CORRELATION BETWEEN ULTRASONIC WAVE VELOCITIES, FRACTURE AND MECHANICAL PROPERTIES OF SARABURI MARBLE AND TRAVERTINE

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A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Engineering in Geotechnology

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ความสัมพันธ์ระหว่างความเร็วคลื่นอัลตราโซนิก รอยแตกและคุณสมบัติทางกลศาสตร์ของหินอ่อนและหินทราเวอร์ทีนสระบุรี

นายจักรพันธ์ เจริญกลาง

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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จักรพันธ์ เจริญกลาง : ความสัมพันธ์ระหว่างความเร็วคลื่นอัลตราโซนิก รอยแตกและคุณสมบัติทางกลศาสตร์ของหินอ่อนและหินทราเวอร์ทีนสระบุรี (CORRELATION BETWEEN ULTRASONIC WAVE VELOCITIES, FRACTURE AND MECHANICAL PROPERTIES OF SARABURI MARBLE AND TRAVERTINE) อาจารย์ที่ปรึกษา : ผู้ช่วยศาตราจารย์ ดร. อานิสงส์ จิตนารินทร์, 112 หน้า

งานวิจัยนี้มีวัตถุประสงค์ 1) เพื่อศึกษาความสัมพันธ์ระหว่างความเร็วคลื่น ความขรุขระของรอยแตก จำนวนรอยแตก กำลังรับแรงและสมบัติความยืดหยุ่นของหินอ่อนและหินทราเวอร์ทีนสระบุรี โดยการวัดคลื่นอัลตราโซนิกและ 2) เพื่อประเมินสมบัติเชิงกลศาสตร์ของหิน การทดสอบอัลตราโซนิกดำเนินการโดยใช้เครื่อง OYO Sonic Viewer 170 (รุ่น 5338) การทดลองในห้องปฏิบัติการเน้นถึงผลกระทบของรูปทรงตัวอย่าง (ทรงกระบอกและบล็อก) ความขรุขระของรอยแตก (ผิวเรียบและผิวขรุขระ) และจำนวนรอยแตก (ผันแปรจาก 0 1 2 ถึง 3 รอย) ต่อความเร็วคลื่น ผลการทดสอบแสดงให้เห็นว่ารูปทรงกระบอกและรูปทรงบล็อกไม่ส่งผลต่อความเร็วของคลื่น ความแตกต่างของความเร็วของคลื่นที่วัดได้อาจเป็นผลมาจากความแปรผันของความหนาแน่นในกลุ่มตัวอย่างที่ทดสอบ การทดสอบยืนยันว่าความเร็วคลื่นปฐมภูมิและทุติยภูมิจะลดลงเมื่อมีจำนวนรอยแตกของหินมากขึ้น ความเร็วคลื่นอัลตราโซนิกที่เคลื่อนที่ผ่านรอยแตกแบบผิวขรุขระจะสูงกว่ารอยแตกแบบผิวเรียบ คลื่นจะเคลื่อนที่ช้าลงเล็กน้อยเมื่อรอยแตกไม่ขนานกัน ดังนั้นลักษณะทางกายภาพของตัวอย่างหินมีความสำคัญมากกว่าทิศทางของรอยแตก ความเร็วคลื่นมีความสัมพันธ์กันอย่างมีนัยสำคัญกับกำลังรับแรงกดในแกนเดียวและ โมดูลัสความยืดหยุ่นของหินอ่อนและหินทราเวอร์ทีน

สาขาวิชา <u>เทคโนโลยีธรณี</u> ลายมือชื่อนักศึกษา__________

ปีการศึกษา 2560 ลายมือชื่ออาจารย์ที่ปรึกษา__________

JAGGAPAN JAROENKLANG : CORRELATION BETWEEN ULTRASONIC WAVE VELOCITIES, FRACTURE AND MECHANICAL PROPERTIES OF SARABURI MARBLE AND TRAVERTINE. THESIS ADVISOR : ASST. PROF. ANISONG CHITNARIN, Ph.D., 112 PP.

P-WAVE VELOCITY/ S-WAVE VELOCITY/ SMOOTH-SURFACE FRACTURE/ ROUGH-SURFACE FRACTURE/ UNIAXIAL COMPRESSIVE STRENGTH/ ELASTIC MODULUS/ POISSON'S RATIO

The objectives of this research are 1) to study correlation between wave velocities, fracture roughness, number of fractures, strength and elastic properties of Saraburi marble and travertine using ultrasonic measurement and 2) to estimate these mechanical properties of the rocks. The ultrasonic test was conducted using OYO Sonic Viewer 170 (Model 5338). Laboratory tests emphasized on effects of sample shape (cylindrical and block), fracture surface roughness (smooth and rough) and number of fractures (varied from 0, 1, 2, to 3) on wave velocities. The results show that cylindrical shape nor block shape do not affect the wave velocities. Differences of the measured wave velocities might be due to variation of density among the tested specimens. The experiments confirm that P-wave and S-wave velocities decrease with increasing number of fractures in the rocks. Ultrasonic wave velocities moving through the rough-surface fracture are higher than through the smooth-surface fracture. The waves move slightly slower when fractures are non-parallel; thus, physical characteristics of the rock samples are more significant than the direction of fractures. The wave velocities have

good correlation with uniaxial compressive strength and elastic modulus of marble and travertine.

School of Geotechnology	Student's Signature ______________

Academic Year 2017	Advisor's Signature ______________

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SYMBOLS AND ABBREVIATIONS

σ_c	=	Uniaxial compressive strength
E	=	Elastic modulus
ν	=	The Poisson's ratio
P	=	Failure load
A	=	Initial cross-sectional area
V_p	=	P-wave velocity
V_s	=	S-wave velocity
ρ	=	Density of specimen
L	=	Thickness of specimen
D	=	Diameter of specimen

CHAPTER I

INTRODUCTION

1.1 Background and rationale

Ultrasonic velocity measurement is a non-destructive, indirect testing method commonly used to determine physical and mechanical properties of rocks. This method has some advantages over other laboratory tests such as the less testing time and little or no sample preparation. The ultrasonic measurement technique have been applied to study carbonate rocks in many countries (e.g., Yasar and Erdogan, 2004; Vasconcelos et al., 2007; Kahraman and Yeken, 2008; Soroush et al., 2011; Zivor et al., 2011; Sheraz et al., 2014; Kurtuluş et al., 2016). In Thailand, the carbonate rocks are important geo-resources. The Saraburi Group, composed mainly of limestones and cropped out in central Thailand has been widely used in various purposes especially for civil and geological engineering projects in Saraburi and Nakhon Ratchasima areas. There are many limestone mines for construction materials, cement plants, and decoration stone. Moreover, to the East and the North of Khorat Plateau, these rocks are overlain by the thick sequences of Khorat Redbeds and play an important role as petroleum reservoirs. However, wave velocity data of the Saraburi carbonates is not well known. Studies concerning wave velocity, physical characteristics and mechanical property are rare. So, this research is aimed to obtain wave velocity data of the particular rocks using the ultrasonic velocity measurement, and understand relationships between the rocks properties. The knowledge gained from this study will be further applied to predict the mechanical property of the rock mass in the field.

1.2 Research objectives

The objectives of this research are 1) to study correlation between wave velocity (P-wave and S-wave) with fracture roughness, number of fractures, uniaxial compressive strength and elastic properties of Saraburi marble and travertine using ultrasonic measurement 2) to estimate the mechanical properties of the rocks. The ultrasonic test will be conducted using OYO Sonic Viewer 170 (Model 5338). A total of 190 specimens were tested. The results will help to understand movement of the waves in various conditions of fractured rock mass.

1.3 Research methodology

The research methodology shown in Figure 1.1 comprises 6 steps; including literature review, sample collection and preparation, laboratory tests, data analysis, discussions and conclusions, and thesis writing.

1.3.1 Literature review

Literature review was carried out to study researches about physical and mechanical properties, ultrasonic measurement and wave velocity of carbonate rocks and effect of shape, size and fracture on wave velocity. The sources of information are from journals, technical reports and conference papers. A summary of the literature review is given in Chapter II.

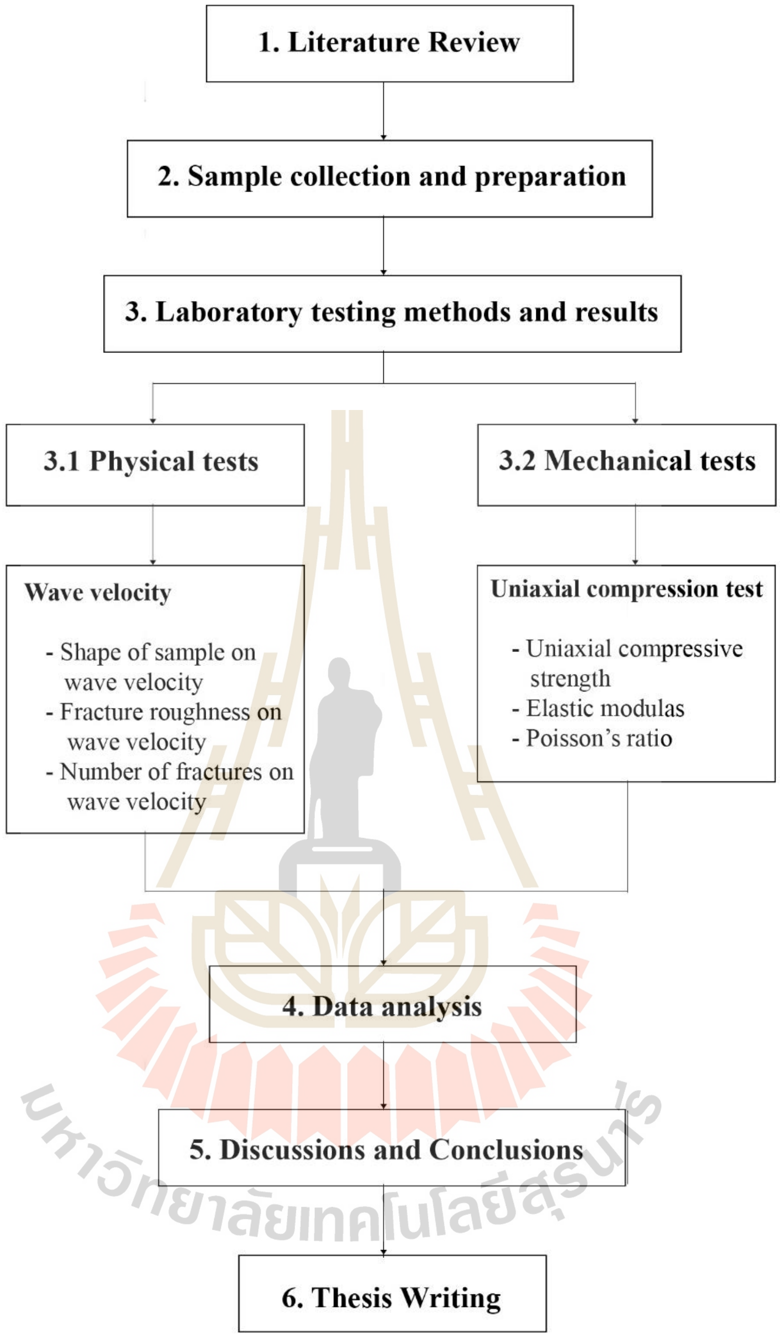


Figure 1.1 Research methodology.

1.3.2 Sample collection and preparation

1) Sample collection

Rock samples used in this research were marble and travertine of the Saraburi Group. In Saraburi province, marbles are locally metamorphosed and exposed in small areas of karst mountains. The marble used in study is from Saraburi Marble quarry in Chalumphrakieat district, Saraburi. The white marble is a part of Lower Permian limestone (Nong Pong Formation) and has been mined for more than 30 years. Travertine was selected from commercial grade stone which was mined in Muak Lek district, Saraburi. The pale brown travertine is a part of Lower- Permian limeand stone (Khao Kad Formation)

The marble and travertine were decided to experiment because generally they are composed mainly of calcite, with small amount of other minerals. This characteristic homogeneous compared to other rocks. Density are varied but in small range. Hardness of the rocks depended on mineral composition is approximately 3 in Mohs scale of hardness, so it is good for preparing fractures in rock specimens.

2) Sample preparation

The samples were prepared at the Geotechnology laboratory, Suranaree University of Technology for the physical (wave velocity) tests and the mechanical (Uniaxial compression test) tests. The sample preparation process for testing is described in Chapter III.

1.3.3 Laboratory experiment and results

1) Physical testing

The physical testing standards are density and wave velocity (ASTM D2845).

2) Mechanical testing

The mechanical testing standard is ASTM D7012 (the uniaxial compression test). A summary of the laboratory experiment is given in Chapter IV.

1.3.4 Data analysis

The results from laboratory are used to establish relationship between wave velocity with shape, fracture roughness, number of fractures and mechanical properties. The data analysis is given in Chapter V.

1.3.5 Discussions and Conclusions

Discussions are made on the reliability and adequacies of the test data and the correctness of the interpretation and analysis. Future research needs are identified. A summary of the discussions and conclusions is given in Chapter VI

1.3.6 Thesis writing

All research activities, methods, and results are documented and compiled in the thesis.

1.4 Scope and limitations

The scope and limitations of the research include as follows.

1. All samples are marble and travertine obtained from the Saraburi Group in Saraburi province.
2. Ultrasonic testing in accordance with ASTM standards and suggested method by ISRM.
3. The sample prepared to test the effect of the shape on wave velocity were of two types: block and cylinder.

4. The sample prepared to test the effect of fracture on wave velocity were varied in number of fracture and roughness of fracture surface.
5. The uniaxial compression test procedure was conducted following the American Society for Testing and Materials standard (ASTM) and suggested method by International Society of Rock Mechanics (ISRM).

1.5 Thesis contents

The first chapter includes background and rationale, research objectives, scope and limitations and research methodology, Chapter II presents the literature reviews, Chapter III describes the sample preparations, Chapter IV explains the laboratory experiment, Chapter V presents the relationship between wave velocity and shape, fracture roughness, number of fractures and mechanical properties. Chapter VI presents the discussions, the conclusions and recommendations for future studies.

CHAPTER II

LITERATURE REVIEW

2.1 Introduction

This chapter summarizes the results of literature review carried out to improve an understanding of the relationship between wave velocity (P-wave and S-wave velocity) with sample shape, fracture roughness, number of fractures and mechanical properties of Saraburi marble and travertine. The topics reviewed here include wave velocity of carbonate rocks, effect of shape on wave velocity, effect of fractures on wave velocity and effect of physical and mechanical properties (Uniaxial compressive strength, elastic modulus and Poisson's ratio) on wave velocity.

2.2 Wave velocity of carbonate rocks

Wave is one of the tools used to explore physical characteristics of materials. Especially, geophysical surveys use the properties of seismic waves to pass through the earth. For the study of the internal structure of the world, characteristics of rock masses in the crust and the phenomena on earth, such as earthquakes etc. In smaller scale surveys, such as mineral areas or project area for foundations on rock. Application of seismic and other wave motion theory will be adapted to nature and purpose of each work. One of them is ultrasonic waves can be created from devices that convert energy into transducers (a transmitter and a receiver). The waves can move through both solid and liquid media. Ultrasonic movement is applied in engineering and geotechnology such as inspection of concrete, metal, ceramic, rocks. Because it is a way to measure the wave velocity passing through the sample and wave velocity can be calculated for mechanical properties by not-destroying the sample (Kahraman, 2001; Yasar and Erdogan, 2004; Kahraman, 2007; Fener, 2011; Soroush et al., 2011; Altindag, 2012; Ercikdi et al., 2016; Nitsungnoen and Wannakao, 2015) and the test equipment is not very large, it can be used easily in both laboratory and field. It has been developed for use in geotechnical engineering, geotechnical and mining such as; grouting, rockbolt reinforcement, blasting efficiencies in the rock mass and inspection of rock properties from specimens (Wannakao et al., 2007, 2009).

Researchers have studied the waves velocity of carbonate rocks, such as limestone, travertine, marble, dolomite, etc. This the study, ultrasonic techniques were used to testing various types of carbonate rocks. The results show the range of wave velocity (P-wave, V_p and S-wave, V_s). Calculated from the time it takes the waves to move and depends on the physical properties of the rock samples. Homogeneous rock samples, the waves move faster (Leucci and De Giorgi, 2006). The values of V_p and V_s are highest, but if there is the fracture in the specimen, it will cause the waves to move slowly. When the fractures increase, the wave velocity decreases (Kahraman, 2001; Altindağ and Guney, 2005 and Kurtulus et al, 2011).

Table 2.1 The wave velocity data table studied by the researchers.

Rock Type	Vp (km/s)	Vs (km/s)	Reference
dolomite	5.55	3.28	Pyrak-nolte (1996)
travertine marble	4.20-5.50 6.26	-	Kahraman (2001)
limestone travertine dolomitic limestone marble	5.93-6.33 4.64-5.28 6.85 6.29-6.64	-	Kahraman (2002a)
travertine marble	4.78 5.96	-	Kahraman (2002b)
limestone	3.30-5.37	2.17-2.93	Assefe et al. (2003)
limestone dolomitic limestone marble dolomite	2.90-5.80 4.20 3.80-5.20 3.10-5.20	-	Yasar and Erdogan (2004)
limestone marble	5.04-5.75 4.96	-	Altindağ and Güney (2005)
limestone marble travertine	4.64-6.19 5.79 5.38	-	Güney et al. (2005)
limestone marble travertine	5.11-5.45 3.40-5.58 4.23-5.24	-	Kahraman (2007)
limestone marble dolomitic limestone	4.89-5.16 5.56 4.52	-	Kahraman et al. (2008)
limestone travertine dolomitic limestone	6.00-6.20 3.70-5.55 6.10	-	Kahraman and Yeken (2008)
limestone	1.83-6.54	-	Moradian and Behnia (2009)
dolomite limestone marble	3.27 3.02-3.20 2.37-3.74	-	Khandelwal and Ranjith (2010)
limestone marble travertine	4.30-5.94 4.00-4.16 5.13	-	Yavuz et al. (2010)
dolomite limestone marble travertine	4.53-6.37 5.63-6.36 3.19-5.36 4.29-6.14	-	Martinez-Martinez et al. (2011)
limestone marble travertine	4.74-6.30 4.94-6.38 5.32-5.46	-	Sengun et al. (2011)

Table 2.1 The wave velocity data table studied by the researchers (Continued).

Rock Type	Vp (km/s)	Vs (km/s)	Reference
limestone travertine dolomite	3.21-6.75 4.50 6.30	-	Altindag (2012)
calcarenite	3.56-3.80	-	Rahmouni et al. (2013)
limestone	4.30-5.80	-	Kurtuluş et al. (2015)
limestone marble	5.32-8.36 6.29-7.44	-	Martinez-Martinez et al. (2016)
dolomite limestone	4.37-5.48 5.40-6.84	2.68-3.16 2.96-3.90	
dolomite limestone	4.37-5.55 5.70-6.84	-	Stan-kleczek (2017)
argillaceous limestone calcarenite marble travertine	4.12-4.74 4.31 2.29-3.29 4.09-4.56	2.73-3.03 2.59 1.40-2.19 2.65-2.88	Jaroenklang et al. (2017)

2.3 Effect of shape and size on wave velocity

Vasconcelos et al. (2008) studied physical and mechanical properties of granite by ultrasonic evaluation. In this study, investigated differences in shape and size of samples on the effect of ultrasonic pulse velocity (UPV) include cubic, cylindrical and prismatic shapes. When comparing the average values of UPV obtained in the specimens with distinct shape and size, only moderate differences are found, see Figure 2.1. No significant differences were found between cubic specimens and the cylindrical compressive specimens. This means that the distinct size and shape of the specimens used in the mechanical tests leads to values of the ultrasonic pulse velocity close.

