Atterberg's limits are index properties of samples. Depending on the water content of the samples, it may appear in four states solid, semi-solid, plastic and liquid. In each state, the difference of consistency and behavior of sample causes the different engineering properties. The Atterberg's limits can be used to differentiate between silt and clay, and it can differentiate between different types of silts and clays. Hence, the RHA has been tested to find these indexes by using the ASTM D4318 and D2487 standard practice. The results are listed in Table 3.2. The RHA sample is classified according to the Unified Soil Classification System is in the OH (organic clay).

Figure 3.1 Rice husk ash used in this study.

Table 3.1 The chemical compositions of the RHA, fly ash, sludge, bentonite and cement samples (Chiangmai, 2016 and Wetchasat, 2013).

Compositions	% weight				
	RHA	Fly ash	Sludge	Bentonite	Cement
	A.T. biopower	Chiangmai, (2016)	Wetchasat, (2013)		SCCC
SiO_2	94.46	40.72	52.57	61.93	18.70
K_2O	2.26	1.77	1.55	0.44	-
Na_2O	0.04	-	0.22	1.63	-
CaO	0.89	16.52	0.79	1.27	-
TiO_2	-	0.50	0.79	0.19	-
V_2O_5	-	-	0.02	-	-
Cr_2O_3	-	0.02	0.02	-	-
MnO_2	-	0.14	-	-	-
MgO	0.36	-	0.96	2.44	1.61
Fe_2O	0.21	-	-	-	-
Fe_2O_3	-	14.40	6.33	4.45	2.93
P_2O_5	0.87	-	0.34	0.05	-
MnO	-	-	0.22	0.02	-
CuO	-	-	0.01	0.01	-
SO_3	0.14	7.48	0.55	1.27	2.76
CI	0.32	-	0.07	-	-
Al_2O_3	0.26	18.33	23.47	19.85	4.71
ZnO	0.02	0.03	-	-	-
As_2O_5	-	0.04	-	-	-
ZrO_2	-	0.03	0.03	0.03	-
Br	<0.01	-	-	-	-
Rb_2O	0.01	0.03	0.01	-	-
BaO	-	-	0.01	0.03	-
Nb_2O_5	-	-	<0.01	0.01	-
SrO	0.01	-	0.01	0.03	-
Y_2O_3	<0.01	-	<0.01	0.01	-
Ir_2O_3	-	0.015	-	-	-
CeO_2	-	-	-	0.04	-
LOI (Loss on ignition)	5.62	-	12.20	6.29	4.66

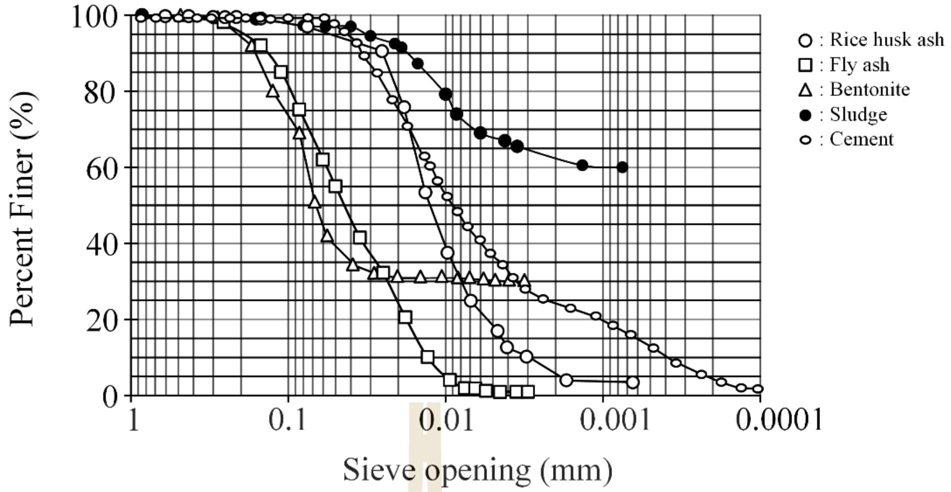


Figure 3.2 The particle size distribution of rice husk ash compared with those of fly ash, sludge, bentonite and cement results (Chiangmai, 2016 and Wetchasat, 2013).

Table 3.2 Atterberg's limits and specific gravity of rice husk ash.

Atterberg's limits	RHA (% weight)
Liquid limit	71.64
Plastic limit	71.60
Plasticity index	0.05
Specific gravity (g/cm^3)	1.96

3.3 Portland cement

Portland cement is the most common type of cement in general use around the world, used as a basic ingredient of concrete, mortar, and most cement grout. It is commonly used in general concrete construction when there is no exposure to sulphates in the soil or groundwater. In order that, Portland cement can be purchased readily and low cost. In this study, Portland cement type I is used in conforms to the ASTM C150 standard practice. Portland cement of bag cement 50 kg, is from the Siam City Cement Public Company Limited, Thailand. The cement is kept in plastic box sealed to prevent moisture, cool-dry area.

The properties of Portland cement conform to SCCC which is autoclave expansion of 0.006%, setting time for initial of 118 minutes and final of 215 minutes. The air content in mortar is 10%. The compressive strength for 7 and 28 days is 37 and 45 MPa. The chemical compositions of Portland cement type I, which is the same type used in this study are summarized in Table 3.1.

The components of cement slurry are commercial grade Portland cement mixed with RHA. The mixing ratios of the RHA-cement (RHA:C) are set to 1:10, 3:10, 5:10 and 10:10 with water-cement (W:C) ratio of 1:1 by weight. The pure cement is used for comparing with the RHA-mixed cement test result. The ratio of pure cement is 0:10 with water-cement (W:C) ratio of 1:1 by weight. The RHA-cement mixtures are poured into the mixing container (Figure 3.3) at a low mixture speed, and all components are added to the materials within 15 seconds. After all the cement is added, the slurry is mixed at high speed for additional 35 seconds. The cement slurry mixtures are poured and cured in 54 mm diameter PVC mold for use in the mechanical testing. Figure 3.4

shows the specimens are cured in PVC mold under water at room temperature for 3, 7, 14 and 28 days before testing. They are out of mold and cut to a L/D ratio as 2.0 to 2.5 for the uniaxial compressive strength test and 0.5 for the Brazilian tensile strength test. (Figure 3.5)

Figure 3.3 The mixing container used to prepare cement slurry.

Figure 3.4 PVC molds with curing cement mixture.

Figure 3.5 Sample is cut to obtain the desired length.

3.4 Sandstone rock samples

The sandstone rock samples are collected from Pakchong district, Nakhon Ratchasima province. The rock belongs to Phra Wihan Formation of the Khorat Group. The age of sandstone is between Upper and Middle Jurassic. Average uniaxial compressive strength and elastic modulus are 71.3 MPa and 13.9 GPa, respectively. The selection criteria for rock sample are that the rock should be homogeneous and availability as much as possible. This is to minimize the intrinsic variability of the test results. Sample preparations are carried out in the laboratory facility at Suranaree University of Technology. Sample preparations have been carried out for series of direct shear test (Figure 3.6) and push-out test (Figure 3.7).

3.4.1 Sandstone rock samples preparation for direct shear test

The sandstone rock samples of direct shear test are prepared to have prismatic block. The size of sandstone block is 100×100×160 mm^3. The fractures are artificially made in the laboratory by applying a line load at the center of length to induce a splitting tensile crack. The fracture area is 100×100 mm^2. The minimum of fifteen sandstone samples are tested for direct shear test under normal stress ranging from 0.5 through 1.5 MPa.

3.4.2 Sandstone rock samples preparation for push-out test

Sandstone rock samples of push-out test is prepared to have rectangular block. The size of sandstone block is 110×110×130 mm^3 and all specimens are drilled as perpendicular to the bottom sample surface. The twenty sandstone samples are prepared for push-out test.

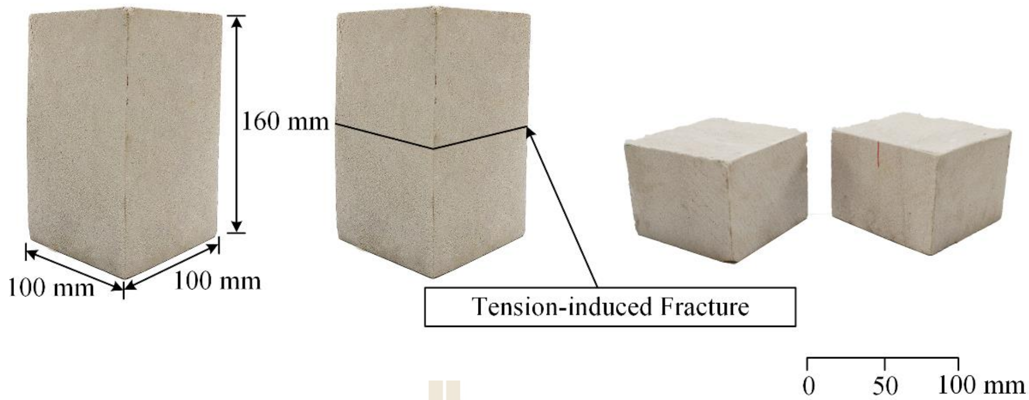


Figure 3.6 Some sandstone samples are prepared for direct shear test.

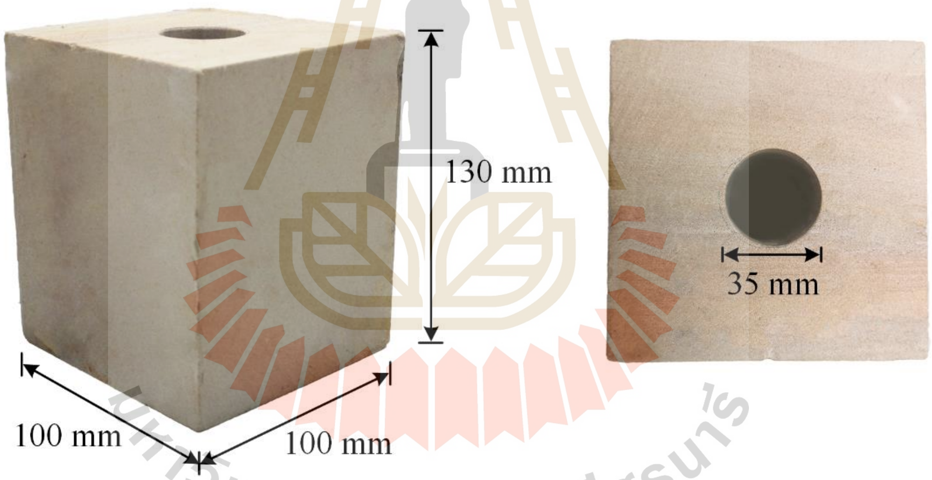


Figure 3.7 Some sandstone sample is prepared for push-out test.

CHAPTER IV

BASIC PROPERTIES TESTING OF GROUTING MATERIALS

4.1 Introduction

The flowability is one of the basic properties of grouting material. It is important parameter related to the grout mixture proportions. This chapter describes the methods and results of flowability tests that measured by determining its viscosity and density.

4.2 Viscosity and density of mixtures

The viscosity and density are preferred for injectability of grouting materials. Viscosity measurement follows, as much as practical, the ASTM D2196 standard practice. Apparatus used in this experiment consist of:

1) Rice husk ash (Figure 4.1),
2) Portland cement (Figure 4.2),
3) Distilled water,
4) Digital weight scale with maximum capacity of 2,200 g and accuracy to 0.01g. (Figure 4.3),
5) Mixer, Kitchenaid Professional 600 6QT 575 watt stand mixer, with maximum capacity of 5,000 cc and 6 speed control (Figure 4.4),
6) Viscometer, Brookfield® viscometer DV2T 150 VA 50/60 Hz (Figure 4.5)

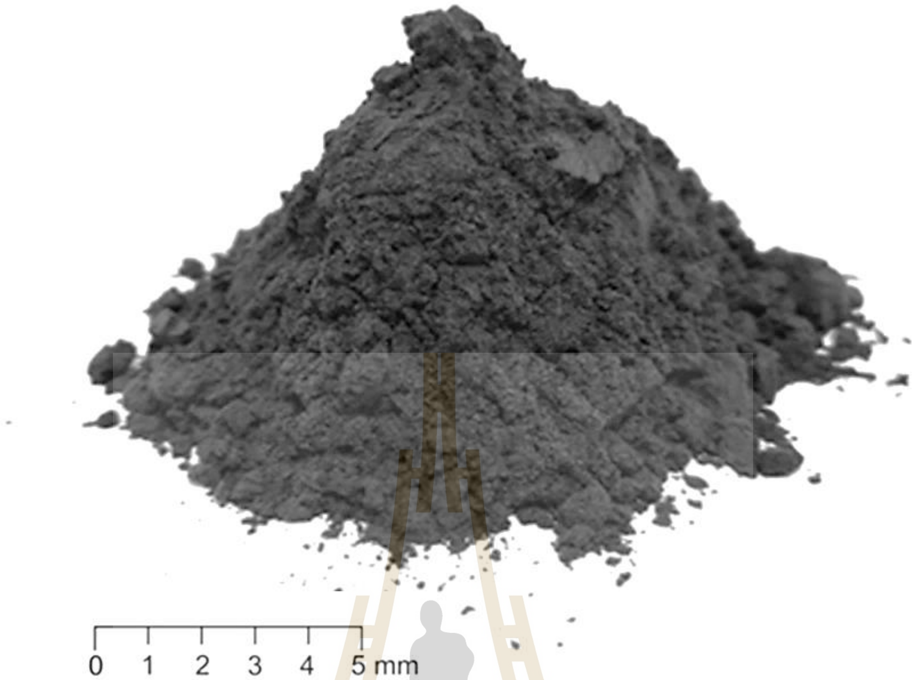


Figure 4.1 Rice husk ash from biomass power plant of A.T. Biopower Co., Ltd.