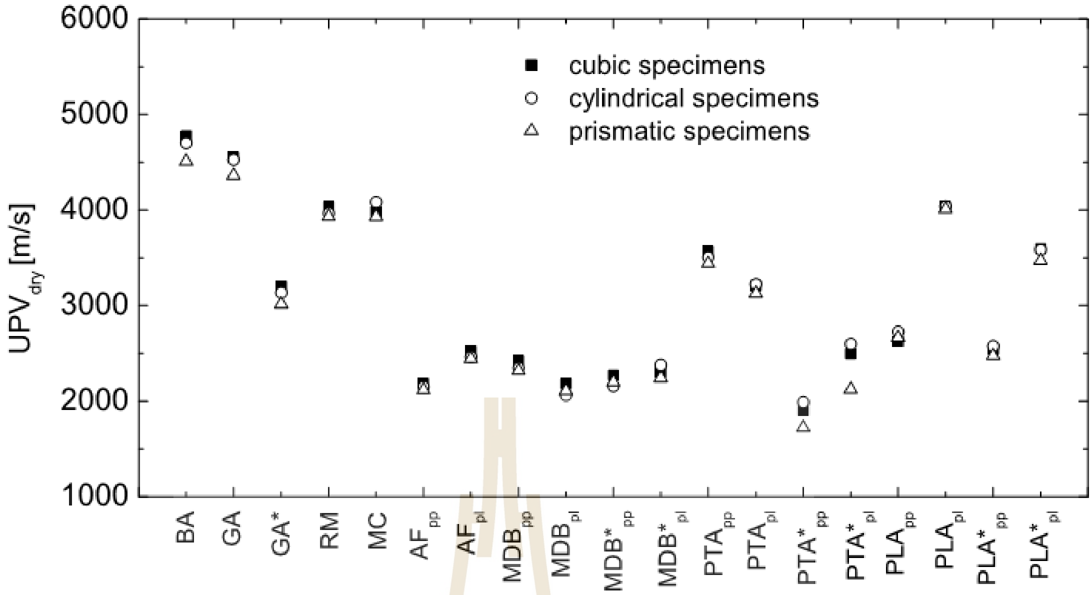


Figure 2.1 Comparison of the UPV_{dry} among the specimens with distinct size and shape (Vasconcelos et al., 2008).

Fener (2011) studied the effect of sample diameter on P-wave velocity. The PUNDIT 6 Pulse Generator Unite controls made by the company and two transducers (transducer's diameter is 50 mm) having a frequency of 1 MHz and direct method was used in this study. The end surfaces of the core samples were polished to provide a good coupling between the transducer face and the sample surface to maximize accuracy of the transit time measurement. Stiffer grease was used as a coupling agent in this study. The minimum diameter 29.68 mm and the maximum diameter 113.50 mm. The result is that the wave velocity changes, when the diameter changes. In the example of Tuff, Basalt, Andesite and Ignimbrite the wave velocity decreases depending on the increase in the diameter of the sample. In the example of limestone, dolomite, tuff, granite and travertine at 78.68 mm in diameter, the wave velocity decreases. And the wave velocity increases in diameter with the greatest value. The test results were statically analyzed using the method of least squares regressions, exponential and polynomial relationship with high correlation coefficient were found between the sample dimension and P-wave velocities. The P-wave velocity value variation (ΔPs) depending on sample dimension, the porosity of rocks and dry density values were statistically evaluated (Figure 2.2-2.3). According to these results, ΔPs is low with the rock groups having low porosity values, and ΔPs is high in rock groups having high porosity values. A polynomial relation with high correlation coefficient was observed between ΔPs and porosity values. Also, there is an inverse polynomial relation with high correlation coefficient between ΔPs and dry density values. ΔPs is low for the samples with high dry density and it is high for the samples with low dry density.

Karaman et al. (2015) studied the effect of the specimen length on ultrasonic P-wave velocity. Rock samples (Volcanic rocks and limestone) from 8 sources in Turkey. The ultrasonic P-wave velocity tests were carried out under dry and saturated conditions for each 200 core specimens. In this study, the lengths of the different samples 50, 75, 100, 125 and 150 mm. Ultrasonic pulse method for the ultrasonic P-wave velocity testing was performed using the Pundit-plus model equipment. An accuracy of 0.1 mm for the length of the measuring base was used. Before the measurements, the cut ends of samples were polished to provide the flat and smooth surface. A thin film of petroleum jelly (vaseline) was fulfilled to the surface of the transducers (receiver and transmitter) so as to provide full contact and to remove the air gap between transducers and the specimen surface. So, core specimens having lengths of 50 mm and 75 mm, an increase in the ultrasonic P-wave velocity values based on an increase in length was shown for the volcanic. Further, a significant increase in the ultrasonic P-wave velocity was obtained for limestone specimens having lengths of 50 mm, 75 mm and 100 mm. Over

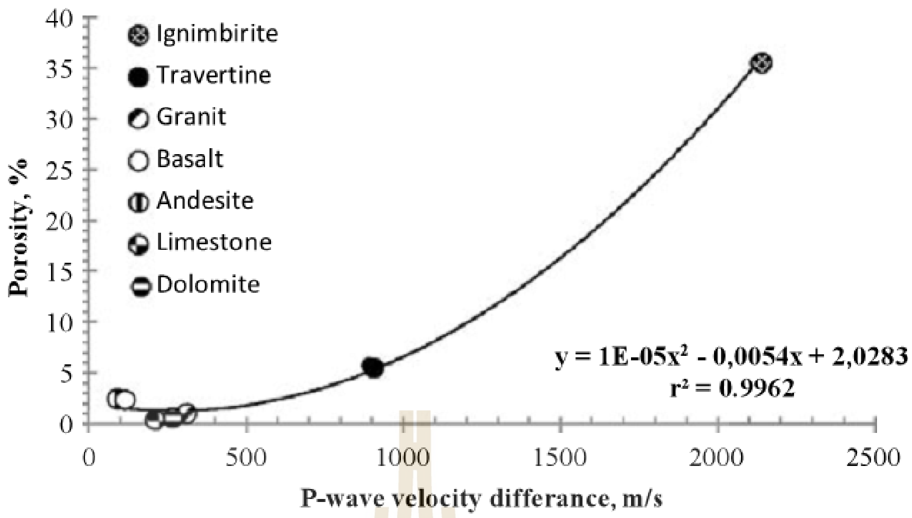


Figure 2.2 A polynomial relationship between P-wave velocity difference and porosity (Fener, 2011).

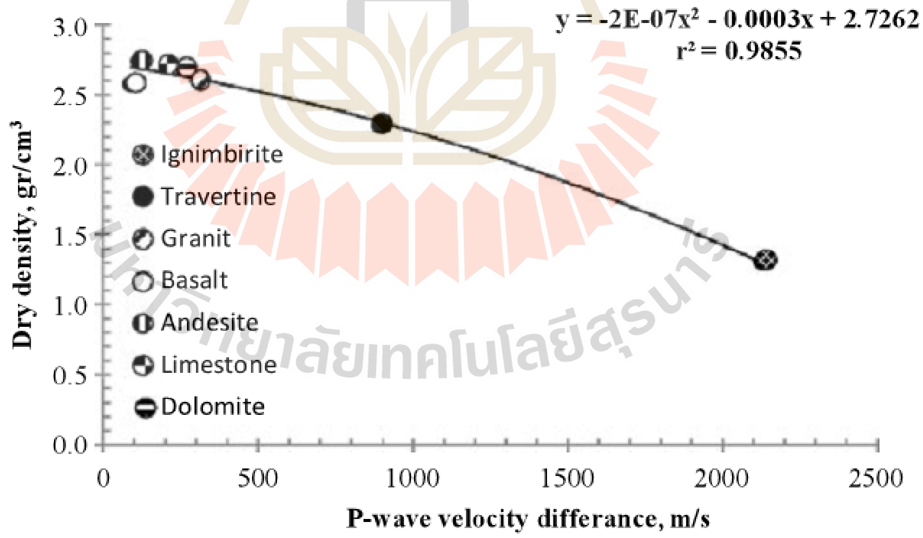


Figure 2.3 A polynomial relationship between P-wave velocity difference and dry density (Fener, 2011).

the length of 75 mm for the volcanic rocks and 100 mm for the limestones, higher decreasing on ultrasonic P-wave velocity values was seen. This study showed that both the ultrasonic P-wave velocity (dry) and ultrasonic P-wave velocity (saturated) are strongly contingent upon the variation of the specimen length (Figure 2.4-2.5). According to the results of the statistical analyses, threshold specimen length for the volcanic rocks and limestones were determined as 79 and 109 mm, respectively. Ultrasonic P-wave velocity (dry) values were remained constant or at least fluctuate closely around a constant mean value for NX-sized cores over the threshold specimen length. However, ultrasonic P-wave velocity (saturated) values were tended to decrease over the critical core specimen length for some rocks (vesicular basalt and grey limestone). These results rendered the ultrasonic P-wave velocity measurements unnecessary for the core samples over the length of 79 and 109 mm for the volcanic rocks and limestones, respectively.

Ercikdi et al. (2016) studied core size effect on the dry and saturated ultrasonic pulse velocity of limestone samples, found that the P-wave velocity values of limestone samples increased or decreased with increasing the samples size and the dry samples produced consistently 1.03–1.46 times higher P-wave velocity (saturated) than those of saturated samples at higher sample lengths (75, 100 and 125 mm). In contrast to the considerable variations (5.8-23%) of P-wave velocity (saturated) at short lengths (between 25 and 75 mm), the P-wave velocity (saturated) in the sample lengths between 75 and 125 mm were close with a variation of only 7.3%. Therefore, a core length of 75 mm can be interpreted as the optimum core sample length for the dry and saturated P-wave velocity test. Five representative core samples were prepared for each core length of a rock type and 25 core samples were totally used for the P-wave velocity test of each

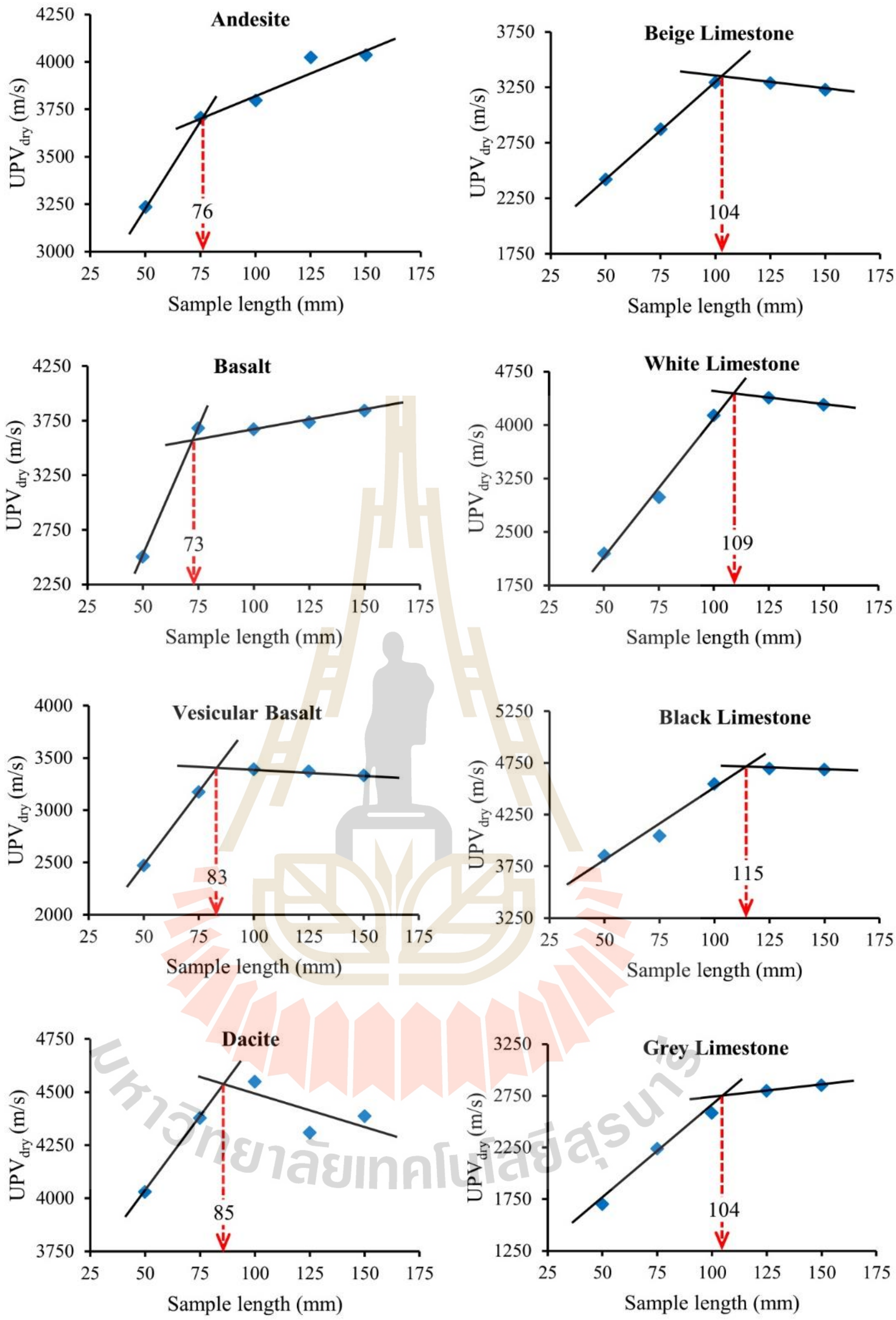


Figure 2.4 Method for threshold specimen length determination for volcanic rocks and limestones using average ultrasonic P-wave velocity (dry) values (Karaman et al. (2015).

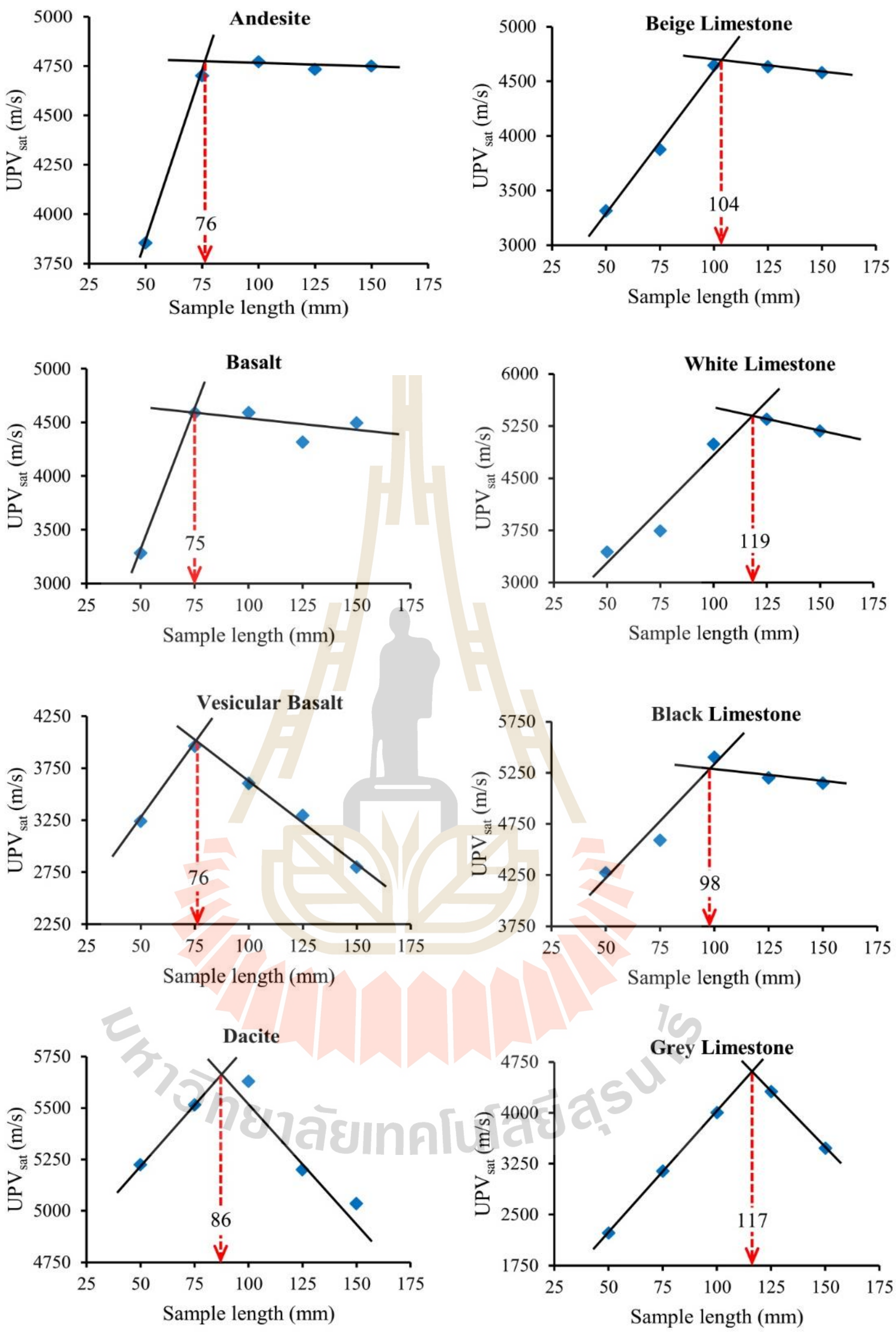


Figure 2.5 Method for threshold specimen length determination for volcanic rocks and limestones using average ultrasonic P-wave velocity (saturated) values (Karaman et al. (2015).

rock type. ultrasonic pulse velocity tests were conducted on the dry and saturated core samples prepared at a constant diameter (NX size) with various lengths (25 mm, 50 mm, 75 mm, 100 mm and 125 mm) (Figure 2.6). A total of 50 P-wave velocity measurements were performed on the dry (a total of 25) and saturated (a total of 25) conditions for each rock type.

Figure 2.6 Samples preparation at different sizes for UPV tests (Ercikdi et al., 2016).

2.4 Effect of fracture on wave velocity

Kahraman (2001) studied the correlation between the P-wave velocity and the number of joints. The rock used in the test is granite, marble and travertine. Test samples having a dimension of 10x20x10 cm were prepared by sawing from block samples. The end surfaces of specimens were polished sufficiently smooth to provide good coupling. After the specimens were subjected to an axial load of 20 kN, P-wave velocities were measured. In the tests, E48 Pulse Generator Unit made by CONTROLS and two transducers (a transmitter and a receiver) having a frequency of 54 kHz were used. The tests were carried out parallel to any visible bedding plane. Firstly, the P-wave velocities were measured on each block specimen. Then, a discontinuity plane perpendicular to the measuring direction was artificially created in each block specimen by sawing and the measurement of the sound velocities was performed. After that, a second discontinuity plane was artificially created in each block specimen and the sound velocity measurements were repeated. The test procedure ended with the measurements on the specimens having three discontinuity planes. The regression equations and the correlation coefficients are following:

Code number 1 (Granite)

Number of joints = $-2.76V_p+12.03$ $\quad r = -0.98$ (2.1)

Code number 2 (Granite)

Number of joints = $-2.56V_p+12.97$ $\quad r = -0.99$ (2.2)

Code number 3 (Travertine)

Number of joints = $-1.52V_p+6.34$ $\quad r = -0.99$ (2.3)

Code number 4 (Travertine)

Number of joints = $-1.35V_p+7.27$ r = -0.98 (2.4)

Code number 5 (Travertine)

Number of joints = $-1.41V_p+7.95$ r = -0.97 (2.5)

Code number 3 (Marble)

Number of joints = $-2.64V_p+16.59$ r = -0.98 (2.6)

The results show that P-wave velocity decreases with an increase in the number of joints.

Altindag and Guney (2005) studied the relationship between the P-wave velocity and the joint density. A number of block samples in size of 10x10x35 cm were prepared and P-wave velocities were measured on each block prior to sawing. Later, the samples were sawn off the blocks in thicknesses of 1, 2, 3, 4, 5, 6 and 7 cm in order to form sets of test samples with consecutive artificial joints varying in number between 0-6 as show in Figure 2.7. Contact surfaces of the sawn-off samples were polished sufficiently for smooth planes. A good coupling along the contact surfaces of joints was satisfactorily maintained even in the absence of vertical load by carefully clamping sample sets at the ends. Then, P-wave velocity measurements were conducted on the sample sets by Ultrasonic Testing Equipment with 54 kHz frequency. The regression equations and the correlation coefficients are following:

Code number 1 (Limestone)

Number of joints = $-1.1441V_p+6.7763$ $r = -0.990$ (2.7)

Code number 2 (Limestone)

Number of joints = $-1.5019V_p+6.9271$ $r = -0.927$ (2.8)

Code number 3 (Limestone)

Number of joints = $-1.5563V_p+7.3248$ $r = -0.970$ (2.9)

Code number 4 (Marble)

Number of joints = $-1.3168V_p+7.1942$ $r = -0.940$ (2.10)

The results of the experiments confirm that P-wave velocity decreases with an increase in the density of joints in rocks.

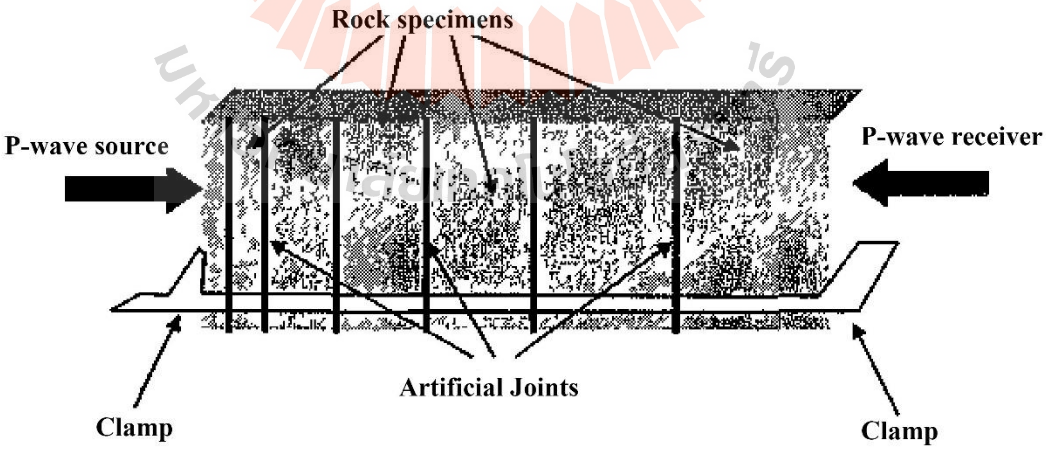


Figure 2.7 Schematic view of a sample set with six artificial joints (Altindag and Guney, 2005).

Kurtulus et al. (2011) studied experiment in wave propagation across a jointed rock mass. Experiments have been conducted to determine the effects of parallel and variable directional joints on ultrasonic pulse propagation in two 60x60x360 mm prismatic marble blocks containing no joints, six parallel joints, and six variable directional joints. Initially, the ultrasonic pulse velocity was measured on each prismatic block using a Dt Qust 120t pulse generator with a frequency of 54 kHz. A 50 mm thick block was then cut from one end of the prismatic block, perpendicular to the measuring direction, creating an artificial discontinuity plane. The ultrasonic pulse velocity was measured and the process repeated using the spacing indicated in Figure 2.8. Subsequently, the second prismatic test block was cut in variable directions to the measuring direction, progressively creating artificial discontinuities in the pattern shown in Figure 2.9. The regression equations and the correlation coefficients are following:

Test block with joints perpendicular to measuring directions.

$$\text{Number of joints} = -0.0021 \times (\text{ultrasonic pulse velocity}) + 13.417 \quad R^2=0.90 \qquad (2.11)$$

Test block with variable directional joints to measuring directions

$$\text{Number of joints} = -0.0015 \times (\text{ultrasonic pulse velocity}) + 10.421 \quad R^2=0.94 \qquad (2.12)$$

The attenuation velocity was higher in the prismatic marble mass with variable directional joints. However, the direction of fracture influences wave motion. The wave moves through the samples slowly and the energy decreases when the direction of the fracture is non-parallel.

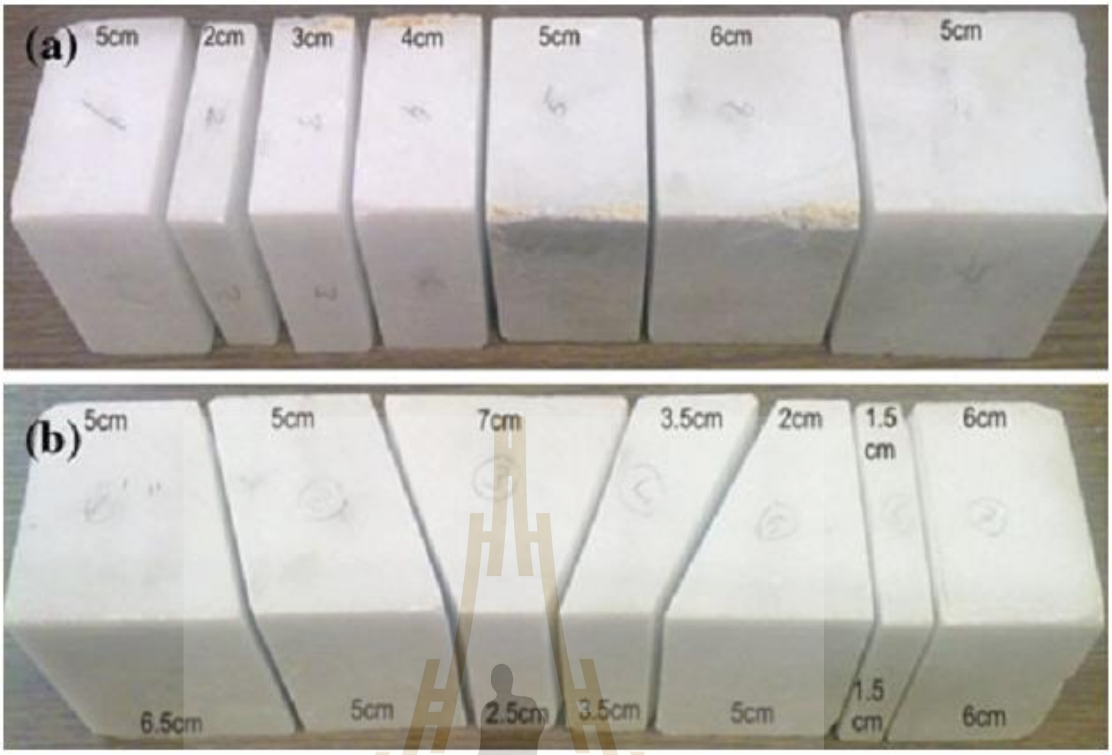


Figure 2.8 (a) Parallel jointed test block, (b) variable directional jointed test block (Kurtulus et al, 2011).

Figure 2.9 Block cut in variable directions (Kurtulus et al, 2011).

2.5 Effects of physical and mechanical properties on wave velocity

Yasar and Erdogan (2004) studied the relationship of sound velocity (SV) with the density (ρ), compressive strength (σ_c), and Young's modulus (E) of carbonate (limestone, marble, and dolomite). The physical and mechanical properties of the carbonate rock were measured using P-wave velocity. The velocities of the P and S waves are calculated from the measured travel time and the distance between transmitter and receiver. In order to measure a SV index value, the Pundit testing machine was used. The Pundit has a pulse generator, transducers, and an electronic counter for time internal measurements. The test results show that the speed of SV increases with increases in σ_c, E and ρ (Figure 2.10). The study also found that, density, compressive strength and Young's modulus in various types of carbonate. Predictable wave velocity using simple linear mathematical relationships according to following:

$$SV = 0.0317\sigma_c + 2.0195 \tag{2.13}$$

$$SV = 0.0937E + 1.7528 \tag{2.14}$$

$$SV = 4.3183\rho + 7.5071 \tag{2.15}$$

Kurtulus et al. (2015) studied relationship of physical and mechanical properties of rock on P-wave velocity. The physico-mechanical properties of five different intact rock types including volcanic (Kızderbent), arkoses (Sopalı), sandstone (Korfez), sandstone (Derince) and limestone (Akveren) were determined through standardized laboratory tests. Ninety-six specimens were tested to obtain the relationships between P-wave velocity (Vp), dry unit weight (DUW), uniaxial compressive strength (UCS),

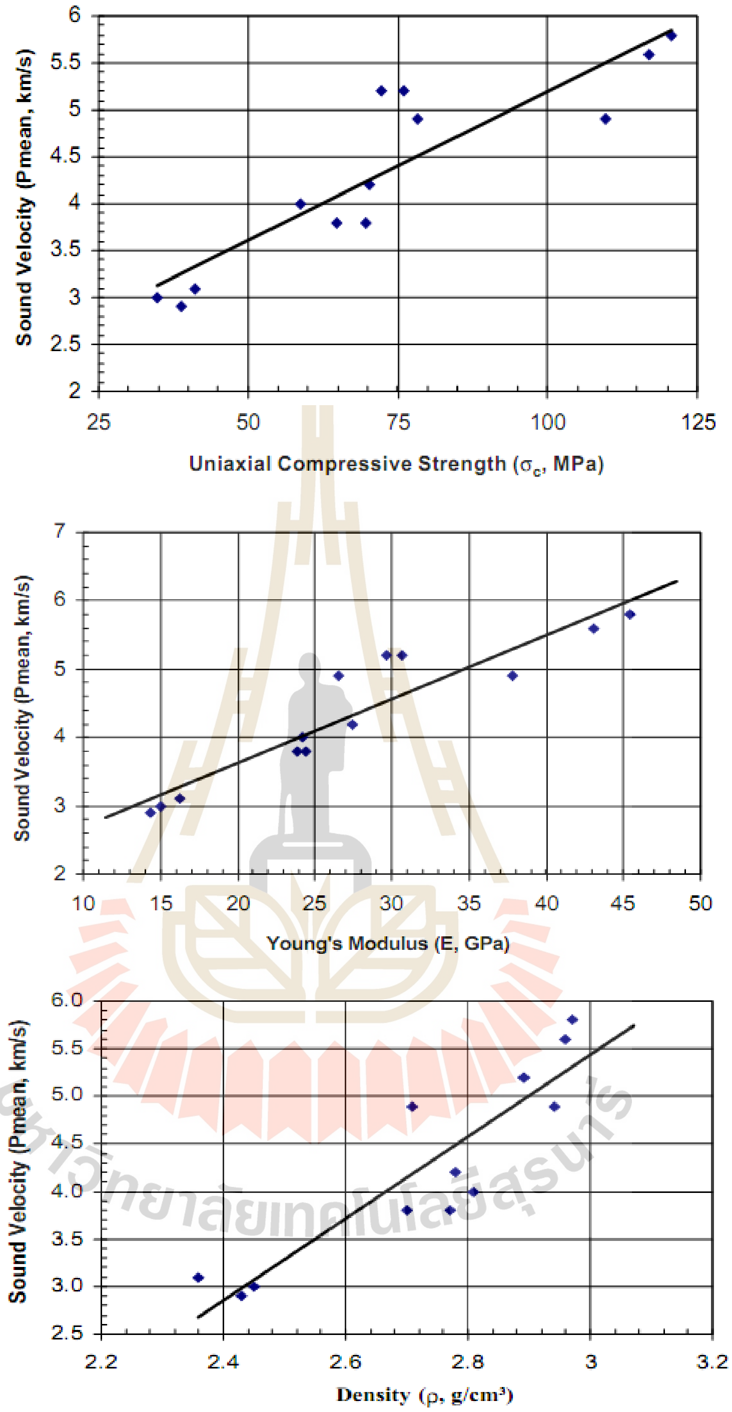


Figure 2.10 Correlation of sound velocity and σ_c, E and ρ (Yasar and Erdogan, 2004).

point load index Is(50), Brazilian tensile strength (TS), porosity (ϕ), and Schmidt hardness (RN). In order to describe the relationships between P-wave velocity and physico-mechanical properties of rocks a regression analysis was carried out. The equation of the best fit line and the coefficient of determination (R^2) were determined for each test result (Figure 2.11-2.16). It can be seen from the figures that, in all cases, the best fit relationships were found to be the best.

There is an exponential relation between P-wave velocity and dry unit weight with a strong correlation of (R^2= 0.795) (Figure 2.11). The equation of this relation is given as;

$$DUW = 0.52V_p^{0.45} \quad (R2=0.795) \tag{2.16}$$

Polynomial relations have been observed between P-wave velocity and UCS and Is(50) (Figure 2.12 and 2.13). The equations are given below:

$$UCS = 8.10^{-6}V_p^2 - 0.024V_p + 31.91 \quad (R^2=0.89) \tag{2.17}$$

$$I_s(50) = 7.10^{-7}V_p^2 - 0.002V_p + 2.839 \ (R^2=0.88) \tag{2.18}$$

A very good correlation (R^2= 0.89) was found between Vp and UCS, and also (R^2= 0.88) between Vp and Is(50) for P-wave velocity and the tensile strength, effective porosity and Schmidt rebound number show linear relationships (Figure 2.14, 2.15 and 2.16).

$$TS = 0.008V_p + 3.84 \quad (R^2=0.78) \tag{2.19}$$

$$Ø = -6E - 0.5V_p + 0.383 \qquad (R^2=0.85) \tag{2.20}$$

$$RN = 0.006V_p + 9.52 \qquad (R^2=0.80) \tag{2.21}$$

A good correlation (R^2= 0.78) was found between P-wave velocity and Brazilian tensile strength, (R2= 0.85) between V_p and Ø, and (R^2= 0.80) between V_p and RN.

The results showed that P-wave velocity increases when dry unit weight, uniaxial compressive strength, point load index, Brazilian tensile strength and Schmidt hardness increased. But the porosity increases, the P-wave velocity decreases. The test results were interpreted statistically and reasonable good relationships were determined with P-wave velocity (ranging between 1890.0 and 6340.0 m/s) to the physico-mechanical properties. This result denotes that P-wave velocities could be used in determination of the physico-mechanical properties of intact rocks.

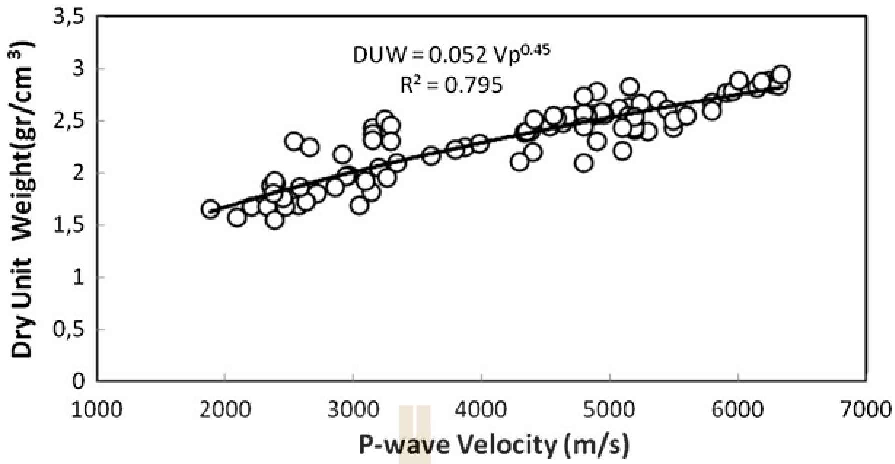


Figure 2.11 Graph of dry unit weight, DUW and P-wave velocity, V_p (Kurtulus et al., 2015).

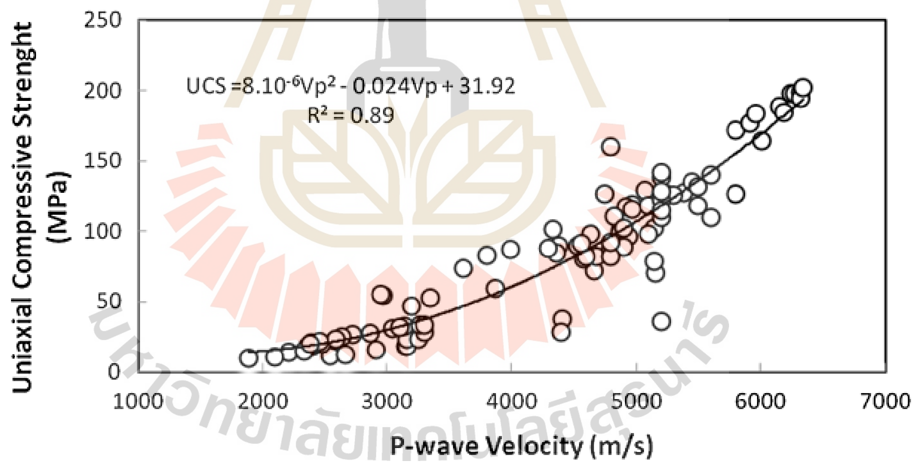


Figure 2.12 Graph of uniaxial compressive strength, UCS and P-wave velocity, V_p (Kurtulus et al., 2015).

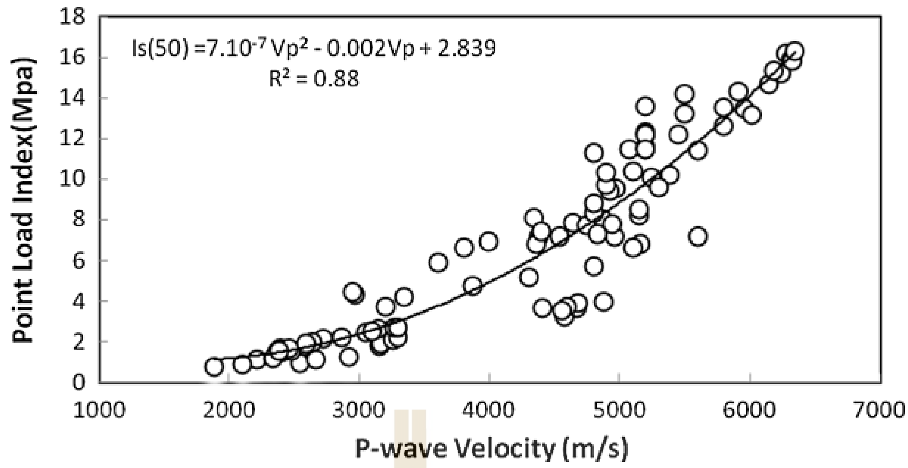


Figure 2.13 Graph of point load index, Is(50) and P-wave velocity, V_p (Kurtulus et al., 2015).

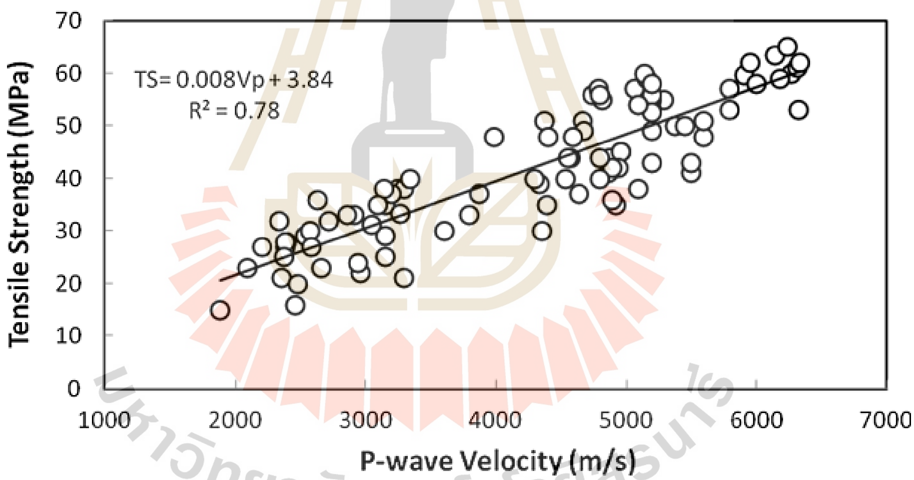


Figure 2.14 Graph of tensile strength, TS and P-wave velocity, V_p (Kurtulus et al., 2015).

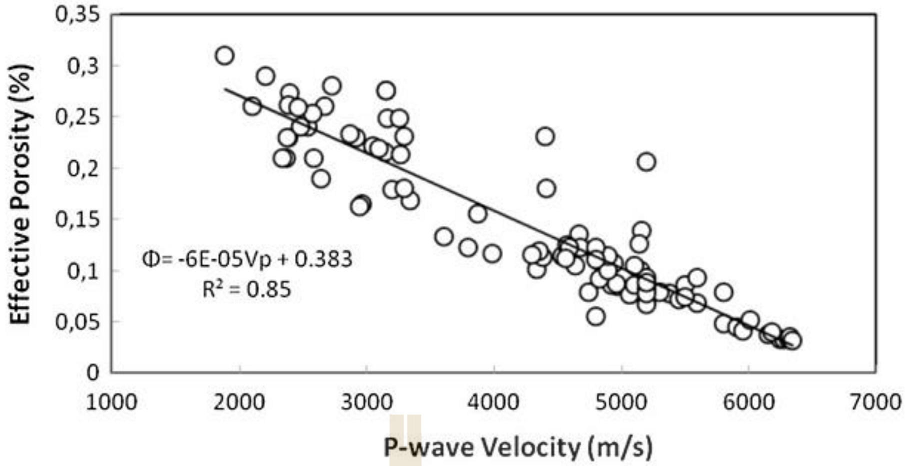


Figure 2.15 Graph of effective porosity, ϕ and P-wave velocity, V_p (Kurtulus et al., 2015).