Figure 4.2 Portland cement is used in this study.

Figure 4.3 Digital weight scale with maximum capacity of 2,200 g and accuracy to 0.01 g.

Figure 4.4 Mixer, Kitchenaid Professional 600 6QT 575 watt stand mixer, with maximum capacity of 5,000 cc and 6 speed control.

Figure 4.5 Viscometer, Brookfield® viscometer DV2T 150 VA 50/60 Hz.

4.2.1 Test methods

The preliminary selection in proportions of mixtures are determined and given by using viscosity values. The mixture material in this study is the RHA-mixed cement. The mixing ratios of the RHA-cement (RHA:C) are set to 1:10, 3:10, 5:10 and 10:10 with water-cement (W:C) ratio of 1:1 by weight. The pure cement is used for comparing with the RHA -mixed cement test result. The ratio of pure cement is 0:10 with water-cement (W:C) ratio of 1:1 by weight. The grout preparation follows the ASTM C938-16 standard practice. Proportions of the mixtures are shown in Table 4.1. Test procedure also follow:

1) The materials are weighed follow the proportions of the mixtures and then put together in a plastic bag. Make a homogeneous mixture by shaking several times.
2) Pour the distilled water and the mixed material in Section 2) into the mixer and turn the mixer speed up to 275 rpm. Mixing of all grouts is accomplished using a blade paddle mixer as suggested in ASTM C938-16 standard practice.
3) Determine the density and viscosity of the mixture slurry by using standard ASTM D2196 standard practice. Pour in a beaker with a volume of the mixture is equal to exactly 500 cc.
4) Weigh the beaker with the mixture. Subtract the weight of the beaker from the results and then divided by the volume of the mixture (500 cc) is the density of mixture slurry.

5) Specific gravity (SG) of the mixture slurry is calculated from equation

$$SG = \rho_{slurry} / \rho_w \quad (4.1)$$

where ρ_{slurry} is a density of mixture slurry and ρ_w is density of distilled water at the time of measurement.

Viscosity test is performed after the weighing of ingredients in the measuring beaker with a volume of 500 cc, which is continuing immediately. The viscosity of the mixture, which is resistant to flow, can be determined by a rotational Viscometer, Brookfield® viscometer DV2T is selected for this test. Testing of viscosity follows the ASTM standard D2196. (Figure 4.6)

1) The resistance is greater as the spindle size and rotational speed increase. The minimum viscosity ranged, is obtained by using the largest spindle at the highest speed; the maximum range by using the smallest spindle at the slowest speed.
2) The sample is placed in glass beaker (500 cc) under viscometer.
3) Measure the viscosity of slurry mixtures and record.
4) Calculating the viscosity in centipoise (cP). The reading of the test Viscosity Brookfield is in units of centipoise or equal mPa·s in dynamic viscosity. The dynamic viscosity is converted to the kinematic viscosity by equation (4.2).

$$\mu = \rho \cdot \nu \quad (4.2)$$

where μ is dynamic viscosity, ν is the kinematic viscosity, and ρ is slurry density.

Table 4.1 Mixture ratios by weight of the total volume of 1,000 cc.

Binder	Sample No.	RHA:C	W:C	Weight (g)		
				RHA	Cement	Water
Cement	RCW0	0:10	10:10	0.00	500.00	500.00
RHA	RCW10	1:10	10:10	47.62	476.20	476.20
	RCW30	3:10	10:10	130.44	434.78	434.78
	RCW50	5:10	10:10	200.00	400.00	400.00
	RCW100	10:10	10:10	333.33	333.33	333.33

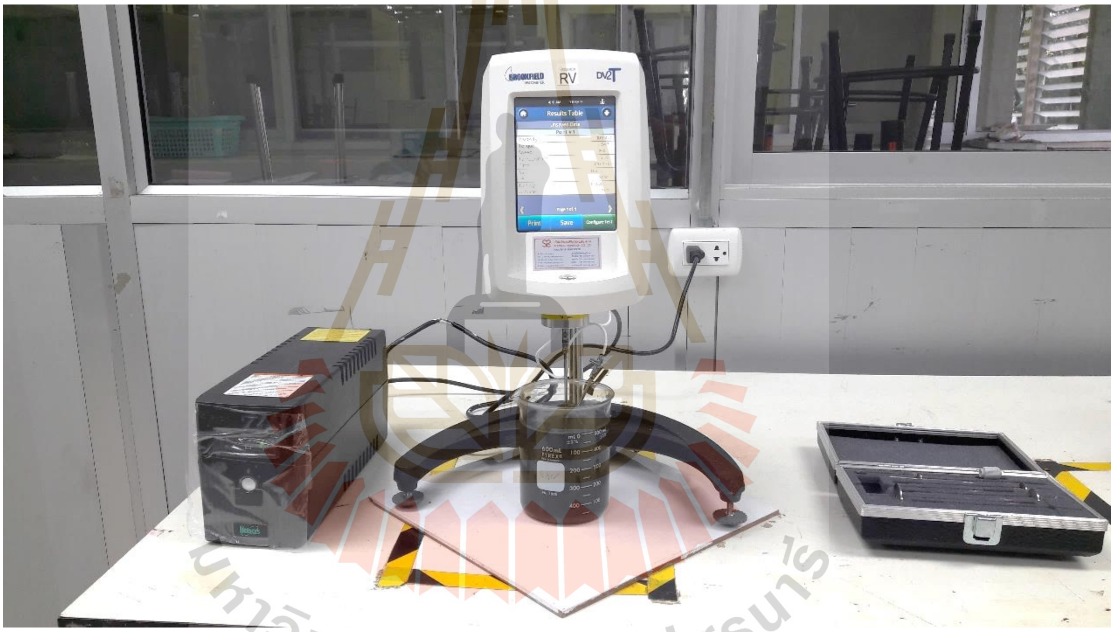


Figure 4.6 The viscosity test of slurry measure by using the viscometer, Brookfield® viscometer DV2T 150 VA 50/60 Hz.

4.2.2 Test results

The results of density and specific gravity tests of the mixture material are summarized in Table 4.2. The viscosity test results of the materials mixtures are listed in Table 4.3 and presented in figure 4.7 as a function of ratio. The test results are compared with the fly ash (F:C), bentonite (B:C) and sludge (S:C) mixed cement from Chiangmai (2016) and Wetchasat (2013).

Table 4.2 The results of the density and specific gravity test.

<table>
<tr><th>Binder</th><th>Sample No.</th><th>RHA:C, F:C, B:C, S:C</th><th>W:C</th><th>Slurry Temperature (°C)</th><th>Slurry Density (g/cc)</th><th>Specific Gravity</th></tr>
<tr><td>Cement</td><td>RCW0</td><td>0:10</td><td>10:10</td><td>27.00</td><td>1.47</td><td>1.47</td></tr>
<tr><td rowspan="4">RHA</td><td>RCW10</td><td>1:10</td><td>10:10</td><td>27.90</td><td>1.49</td><td>1.49</td></tr>
<tr><td>RCW30</td><td>3:10</td><td>10:10</td><td>27.70</td><td>1.50</td><td>1.51</td></tr>
<tr><td>RCW50</td><td>5:10</td><td>10:10</td><td>28.20</td><td>1.58</td><td>1.58</td></tr>
<tr><td>RCW100</td><td>10:10</td><td>10:10</td><td>28.50</td><td>1.75</td><td>1.76</td></tr>
<tr><td rowspan="4">Fly ash (Chiangmai, 2016)</td><td>FC10</td><td>1:10</td><td>10:10</td><td>28.40</td><td>1.54</td><td>1.55</td></tr>
<tr><td>FC30</td><td>3:10</td><td>10:10</td><td>27.50</td><td>1.59</td><td>1.60</td></tr>
<tr><td>FC50</td><td>5:10</td><td>10:10</td><td>27.00</td><td>1.66</td><td>1.67</td></tr>
<tr><td>FC100</td><td>10:10</td><td>10:10</td><td>26.40</td><td>1.75</td><td>1.75</td></tr>
<tr><td rowspan="3">Bentonite (Wetchasat, 2013)</td><td>BC10</td><td>1:10</td><td>10:10</td><td>28.20</td><td>1.41</td><td>1.42</td></tr>
<tr><td>BC20</td><td>2:10</td><td>10:10</td><td>27.90</td><td>1.45</td><td>1.46</td></tr>
<tr><td>BC30</td><td>3:10</td><td>10:10</td><td>29.40</td><td>1.51</td><td>1.52</td></tr>
<tr><td rowspan="4">Sludge (Wetchasat, 2013)</td><td>SC10</td><td>1:10</td><td>10:10</td><td>28.60</td><td>1.47</td><td>1.47</td></tr>
<tr><td>SC30</td><td>3:10</td><td>10:10</td><td>30.20</td><td>1.48</td><td>1.49</td></tr>
<tr><td>SC50</td><td>5:10</td><td>10:10</td><td>30.30</td><td>1.59</td><td>1.60</td></tr>
<tr><td>SC100</td><td>10:10</td><td>10:10</td><td>30.60</td><td>1.86</td><td>1.87</td></tr>
</table>

Table 4.3 The results of the mixture material viscosity tests.

Binder	RHA:C, F:C, B:C, S:C	W:C	Slurry Temperature (°C)	Slurry Density (g/cc)	Dynamic Viscosity (mPa·s)	Kinematic Viscosity (10^{-4} m^2/s)
Cement	0:10	10:10	27.00	1.47	64.80	0.441
RHA	1:10	10:10	27.90	1.49	110.20	0.741
	3:10	10:10	27.70	1.50	277.00	1.847
	5:10	10:10	28.20	1.58	631.00	4.001
	10:10	10:10	28.50	1.75	1,472.00	8.418
Fly ash (Chiangmai, 2016)	1:10	10:10	28.40	1.54	477.40	3.101
	3:10	10:10	27.50	1.59	651.90	4.094
	5:10	10:10	27.00	1.66	763.60	4.593
	10:10	10:10	26.40	1.75	6,807.50	38.974
Bentonite (Wetchasat, 2013)	1:10	10:10	28.20	1.41	308.79	2.189
	2:10	10:10	27.90	1.45	1,059.95	7.310
	3:10	10:10	29.40	1.51	3,454.88	22.817
Sludge (Wetchasat, 2013)	1:10	10:10	28.60	1.47	82.32	0.561
	3:10	10:10	30.20	1.48	156.88	1.057
	5:10	10:10	30.30	1.59	375.24	2.361
	10:10	10:10	30.60	1.86	2,598.42	13.965

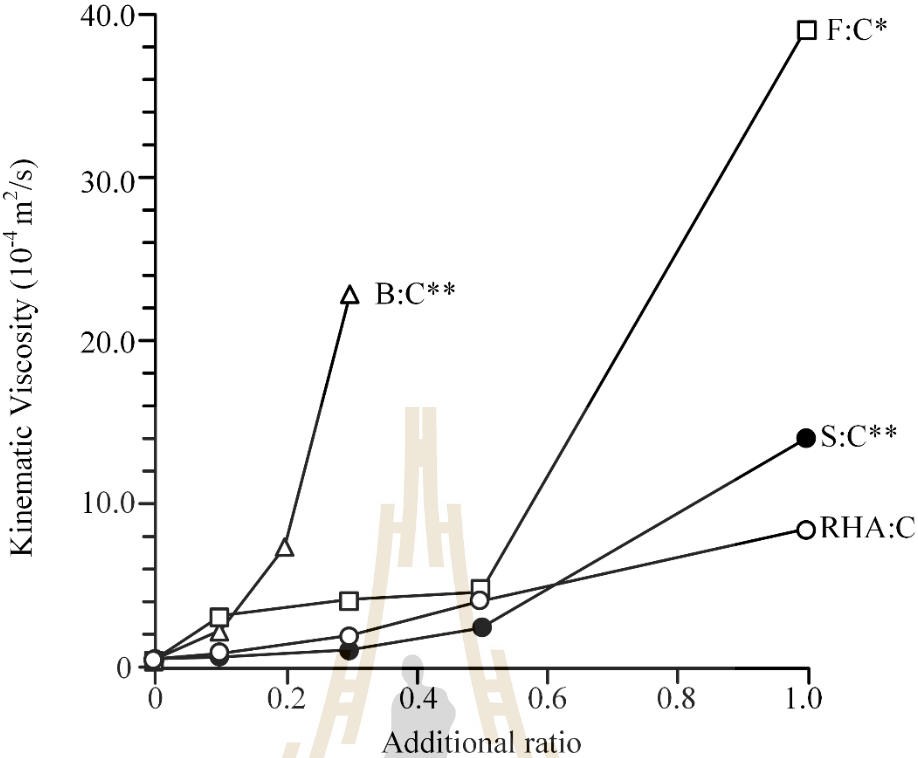


Figure 4.7 Kinematic viscosity of mixture material for different ratios (*Chiangmai, 2016 and ** Wetchasat, 2013).

CHAPTER V

MECHANICAL PROPERTIES TESTING

5.1 Introduction

This chapter describes the methods and results of laboratory tests used to determinate the maximum compressive strength, elastic modulus, indirect tensile strength, shear strength and axial mechanical strength of grouting materials. The proportions of grouting materials are prepared from the RHA-mixed cement as Table 4.1 in Chapter IV. Pure cement is used for comparing with the RHA-mixed cement test results.