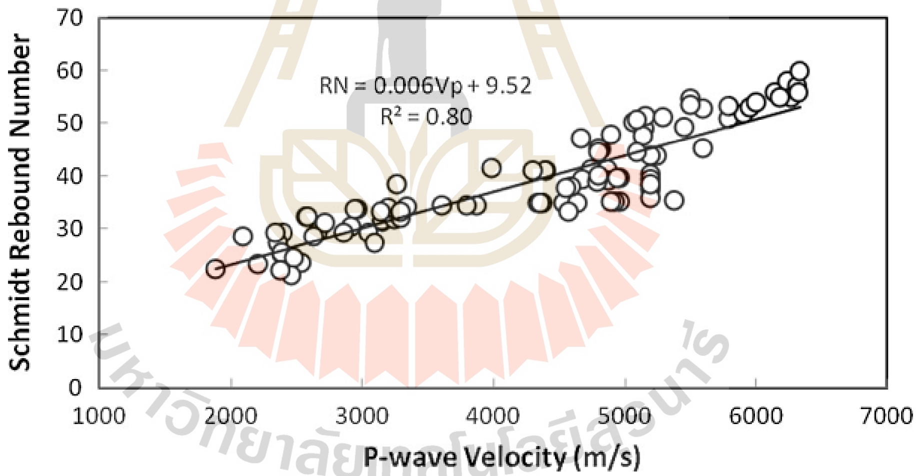


Figure 2.16 Graph of Schmidt rebound number, RN and P-wave velocity, V_p (Kurtulus et al., 2015).

CHAPTER III

SAMPLE COLLECTION AND PREPARATION

3.1 Introduction

This chapter describes the coding for specimens, sample collection and sample preparation of marble and travertine to be used in the ultrasonic tests and uniaxial compression tests. The rock is obtained from Saraburi group.

3.2 Coding for specimens

Coding for specimens following:

T	=	Travertine
M	=	Marble
S	=	Smooth-surface fracture
R	=	Rough-surface fracture
P	=	Parallel direction
NP	=	Non-parallel direction
C	=	Cylinder shape
B	=	Block shape
UCS	=	Uniaxial compressive strength test
One digit	=	Number of fractures
Two digits	=	Number of specimen

For example, **MS-P-0-01 M** is marble **S** is smooth-surface fracture **P** is parallel direction **0** is number of fracture (no fracture) and **01** is number of specimen. Total number of specimen is shown in Table 3.1-3.8.

3.3 Sample collection

Rock samples used in this research were marble and travertine of the Saraburi Group. In Saraburi province, marbles are locally metamorphosed and exposed in small areas of karst mountains. The marble used in study is from Saraburi Marble quarry in Chalumphrakieat district, Saraburi. The white marble is a part of Lower Permian limestone (Nong Pong Formation) and has been mined for more than 30 years. Travertine was selected from commercial grade stone which was mined in Muak Lek district, Saraburi. The pale brown travertine is a part of Lower- Permian lime and stone (Khao Kad Formation)

The marble and travertine were decided to experiment because generally they are composed mainly of calcite, with small amount of other minerals. This characteristic homogeneous compared to other rocks. Density are varied but in small range. Hardness of the rocks depended on mineral composition is approximately 3 in Mohs scale of hardness, so it is good for preparing fractures in rock specimens.

3.4 Sample preparation

3.4.1 Sample preparation following American Society of Testing Materials (ASTM)

The specimen should have a length-to-diameter ratio (L/D) of 2.0 to 2.5 and a diameter of not less than 47 mm (ASTM D4543-07).

1) Preparation for testing the relationship between wave velocity and shape

Sample preparation for testing the relationship between wave velocity and shape was divided into 2 types: dimensions 54x54x108 mm^3 for the block shape and the cylinder shape specimens of 54 mm of diameter with L/D ratio of 2.0 (Figure 3.1).

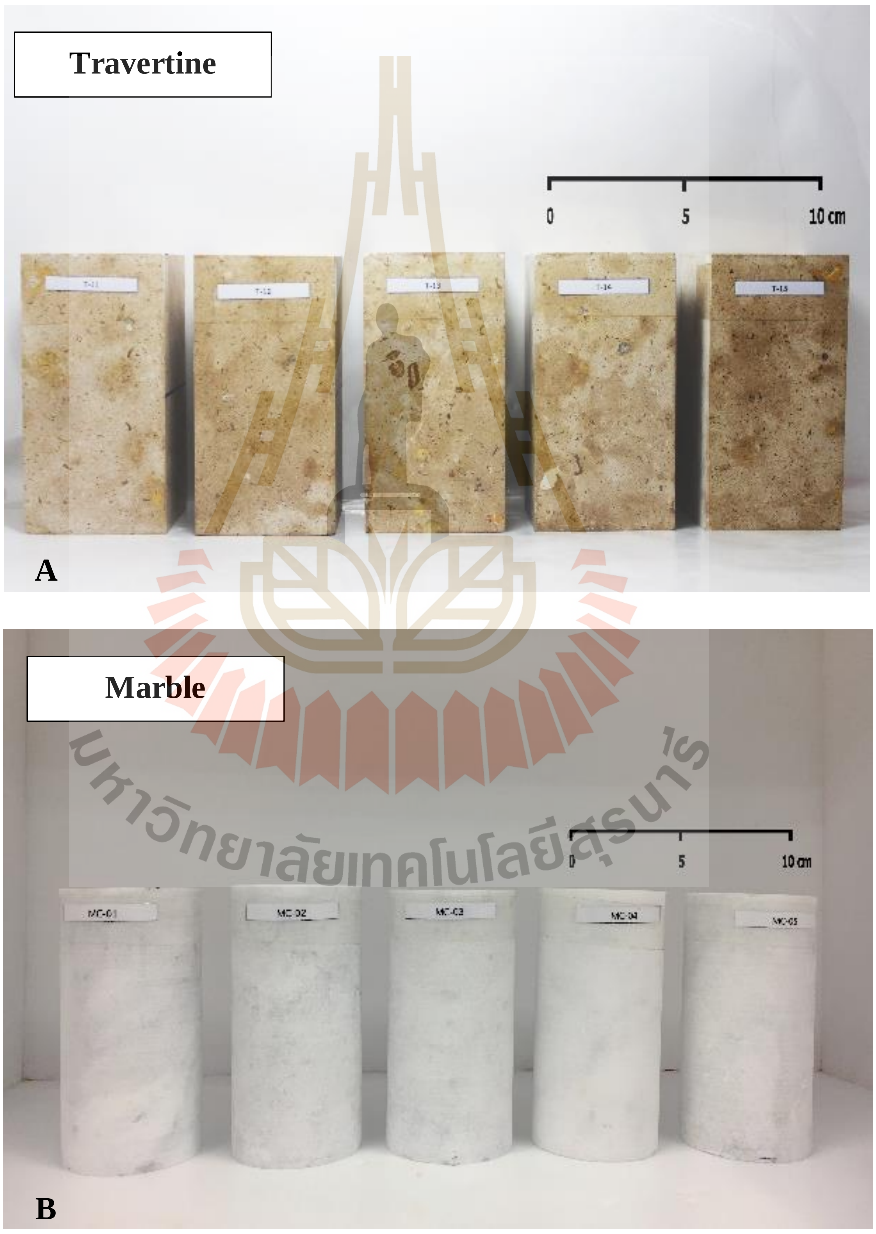


Figure 3.1 Samples at two different shape: (A) block shape and (B) cylinder shape.

2) Preparation for testing the relationship between wave velocity and mechanical properties

The cylindrical specimens of 54 mm of diameter with L/D ratio of 2.0 were prepared for the uniaxial compression test (Figure 3.2).

3.4.2 Sample preparation following researcher studies.

Specimens are prepared which follow those of Kahraman (2001, 2002a, 2002b), Altindağ et al., (2005), Leucci and De Giorgi, (2006), Kahraman et al., (2008) by sample prepared in a block shape. The width and length of the sample design are based on the purpose will study.

1) Preparation for testing the relationship between wave velocity and fracture roughness

The specimens (60x60x120 mm^3) prepared for fracture surface roughness (Figure 3.3) in the rocks are divided into 2 types, rough-surface fracture, which is created by pressing the tensile fracture along the lines (Tension-induced fracture) and smooth-surface fracture is created using a saw. The fracture is created transverse to sample and divided into 4 groups according to the number of fractures varied from 0, 1, 2 and 3 and the direction of fracture parallel (Figure 3.4) and non-parallel (Figure 3.5).

2) Preparation for testing the relationship between wave velocity and number of fractures

Sample preparation for the test can be prepared in conjunction with the preparation for testing the relationship between wave velocity and fracture roughness. Both of these tests are well prepared and tested the same. The test results are different and can be analyzed for each test.

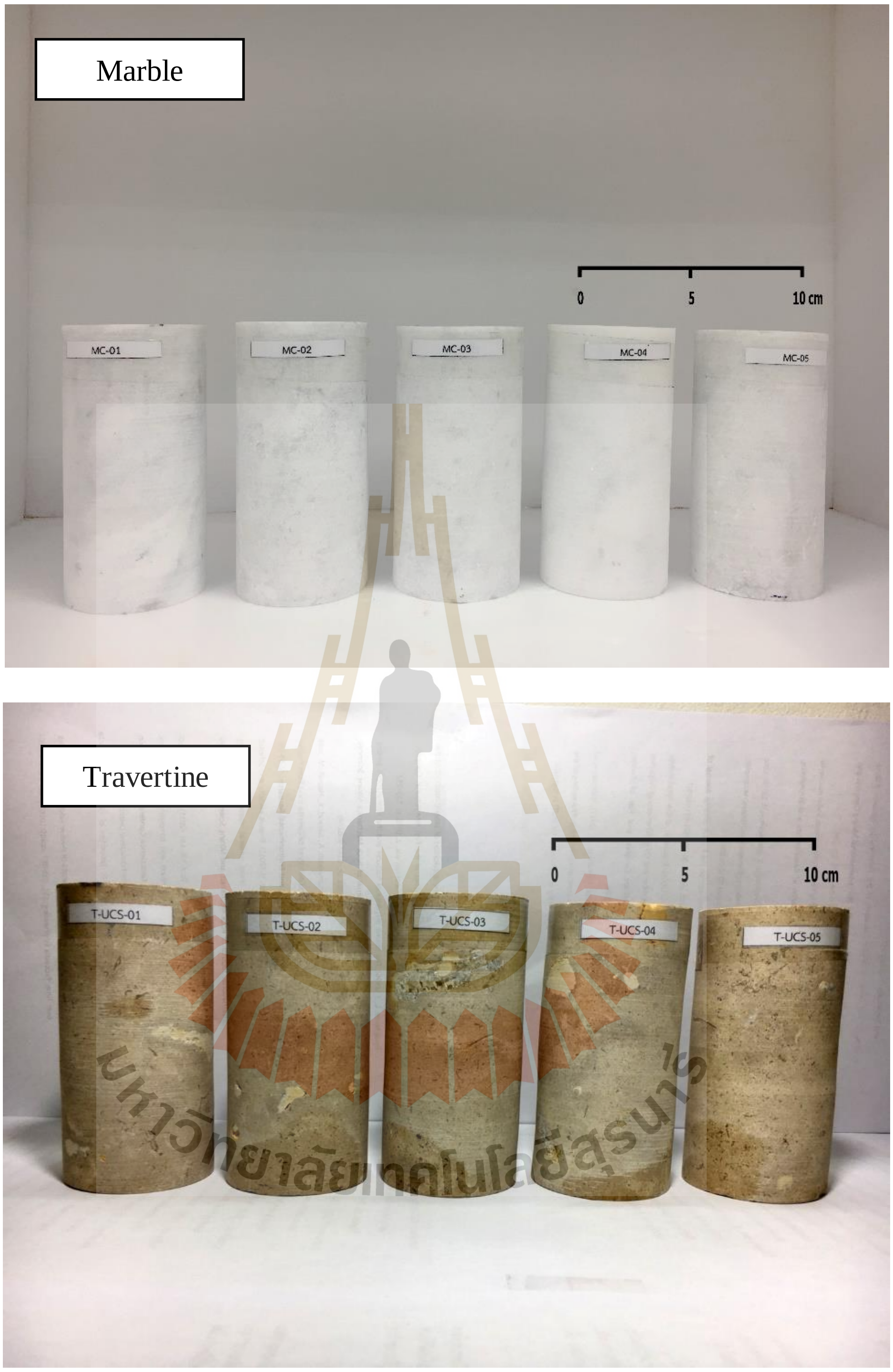


Figure 3.2 Examples of cylindrical specimens prepared for the uniaxial compression test**.**

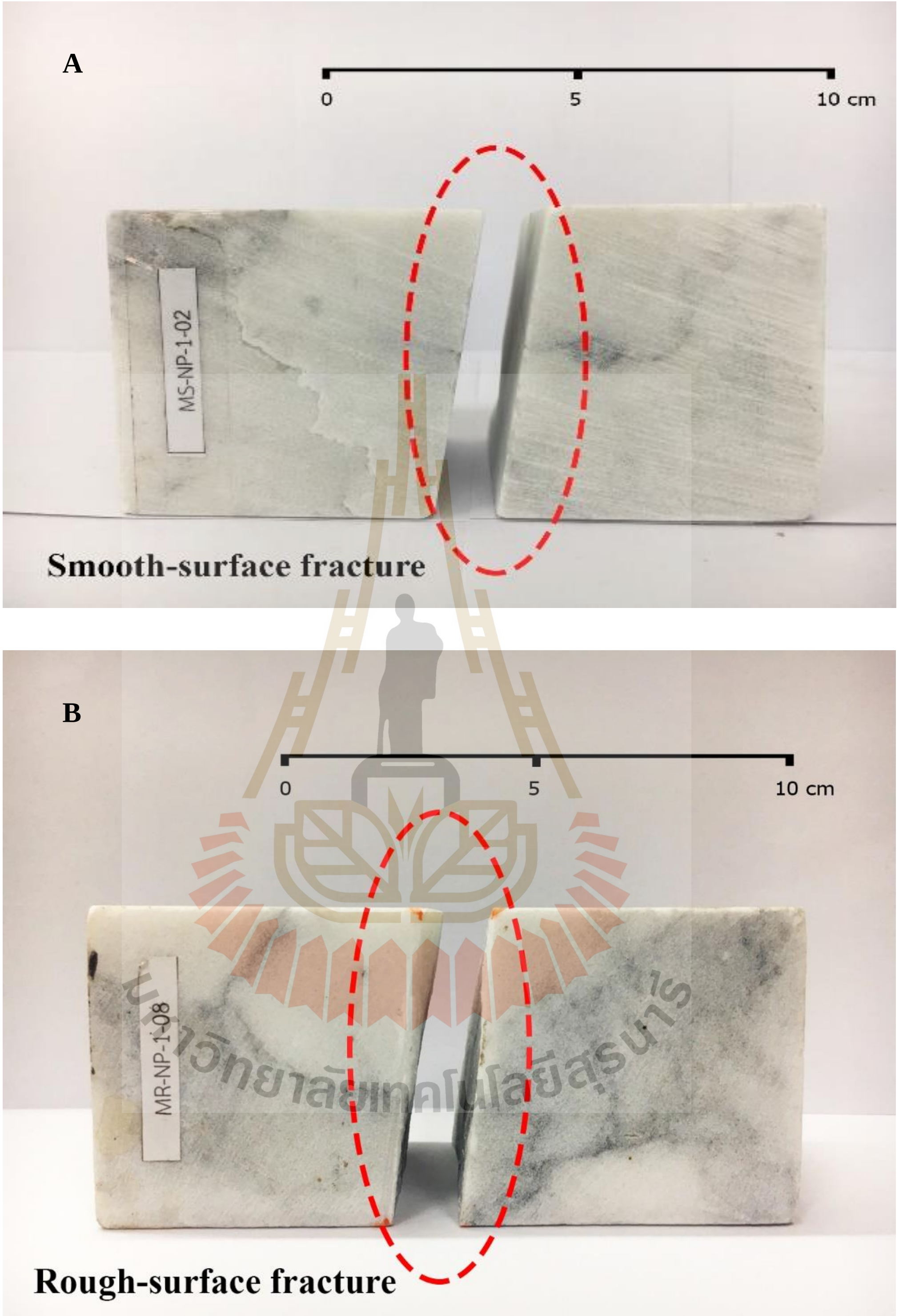


Figure 3.3 The samples different smooth-surface fracture (**A**) and rough-surface fracture (**B**).

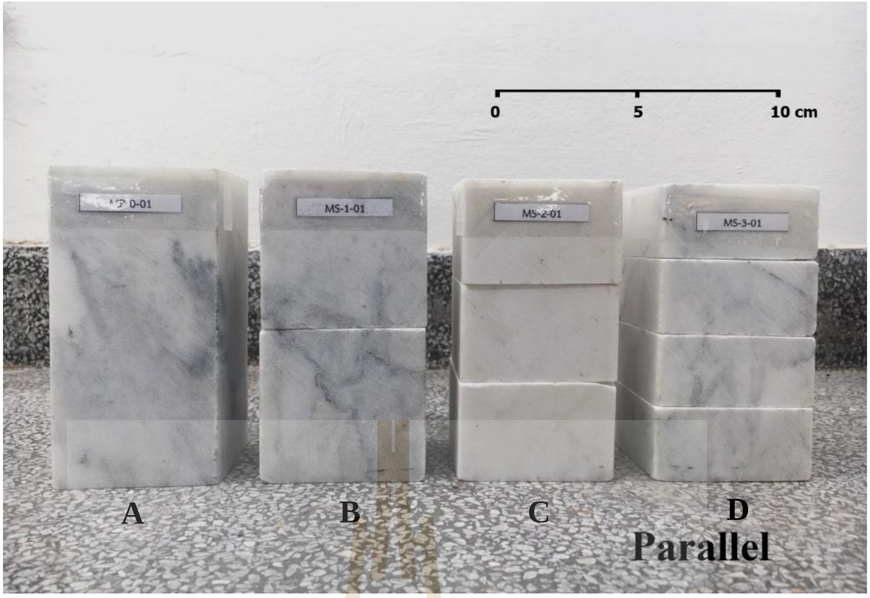


Figure 3.4 The number of fractures that were simulated different and the parallel direction of fracture (A) No fracture, (B) one fracture, (C) two fracture and (D) three fracture.

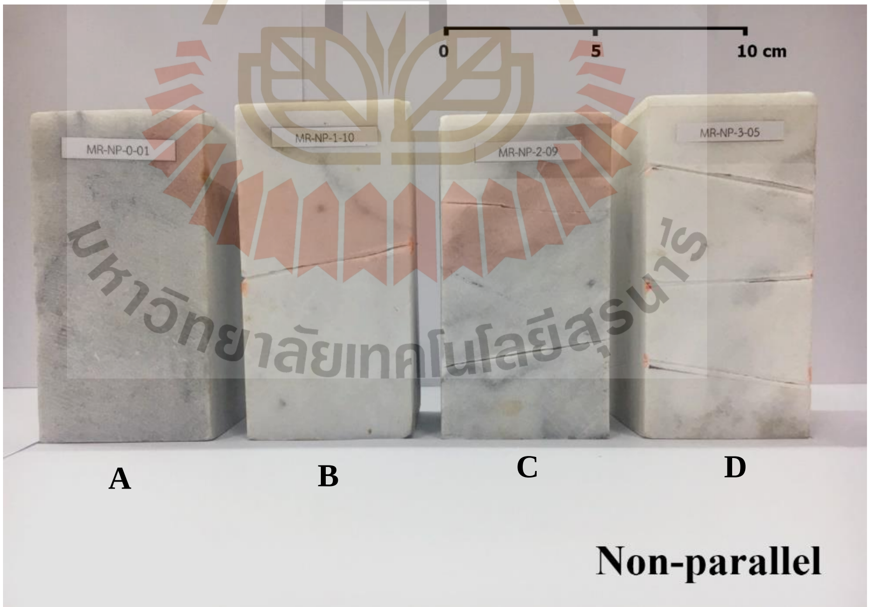


Figure 3.5 The number of fractures that were simulated different and the non-parallel direction of fracture (A) No fracture, (B) one fracture, (C) two fracture and (D) three fracture.

Tables 3.1-3.8 show summary of nominal sizes and density of marble and travertine specimen prepared for each test.

One hundred and sixty marble and travertine specimens prepared for the ultrasonic tests have 60 mm in diameter. The ratio of specimen length to specimen diameter (L/D) is 2.0. Twenty marble and travertine specimens prepared for the effects of sample shape tests have 54 mm in diameter. The ratio of specimen length to specimen diameter (L/D) is 2.0. Ten marble and travertine specimens prepared for the uniaxial compression tests have 54 mm in diameter. The ratio of specimen length to specimen diameter (L/D) is 2.0.

Table 3.1 Dimension and density of smooth-surface fracture and parallel direction of travertine specimen prepared for ultrasonic tests.

Number of specimens	Width (mm)	Length (mm)	Height (mm)	Density (kg/m^3)
TS-P-0-01	59.85	60.65	119.32	2.50
TS-P-0-02	60.48	59.17	120.20	2.54
TS-P-0-03	60.00	60.10	119.70	2.53
TS-P-0-04	60.32	59.68	120.02	2.50
TS-P-0-05	59.95	60.75	120.43	2.50
TS-P-1-01	60.82	59.80	120.57	2.50
TS-P-1-02	60.00	63.13	119.77	2.58
TS-P-1-03	60.38	60.35	120.13	2.55
TS-P-1-04	60.82	59.53	119.70	2.53
TS-P-1-05	60.35	59.17	119.32	2.50
TS-P-2-01	60.37	60.58	120.03	2.52
TS-P-2-02	60.57	59.62	120.07	2.52
TS-P-2-03	60.73	59.67	120.82	2.48
TS-P-2-04	59.98	60.93	120.63	2.54
TS-P-2-05	60.60	60.78	120.22	2.49
TS-P-3-01	60.17	59.23	120.23	2.54
TS-P-3-02	60.77	59.55	120.03	2.52
TS-P-3-03	60.75	60.55	119.82	2.52
TS-P-3-04	60.33	60.88	120.23	2.54
TS-P-3-05	60.42	59.20	119.70	2.51

Table 3.2 Dimension and density of rough-surface fracture and parallel direction of travertine specimen prepared for ultrasonic tests.

Number of specimens	Width (mm)	Length (mm)	Height (mm)	Density (kg/m^3)
TR-P-0-01	60.00	60.88	118.97	2.52
TR-P-0-02	60.87	59.68	120.53	2.56
TR-P-0-03	60.68	59.52	119.82	2.53
TR-P-0-04	60.05	59.63	119.82	2.50
TR-P-0-05	60.18	60.15	119.20	2.53
TR-P-1-01	60.00	60.68	118.98	2.54
TR-P-1-02	60.77	61.98	119.12	2.58
TR-P-1-03	60.47	60.73	118.45	2.45
TR-P-1-04	60.50	59.40	119.62	2.56
TR-P-1-05	59.75	60.53	118.40	2.49
TR-P-2-01	60.50	60.88	118.98	2.51
TR-P-2-02	60.00	60.93	119.20	2.52
TR-P-2-03	60.25	60.65	118.23	2.51
TR-P-2-04	60.18	59.98	119.27	2.52
TR-P-2-05	60.28	60.37	119.63	2.53
TR-P-3-01	60.42	61.35	118.92	2.53
TR-P-3-02	60.48	60.28	119.35	2.56
TR-P-3-03	60.92	59.63	119.47	2.50
TR-P-3-04	60.12	60.38	119.65	2.48
TR-P-3-05	60.72	60.15	119.20	2.54

Table 3.3 Dimension and density of smooth-surface fracture and parallel direction of marble specimen prepared for ultrasonic tests.

Number of specimens	Width (mm)	Length (mm)	Height (mm)	Density (kg/m^3)
MS-P-0-01	61.76	61.97	119.25	2.69
MS-P-0-02	59.39	60.72	120.15	2.68
MS-P-0-03	61.62	62.63	119.57	2.66
MS-P-0-04	60.23	59.89	120.24	2.67
MS-P-0-05	62.33	61.76	119.33	2.64
MS-P-1-01	62.32	60.65	119.56	2.67
MS-P-1-02	60.48	59.23	118.34	2.68
MS-P-1-03	61.85	59.18	120.07	2.65
MS-P-1-04	60.45	60.55	118.17	2.67
MS-P-1-05	61.57	61.53	118.66	2.68
MS-P-2-01	60.85	59.90	119.73	2.66
MS-P-2-02	60.96	61.63	119.62	2.64
MS-P-2-03	60.84	61.39	119.87	2.68
MS-P-2-04	61.74	60.41	120.01	2.67
MS-P-2-05	61.66	61.99	118.68	2.67
MS-P-3-01	61.79	60.35	120.63	2.67
MS-P-3-02	59.12	60.30	119.31	2.66
MS-P-3-03	61.23	59.97	117.66	2.68
MS-P-3-04	61.27	59.37	117.89	2.64
MS-P-3-05	60.40	61.21	120.08	2.67

Table 3.4 Dimension and density of rough-surface fracture and parallel direction of marble specimen prepared for ultrasonic tests.

Number of specimens	Width (mm)	Length (mm)	Height (mm)	Density (kg/m^3)
MR-P-0-01	58.41	60.43	118.41	2.68
MR-P-0-02	60.75	59.89	118.25	2.66
MR-P-0-03	59.80	60.17	117.97	2.68
MR-P-0-04	59.99	59.50	117.23	2.68
MR-P-0-05	58.95	60.88	120.20	2.74
MR-P-1-01	59.40	60.57	119.32	2.71
MR-P-1-02	60.65	60.82	118.47	2.70
MR-P-1-03	60.73	60.50	117.53	2.73
MR-P-1-04	59.70	59.80	118.50	2.72
MR-P-1-05	60.27	60.80	120.33	2.73
MR-P-2-01	61.17	60.53	120.20	2.67
MR-P-2-02	60.90	60.70	118.80	2.66
MR-P-2-03	59.53	61.07	120.57	2.67
MR-P-2-04	59.53	60.67	118.11	2.69
MR-P-2-05	60.60	60.50	117.87	2.66
MR-P-3-01	61.08	61.00	120.30	2.68
MR-P-3-02	58.93	60.63	119.37	2.67
MR-P-3-03	60.79	61.27	119.47	2.67
MR-P-3-04	60.50	59.95	117.83	2.68
MR-P-3-05	60.57	61.37	119.23	2.67

Table 3.5 Dimension and density of smooth-surface fracture and non-parallel direction of marble specimen prepared for ultrasonic tests.

Number of specimens	Width (mm)	Length (mm)	Height (mm)	Density (kg/m^3)
MS-NP-0-01	61.76	61.97	119.25	2.69
MS-NP-0-02	59.39	60.72	120.15	2.68
MS-NP-0-03	61.62	62.63	119.57	2.66
MS-NP-0-04	60.23	59.89	120.24	2.67
MS-NP-0-05	62.33	61.76	119.33	2.64
MS-NP-0-06	58.41	60.43	118.41	2.68
MS-NP-0-07	60.75	59.89	118.25	2.66
MS-NP-0-08	59.80	60.17	117.97	2.68
MS-NP-0-09	59.99	59.50	117.23	2.68
MS-NP-1-10	58.95	60.88	120.20	2.74
MS-NP-1-01	61.89	60.01	119.27	2.71
MS-NP-1-02	61.75	62.22	119.81	2.72
MS-NP-1-03	60.25	60.07	118.86	2.70
MS-NP-1-04	60.66	61.00	120.79	2.68
MS-NP-1-05	61.69	61.39	120.93	2.68
MS-NP-1-06	61.54	61.87	118.82	2.69

Table 3.5 Dimension and density of smooth-surface fracture and non-parallel direction of marble specimen prepared for ultrasonic tests (Continued).

Number of specimens	Width (mm)	Length (mm)	Height (mm)	Density (kg/m^3)
MS-NP-1-07	60.27	60.04	119.17	2.68
MS-NP-1-08	59.37	59.73	118.55	2.71
MS-NP-1-09	60.91	61.40	118.08	2.70
MS-NP-1-10	60.87	60.85	118.27	2.69
MS-NP-2-01	60.83	60.90	120.50	2.71
MS-NP-2-02	60.93	61.06	120.99	2.71
MS-NP-2-03	60.77	59.85	117.42	2.69
MS-NP-2-04	60.36	60.20	120.43	2.71
MS-NP-2-05	59.68	59.68	119.03	2.72
MS-NP-2-06	60.74	59.77	121.66	2.70
MS-NP-2-07	61.77	61.57	118.17	2.70
MS-NP-2-08	61.13	60.84	116.26	2.71
MS-NP-2-09	60.51	61.43	122.45	2.71
MS-NP-2-10	61.37	62.23	116.28	2.72
MS-NP-3-01	61.27	61.79	115.33	2.71
MS-NP-3-02	60.92	60.77	121.78	2.68
MS-NP-3-03	61.39	61.57	120.95	2.68
MS-NP-3-04	60.17	60.72	116.77	2.71
MS-NP-3-05	62.23	63.06	119.27	2.68
MS-NP-3-06	61.49	62.17	120.05	2.69
MS-NP-3-07	61.59	62.32	118.00	2.68
MS-NP-3-08	60.28	60.57	120.27	2.69
MS-NP-3-09	60.27	60.97	117.76	2.69
MS-NP-3-10	60.37	61.63	117.33	2.69

Table 3.6 Dimension and density of rough-surface fracture and non-parallel direction of marble specimen prepared for ultrasonic tests.

Number of specimens	**Width (mm)**	**Length (mm)**	**Height (mm)**	**Density (kg/m^3)**
MR-NP-0-01	61.76	61.97	119.25	2.69
MR-NP-0-02	59.39	60.72	120.15	2.68
MR-NP-0-03	61.62	62.63	119.57	2.66
MR-NP-0-04	60.23	59.89	120.24	2.67
MR-NP-0-05	62.33	61.76	119.33	2.64
MR-NP-0-06	58.41	60.43	118.41	2.68
MR-NP-0-07	60.75	59.89	118.25	2.66
MR-NP-0-08	59.80	60.17	117.97	2.68
MR-NP-0-09	59.99	59.50	117.23	2.68
MR-NP-0-10	58.95	60.88	120.20	2.74
MR-NP-1-01	60.08	60.07	120.21	2.69
MR-NP-1-02	60.35	60.13	117.82	2.68
MR-NP-1-03	60.77	60.43	121.23	2.68
MR-NP-1-04	61.07	61.08	117.13	2.68
MR-NP-1-05	61.07	61.03	117.69	2.69
MR-NP-1-06	61.57	60.89	120.34	2.70
MR-NP-1-07	59.17	59.39	119.15	2.70
MR-NP-1-08	59.41	59.90	118.26	2.68
MR-NP-1-09	62.29	61.87	118.01	2.69
MR-NP-1-10	61.93	61.81	120.67	2.71
MR-NP-2-01	62.10	62.61	120.42	2.69
MR-NP-2-02	61.85	62.56	117.69	2.70
MR-NP-2-03	60.20	60.97	120.06	2.69
MR-NP-2-04	61.27	61.63	121.31	2.68
MR-NP-2-05	60.46	61.47	118.23	2.68

Table 3.6 Dimension and density of rough-surface fracture and non-parallel direction of marble specimen prepared for ultrasonic tests (Continued).

Number of specimens	**Width (mm)**	**Length (mm)**	**Height (mm)**	**Density (kg/m^3)**
MR-NP-2-06	61.53	61.37	117.27	2.70
MR-NP-2-07	56.90	61.53	116.37	2.72
MR-NP-2-08	59.60	59.77	120.80	2.69
MR-NP-2-09	59.90	60.60	116.57	2.70
MR-NP-2-10	61.93	62.13	119.83	2.70
MR-NP-3-01	58.41	60.43	118.41	2.71
MR-NP-3-02	60.75	59.89	118.25	2.70
MR-NP-3-03	59.80	60.17	117.97	2.70
MR-NP-3-04	59.99	59.50	117.23	2.72
MR-NP-3-05	58.95	60.88	120.20	2.71
MR-NP-3-06	61.76	61.97	119.25	2.72
MR-NP-3-07	59.39	60.72	120.15	2.72
MR-NP-3-08	61.62	62.63	119.57	2.70
MR-NP-3-09	60.23	59.89	120.24	2.69
MR-NP-3-10	62.33	61.76	119.33	2.68

Table 3.7 Dimension and density of specimen prepared for shape on wave velocity.

Number of specimens	Width (mm)	Length (mm)	Height (mm)	Density (kg/m^3)
TC-01	54.13	-	108.90	2.52
TC-02	53.83	-	108.87	2.52
TC-03	53.58	-	109.77	2.51
TC-04	53.71	-	108.57	2.51
TC-05	53.83	-	108.43	2.50
TB-01	54.63	52.77	107.73	2.50
TB-02	53.47	53.23	109.23	2.51
TB-03	53.57	53.60	107.33	2.50
TB-04	53.33	53.27	107.77	2.50
TB-05	53.57	54.10	108.83	2.52
MC-01	53.83	-	108.60	2.72
MC-02	53.80	-	109.47	2.73
MC-03	53.87	-	108.27	2.72
MC-04	53.89	-	109.07	2.71
MC-05	53.93	-	108.17	2.71
MB-01	53.87	53.53	110.07	2.70
MB-02	53.03	52.77	109.97	2.73
MB-03	53.80	54.23	108.43	2.73
MB-04	54.00	53.67	108.80	2.72
MB-05	54.57	54.40	107.63	2.70

Table 3.8 Dimension and density of specimen prepared for uniaxial compression tests.

Number of specimens	Width (mm)	Length (mm)	Height (mm)	Density (kg/m^3)
T-UCS-01	54.13	-	108.90	2.52
T-UCS-02	53.83	-	108.87	2.52
T-UCS-03	53.58	-	109.77	2.51
T-UCS-04	53.71	-	108.57	2.51
T-UCS-05	53.83	-	108.43	2.50
M-UCS-01	53.83	-	108.60	2.72
M-UCS-02	53.80	-	109.47	2.73
M-UCS-03	53.87	-	108.27	2.72
M-UCS-04	53.89	-	109.07	2.71
M-UCS-05	53.93	-	108.17	2.71

CHAPTER IV

LABORATORY EXPERIMENT AND RESULTS

4.1 Introduction

The laboratory experiment performed can be divided into two main types: physical tests (density and wave velocity) and mechanical tests (uniaxial compressive strength, elastic modulus and Poison's ratio) determinations. All experiments were conducted under the scope and limitations of the study proposed in the first chapter and sample preparation in the third chapter. This chapter describes the test methods and results.

4.2 Physical property testing

4.2.1 Density measurement

The purpose of this test is to determine the density of each sample. Density is the relationship between the mass and volume of material, thus general relationship is:

$$\rho = \frac{m}{V} \tag{4.1}$$

where ρ is density (kg/m^3)

m is mass (kg)

V is volume (m^3)

The marble and travertine samples were prepared according to the designed experiments. Sizes were measured precisely. The specimen bulk volume (V) is calculated from an average of several caliper readings for each dimension. Each caliper reading should be accurate to 0.02 mm. Then the samples were soaked in water for 48 hours, and dried at 105 ° C for 24 hours, they were removed from the oven and waited to cool down 30 minutes, then weighed. Dry density was calculated from:

$$\rho_d = \frac{m_d}{V} \quad (4.2)$$

where ρ_d is dry density (kg/m^3)

m_d is mass (kg)

V is volume (m^3)

The dry density of marble ranges from 2.64-2.74 kg/m^3, the average is 2.69±0.02 kg/m^3. The dry density of travertine ranges from 2.45-2.58 kg/m^3, the average is 2.52±0.03 kg/m^3. The density of each specimen was identified before conducting the physical and mechanical testing. The dry density value was required as an input data for the ultrasonic velocity measurement of each sample. The densities of the tested rocks range in normal value of carbonate rocks (Manager, 1963; Rafferty, 2012). The dry density test results are shown in Table 4.1.

The standard deviation (SD) the dry density of the marble 0.02 and the standard deviation (SD) of travertine is 0.03. The dry density values of the tested rocks are very similar which is more than 95% of reliability. Hence the density is an important factor controlling velocity of wave moving through the rock mass, this suggest that the tested rocks have similar physical characteristics as basis for wave velocity measurement.

Table 4.1 The test result of dry density.

Number of specimens	Dry density, ρ_d (kg/m^3)	Number of specimens	Dry density, ρ_d (kg/m^3)
TS-P-0-01	2.50	MS-P-0-01	2.69
TS-P-0-02	2.54	MS-P-0-02	2.68
TS-P-0-03	2.53	MS-P-0-03	2.66
TS-P-0-04	2.50	MS-P-0-04	2.67
TS-P-0-05	2.50	MS-P-0-05	2.64
TS-P-1-01	2.50	MS-P-1-01	2.67
TS-P-1-02	2.58	MS-P-1-02	2.68
TS-P-1-03	2.55	MS-P-1-03	2.65
TS-P-1-04	2.53	MS-P-1-04	2.67
TS-P-1-05	2.50	MS-P-1-05	2.68
TS-P-2-01	2.52	MS-P-2-01	2.66
TS-P-2-02	2.52	MS-P-2-02	2.64
TS-P-2-03	2.48	MS-P-2-03	2.68
TS-P-2-04	2.54	MS-P-2-04	2.67
TS-P-2-05	2.49	MS-P-2-05	2.67
TS-P-3-01	2.54	MS-P-3-01	2.67
TS-P-3-02	2.52	MS-P-3-02	2.66
TS-P-3-03	2.52	MS-P-3-03	2.68
TS-P-3-04	2.54	MS-P-3-04	2.64
TS-P-3-05	2.51	MS-P-3-05	2.67
TR-P-0-01	2.52	MR-P-0-01	2.68
TR-P-0-02	2.56	MR-P-0-02	2.66
TR-P-0-03	2.53	MR-P-0-03	2.68
TR-P-0-04	2.50	MR-P-0-04	2.68
TR-P-0-05	2.53	MR-P-0-05	2.74
TR-P-1-01	2.54	MR-P-1-01	2.71
TR-P-1-02	2.58	MR-P-1-02	2.70
TR-P-1-03	2.45	MR-P-1-03	2.73
TR-P-1-04	2.56	MR-P-1-04	2.72
TR-P-1-05	2.49	MR-P-1-05	2.73
TR-P-2-01	2.51	MR-P-2-01	2.67
TR-P-2-02	2.52	MR-P-2-02	2.66
TR-P-2-03	2.51	MR-P-2-03	2.67
TR-P-2-04	2.52	MR-P-2-04	2.69
TR-P-2-05	2.53	MR-P-2-05	2.66
TR-P-3-01	2.53	MR-P-3-01	2.68
TR-P-3-02	2.56	MR-P-3-02	2.67
TR-P-3-03	2.50	MR-P-3-03	2.67
TR-P-3-04	2.48	MR-P-3-04	2.68
TR-P-3-05	2.54	MR-P-3-05	2.67

Table 4.1 The test result of dry density (Continued).

Number of specimens	Dry density, ρ_d (kg/m^3)	Number of specimens	Dry density, ρ_d (kg/m^3)
MS-NP-0-01	2.69	MR-NP-0-01	2.69
MS-NP-0-02	2.68	MR-NP-0-02	2.68
MS-NP-0-03	2.66	MR-NP-0-03	2.66
MS-NP-0-04	2.67	MR-NP-0-04	2.67
MS-NP-0-05	2.64	MR-NP-0-05	2.64
MS-NP-0-06	2.68	MR-NP-0-06	2.68
MS-NP-0-07	2.66	MR-NP-0-07	2.66
MS-NP-0-08	2.68	MR-NP-0-08	2.68
MS-NP-0-09	2.68	MR-NP-0-09	2.68
MS-NP-1-10	2.74	MR-NP-0-10	2.74
MS-NP-1-01	2.71	MR-NP-1-01	2.69
MS-NP-1-02	2.72	MR-NP-1-02	2.68
MS-NP-1-03	2.70	MR-NP-1-03	2.68
MS-NP-1-04	2.68	MR-NP-1-04	2.68
MS-NP-1-05	2.68	MR-NP-1-05	2.69
MS-NP-1-06	2.69	MR-NP-1-06	2.70
MS-NP-1-07	2.68	MR-NP-1-07	2.70
MS-NP-1-08	2.71	MR-NP-1-08	2.68
MS-NP-1-09	2.70	MR-NP-1-09	2.69
MS-NP-1-10	2.69	MR-NP-1-10	2.71
MS-NP-2-01	2.71	MR-NP-2-01	2.69
MS-NP-2-02	2.71	MR-NP-2-02	2.70
MS-NP-2-03	2.69	MR-NP-2-03	2.69
MS-NP-2-04	2.71	MR-NP-2-04	2.68
MS-NP-2-05	2.72	MR-NP-2-05	2.68
MS-NP-2-06	2.70	MR-NP-2-06	2.70
MS-NP-2-07	2.70	MR-NP-2-07	2.72
MS-NP-2-08	2.71	MR-NP-2-08	2.69
MS-NP-2-09	2.71	MR-NP-2-09	2.70
MS-NP-2-10	2.72	MR-NP-2-10	2.70
MS-NP-3-01	2.71	MR-NP-3-01	2.71
MS-NP-3-02	2.68	MR-NP-3-02	2.70
MS-NP-3-03	2.68	MR-NP-3-03	2.70
MS-NP-3-04	2.71	MR-NP-3-04	2.72
MS-NP-3-05	2.68	MR-NP-3-05	2.71
MS-NP-3-06	2.69	MR-NP-3-06	2.72
MS-NP-3-07	2.68	MR-NP-3-07	2.72
MS-NP-3-08	2.69	MR-NP-3-08	2.70
MS-NP-3-09	2.69	MR-NP-3-09	2.69
MS-NP-3-10	2.69	MR-NP-3-10	2.68

4.2.2 Wave velocity measurement

The purpose of this test is to obtain the wave velocity (P- and S-wave) moving through the samples in different cases such as shapes, different fracture roughness and different number of fracture. OYO Sonic viewer 170 (Model 5338) was used. The application was carried out in accordance with ASTM D2845-00 test designation. Direct method was used in this study (Figure. 4.1). The end surfaces of each sample were polished to provide a good coupling between the transducer face and the sample surface to maximize accuracy of the transit time measurement. Stiffer grease was used as a coupling agent in this study. The sample heights are approximately the same for each rock group in order to minimize the time differences. Transmitter and receiver were held tightly at the end surfaces and then pulse transmitting time was measured. Wave velocity through the specimen was calculated from one end to another. Wave velocity testing is divided into 5 subtests.