5.2 Uniaxial compressive strength test

The objective of the uniaxial compressive strength test is to determine the uniaxial compressive strength (σ_c) and elastic modulus (E) of grouting material. The test procedure follows, as much as practical, the ASTM D7012 standard practice. The grouting materials are the RHA-mixed cement. The ratios of the RHA-cement (RHA:C) are set as 1:10, 3:10, 5:10 and 10:10 with water-cement (W:C) ratio of 1:1 by weight. The grouting material are placed in the 54 mm PVC mold and cured under water at ambient temperature for 3, 7, 14 and 28 days before testing. The cylindrical specimens are prepared from grouting material with length (L) to diameter (D) ratios (L/D) between 2.0 to 2.5 (Figure 5.1). The test applies a loading rate of 1 MPa/s until failure (Figure 5.2).

During the test, the axial deformation, lateral deformation and failure modes are monitored and recorded (Figure 5.3). The maximum loaded at the failure is recorded.

The failure stress is calculated by dividing the axial load by the cross-section area of specimen. The compressive strength is determined from the maximum load (P_f) divided by the original cross-section area (A):

$$\sigma_c = P_f/A \tag{5.1}$$

Table 5.1 lists the specimen number, dimensions, weight (W), density (ρ), uniaxial compressive strength (σ_c) and elastic modulus (E) of grouting materials and the results are summarized in Table 5.2. Figure 5.4 and 5.5 show the uniaxial compressive strength and elastic modulus of grouting material as a function of curing time, respectively.

Figure 5.1 Cylindrical specimens are prepared to the desired length with L/D ratio between 2.0 to 2.5.

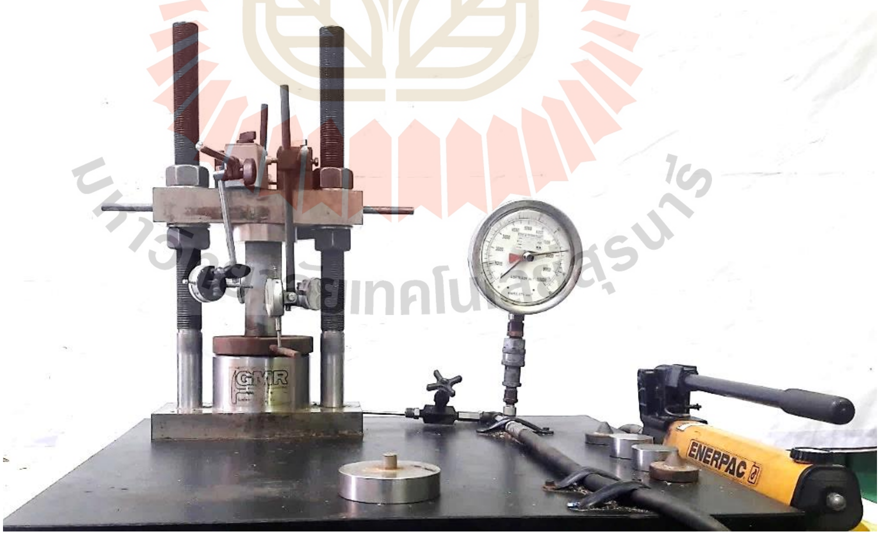
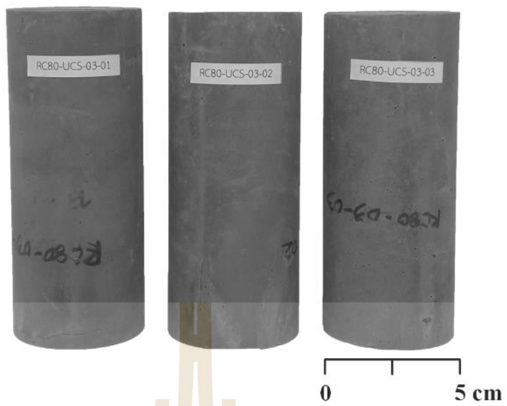
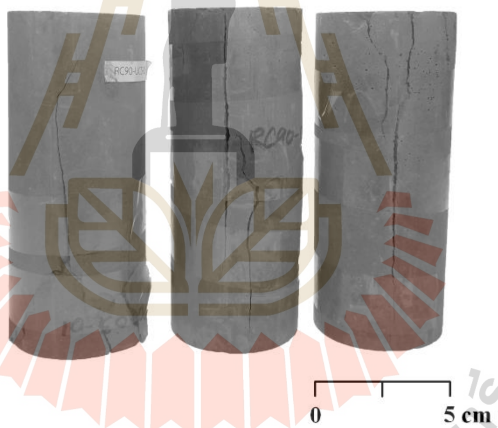


Figure 5.2 Uniaxial compressive strength test with constant loading rate. The cylindrical specimen is loaded vertically using the compression machine.



(a)



(b)

Figure 5.3 Cylindrical specimens (a) before testing and (b) after testing.

Table 5.1 Lists of specimen dimensions, weight, density, uniaxial compressive strength and elastic modulus of grouting materials.

Types	Sample no.	L (mm)	D (mm)	L/D	W (g)	ρ (g/cc)	σ_c (MPa)	E (GPa)
Cement (0:10)	C-03-1	139.40	55.80	2.50	512.3	1.50	6.50	1.23
	C-03-2	140.20	56.00	2.50	401.8	1.46	6.50	1.22
	C-03-3	140.00	56.00	2.50	502.0	1.46	6.87	1.19
	Average	**139.87**	**55.93**	**2.50**	**472.0**	**1.47**	**6.62**	**1.22**
	C-07-1	140.00	56.00	2.50	502.8	1.46	7.51	1.26
	C-07-2	139.50	56.00	2.49	510.5	1.49	7.52	1.24
	C-07-3	138.70	56.00	2.48	509.4	1.49	7.70	1.28
	Average	**139.40**	**56.00**	**2.49**	**507.6**	**1.48**	**7.58**	**1.26**
	C-14-1	141.00	56.00	2.52	521.6	1.50	8.12	1.29
	C-14-2	140.30	55.90	2.51	502.6	1.46	8.15	1.29
	C-14-3	140.70	55.80	2.52	512.0	1.49	8.11	1.27
	Average	**140.67**	**55.90**	**2.52**	**512.1**	**1.48**	**8.13**	**1.28**
	C-28-1	139.00	56.60	2.46	463.0	1.32	9.94	1.34
	C-28-2	140.30	56.00	2.51	478.0	1.38	9.95	1.34
	C-28-3	139.70	56.00	2.49	443.0	1.29	9.91	1.40
	Average	**139.67**	**56.20**	**2.49**	**461.3**	**1.33**	**9.93**	**1.36**

Table 5.1 Lists of specimen dimensions, weight, density, uniaxial compressive strength and elastic modulus of grouting materials (continued).

Types	Sample no.	L (mm)	D (mm)	L/D	W (g)	ρ (g/cc)	σ_c (MPa)	E (GPa)
RHA (RHA:C= 1:10)	R10-03-1	140.50	55.00	2.55	596.7	1.79	6.94	1.17
	R10-03-2	138.00	54.60	2.53	578.2	1.79	6.83	1.33
	R10-03-3	139.15	54.50	2.56	588.9	1.81	7.07	1.26
	Average	**139.22**	**54.70**	**2.55**	**587.9**	**1.80**	**6.95**	**1.25**
	R10-07-1	138.50	55.30	2.50	544.7	1.64	7.91	1.36
	R10-07-2	138.70	55.40	2.50	554.6	1.66	8.09	1.30
	R10-07-3	139.00	55.20	2.52	543.9	1.64	8.36	1.35
	Average	**138.73**	**55.30**	**2.51**	**547.7**	**1.65**	**8.12**	**1.34**
	R10-14-1	138.00	54.00	2.56	525.3	1.66	10.92	1.60
	R10-14-2	139.20	56.29	2.47	558.5	1.61	9.24	1.46
	R10-14-3	138.00	55.00	2.51	526.0	1.60	10.52	1.56
	Average	**138.40**	**55.10**	**2.51**	**536.6**	**1.62**	**10.23**	**1.54**
	R10-28-1	137.00	55.80	2.46	515.7	1.54	11.65	1.41
	R10-28-2	137.70	56.40	2.44	550.7	1.60	10.01	1.74
	R10-28-3	138.40	54.20	2.55	515.2	1.61	11.49	1.66
	Average	**137.70**	**55.47**	**2.48**	**527.2**	**1.58**	**11.05**	**1.60**

Table 5.1 Lists of specimen dimensions, weight, density, uniaxial compressive strength and elastic modulus of grouting materials (continued).

Types	Sample no.	L (mm)	D (mm)	L/D	W (g)	ρ (g/cc)	σ_c (MPa)	E (GPa)
RHA (RHA:C= 3:10)	R30-03-1	138.00	56.00	2.46	590.4	1.74	6.90	1.40
	R30-03-2	138.00	56.02	2.46	587.0	1.73	7.20	1.42
	R30-03-3	138.00	54.75	2.52	590.4	1.82	7.22	1.38
	Average	**138.00**	**55.59**	**2.48**	**589.3**	**1.76**	**7.11**	**1.40**
	R30-07-1	138.20	55.40	2.49	543.2	1.63	10.16	1.38
	R30-07-2	138.32	55.10	2.51	532.8	1.62	10.48	1.48
	R30-07-3	138.00	54.60	2.53	543.9	1.68	10.46	1.49
	Average	**138.17**	**55.03**	**2.51**	**540.0**	**1.64**	**10.37**	**1.45**
	R30-14-1	140.40	56.00	2.51	550.0	1.59	11.37	1.63
	R30-14-2	139.60	55.80	2.50	558.9	1.64	12.27	1.70
	R30-14-3	139.70	55.00	2.54	554.3	1.67	11.68	1.68
	Average	**139.90**	**55.60**	**2.52**	**554.4**	**1.63**	**11.77**	**1.67**
	R30-28-1	138.40	55.60	2.49	522.4	1.55	14.42	2.00
	R30-28-2	137.30	54.40	2.52	517.7	1.62	15.49	2.64
	R30-28-3	138.00	55.50	2.49	554.8	1.66	15.29	1.67
	Average	**137.90**	**55.17**	**2.50**	**531.6**	**1.61**	**15.07**	**2.10**

Table 5.1 Lists of specimen dimensions, weight, density, uniaxial compressive strength and elastic modulus of grouting materials (continued).

Types	Sample no.	L (mm)	D (mm)	L/D	W (g)	ρ (g/cc)	σ_c (MPa)	E (GPa)
RHA (RHA:C= 5:10)	R50-03-1	139.50	56.80	2.46	601.2	1.70	8.49	1.56
	R50-03-2	140.00	55.30	2.53	554.1	1.65	8.74	1.68
	R50-03-3	138.00	56.27	2.45	527.8	1.54	8.65	1.64
	Average	**139.17**	**56.12**	**2.48**	**561.0**	**1.63**	**8.63**	**1.63**
	R50-07-1	137.21	56.00	2.45	568.8	1.68	10.96	1.54
	R50-07-2	138.85	56.00	2.48	572.3	1.67	11.37	1.56
	R50-07-3	139.00	55.00	2.53	531.1	1.61	11.79	1.67
	Average	**138.35**	**55.67**	**2.49**	**557.4**	**1.65**	**11.37**	**1.59**
	R50-14-1	140.00	54.00	2.59	522.3	1.63	13.32	2.06
	R50-14-2	144.00	55.00	2.62	520.9	1.52	13.048	1.81
	R50-14-3	142.00	55.00	2.58	512.0	1.52	13.92	1.71
	Average	**142.00**	**54.67**	**2.60**	**518.4**	**1.56**	**13.43**	**1.86**
	R50-28-1	138.00	55.70	2.48	534.5	1.59	15.39	1.91
	R50-28-2	137.00	56.00	2.45	537.0	1.59	16.58	2.31
	R50-28-3	138.00	55.80	2.47	511.9	1.52	16.36	2.26
	Average	**137.67**	**55.83**	**2.47**	**527.8**	**1.57**	**16.11**	**2.16**

Table 5.1 Lists of specimen dimensions, weight, density, uniaxial compressive strength and elastic modulus of grouting materials (continued).

Types	Sample no.	L (mm)	D (mm)	L/D	W (g)	ρ (g/cc)	σ_c (MPa)	E (GPa)
RHA (RHA:C= 10:10)	R100-03-1	139.86	56.50	2.48	566.3	1.62	6.98	1.30
	R100-03-2	138.00	56.00	2.46	562.0	1.65	7.11	1.32
	R100-03-3	138.40	54.80	2.53	554.0	1.70	7.00	1.30
	Average	**138.75**	**55.77**	**2.49**	**560.8**	**1.66**	**7.03**	**1.31**
	R100-07-1	138.00	55.70	2.48	548.0	1.63	9.44	1.31
	R100-07-2	137.50	54.90	2.50	541.6	1.66	9.29	1.35
	R100-07-3	138.30	55.30	2.50	542.2	1.63	9.58	1.39
	Average	**137.93**	**55.30**	**2.49**	**543.9**	**1.64**	**9.44**	**1.35**
	R100-14-1	139.00	56.30	2.47	533.7	1.54	11.25	1.70
	R100-14-2	141.00	55.40	2.56	506.0	1.51	10.42	1.42
	R100-14-3	138.25	55.00	2.51	509.0	1.55	10.73	1.38
	Average	**139.42**	**55.57**	**2.51**	**516.2**	**1.53**	**10.80**	**1.50**
	R100-28-1	137.00	55.00	2.49	517.9	1.59	14.31	1.52
	R100-28-2	138.40	55.40	2.50	532.6	1.60	13.90	2.54
	R100-28-3	138.00	55.00	2.51	513.2	1.57	13.78	2.03
	Average	**137.80**	**55.13**	**2.50**	**521.2**	**1.59**	**14.00**	**2.03**

Table 5.2 Results of the uniaxial compressive strength and elastic modulus of grouting material.