1) Testing effect of shape on wave velocity

2) Testing effect of parallel and smooth-surface fracture on wave velocity

3) Testing effect of parallel and rough-surface fracture on wave velocity

4) Testing effect of non-parallel and smooth-surface fracture on wave velocity

5) Testing effect of non-parallel and rough-surface fracture on wave velocity

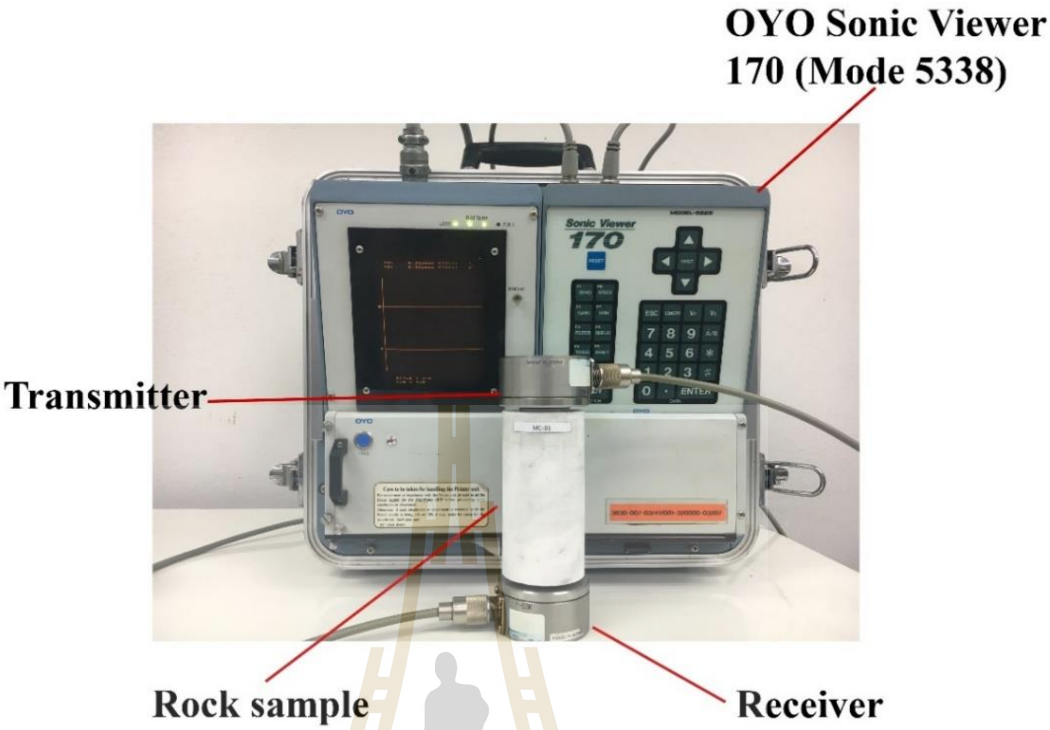


Figure 4.1 Direct method of wave velocity measurement (specimen no. MC-01).

1) Testing effect of shape on wave velocity

The purpose of this test is to study the effect of shapes on wave motion. Samples were prepared to have the cylindrical and the block shapes. Total 20 samples were tested including the sample numbers TC-01 to TC-05 (cylindrical travertine), numbers TB-01 to TB-05 (block travertine), numbers MC-01 to MC-05 (cylindrical marble), numbers MB-01 to MB-05 (block marble).

Twenty data obtained from laboratory tests and were analyzed in order to correlate wave velocity with different shape (Tables 4.2-4.3).

The P-wave velocity of cylindrical marble ranges from 4.92 to 5.47 km/sec, the average is 5.18 km/sec and S-wave velocity ranges from 2.89 to 3.20 km/sec, the average is 3.03 km/sec. The P-wave velocity of block marble ranges from 5.03 to 5.44 km/sec, the average is 5.24 km/sec and S-wave velocity ranges from 3.09 to 3.48 km/sec, the average is 3.27 km/sec.

The P-wave velocity of cylindrical travertine ranges from 4.82 to 4.95 km/sec, the average is 4.89 km/sec and S-wave velocity ranges from 2.79 to 2.88 km/sec, the average is 2.85 km/sec. The P-wave velocity of block travertine ranges from 4.79 to 4.88 km/sec, the average is 4.83 km/sec and S-wave velocity ranges from 2.80 to 3.05 km/sec, the average is 2.91 km/sec. Block samples caused little

The differences of the wave velocities measured from cylindrical and block shapes are of small values. Block samples caused little higher or little lower velocities than those of the standard cylindrical samples (see tables 4.2 and 4.3). For marble, percentage of difference of the P-wave and S-wave velocities between different shape range from 0.54-4.03 and 5.16-9.37, respectively. These values are equivalent to more than 95% and 90% of reliability. For travertine, percentage of difference of the P-wave and S-wave velocities between different shape range from 0.20-2.24 and 0.35-6.29, respectively. These values are equivalent to more than 95% and 90% of reliability. The results suggest that cylindrical shape nor block shape of the tested specimens do not affect the wave velocity. Differences of the measured wave velocity might be due to the difference of the density within the specimen groups. Thus, the block specimens can be used in this study.

Table 4.2 The results tested of the relationship between P-wave velocity and shape.

Number of specimens	$V_{p(cylindrical)}$ (km/sec)	Number of specimens	$V_{p(block)}$ (km/sec)	Percentage of differences
TC-01	4.95	TB-01	4.85	2.02
TC-02	4.82	TB-02	4.83	0.20
TC-03	4.90	TB-03	4.79	2.24
TC-04	4.85	TB-04	4.80	1.03
TC-05	4.93	TB-05	4.88	1.01
MC-01	5.22	MB-01	5.10	2.29
MC-02	5.47	MB-02	5.44	0.54
MC-03	5.21	MB-03	5.42	4.03
MC-04	5.10	MB-04	5.23	2.54
MC-05	4.92	MB-05	5.03	2.23

Table 4.3 The results tested of the relationship between S-wave velocity and shape.

Number of specimens	$V_{s(cylindrical)}$ (km/sec)	Number of specimens	$V_{s(block)}$ (km/sec)	Percentage of differences
TC-01	2.87	TB-01	2.85	0.69
TC-02	2.84	TB-02	2.83	0.35
TC-03	2.79	TB-03	2.80	0.35
TC-04	2.86	TB-04	3.04	6.29
TC-05	2.88	TB-05	3.05	5.90
MC-01	3.10	MB-01	3.26	5.16
MC-02	3.20	MB-02	3.48	8.75
MC-03	3.01	MB-03	3.31	9.37
MC-04	2.95	MB-04	3.20	8.47
MC-05	2.89	MB-05	3.09	6.90

2) Testing effect of parallel and smooth-surface fracture on wave velocity

The purpose of this test is to study the effect of parallel and smooth-surface fracture on wave velocity. The block samples were prepared and fractures were created (see Chapter III). Space between fractures were equal and all fractures were parallel. Number of the fractures were varied from 0 1 2 and 3. The fracture surfaces were polished to have smooth surfaces. The tested specimens were divided by the number of fractures into four groups (0, 1, 2, 3 fractures). Five specimens were prepared for each group. Totally, 40 specimens were prepared and tested (20 for marble, 20 for travertine). P-wave and S-wave were transmitted from one end to another end of each specimen (Figure 4.2).

Forty data obtained from laboratory tests were analyzed in order to understand the effect of the parallel and smooth-surface fracture on wave velocity (Tables 4.4-4.5).

The P-wave velocity of the travertine with the smooth-surface fracture and the direction of the fracture are parallel ranges from 2.42 to 4.36 km/sec, the average is 3.78 km/sec and S-wave velocity ranges from 1.47 to 3.00 km/sec, the average is 2.37 km/sec.

The P-wave velocity of the marble with smooth-surface fracture and the direction of the fracture are parallel ranges from 2.81 to 6.70 km/sec, the average is 4.96 km/sec and S-wave velocity ranges from 1.84 to 3.53 km/sec, the average is 2.73 km/sec.

The results shows relationships between the number of fractures and reduction rates of V_p and V_s (Tables 4.6-4.7) indicating that P-wave and S-wave velocities were attenuated rapidly as the number of fracture increased show in Table 4.6-4.7.

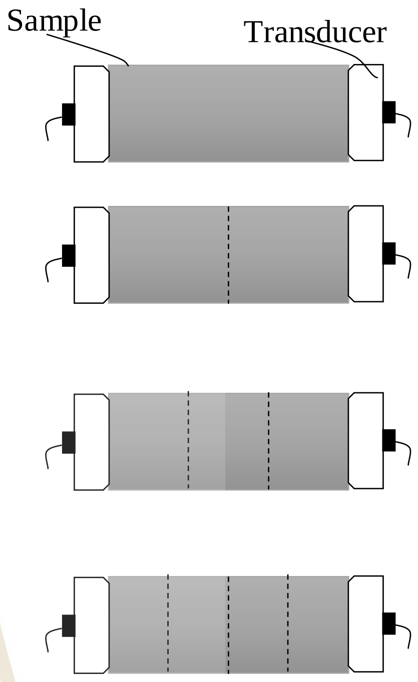
Number of fractures	Model
0 (No fracture)	
1	
2	
3	

Figure 4.2 Schematic design of wave velocity measurement in specimens with parallel fractures.

Table 4.4 Wave velocity of the tested travertine specimens with parallel and smooth-surface fractures.

Number of fractures	Number of specimen	Smooth-surface fracture	
		P-wave velocity, V_p (km/sec)	S-wave velocity, V_s (km/sec)
0	TS-P-0-01	4.32	2.79
	TS-P-0-02	4.36	3.00
	TS-P-0-03	4.31	2.80
	TS-P-0-04	4.26	2.73
	TS-P-0-05	4.21	2.74
	Average	4.29±0.05	2.81±0.10
1	TS-P-1-01	4.01	2.56
	TS-P-1-02	4.27	2.64
	TS-P-1-03	4.26	2.77
	TS-P-1-04	4.16	2.56
	S-P-1-05	4.11	2.40
	Average	4.16±0.10	2.59±0.12
2	TS-P-2-01	4.06	2.52
	TS-P-2-02	3.57	2.21
	TS-P-2-03	3.87	2.39
	TS-P-2-04	4.10	2.51
	TS-P-2-05	4.03	2.46
	Average	3.93±0.19	2.42±0.11
3	TS-P-3-01	2.99	1.80
	TS-P-3-02	2.86	1.75
	TS-P-3-03	2.67	1.64
	TS-P-3-04	2.42	1.47
	TS-P-3-05	2.82	1.71
	Average	2.75±0.19	1.67±0.11

Table 4.5 Wave velocity of the tested marble specimens with parallel and smooth-surface fractures.

Number of fractures	Number of specimen	Smooth-surface fracture	
		P-wave velocity, V_p (km/sec)	S-wave velocity, V_s (km/sec)
0	MS-P-0-01	6.70	3.53
	MS-P-0-02	6.01	3.25
	MS-P-0-03	6.50	3.46
	MS-P-0-04	5.27	3.04
	MS-P-0-05	6.42	3.41
	Average	6.18±0.51	3.34±0.18
1	MS-P-1-01	5.64	3.10
	MS-P-1-02	5.66	3.21
	MS-P-1-03	5.56	2.97
	MS-P-1-04	5.09	2.51
	MS-P-1-05	5.70	3.03
	Average	5.53±0.22	2.96±0.24
2	MS-P-2-01	5.07	2.82
	MS-P-2-02	4.15	2.01
	MS-P-2-03	4.47	2.25
	MS-P-2-04	4.62	2.56
	MS-P-2-05	4.86	2.67
	Average	4.63±0.32	2.46±0.29
3	MS-P-3-01	3.77	2.36
	MS-P-3-02	3.55	2.13
	MS-P-3-03	3.68	2.23
	MS-P-3-04	2.81	1.84
	MS-P-3-05	3.75	2.31
	Average	3.51±0.36	2.17±0.18

Table 4.6 Rate of reduction of P-wave velocity in specimens with parallel and smooth-surface fractures.

Rock type	Number of fractures	P-wave velocity, V_p (km/sec)	Rate of reduction in V_p with an increase in number of fractures (%)
Travertine	0	4.29	100
	1	4.16	97
	2	3.93	92
	3	2.75	64
Marble	0	6.18	100
	1	5.53	89
	2	4.63	75
	3	3.51	57

Table 4.7 Rate of reduction of S-wave velocity in specimens with parallel and smooth-surface fractures.

Rock type	Number of fractures	S-wave velocity, V_s (km/sec)	Rate of reduction in V_s with an increase in number of fractures (%)
Travertine	0	2.81	100
	1	2.59	92
	2	2.42	86
	3	1.67	59
Marble	0	3.34	100
	1	2.96	89
	2	2.46	74
	3	2.17	65

3) Testing effect of parallel and rough-surface fracture on wave velocity

The purpose of this test is to study the effect of the parallel direction and rough-surface fracture on wave velocity. Prepare a block size 60x60x120 mm^3. The rough-surface fracture which is created by pressing the tensile fracture along the lines (Tension-induced fracture). Create a number of fractures in the sample are 4 group varied from 0 1 2 and 3 as shown in Figure 4.2. The test specimens are classified into rock types. The number of fractures (0) 5 sample. The number of fractures (1) 5 sample. The number of fractures (2) 5 sample. The number of fractures (3) 5 sample. All sample for test 40 samples.

40 data obtained from laboratory tests and were analyzed in order to correlate wave velocity with the rough-surface fracture and parallel direction show in Table 4.8-4.9.

The P-wave velocity of the marble with the rough-surface fracture and the direction of the fracture are parallel ranges from 3.73 to 6.88 km/sec, the average is 5.15 km/sec and S-wave velocity ranges from 2.29 to 3.53 km/sec, the average is 2.83 km/sec.

The P-wave velocity of the travertine with the rough-surface fracture and the direction of the fracture are parallel ranges from 2.27 to 4.64 km/sec, the average is 3.95 km/sec and S-wave velocity ranges from 1.36 to 3.03 km/sec, the average is 2.45 km/sec.

Furthermore, the result shows that the number of fractures and the reduction rates in Vp and Vs (%) indicating that P-wave and S-wave velocities are attenuated rapidly as the number of fracture increases show in Table 4.10-4.11.

Table 4.8 The results tested physical properties of rough-surface fracture and parallel direction of travertine.

Number of fractures	Number of specimen	Rough-surface fracture	
		P-wave velocity, V_p (km/sec)	S-wave velocity, V_s (km/sec)
0	TR-P-0-01	4.17	2.66
	TR-P-0-02	4.64	3.03
	TR-P-0-03	4.56	2.72
	TR-P-0-04	4.15	2.64
	TR-P-0-05	4.29	2.79
	Average	4.36±0.20	2.77±0.14
1	TR-P-1-01	4.19	2.75
	TR-P-1-02	4.38	3.00
	TR-P-1-03	3.70	2.18
	TR-P-1-04	4.40	2.80
	TR-P-1-05	4.35	2.39
	Average	4.20±0.26	2.62±0.30
2	TR-P-2-01	4.35	2.76
	TR-P-2-02	4.14	2.46
	TR-P-2-03	3.69	2.20
	TR-P-2-04	4.38	2.55
	TR-P-2-05	4.15	2.67
	Average	4.14±0.25	2.53±0.19
3	TR-P-3-01	2.75	1.77
	TR-P-3-02	3.93	2.13
	TR-P-3-03	2.77	1.78
	TR-P-3-04	2.27	1.36
	TR-P-3-05	3.72	2.40
	Average	3.09±0.63	1.89±0.35

Table 4.9 The results tested physical properties of rough-surface fracture and parallel direction of marble.

Number of fractures	Number of specimen	Rough-surface fracture	
		P-wave velocity, V_p (km/sec)	**S-wave velocity, V_s (km/sec)**
0	MR-P-0-01	6.23	3.50
	MR-P-0-02	5.47	3.41
	MR-P-0-03	6.00	3.10
	MR-P-0-04	6.04	3.39
	MR-P-0-05	6.88	3.53
	Average	6.12±0.45	3.39±0.15
1	MR-P-1-01	6.09	3.27
	MR-P-1-02	5.48	2.77
	MR-P-1-03	5.88	3.10
	MR-P-1-04	5.70	2.85
	MR-P-1-05	5.78	3.03
	Average	5.79±0.20	3.00±0.18
2	MR-P-2-01	5.01	2.59
	MR-P-2-02	4.95	2.47
	MR-P-2-03	4.71	2.40
	MR-P-2-04	5.27	2.91
	MR-P-2-05	4.68	2.38
	Average	4.92±0.22	2.55±0.19
3	MR-P-3-01	3.89	2.51
	MR-P-3-02	3.73	2.30
	MR-P-3-03	3.73	2.30
	MR-P-3-04	3.80	2.45
	MR-P-3-05	3.73	2.29
	Average	3.78±0.06	2.37±0.09

Table 4.10 Rate of reduction with P-wave velocity for parallel direction and rough-surface fracture.

Rock type	**Number of fractures**	**P-wave velocity, V_p (km/sec)**	**Rate of reduction in V_p with an increase in number of fractures (%)**
Travertine	0	4.36	100
	1	4.20	96
	2	4.14	95
	3	3.09	71
Marble	0	6.12	100
	1	5.79	95
	2	4.92	80
	3	3.78	62

Table 4.11 Rate of reduction with S-wave velocity for parallel direction and rough-surface fracture.

Rock type	**Number of fractures**	**S-wave velocity, V_s (km/sec)**	**Rate of reduction in V_s with an increase in number of fractures (%)**
Travertine	0	2.77	100
	1	2.62	95
	2	2.53	91
	3	1.89	68
Marble	0	3.39	100
	1	3.00	88
	2	2.55	75
	3	2.37	70

4) Testing effect of non-parallel and smooth-surface fracture on wave velocity

The purpose of this test is to study the effect of non-parallel and smooth-surface fracture on wave velocity. The block samples were prepared and fractures were created (see Chapter III). However, there were some difficulties in the preparation of rough-surface samples especially for travertine. The travertine samples usually had spots of carbonate mud which were loosely and caused the rock to break in unexpected direction. Thus, only marble specimens were decided for the non-parallel fracture tests (4 and 5). The non-parallel fractures were artificially created in the specimens with equal space between them. Number of the fractures were varied from 0 1 2 and 3. The fracture surfaces were polished to have smooth surfaces. The tested specimens were divided by the number of fractures into four groups (0, 1, 2, 3 fractures). Ten specimens were prepared for each group. Totally, 40 specimens were prepared and tested. P-wave and S-wave were transmitted from one end to another end of each specimen (Figure 4.3).

Data obtained from laboratory tests were analyzed in order understand the effect of the non-parallel and smooth-surface fracture on wave velocity (Table 4.12).

The P-wave velocity of the tested marble specimens with smooth-surface fractures and the direction of the fracture were non-parallel ranges from 3.39 to 6.88 km/sec, the average is 4.77 km/sec and S-wave velocity ranges from 1.95 to 3.53 km/sec, the average is 2.64 km/sec.

The results shows that reduction rate of P-wave and S-wave velocities increases with increasing number of fractures (Table 4.13-4.14).

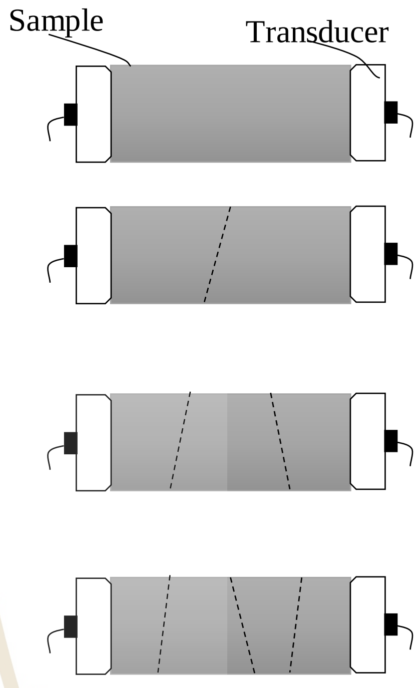
Number of fractures	Model
0 (No fracture)	
1	
2	
3	

Figure 4.3 Schematic design of wave velocity measurement in specimens with non-parallel fractures.

Table 4.12 Wave velocity of the tested marble specimens with non-parallel and smooth-surface fractures.

Number of fractures	**Number of specimen**	**Smooth-surface fracture**	
		P-wave velocity, V_p (km/sec)	**S-wave velocity, V_s (km/sec)**
0	MS-NP-0-01	6.70	3.53
	MS-NP-0-02	6.01	3.25
	MS-NP-0-03	6.50	3.46
	MS-NP-0-04	5.27	3.04
	MS-NP-0-05	6.42	3.41
	MS-NP-0-06	6.23	3.50
	MS-NP-0-07	5.47	3.41
	MS-NP-0-08	6.00	3.10
	MS-NP-0-09	6.04	3.39
	MS-NP-0-10	6.88	3.53
	Average	6.15±0.48	3.36±0.17
1	MS-NP-1-01	5.25	2.98
	MS-NP-1-02	5.24	2.96
	MS-NP-1-03	5.23	2.88
	MS-NP-1-04	5.25	2.98
	MS-NP-1-05	5.25	2.78
	MS-NP-1-06	5.24	2.85
	MS-NP-1-07	5.25	2.96
	MS-NP-1-08	5.25	2.74
	MS-NP-1-09	5.27	2.79
	MS-NP-1-10	5.26	2.85
	Average	5.25±0.01	2.88±0.08
2	MS-NP-2-01	4.22	2.31
	MS-NP-2-02	4.24	2.29
	MS-NP-2-03	4.25	2.35
	MS-NP-2-04	4.25	2.33
	MS-NP-2-05	4.23	2.29
	MS-NP-2-06	4.20	2.30
	MS-NP-2-07	4.29	2.25
	MS-NP-2-08	4.21	2.32
	MS-NP-2-09	4.26	2.22
	MS-NP-2-10	4.27	2.34
	Average	4.24±0.03	2.30±0.04
3	MS-NP-3-01	3.42	2.07
	MS-NP-3-02	3.42	2.01
	MS-NP-3-03	3.39	2.13
	MS-NP-3-04	3.40	2.14
	MS-NP-3-05	3.44	2.00
	MS-NP-3-06	3.43	1.95

Table 4.12 Wave velocity of the tested marble specimens with non-parallel and smooth-surface fractures (Continued).

Number of fractures	Number of specimen	Smooth-surface fracture	
		P-wave velocity, V_P (km/sec)	S-wave velocity, V_s (km/sec)
3	MS-NP-3-07	3.41	2.00
	MS-NP-3-08	3.44	1.99
	MS-NP-3-09	3.42	1.98
	MS-NP-3-10	3.44	2.03
	Average	3.42±0.02	2.03±0.06

Table 4.13 Rate of reduction of P-wave velocity in specimens with non-parallel and smooth-surface fractures.

Rock type	Number of fractures	P-wave velocity, V_P (km/sec)	Rate of reduction in V_P with an increase in number of fractures (%)
Marble	0	6.15	100
	1	5.25	85
	2	4.24	69
	3	3.42	56

Table 4.14 Rate of reduction of S-wave velocity in specimens with non-parallel and rough-surface fractures.

Rock type	Number of fractures	S-wave velocity, V_s (km/sec)	Rate of reduction in V_s with an increase in number of fractures (%)
Marble	0	3.36	100
	1	2.88	86
	2	2.30	69
	3	2.03	60

5**) Testing effect of non-parallel and rough-surface fracture on wave velocity**

The purpose of this test is to study the effect of non-parallel and rough-surface fracture on wave velocity. The block marble specimens were prepared and the non-parallel fractures were artificially created with equal space between them. Number of the fractures were varied from 0 1 2 and 3. The fracture surfaces were natural and not polished. The tested specimens were divided by the number of fractures into four groups (0, 1, 2, 3 fractures). Ten specimens were prepared for each group. Totally, 40 specimens were prepared and tested. P-wave and S-wave were transmitted from one end to another end of each specimen (see Figure 4.3).

Data obtained from laboratory tests were analyzed in order understand the effect of the non-parallel and rough-surface fracture on wave velocity (Table 4.15).

The P-wave velocity of the tested marble specimens with rough-surface fractures and the direction of the fracture was non-parallel ranges from 3.39 to 6.88 km/sec, the average is 4.96 km/sec and S-wave velocity ranges from 2.22 to 3.53 km/sec, the average is 2.75 km/sec.

The results show that reduction rate of P-wave and S-wave velocities increases with increasing number of fractures (Tables 4.16-4.17).

Table 4.15 Wave velocity of the tested marble specimens with non-parallel and rough-surface fractures.

Number of fractures	Number of specimen	Rough-surface fracture	
		P-wave velocity, V_p (km/sec)	S-wave velocity, V_s (km/sec)
.0	MR-NP-0-01	6.70	3.53
	MR-NP-0-02	6.01	3.25
	MR-NP-0-03	6.50	3.46
	MR-NP-0-04	5.27	3.04
	MR-NP-0-05	6.42	3.41
	MR-NP-0-06	6.23	3.50
	MR-NP-0-07	5.47	3.41
	MR-NP-0-08	6.00	3.10
	MR-NP-0-09	6.04	3.39
	MR-NP-0-10	6.88	3.53
	Average	6.15±0.48	3.36±0.17
1	MR-NP-1-01	5.56	2.94
	MR-NP-1-02	5.55	2.94
	MR-NP-1-03	5.54	2.92
	MR-NP-1-04	5.55	2.95
	MR-NP-1-05	5.56	2.91
	MR-NP-1-06	5.55	2.92
	MR-NP-1-07	5.56	2.94
	MR-NP-1-08	5.56	2.90
	MR-NP-1-09	5.56	2.91
	MR-NP-1-10	5.56	2.93
	Average	5.55±0.01	2.92±0.02
2	MR-NP-2-01	4.55	2.49
	MR-NP-2-02	4.56	2.48
	MR-NP-2-03	4.58	2.50
	MR-NP-2-04	4.57	2.49
	MR-NP-2-05	4.56	2.48
	MR-NP-2-06	4.55	2.48
	MR-NP-2-07	4.59	2.46
	MR-NP-2-08	4.56	2.47
	MR-NP-2-09	4.57	2.44
	MR-NP-2-10	4.58	2.49
	Average	4.57±0.01	2.48±0.02
3	MR-NP-3-01	3.55	2.26
	MR-NP-3-02	3.56	2.25
	MR-NP-3-03	3.54	2.26
	MR-NP-3-04	3.54	2.27
	MR-NP-3-05	3.57	2.25
	MR-NP-3-06	3.56	2.22

Table 4.15 Wave velocity of the tested marble specimens with non-parallel and rough-surface fractures (Continued).

Number of fractures	Number of specimen	Rough-surface fracture	
		P-wave velocity, V_p (km/sec)	**S-wave velocity, V_s (km/sec)**
3	MR-NP-3-07	3.55	2.24
	MR-NP-3-08	3.56	2.24
	MR-NP-3-09	3.55	2.23
	MR-NP-3-10	3.56	2.25
	Average	3.55±0.01	2.25±0.01

Table 4.16 Rate of reduction of P-wave velocity in specimens with non-parallel and rough-surface fractures.

Rock type	Number of fractures	P-wave velocity, V_p (km/sec)	Rate of reduction in V_p with an increase in number of fractures (%)
Marble	0	6.15	100
	1	5.55	90
	2	4.57	74
	3	3.55	58

Table 4.17 Rate of reduction of S-wave velocity in specimens with non-parallel and rough-surface fractures.

Rock type	Number of fractures	S-wave velocity, V_s (km/sec)	Rate of reduction in V_s with an increase in number of fractures (%)
Marble	0	3.36	100
	1	2.92	87
	2	2.48	74
	3	2.25	67

4.3 Mechanical property testing

The purpose of this test is to find out the basic mechanical properties of the tested marble and travertine. The uniaxial compression test was carried out to determine uniaxial compressive strength (UCS), Elastic modulus (E) and Poisson's ratio (ν). Five specimens of the marble and travertine were tested. Prior to the uniaxial compression test, the tested specimens had been measured for their sizes, density and wave velocity. The procedure was conducted following the American Society for Testing and Materials standard (ASTM D7012) and International Society of Rock Mechanics suggested (ISRM, 1981). The compression load frame was used (Figure.4.4). Each specimen was axially loaded with a loading rate of 0.5 MPa/sec until failure, then the UCS was calculated by dividing the maximum load by the original cross sectional area following this equation:

$$\sigma_c = \frac{P}{A} \tag{4.3}$$

where σ_c is the uniaxial compressive strength (MPa).

P is the failure load (N/m^2).

A is the initial cross-sectional area (m^2).

The elastic modulus and Poisson's ratio was calculated from the stress-strain curves at 50% of the maximum stress level. The results from this test with standard deviations are given in Table 4.18.

The results show that the uniaxial compressive strength of marble ranges from 61.28 to 83.53 MPa with the average of 71.12 MPa and Elastic modulus ranges from

10.09 to 13.54 GPa with the average of 11.50 GPa and Poisson's ratio ranges from 0.13 to 0.18 with the average of 0.16.

The uniaxial compressive strength of travertine ranges from 45.58 to 55.00 MPa with the average of 50.08 MPa and Elastic modulus ranges from 8.07 to 8.36 GPa with the average of 8.20 GPa and Poisson's ratio ranges from 0.28 to 0.32 with the average of 0.30.

All samples can be classified as medium strong to very strong rock according to British Standards Institution (BSI 2003).

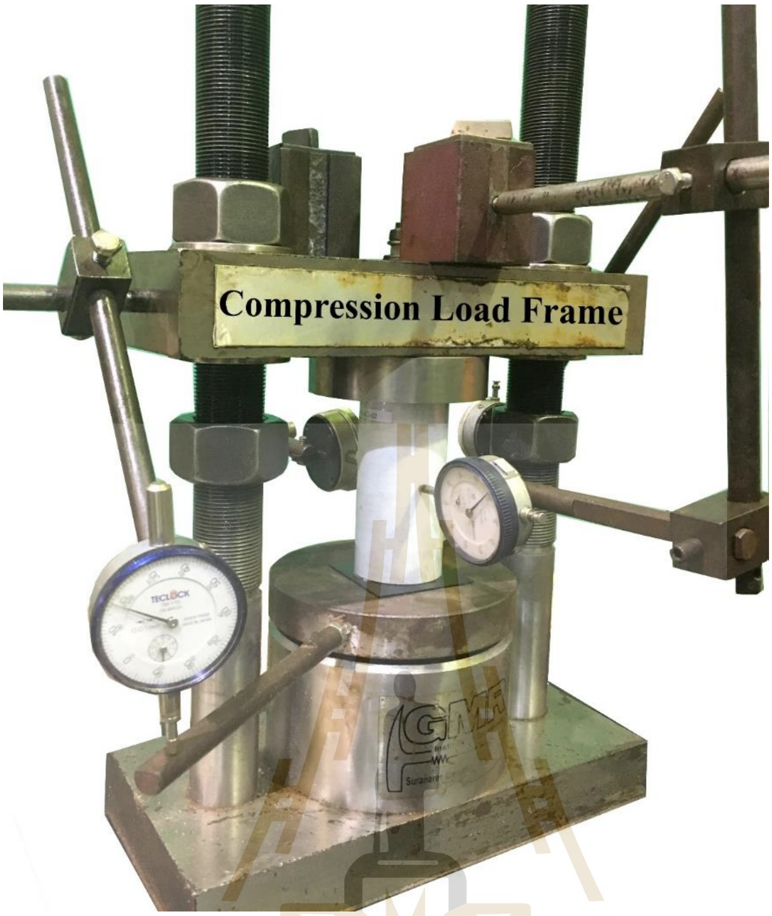


Figure 4.4 Uniaxial compression test device (specimen no. M-UCS-02).

Table 4.18 The results from the uniaxial compression test.

Number of specimen	V_p (km/sec)	V_s (km/sec)	σ_c (MPa)	E (GPa)	ν
T-UCS-01	4.90	2.97	55.00	8.27	0.32
T-UCS-02	4.82	2.84	48.33	8.07	0.30
T-UCS-03	4.86	2.95	48.79	8.21	0.28
T-UCS-04	4.85	2.86	45.58	8.10	0.32
T-UCS-05	4.93	2.88	52.72	8.36	0.28
Average	4.87±0.05	2.90±0.06	50.08±3.35	8.20±0.11	0.30±.02
M-UCS-01	5.22	3.20	79.08	12.00	0.16
M-UCS-02	5.47	3.22	83.53	13.54	0.18
M-UCS-03	5.21	3.01	61.56	10.50	0.13
M-UCS-04	5.19	3.00	70.16	10.09	0.18
M-UCS-05	5.00	3.05	61.28	11.36	0.15
Average	5.22±0.15	3.10±0.09	71.12±9.02	11.50±1.22	0.16±0.02

CHAPTER V

DATA ANALYSIS

5.1 Introduction

The purpose of this chapter is to the relationship between wave velocity (P-wave and S-wave velocity), fractures (smooth-surface fracture and rough-surface fracture), number of fractures and mechanical properties of the studied rock specimens. Mechanical properties include uniaxial compressive strength, Elastic modulus and Poisson's ratio.

5.2 Relationship between wave velocity and fracture roughness

The fracture roughness is divided into 2 types: smooth-surface fracture and rough-surface fracture. The linear relation is represented by a dash line (Figure 5.3 to 5.6) with R^2= 0.8356 for the P-wave velocity of the relationship between smooth versus rough-surface fracture and the direction of the fracture are parallel. The S-wave velocity of the relationship between smooth versus rough-surface fracture and the direction of the fracture are parallel (R^2= 0.8066).

The P-wave velocity of the relationship between smooth versus rough-surface fracture and the direction of the fracture are non-parallel (R^2=0.9832). The S-wave velocity of the relationship between smooth versus rough-surface fracture and the direction of the fracture are non-parallel (R^2=0.9916). Thus, it is proposed here that a power correlation was found between fracture roughness and P-wave and S-wave velocity within the tested specimens. The following equation defines this relationship:

The P-wave velocity (V_p) of smooth-surface fracture versus rough-surface fracture and the direction of the fracture are parallel.

$$y = 0.8116x + 1.1236 \tag{5.1}$$

The S-wave velocity (V_s) of smooth-surface fracture versus rough-surface fracture and the direction of the fracture are parallel.

$$y = 0.788x + 0.694 \tag{5.2}$$

The P-wave velocity (V_p) of smooth-surface fracture versus rough-surface fracture and the direction of the fracture are non-parallel.

$$y = 0.9495x + 0.4355 \tag{5.3}$$

The S-wave velocity (V_s) of smooth-surface fracture versus rough-surface fracture and the direction of the fracture are non-parallel.

$$y = 0.8261x + 0.5701 \tag{5.4}$$

where both P-wave, V_p and S-wave velocity, V_s are in km/sec.

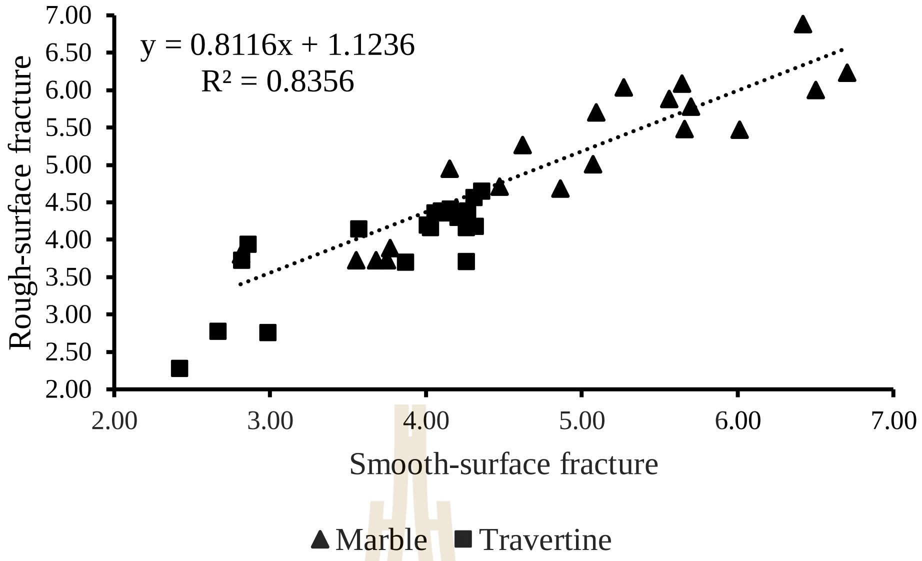


Figure 5.1 The P-wave velocity (V_P) of smooth-surface fracture versus rough-surface fracture and the direction of the fracture are parallel.

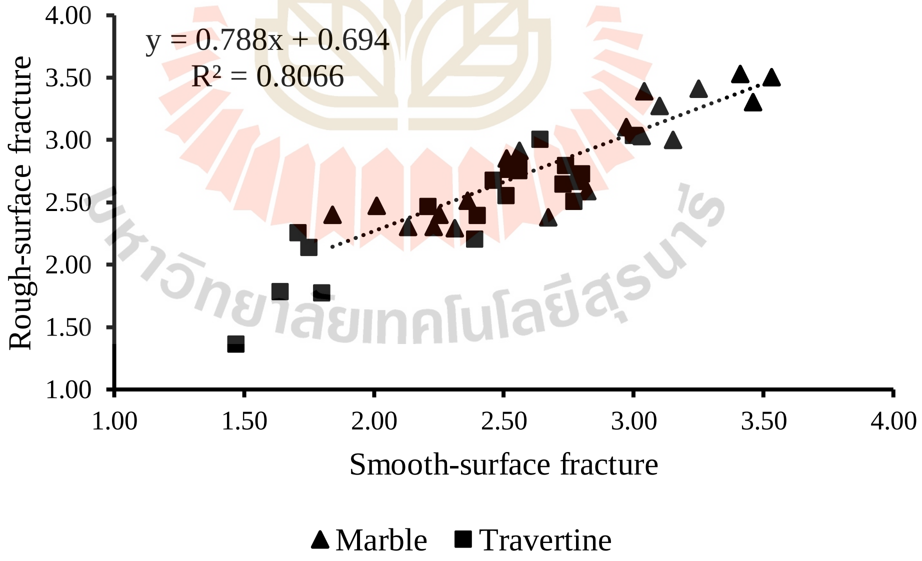


Figure 5.2 The S-wave velocity (V_S) of smooth-surface fracture versus rough-surface fracture the direction of the fracture are parallel.

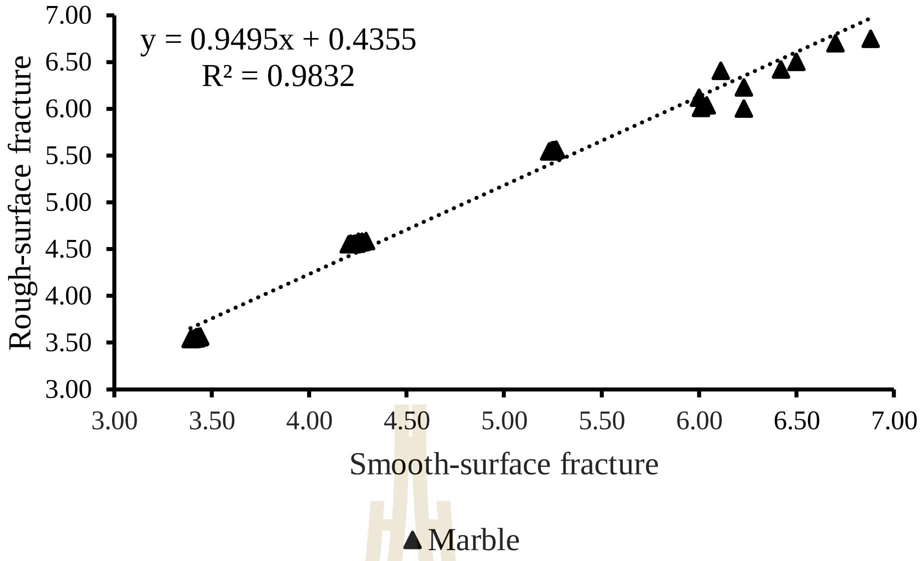


Figure 5.3 The P-wave velocity (V_P) of smooth-surface fracture versus rough-surface fracture and the direction of the fracture are non-parallel.