Types	Curing Time (days)	Number of Samples	σ_C (MPa)	E (GPa)
Cement (0:10)	3	3	6.62±0.17	1.21±0.02
	7	3	7.58±0.09	1.26±0.02
	14	3	8.13±0.02	1.28±0.01
	28	3	9.93±0.02	1.36+0.03
RHA (RHA:C=1:10)	3	3	6.95±0.10	1.25±0.07
	7	3	8.12±0.18	1.34±0.03
	14	3	10.23±0.72	1.54±0.06
	28	3	11.05±0.74	1.60±0.14
RHA (RHA:C=3:10)	3	3	7.11±0.15	1.40±0.02
	7	3	10.37±0.15	1.45±0.05
	14	3	11.77±0.37	1.67±0.03
	28	3	15.07±0.46	2.10±0.40
RHA (RHA:C=5:10)	3	3	8.63±0.10	1.63±0.05
	7	3	11.37±0.34	1.59±0.06
	14	3	13.43±0.36	1.86±0.15
	28	3	16.11±0.52	2.16±0.18
RHA (RHA:C=10:10)	3	3	7.03±0.06	1.31±0.01
	7	3	9.44±0.12	1.35±0.03
	14	3	10.80±0.34	1.50±0.14
	28	3	14.00±0.23	2.03±0.42

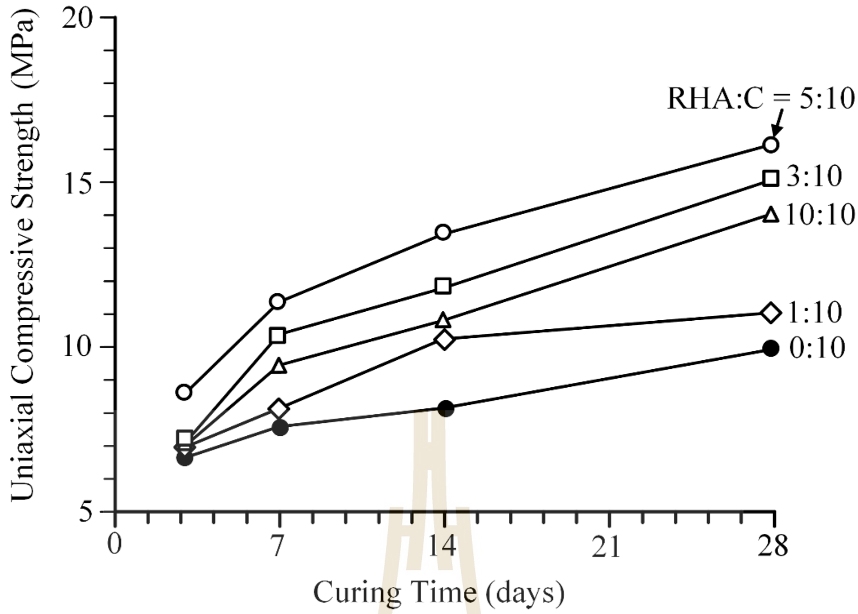


Figure 5.4 Uniaxial compressive strengths of grouting materials as a function of curing time.

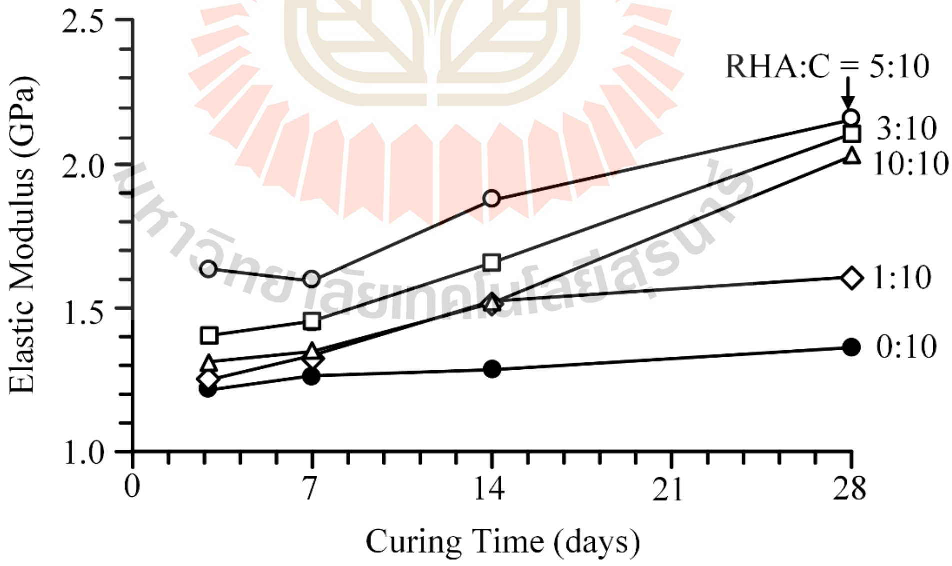


Figure 5.5 Elastic modulus of grouting materials as a function of curing time.

5.3 Brazilian tensile strength test

The Brazilian tensile strength test is the test to determine the indirect tensile strength (σ_B) of grouting material. The test procedure follows, as much as practical, the ASTM D3967 standard practice. The Brazilian tensile strength test is carried out at the ages of 3, 7, 14 and 28 days. The specimens are prepared in 54 mm of diameter with length to diameter ratio is 0.5 (Figure 5.6). The test is performed by increasing the axial loaded at the constant rate of 0.1 to 0.5 MPa/s until the failure occurred (Figure 5.7). At the failure, the indirect tensile strength of the grouting material is calculated as follows:

$$\sigma_B = 2P/\pi Dt \quad (5.2)$$

where σ_B is Brazilian tensile strength, P is applied load, D is diameter of the sample and t is thickness of the sample.

Figure 5.6 Some cylindrical specimens prepared for Brazilian tensile strength test.

Table 5.3 summarizes the results of the Brazilian tensile strength of grouting materials and Table 5.4 lists the specimen number, dimensions and Brazilian tensile strength (σ_B) of grouting materials. Figure 5.8 shows the Brazilian tensile strength of grouting material as a function of curing time. The curing time increases the Brazilian tensile strength of grouting material increases.

Table 5.3 Results of the Brazilian tensile strength of grouting materials.

Types	Curing Time (days)	Number of Samples	σ_B (MPa)
Cement (0:10)	3	5	0.92±0.07
	7	5	1.20±0.17
	14	5	1.48±0.09
	28	5	1.55±0.05
RHA (RHA:C=1:10)	3	5	1.04±0.14
	7	5	1.24±0.10
	14	5	1.50±0.05
	28	5	1.60±0.10
RHA (RHA:C=3:10)	3	5	1.18±0.15
	7	5	1.40±0.08
	14	5	1.56±0.03
	28	5	1.64±0.11
RHA (RHA:C=5:10)	3	5	1.24±0.09
	7	5	1.48±0.04
	14	5	1.68±0.06
	28	5	1.70±0.05
RHA (RHA:C=10:10)	3	5	1.05±0.16
	7	5	1.30±0.06
	14	5	1.52±0.06
	28	5	1.60±0.11

Table 5.4 Lists of specimen dimensions and Brazilian tensile strength of grouting materials.

Types	Sample no.	L (mm)	D (mm)	L/D	σ_B (MPa)
Cement (0:10)	CB-03-01	27.00	56.00	0.48	1.05
	CB-03-02	25.10	56.00	0.45	0.91
	CB-03-03	26.50	56.00	0.47	0.86
	CB-03-04	27.02	56.00	0.48	0.84
	CB-03-05	24.32	56.00	0.43	0.94
	Average	**25.99**	**56.00**	**0.46**	**0.92**
	CB-07-01	28.04	56.14	0.50	1.02
	CB-07-02	26.71	56.14	0.48	1.49
	CB-07-03	29.30	56.14	0.52	1.16
	CB-07-04	27.43	56.16	0.49	1.04
	CB-07-05	26.50	56.16	0.47	1.29
	Average	**27.60**	**56.15**	**0.49**	**1.20**
	CB-14-01	28.05	55.50	0.50	1.43
	CB-14-02	27.84	55.50	0.50	1.65
	CB-14-03	28.06	55.50	0.50	1.45
	CB-14-04	28.11	55.50	0.51	1.43
	CB-14-05	28.04	55.50	0.51	1.43
	Average	**28.02**	**55.50**	**0.50**	**1.48**
	CB-28-01	29.21	56.00	0.52	1.56
	CB-28-02	28.06	56.00	0.50	1.62
	CB-28-03	27.20	56.00	0.49	1.46
	CB-28-04	29.14	56.00	0.52	1.57
	CB-28-05	29.50	56.00	0.53	1.54
	Average	**28.62**	**56.00**	**0.51**	**1.55**

Table 5.4 Lists of specimen dimensions and Brazilian tensile strength of grouting materials (continued).

Types	Sample no.	L (mm)	D (mm)	L/D	σ_B (MPa)
RHA (RHA:C=1:10)	RB10-03-01	27.04	56.00	0.48	1.26
	RB10-03-02	27.80	56.00	0.50	1.02
	RB10-03-03	26.80	56.00	0.48	1.06
	RB10-03-04	27.50	56.00	0.49	1.03
	RB10-03-05	28.00	56.00	0.50	0.81
	Average	**27.43**	**56.00**	**0.49**	**1.04**
	RB10-07-01	27.04	55.30	0.49	1.28
	RB10-07-02	27.50	55.30	0.50	1.36
	RB10-07-03	26.44	55.30	0.48	1.09
	RB10-07-04	26.81	55.30	0.48	1.29
	RB10-07-05	27.20	55.30	0.49	1.16
	Average	**27.00**	**55.30**	**0.49**	**1.24**
	RB10-14-01	26.51	55.00	0.48	1.53
	RB10-14-02	26.40	55.00	0.48	1.42
	RB10-14-03	26.03	55.00	0.47	1.56
	RB10-14-04	27.14	55.00	0.49	1.50
	RB10-14-05	27.50	55.00	0.50	1.47
	Average	**26.72**	**55.00**	**0.48**	**1.50**
	RB10-28-01	26.02	56.00	0.46	1.64
	RB10-28-02	26.80	55.50	0.48	1.50
	RB10-28-03	27.40	55.50	0.49	1.47
	RB10-28-04	26.40	55.50	0.48	1.74
	RB10-28-05	26.10	55.50	0.47	1.65
	Average	**26.54**	**55.60**	**0.48**	**1.60**

Table 5.4 Lists of specimen dimensions and Brazilian tensile strength of grouting materials (continued).

Types	Sample no.	L (mm)	D (mm)	L/D	σ_B (MPa)
RHA (RHA:C=3:10)	RB30-03-01	27.60	56.00	0.49	1.24
	RB30-03-02	27.70	56.00	0.49	1.03
	RB30-03-03	27.50	56.00	0.49	1.45
	RB30-03-04	27.70	56.00	0.49	1.09
	RB30-03-05	28.00	56.00	0.50	1.08
	Average	**27.70**	**56.00**	**0.49**	**1.18**
	RB30-07-01	27.10	55.40	0.49	1.48
	RB30-07-02	27.04	55.40	0.49	1.28
	RB30-07-03	27.81	55.40	0.50	1.45
	RB30-07-04	27.63	55.40	0.50	1.35
	RB30-07-05	27.50	55.40	0.50	1.46
	Average	**27.42**	**55.40**	**0.50**	**1.40**
	RB30-14-01	28.50	56.80	0.50	1.57
	RB30-14-02	28.04	57.00	0.49	1.60
	RB30-14-03	27.70	56.00	0.49	1.54
	RB30-14-04	27.72	56.50	0.49	1.53
	RB30-14-05	27.40	56.50	0.48	1.54
	Average	**27.87**	**56.56**	**0.49**	**1.56**
	RB30-28-01	25.80	54.50	0.47	1.81
	RB30-28-02	27.50	55.60	0.49	1.56
	RB30-28-03	26.60	56.00	0.48	1.71
	RB30-28-04	26.50	56.00	0.47	1.61
	RB30-28-05	26.10	56.00	0.47	1.52
	Average	**26.50**	**55.62**	**0.48**	**1.64**

Table 5.4 Lists of specimen dimensions and Brazilian tensile strength of grouting materials (continued).

Types	Sample no.	L (mm)	D (mm)	L/D	σ_B (MPa)
RHA (RHA:C=5:10)	RB50-03-01	25.80	56.00	0.46	1.32
	RB50-03-02	26.30	56.00	0.47	1.08
	RB50-03-03	27.50	56.00	0.49	1.24
	RB50-03-04	26.10	56.00	0.47	1.31
	RB50-03-05	27.80	56.00	0.50	1.23
	Average	**26.70**	**56.00**	**0.48**	**1.24**
	RB50-07-01	27.04	56.00	0.48	1.47
	RB50-07-02	26.12	56.00	0.46	1.53
	RB50-07-03	27.80	56.00	0.50	1.53
	RB50-07-04	27.50	56.00	0.49	1.45
	RB50-07-05	28.32	56.00	0.50	1.42
	Average	**27.36**	**56.00**	**0.49**	**1.48**
	RB50-14-01	27.31	54.40	0.50	1.71
	RB50-14-02	26.14	56.30	0.46	1.74
	RB50-14-03	27.30	54.40	0.50	1.71
	RB50-14-04	27.05	56.00	0.48	1.58
	RB50-14-05	27.10	56.00	0.48	1.68
	Average	**26.98**	**55.42**	**0.48**	**1.68**
	RB50-28-01	27.00	54.70	0.49	1.72
	RB50-28-02	28.03	56.30	0.50	1.62
	RB50-28-03	27.40	56.30	0.49	1.65
	RB50-28-04	26.07	56.30	0.46	1.74
	RB50-28-05	25.70	56.30	0.46	1.76
	Average	**26.84**	**55.98**	**0.48**	**1.70**

Table 5.4 Lists of specimen dimensions and Brazilian tensile strength of grouting materials (continued).

Types	Sample no.	L (mm)	D (mm)	L/D	σ_B (MPa)
RHA (RHA:C=10:10)	RB100-03-01	29.50	56.00	0.53	0.96
	RB100-03-02	29.20	56.00	0.52	1.07
	RB100-03-03	29.80	56.00	0.53	0.86
	RB100-03-04	29.50	56.40	0.52	1.05
	RB100-03-05	27.50	56.40	0.49	1.33
	Average	**29.10**	**56.16**	**0.52**	**1.05**
	RB100-07-01	28.60	55.80	0.51	1.30
	RB100-07-02	28.21	55.80	0.51	1.31
	RB100-07-03	28.80	55.80	0.52	1.19
	RB100-07-04	29.14	55.80	0.52	1.38
	RB100-07-05	28.50	55.80	0.51	1.30
	Average	**28.65**	**55.80**	**0.51**	**1.30**
	RB100-14-01	26.52	55.70	0.48	1.62
	RB100-14-02	27.42	56.30	0.49	1.55
	RB100-14-03	26.04	55.70	0.47	1.54
	RB100-14-04	29.30	56.30	0.52	1.45
	RB100-14-05	29.03	56.30	0.52	1.46
	Average	**27.66**	**56.06**	**0.50**	**1.52**
	RB100-28-01	28.50	56.60	0.50	1.48
	RB100-28-02	27.60	54.00	0.51	1.60
	RB100-28-03	26.80	54.00	0.50	1.76
	RB100-28-04	27.90	54.00	0.52	1.48
	RB100-28-05	28.10	54.00	0.52	1.68
	Average	**27.78**	**54.52**	**0.51**	**1.60**

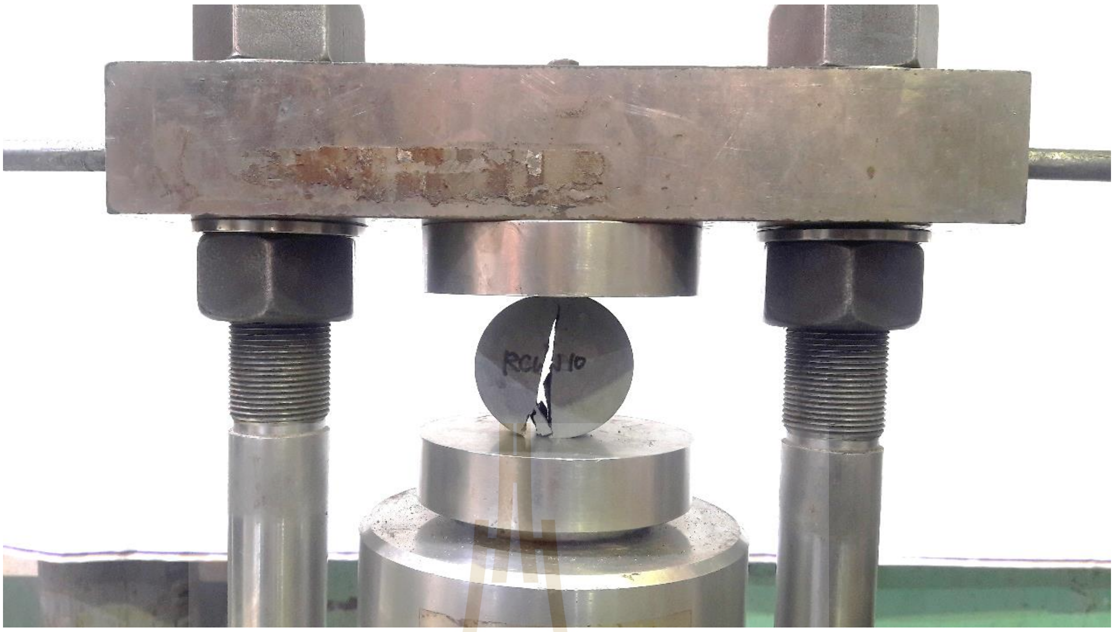


Figure 5.7 Brazilian tensile strength test with constant loading rate.

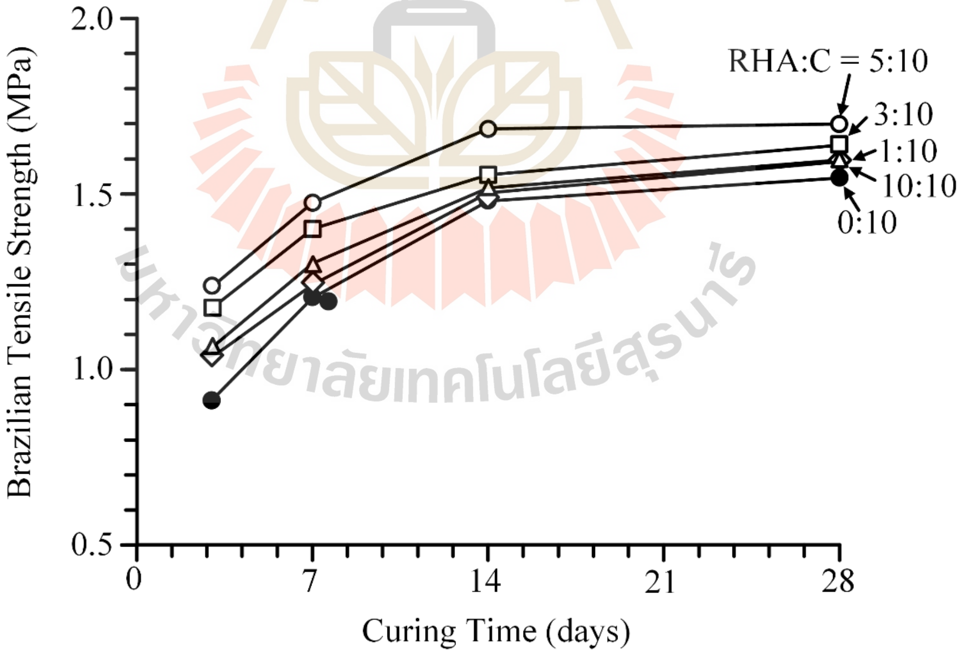


Figure 5.8 Brazilian tensile strength of grouting materials as a function of curing time.

5.4 Direct shear test

The objective of this test is to determine the direct shear strength of grouting material in rock fracture. The test method and calculation similar to the ASTM D5607 standard practice. Grouting materials are the RHA- mixed cement that ratios are prepared same with the uniaxial compressive strength test. The grouting material are placed in prismatic block shape between sandstone rock samples that fracture are artificially made by applying a line load to induce tensile crack (Figure 5.9). The shear strength test is carried out at the age of 7 days curing time. Laboratory arrangement for direct shear test equipment (Boonyord, 2017) is shown in Figure 5.10. The direct shear test is performed with the normal stresses of 0.5, 1.0 and 1.5 MPa. The shear stresses are applied while the shear displacement. The head drops are monitored is every 0.2 mm of shear displacement.

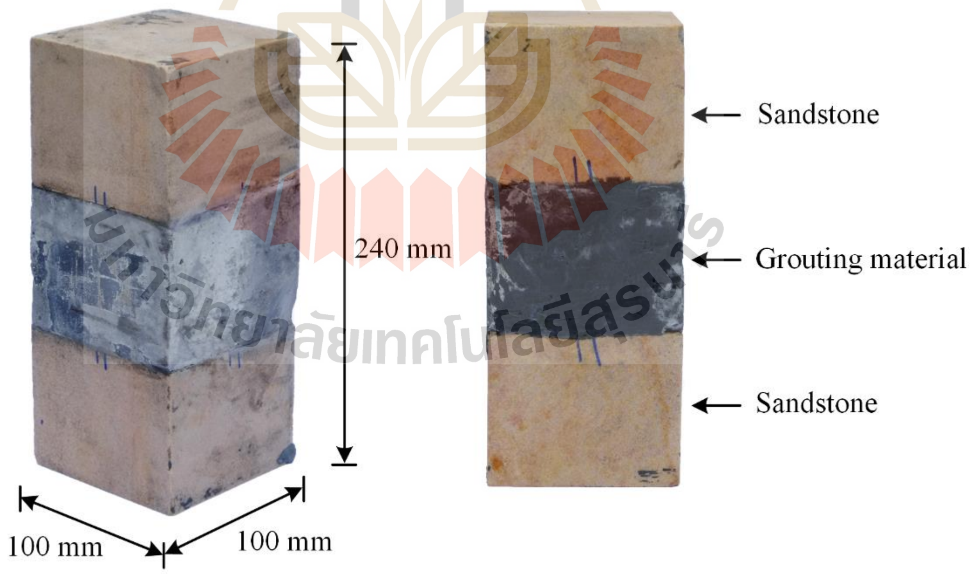
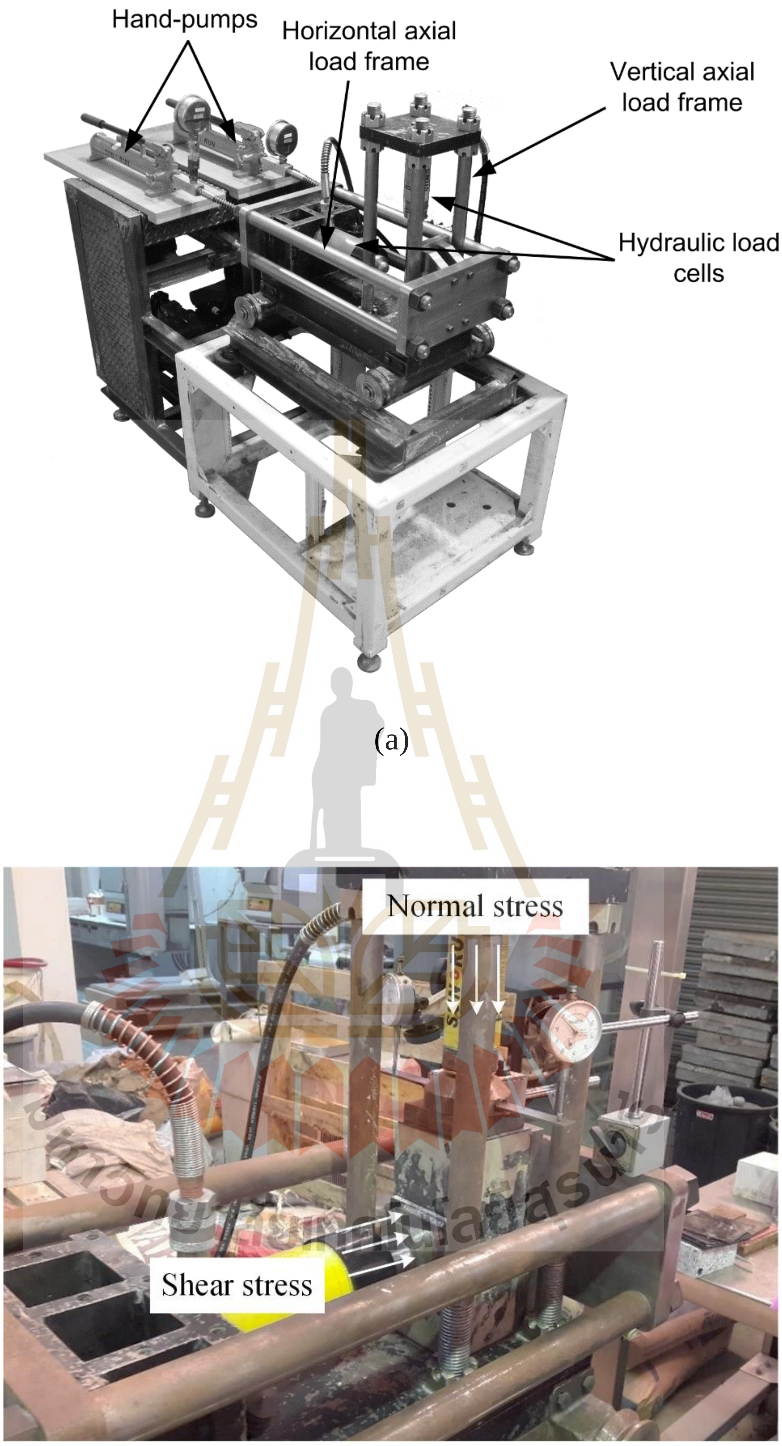


Figure 5.9 Specimen is prepared for direct shear test.



(a)

(b)

Figure 5.10 Laboratory arrangement for direct shear test (Boonyord, 2017) (a) and during testing (b).

During the test, the failure modes are recorded. The test results are presented in forms of the shear strength as a function of normal stress as follows:

$$\tau = F/2A \qquad (5.3)$$

$$\sigma_n = P/A \qquad (5.4)$$

where τ is the shear stress, F is sheared force, A is cross section area, σ_n is normal stress and P is normal load.

The results are presented in form of the Coulomb's criterion. The line tangent to each of these circles defines the Coulomb's criterion and can be expressed by:

$$\tau = c_p + \sigma \tan\phi_p \qquad (5.5)$$

where τ is the shear stress, σ is normal stress, ϕ_p is the angle of internal friction and c_p is cohesion.

Some sample before and after testing are shown in Figure 5.11. Table 5.5 lists the result of shear strength. Shearing resistance between grouting material and rock fracture are shown in Figure 5.12 to 5.16. The results in form of the Coulomb's criterion are shown in Figure 5.17. Table 5.6 lists the Coulomb's parameter.

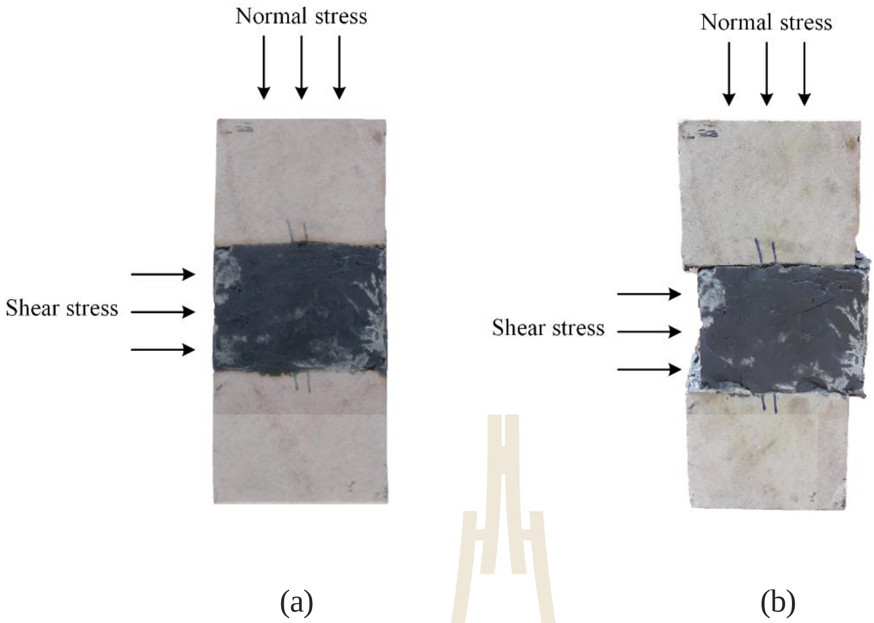


Figure 5.11 Some specimen of grouting material in sandstone rock fracture before (a) and after (b) failure under shearing.

Table 5.5 Summary of direct shear strength test results.

Normal Stress (MPa)	Peak Shear Stress (MPa)				
	Pure cement	RHA:C			
	0:10	1:10	3:10	5:10	10:10
0.50	1.03	1.25	1.37	1.53	1.31
1.00	1.37	1.48	1.65	1.81	1.59
1.50	1.92	1.93	2.15	2.37	2.09

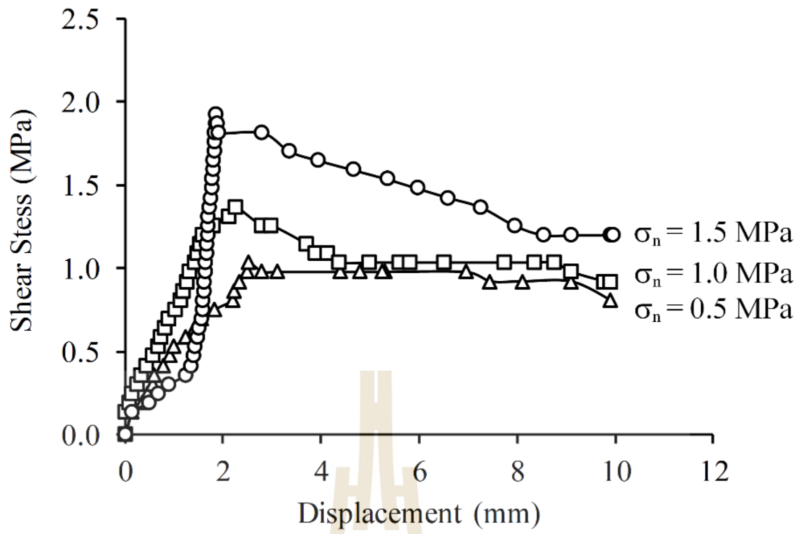


Figure 5.12 Shear stress as a function of shear displacement for pure cement.

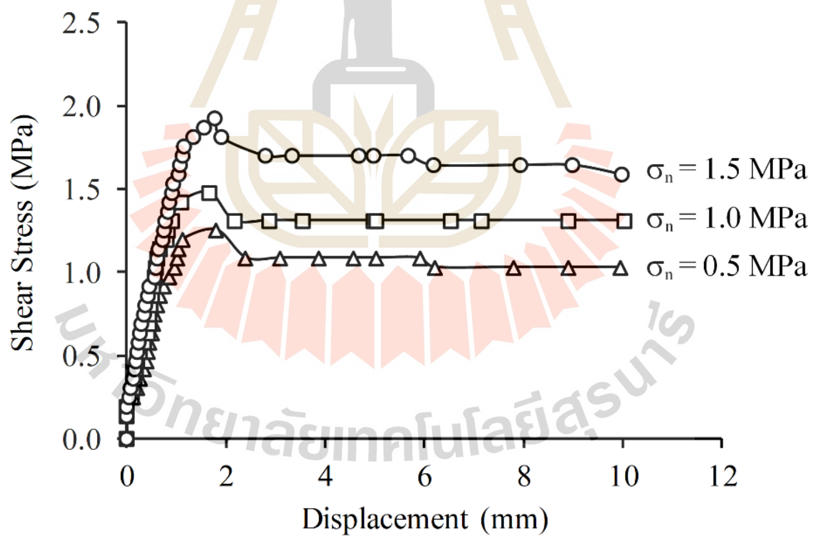


Figure 5.13 Shear stress as a function of shear displacement for RHA:C = 1:10.

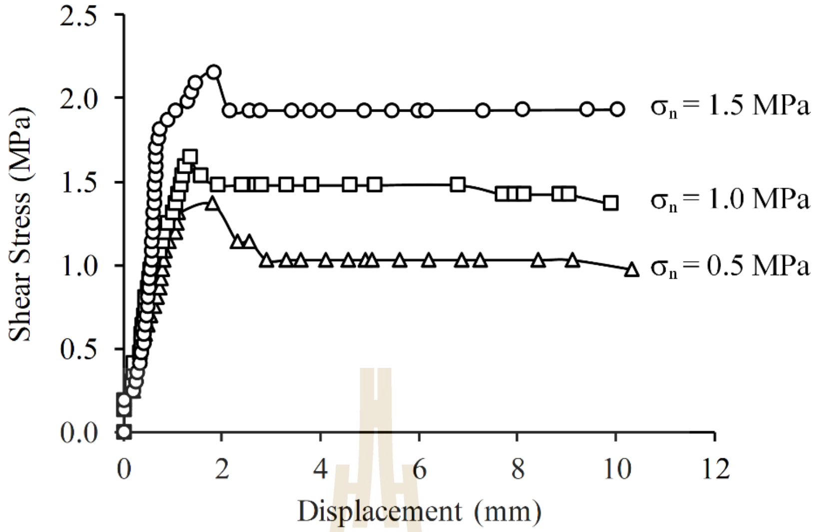


Figure 5.14 Shear stress as a function of shear displacement for RHA:C = 3:10.

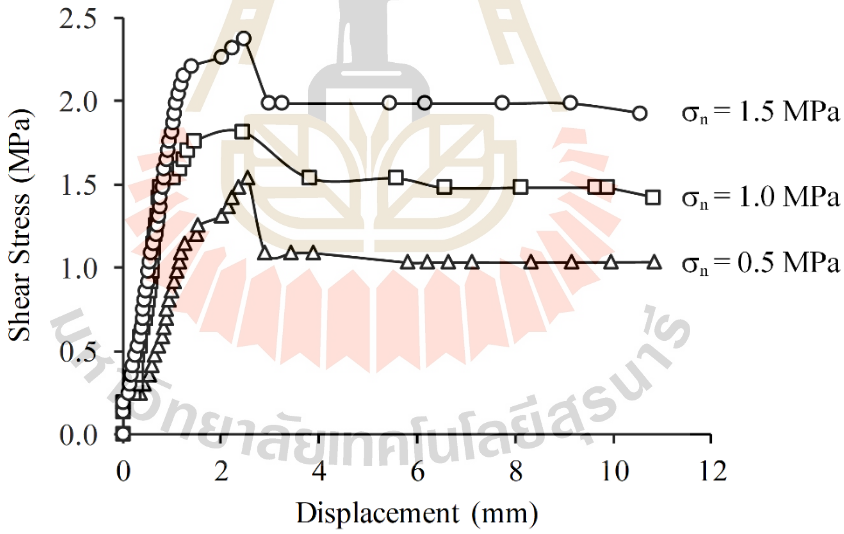


Figure 5.15 Shear stress as a function of shear displacement for RHA:C = 5:10.

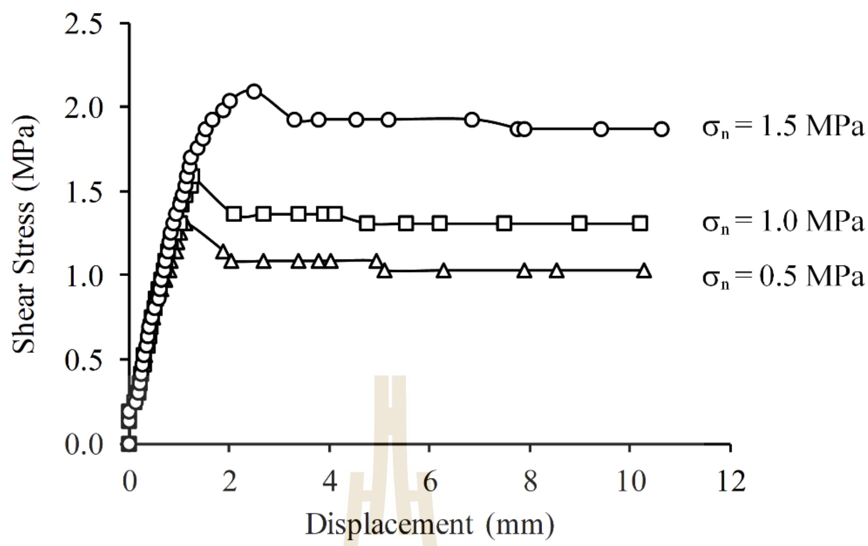


Figure 5.16 Shear stress as a function of shear displacement for RHA:C = 10:10.

Table 5.6 Summary of shear strength parameter calibrated from direct shear tests using Coulomb's criteria.

Types	c_p (MPa)	$\tan\phi_p$	ϕ_p (degrees)	R^2
Cement = 0:10	0.73	0.62	31.63	0.99
RHA:C = 1:10	0.88	0.67	33.90	0.96
RHA:C = 3:10	0.94	0.78	38.10	0.97
RHA:C = 5:10	1.07	0.84	40.03	0.96
RHA:C = 10:10	0.92	0.73	36.05	0.98

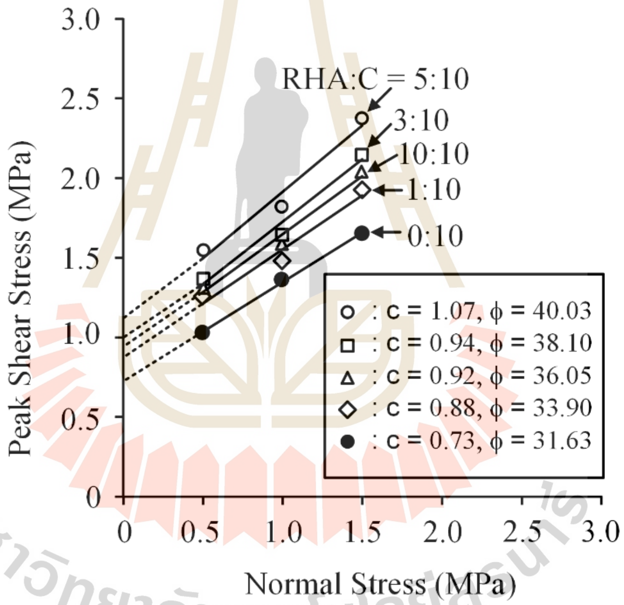


Figure 5.17 Shear stress as a function of normal stress.

5.5 Push-out test

The objective of this test is to determine the bond strength of grouting material cast in a hole at the center of the rock specimen with a diameter of 35 mm and length 70 mm. The grouting material cast in the hole as a cement plug is axially loaded at the constant rate of 0.1 to 0.5 MPa/s until sliding occurred. Grouting materials are prepared in the same ratio as the previous tests. The curing periods for push-out test are 3, 7, 14 and 28 days. Figure 5.18 shows the schematic drawing of the push-out test laboratory setup. A cylinder steel rod applies an axial load to a cement plug. The top and bottom displacement of the cement plug are recorded. Figure 5.19 shows the laboratory testing. The axial load is measured by a load gage of the hydraulic pump. The displacement is measured by dial gages with a resolution of 0.02 mm. A loading frame with a hydraulic cylinder applied the load. The machine has a capacity of 50 kN with a resolution of 0.5 kN. The bond strength or the average shear stress (τ_{av}) is distribution by push-out test loading along the cement plug interface can be calculated by the following equation:

$$\tau_{av} = F/\pi DL \tag{5.6}$$

where F is the failure load, D is the diameter of cement sample and L is the length of cement sample.

Table 5.7 lists the specimen number, dimensions and average bond strength (τ_{av}) and the results are summarized in Table 5.8. Figure 5.20 plots the average shear strength as a function of curing time. Figure 5.21 shows rock sample which was cut along the axis after failure.

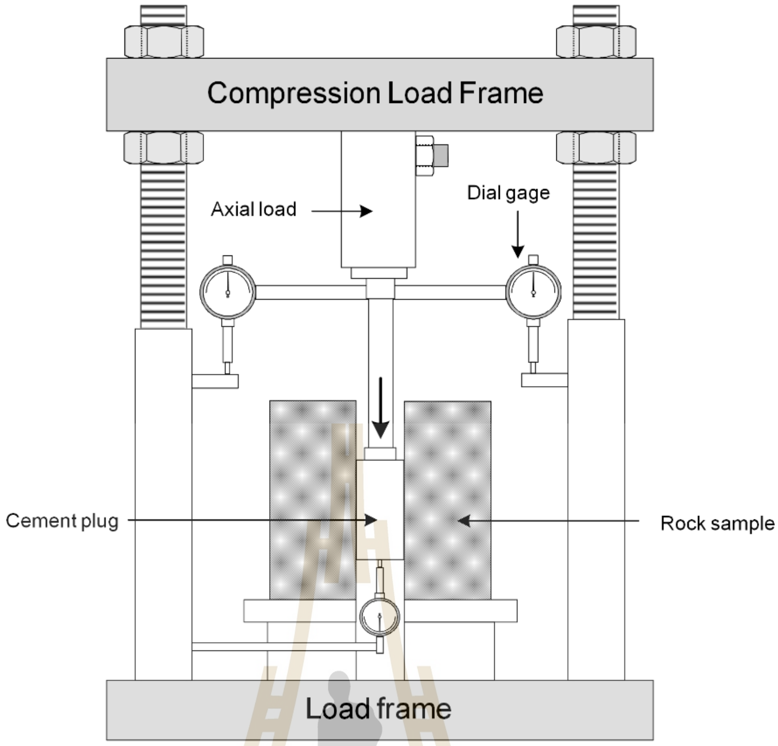


Figure 5.18 Schematic drawing of push-out test.

Figure 5.19 Push-out test laboratory setup.

Table 5.7 Lists of specimen dimensions and average bond strength of grouting materials.

Types	Sample no.	L (mm)	D (mm)	L/D	τ_{av} (MPa)
Cement (0:10)	CP-03-01	35.50	33.57	1.06	0.80
	CP-03-02	35.40	34.00	1.04	0.79
	CP-03-03	35.50	35.68	0.99	0.88
	Average	**35.47**	**34.42**	**1.03**	**0.82**
	CP-07-01	35.09	34.15	1.03	0.93
	CP-07-02	35.09	33.59	1.04	0.88
	CP-07-03	35.36	34.84	1.01	0.90
	Average	**35.18**	**34.19**	**1.03**	**0.90**
	CP-14-01	35.74	33.64	1.06	1.26
	CP-14-02	35.74	33.95	1.05	1.18
	CP-14-03	35.11	33.04	1.06	1.30
	Average	**35.53**	**33.54**	**1.06**	**1.25**
	CP-28-01	35.16	33.45	1.05	1.56
	CP-28-02	35.76	33.55	1.07	1.59
	CP-28-03	35.11	33.81	1.04	1.61
	Average	**35.34**	**33.60**	**1.05**	**1.59**

Table 5.7 Lists of specimen dimensions and average bond strength of grouting materials (continued).

Types	Sample no.	L (mm)	D (mm)	L/D	τ_{av} (MPa)
RHA (RHA:C=1:10)	RP10-03-01	35.24	34.08	1.03	0.86
	RP10-03-02	35.04	34.95	1.00	0.91
	RP10-03-03	35.78	34.02	1.05	0.85
	Average	**35.35**	**34.35**	**1.03**	**0.87**
	RP10-07-01	37.58	35.11	1.07	0.84
	RP10-07-02	36.75	34.71	1.06	1.06
	RP10-07-03	36.47	34.36	1.06	1.08
	Average	**36.93**	**34.73**	**1.06**	**0.99**
	RP10-14-01	37.14	35.43	1.05	1.27
	RP10-14-02	37.40	35.25	1.06	1.33
	RP10-14-03	37.80	35.51	1.06	1.42
	Average	**37.45**	**35.40**	**1.06**	**1.34**
	RP10-28-01	38.14	35.71	1.07	1.64
	RP10-28-02	38.15	35.08	1.09	1.67
	RP10-28-03	38.70	35.31	1.10	1.64
	Average	**38.33**	**35.37**	**1.09**	**1.65**

Table 5.7 Lists of specimen dimensions and average bond strength of grouting materials (continued).

Types	Sample no.	L (mm)	D (mm)	L/D	τ_{av} (MPa)
RHA (RHA:C=3:10)	RP30-03-01	37.25	35.11	1.06	1.03
	RP30-03-02	37.28	35.34	1.05	1.09
	RP30-03-03	37.84	35.74	1.06	1.00
	Average	**37.46**	**35.40**	**1.06**	**1.04**
	RP30-07-01	37.20	35.14	1.06	1.52
	RP30-07-02	37.19	35.09	1.06	1.59
	RP30-07-03	37.45	34.90	1.07	1.58
	Average	**37.28**	**35.04**	**1.06**	**1.56**
	RP30-14-01	37.86	35.56	1.07	1.77
	RP30-14-02	38.14	35.74	1.07	1.81
	RP30-14-03	38.11	35.36	1.08	1.77
	Average	**38.04**	**35.55**	**1.07**	**1.78**
	RP30-28-01	38.43	35.47	1.08	1.98
	RP30-28-02	38.62	35.18	1.10	2.05
	RP30-28-03	38.26	35.52	1.08	2.11
	Average	**38.44**	**35.39**	**1.09**	**2.05**

Table 5.7 Lists of specimen dimensions and average bond strength of grouting materials (continued).

Types	Sample no.	L (mm)	D (mm)	L/D	τ_{av} (MPa)
RHA (RHA:C=5:10)	RP50-03-01	38.14	35.75	1.07	1.11
	RP50-03-02	38.08	35.45	1.07	1.12
	RP50-03-03	38.85	35.91	1.08	1.14
	Average	**38.36**	**35.70**	**1.07**	**1.12**
	RP50-07-01	37.84	35.08	1.08	2.16
	RP50-07-02	37.57	35.05	1.07	2.18
	RP50-07-03	37.65	35.19	1.07	2.23
	Average	**37.69**	**35.11**	**1.07**	**2.19**
	RP50-14-01	37.71	35.14	1.07	2.28
	RP50-14-02	38.54	35.54	1.08	2.21
	RP50-14-03	38.11	35.11	1.09	2.26
	Average	**38.12**	**35.26**	**1.08**	**2.25**
	RP50-28-01	38.86	35.57	1.09	2.36
	RP50-28-02	38.79	35.32	1.10	2.44
	RP50-28-03	37.89	35.74	1.06	2.64
	Average	**38.51**	**35.54**	**1.08**	**2.48**

Table 5.7 Lists of specimen dimensions and average bond strength of grouting materials (continued).

Types	Sample no.	L (mm)	D (mm)	L/D	τ_{av} (MPa)
RHA (RHA:C=10:10)	RP100-03-01	37.81	35.84	1.05	0.94
	RP100-03-02	38.28	35.96	1.06	0.92
	RP100-03-03	39.42	35.94	1.10	0.84
	Average	**38.50**	**35.91**	**1.07**	**0.90**
	RP100-07-01	39.12	35.48	1.10	1.20
	RP100-07-02	36.52	34.81	1.05	1.13
	RP100-07-03	36.14	34.70	1.04	1.08
	Average	**37.26**	**35.00**	**1.06**	**1.14**
	RP100-14-01	38.14	35.43	1.08	1.41
	RP100-14-02	37.82	35.10	1.08	1.38
	RP100-14-03	37.86	35.36	1.07	1.55
	Average	**37.94**	**35.30**	**1.08**	**1.45**
	RP100-28-01	38.71	35.44	1.09	1.74
	RP100-28-02	38.31	35.52	1.08	1.75
	RP100-28-03	38.48	35.00	1.10	1.77
	Average	**38.50**	**35.32**	**1.09**	**1.75**

Table 5.8 Summary of average bond strength results of the grouting material.

Types	Curing Time (days)	Number of Samples	τ_{av} (MPa)
Cement (0:10)	3	3	0.82±0.04
	7	3	0.90±0.02
	14	3	1.25±0.05
	28	3	1.59±0.02
RHA (RHA:C=1:10)	3	3	0.87±0.03
	7	3	0.99±0.11
	14	3	1.34±0.06
	28	3	1.65±0.01
RHA (RHA:C=3:10)	3	3	1.04±0.04
	7	3	1.56±0.03
	14	3	1.78±0.02
	28	3	2.05±0.05
RHA (RHA:C=5:10)	3	3	1.12±0.01
	7	3	2.19±0.03
	14	3	2.25±0.03
	28	3	2.48±0.12
RHA (RHA:C=10:10)	3	3	0.90±0.04
	7	3	1.14±0.05
	14	3	1.45±0.07
	28	3	1.75±0.01

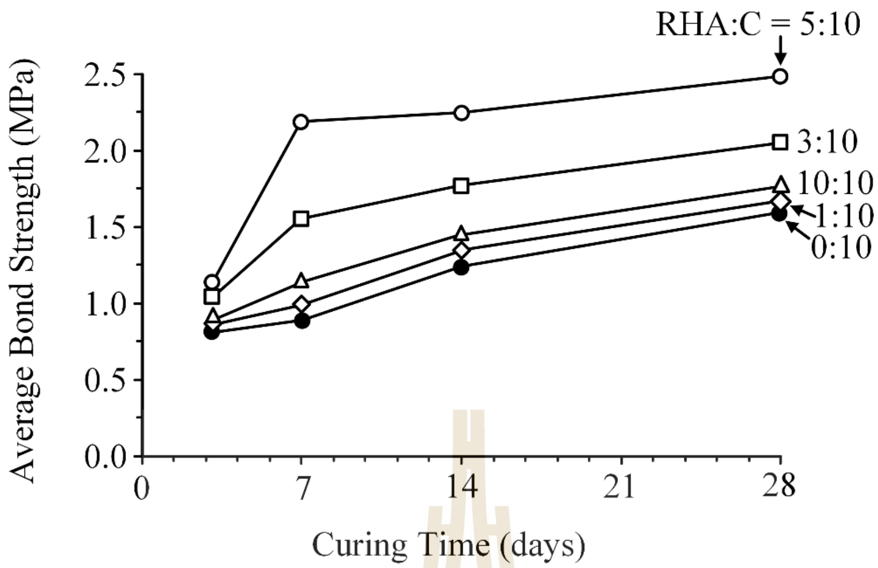


Figure 5.20 Average bond strength as a function of curing time.

Figure 5.21 Cut section of rock sample after failure in the push-out test.

CHAPTER VI

HYDRAULIC PROPERTIES TESTING

6.1 Introduction

This chapter describes the methods and results of laboratory tests to determine the permeability of grouting materials. The permeability of the grouting materials is an important factor to show the hydraulic potential, the ability to reduce the permeability of rock fractures. The objective of this test is to determine the water permeability of grouting materials specimen using a constant head flow test.

6.2 Test methods

The procedure for determining the grout permeability is similar to the ASTM C938 standard practice. The specimens are prepared from grouting materials that placed in PVC mold. The grouting materials in this study are the RHA-mixed cement. The pure cement is used for comparing with the RHA-mixed cement test result. The proportions of RHA:C mixtures are 1:10, 3:10, 5:10 and 10:10 with W:C ratio of 1:1 by weight. The ratio of pure cement is 0:10 with W:C ratio of 1:1 by weight. These tests are conducted and measured at 3, 7, 14, 28 and 60 days of curing time. The PVC mold has an inner diameter of 98 mm with a length of 150 mm. The prepared specimen is sealed between the PVC caps (Figure 6.1). Inlet port is installed at the center of a PVC cap and connect to a water pressure tube. Nitrogen compressed pressure gas about 137.895 kPa. The outlet port is installed at another PVC cap and connected to a high precision pipette for measuring the outflow. The permeability of the system is measured using a constant head apparatus as shown in Figure 6.2. The permeability of grouting materials is determined in term of intrinsic permeability (k). The constant head flow test is conducted to measure the longitudinal permeability of the specimen. The flow in the longitudinal direction of a tested system is described by Darcy's law. The coefficient of permeability, K, can be calculated from the equation. (Indraratna and Ranjith, 2001)

$$K = Q/Ai \tag{6.1}$$

where Q is volume flow rate, A is cross-sectional area of grout specimen and i is hydraulic gradient. The intrinsic permeability (k) can be determined from the equation.

$$k = K\mu/\gamma_w \tag{6.2}$$

where K is the coefficient of permeability, μ is dynamic viscosity of liquid water from 25 degree Celsius and γ_w is density of liquid water from 25 degree Celsius.

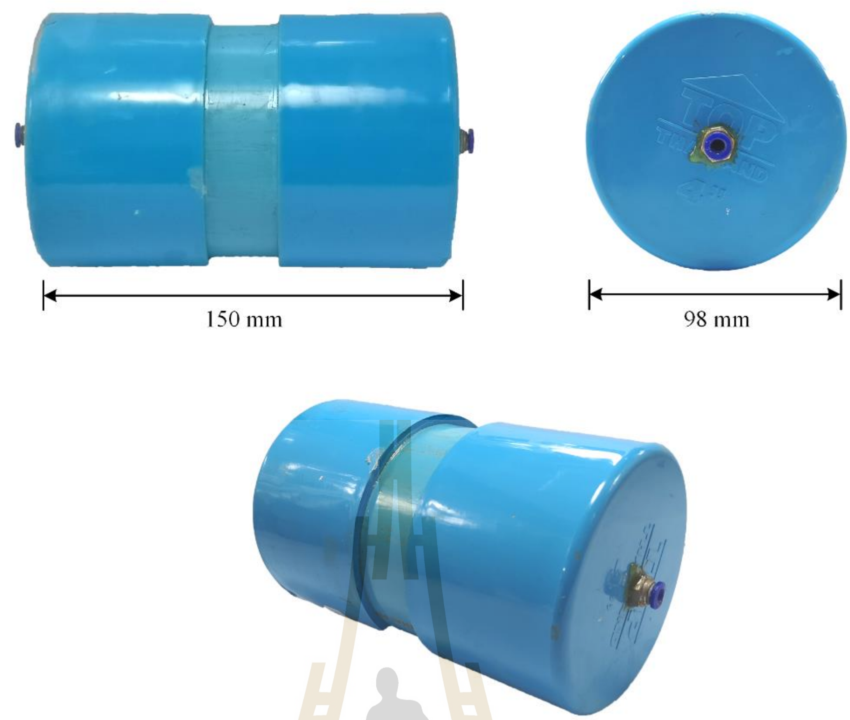
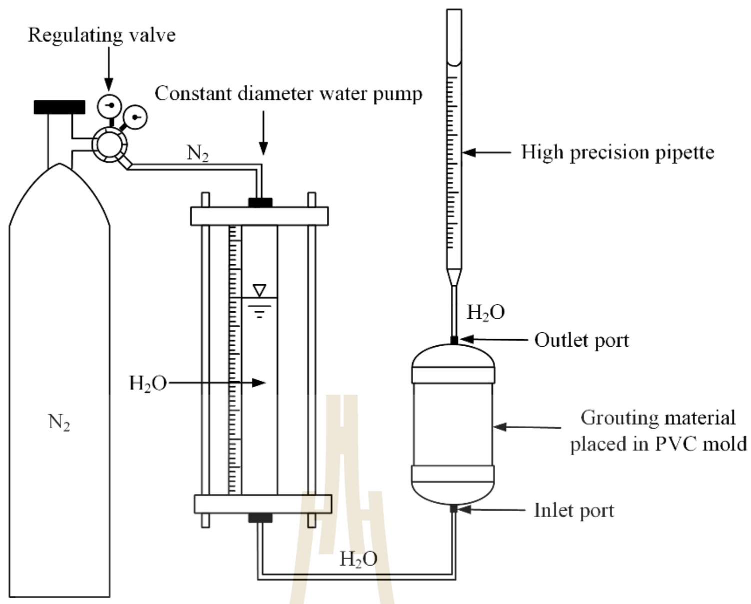
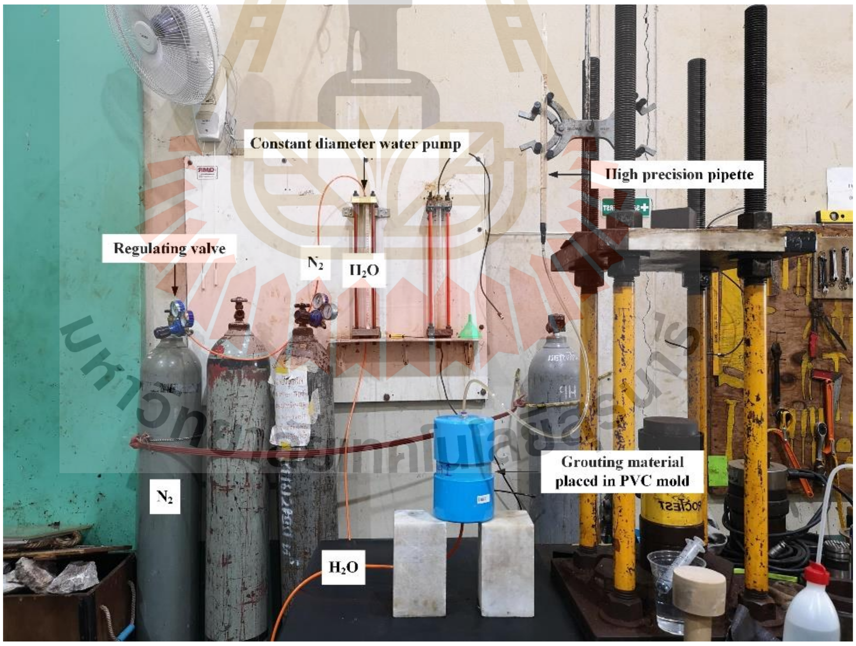


Figure 6.1 Grouting materials are placed in PVC mold and sealed with PVC caps.



(a)



(b)

Figure 6.2 Diagram of laboratory apparatus (a) and laboratory apparatus (b) for permeability testing.

6.3 Test results

The results of permeability of grouting materials at 3, 7, 14, 28 and 60 days of curing are summarized in Table 6.1. Intrinsic permeability as a function of curing time are shown in Figure 6.3.

Table 6.1 Summary of permeability testing of grouting material results at 3, 7, 14, 28 and 60 days of curing.

Curing Time (days)	Intrinsic Permeability ($\times 10^{-18}$ m^2)				
	Cement	RHA:C			
	0:10	1:10	3:10	5:10	10:10
3	511.99	482.00	407.00	321.80	295.16
7	271.27	315.80	139.93	68.02	50.00
14	108.20	226.00	95.00	48.00	30.92
28	24.57	210.00	86.00	36.58	20.30
60	4.42	206.49	85.77	34.24	15.54

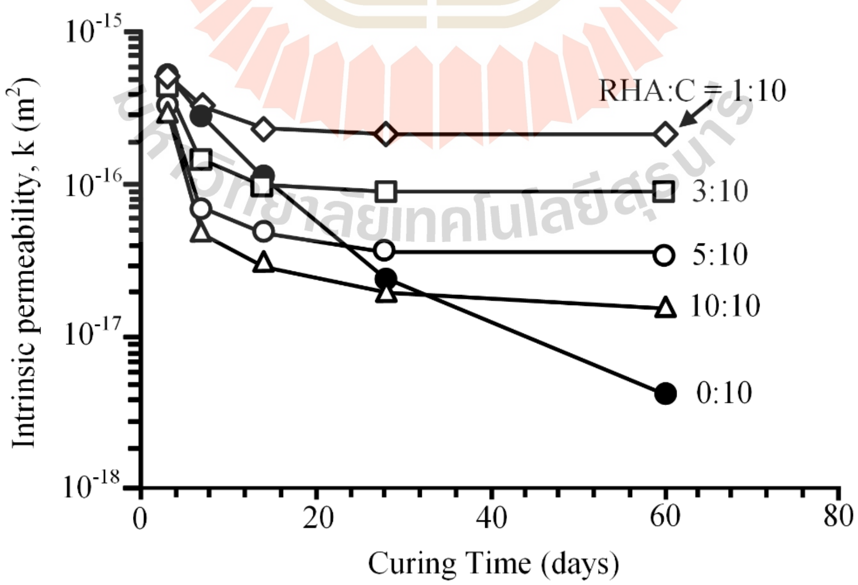


Figure 6.3 Intrinsic permeability as a function of curing time.

CHAPTER VII

DISCUSSIONS CONCLUSION AND RECOMMENDATION FOR FUTURE STUDIES

7.1 Discussions

The mechanical and hydraulic performance of RHA-mixed cement as grouting materials are discussed base on the test results. The results of the RHA-mixed cement are compared with the pure cement results as usually used for grouting material. Comparisons of the results and findings from this study with those obtained elsewhere under similar test conditions have also been made.

The mixture material in this study is the RHA-mixed cement. The mixing ratios of the RHA-cement (RHA:C) are set to 1:10, 3:10, 5:10 and 10:10 with water-cement (W:C) ratio of 1:1 by weight. The test results of pure cement is used for comparing with the RHA -mixed cement test result. The ratio of pure cement is 0:10 with water-cement (W:C) ratio of 1:1 by weight.

The viscosity grouts are preferred for injectability for grouting materials. Viscosity measurement follows, as much as practical, the ASTM D2196 standard practice. The results indicated that the average viscosity of the RHA-mixed cement tends to increase as RHA:C ratio increase. The mixture of proportions (RHA:C) as 10:10 with W:C as1:1 by weight that cannot making for grouting material because it is high viscosity, sticky and semi-solid condition. This finding agrees with the test results obtained by Wetchasat (2013).

For assessing the mechanical performance of RHA-mixed cement. The laboratory testing consists of Uniaxial compressive strength test, Brazilian tensile strength test, Direct shear test and Push out test.

The uniaxial compressive strength and elastic modulus of grouting materials are determined. All specimens are cured for 3, 7, 14 and 28 days before testing. The uniaxial compressive strength of grouting material increases with curing times increasing. Figure 5.4 and 5.5 show the uniaxial compressive strengths and elastic modulus test as a function of curing time, respectively. At 28 days of curing time shows the highest compressive strength and elastic modulus of RHA-mixed cement are 16.11 MPa and 2.16 GPa. The highest compressive strength is obtained from the RHA: C ratio as 5:10. This ratio is similar to the result from Chiangmai (2016). The compressive strength results of RHA-mixed cement are more than the pure cement that used as common for grouting material in rock fractures.

The Brazilian tensile strength test is the test to determine the indirect tensile strength of grouting material. All specimens are cured for 3, 7, 14 and 28 days before testing. The indirect tensile strength of grouting material increases with curing times increasing. The results are given in Table 5.3 and Figure 5.8. The highest Brazilian tensile strength is show at the 5:10 of RHA-cement ratio with 28 days of curing times as equal to 1.70 MPa and more than the pure cement that used as common for grouting material in rock fractures.

The direct shear test method and calculation similar to the ASTM D5607-16 standard practice that represents the shearing resistance between grouting materials and rock fracture. The test is carried out at the age of 7 days curing times. The direct shear test is performed with the normal stresses of 0.5, 1.0 and 1.5 MPa (Figure 5.12 to 5.16).

The results in form of the Coulomb's criterion are shown in Figure 5.17. Table 5.5 lists the Coulomb's parameter. The RHA:C ratio as 5:10 show the highest shear strength between grouting materials and rock fractures. The peak shear strength, cohesion and friction angle is 2.37 MPa, 1.07 MPa and 40 degrees, respectively.

The push-out test aims to determine the bond strength of grouting material cast in a hole at the center of the rock specimen. All specimens are cured for 3, 7, 14 and 28 days before testing. The bond strength of grouting material increases with curing times increasing. The results are shown in Figure 5.20. The highest bond strength is obtained from the RHA-mixed cement ratio of 5:10 after 28 days as equal to 2.48 MPa. The finding is consistent with Chiangmai (2016) as they obtained the highest bond strength from the same ratio.

The hydraulic performance of RHA-mixed cement can present as the permeability of grouting materials. The water permeability of grouting materials specimen using a constant head flow test. All specimens are cured for 3, 7, 14, 28 and 60 days before testing. Table 6.1 summarizes the result of the permeability testing of grouting material. The intrinsic permeability of all mixtures is in the range of 10^{-18} to 10^{-16} m^2. The RHA:C ratio of 10:10 gives the lowest permeability. The results indicate that the intrinsic permeability tends to rapidly decrease at 3 days curing times after that it starts gradually decreasing. This trend result is similar to Wetchasat's (2013) study.

7.2 Conclusions

The performance of RHA-mixed cement for grouting materials can assess from mechanical and hydraulic properties. Based on laboratory results of mechanical properties, the RHA-cement ratio as 5:10 that clearly shows the highest compressive strength, elastic modulus, indirect tensile strength and bond strength after 28 days of curing time. In addition, this mixtures ratio represents the highest shear strength between grouting material and rock fractures in direct shear after 7 days curing time. The mechanical properties are more than the pure cement that used as common for grouting material in rock fractures. The permeability of the grouting material is an important factor to show the ability to reduce the permeability of rock fracture. The RHA:C ratio of 10:10 gives the lowest permeability but the mixture slurry was high viscosity, sticky to semi-solid condition that is unsuitable for grouting material. On the contrary, the results of the 5:10 ratio are more interesting. The ratio gives low permeability results that approaches the result of 10:10 ratio but the RHA-mixed cement had the low viscosity and highest mechanical properties including compressive strength, elastic modulus, indirect tensile strength and bond strength. Thus, the 5:10 ratio of RHA:C probably has potential to be the suitable ratio that will be used as grouting materials.

7.3 Recommendations for future studies

To confirm the conclusions drawn in this study, more testing and measurements are recommended as follows:

1. The laboratory testing should be performed using different types of RHA.
2. The permeability testing of RHA-mixed cement that filled in rock fracture as vary fracture apertures should be test.
3. More grout mixtures are needed long-term performance and under in-situ condition.

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