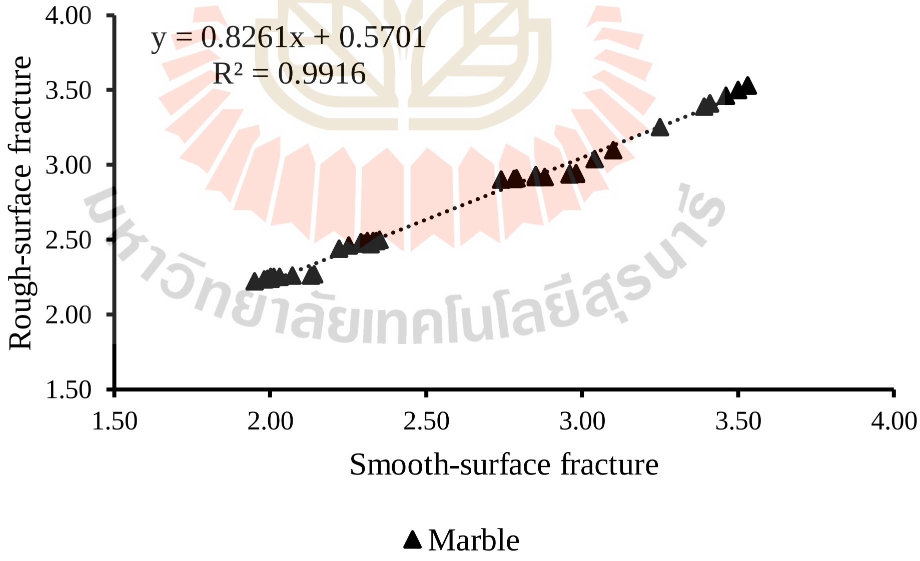


Figure 5.4 The S-wave velocity (V_s) of smooth-surface fracture versus rough-surface fracture and the direction of the fracture are non-parallel.

The comparison between the values of the wave velocity measured in smooth-surface fracture and rough-surface fracture is shown in Figure 5.7-5.8. From the test results, one can observe that the fracture roughness influences the velocity of propagation of the wave velocity through the samples for smooth-surface fracture and rough-surface fracture. The graph shows that the wave velocity of the rough-surface fracture is faster than the smooth-surface fracture. The linear relation is represented by a dash line with R^2=0.9640 for the P-wave velocity and rough-surface fracture and R^2=9912 is smooth-surface fracture. S-wave velocity and rough-surface fracture are R^2=0.9994 and smooth-surface fracture is R^2=0.9991 show in Figure 5.7-5.8.

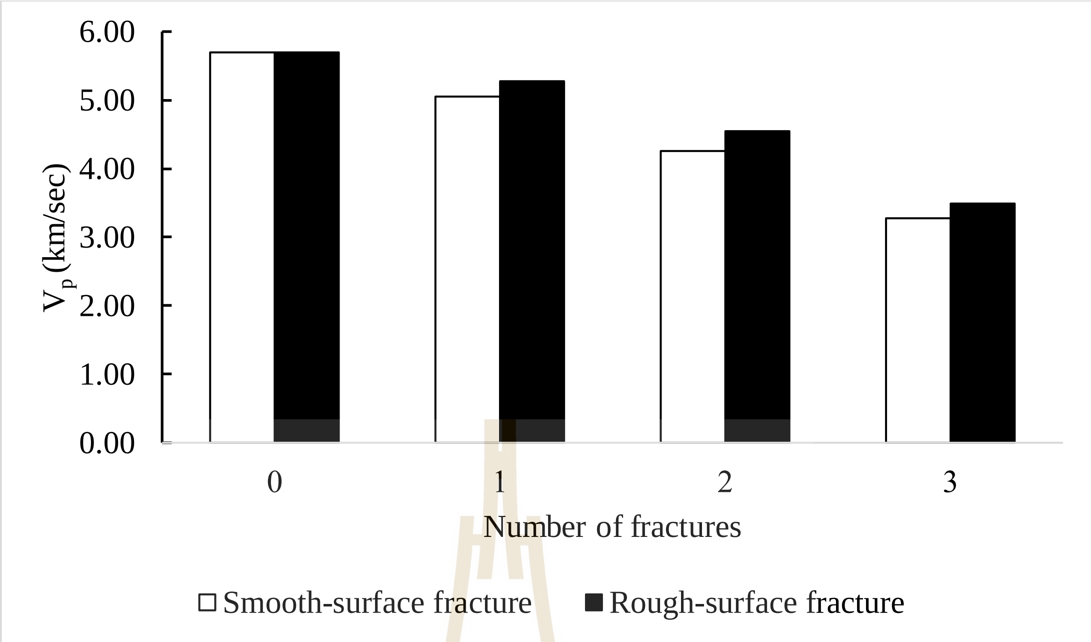


Figure 5.5 The average P-waves velocity between fracture roughness and the number of fractures.

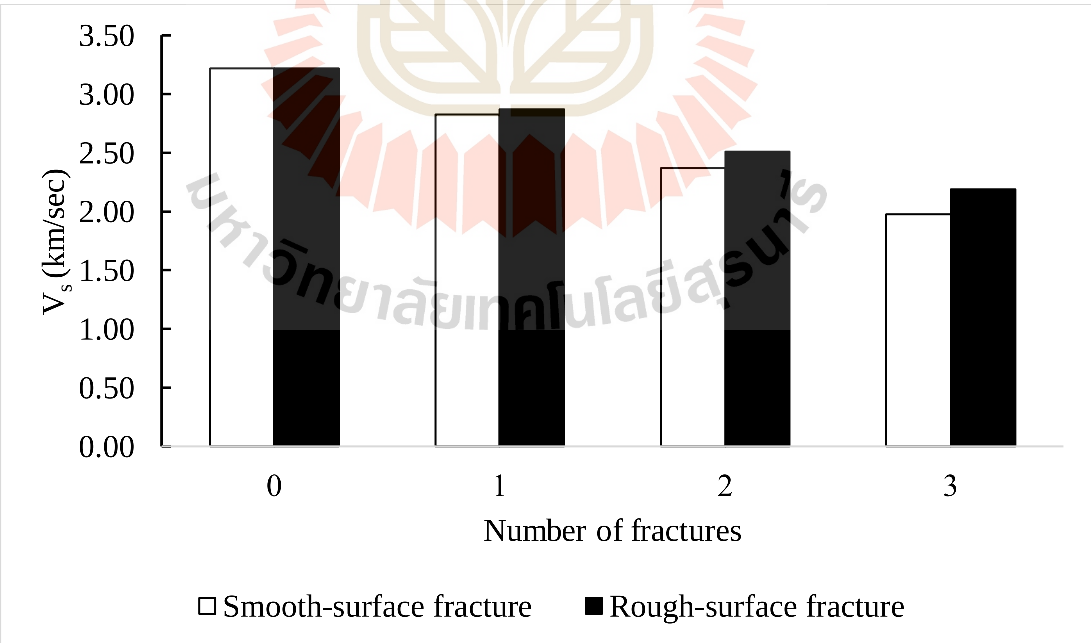


Figure 5.6 The average S-waves velocity between fracture roughness and the number of fractures.

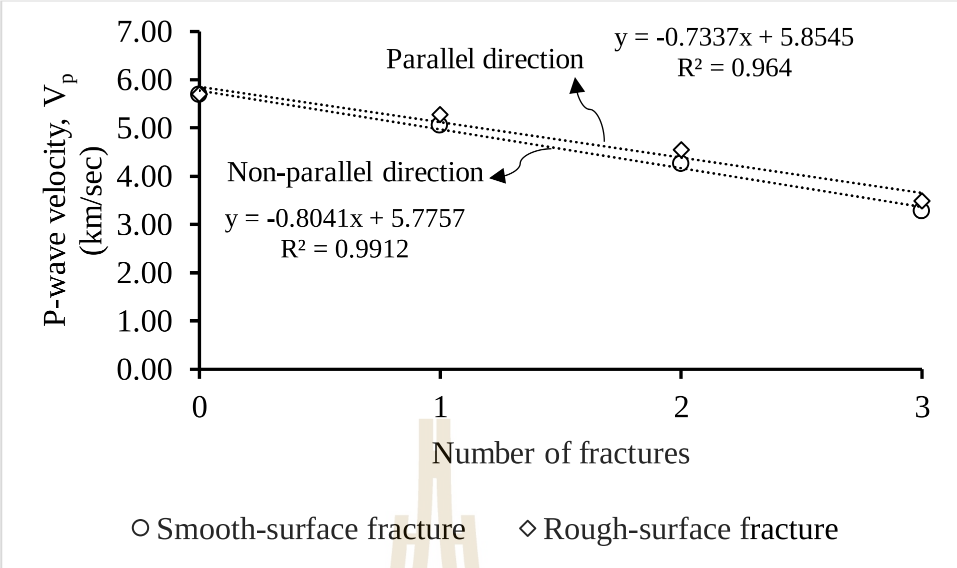


Figure 5.7 The average P-wave velocity (V_p) of smooth-surface fracture and rough-surface fracture versus number of fractures.

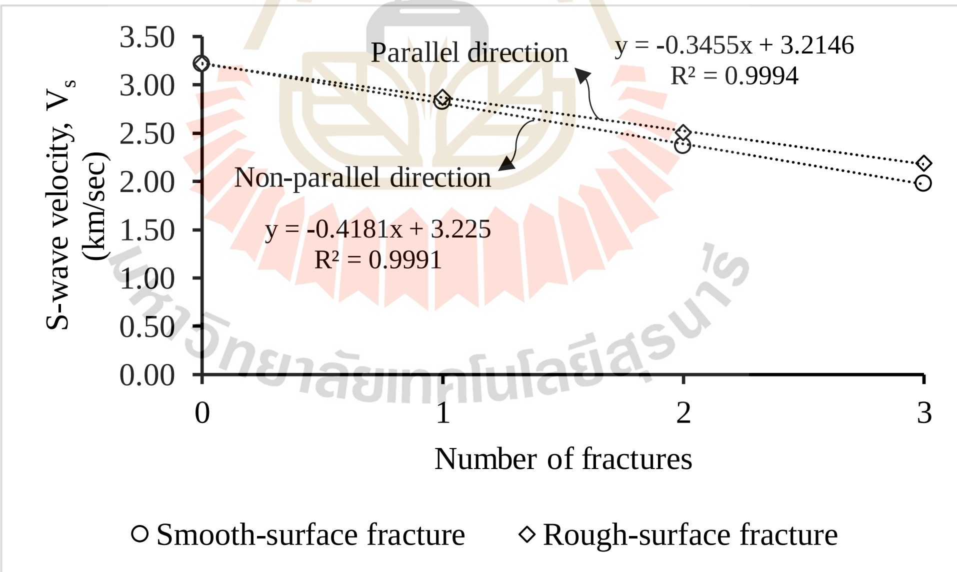


Figure 5.8 The average S-wave velocity (V_s) of smooth-surface fracture and rough-surface fracture versus number of fractures.

5.3 Relationship between wave velocity and number of fractures

The variation of wave velocity and number of fractures with parallel and non-parallel directional fracture was analyzed using the least square techniques. The equation of the best fit lines and the correlation coefficient (R^2) determined for the two cases (Parallel and non-parallel direction). The relationships between wave velocity and parallel and non-parallel directional fractures (Figure 5.7-5.8), which show an inverse relationship between the number of fracture and P-wave and S-wave velocity values for both cases.

The decrease in P-wave velocity (Marble and smooth-surface fracture) for non-parallel directional fractures is higher (27%) than that of parallel fractures (26%) and S-wave velocity for non-parallel directional fractures is higher (13%) than that of parallel fractures (12%).

The decrease in P-wave velocity (Marble and rough-surface fracture) for non-parallel directional fractures is higher (26%) than that of parallel fractures (23%) and S-wave velocity for non-parallel directional fractures is higher (11%) than that of parallel fractures (10%).

The direction of the fracture is another factor that causes the waves to move slowly when there is the non-parallel direction of the fracture. The results obtained from the relationship wave velocity and parallel and non-parallel directional fractures agree with the conclusion drawn by Kurtulus et al. (2011), Nitsungnoen and Wannakao (2015) and the results of the experiments confirm that P-wave and S-wave velocity decreases with an increase in the number of fractures in rocks, agreeing with the results obtained by Kahraman (2001), Altindag and Guney (2005), Leucci and De Giorgi (2006) and Vilhelm et al. (2013).

The linear relation is represented by a dash line for travertine with R^2=0.9757 for the number of fractures versus V_p and V_s (R^2=0.9730) for parallel direction and smooth-surface fracture (Figure 5.9). The number of fractures versus V_p (R^2=0.9410) and V_s (R^2=0.9588) for parallel direction and rough-surface fracture (Figure 5.10). Thus, it is proposed here that a high correlation was found between the number of fractures and P-wave and S-wave velocity within the tested specimens. The following equation defines this relationship:

The relationship between the number of fractures versus P-wave velocity (V_p) with the parallel direction and smooth-surface fracture for travertine.

$$y = -0.2625x^2 + 0.3025x + 4.2475 \tag{5.5}$$

The relationship between the number of fractures versus S-wave velocity (V_s) with the parallel direction and smooth-surface fracture for travertine.

$$y = -0.1325x^2 + 0.0385x + 2.7785 \tag{5.6}$$

The relationship between the number of fractures versus P-wave velocity (V_p) with the parallel direction and rough-surface fracture for travertine.

$$y = -0.2225x^2 + 0.2805x + 4.3055 \tag{5.7}$$

The relationship between the number of fractures versus S-wave velocity (V_s) with the parallel direction and rough-surface fracture for travertine.

$$y = -0.1225x^2 + 0.0945x + 2.7395 \tag{5.8}$$

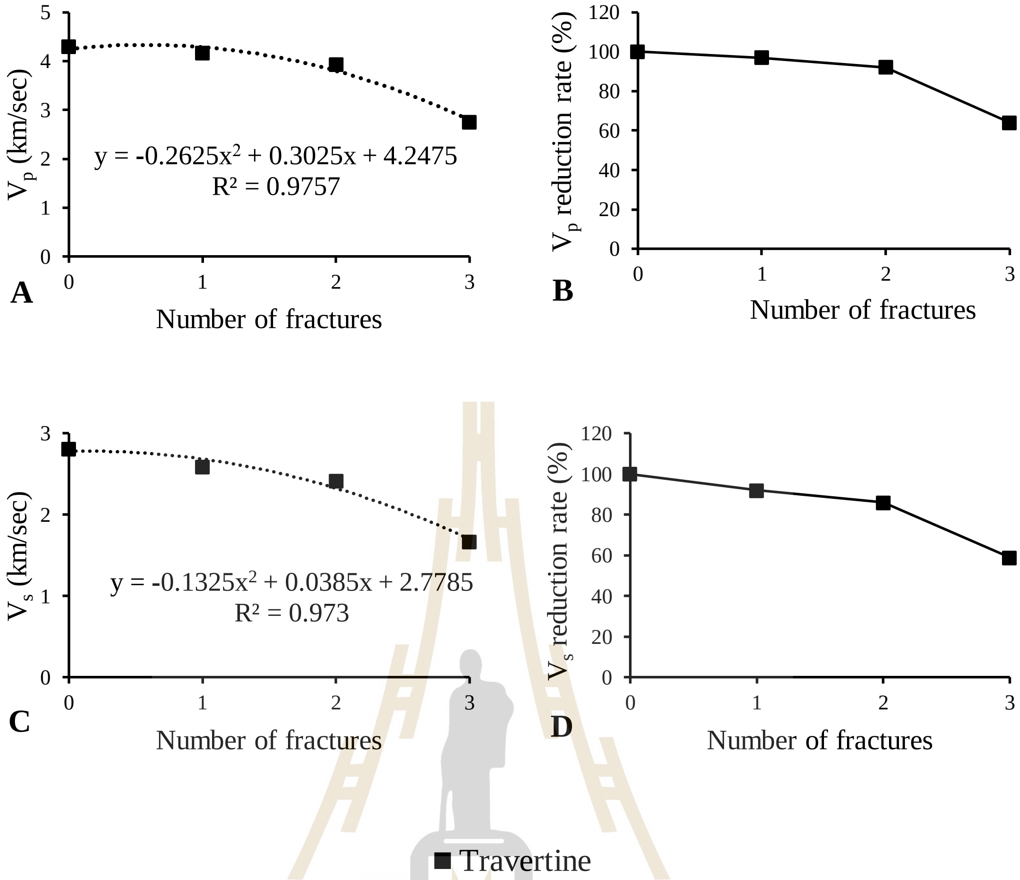


Figure 5.9 **A** number of fractures versus V_p, **B** V_p reduction rate versus number of fractures form parallel direction. **C** Number of fractures versus V_s, **D** V_s reduction rate versus number of fractures for parallel direction (Smooth-surface fracture).

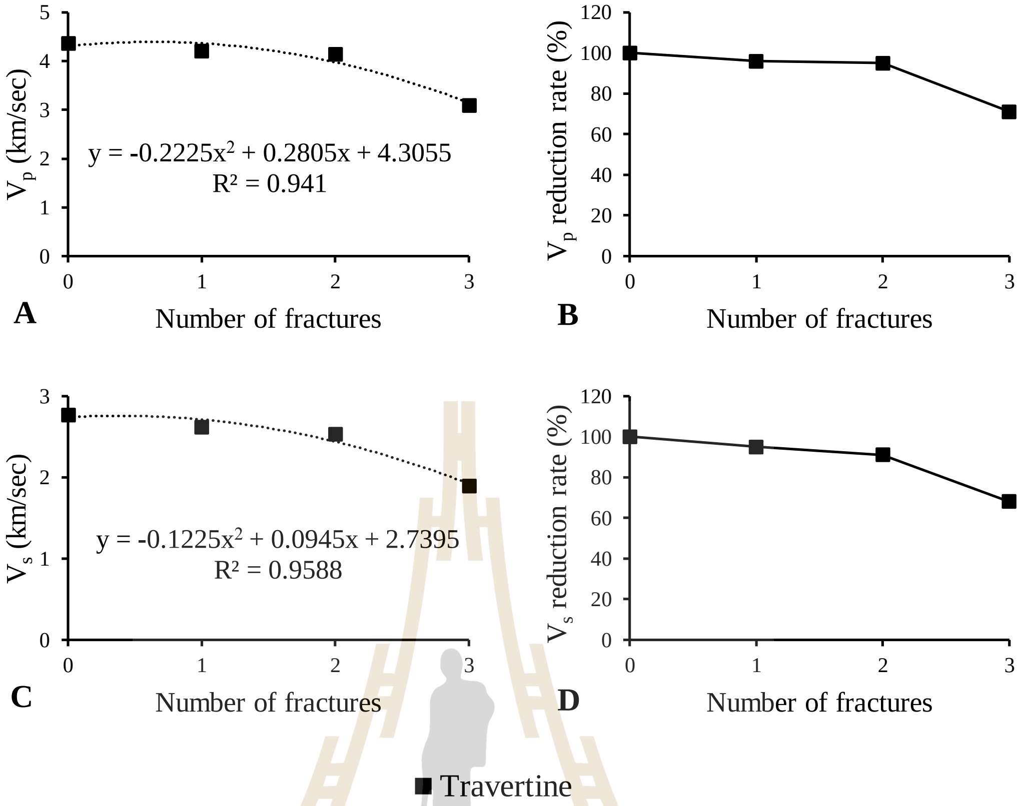


Figure 5.10 A number of fractures versus V_p, **B** V_p reduction rate versus number of fractures for parallel direction. **C** Number of fractures versus V_s, **D** V_s reduction rate versus number of fractures for parallel direction (Rough surface fracture).

The linear relation is represented by a dash line for marble with R^2=0.9863 for the number of fractures versus V_p and V_s (R^2=0.9908) for parallel direction and smooth-surface fracture (Figure 5.11). The number of fractures versus V_p (R^2=0.9489) and V_s (R^2=0.9740) for parallel direction and rough-surface fracture (Figure 5.12). Thus, it is proposed here that a high correlation was found between the number of fractures and P-wave and S-wave velocity within the tested specimens. The following equation defines this relationship:

The relationship between the number of fractures versus P-wave velocity (V_p) with the parallel direction and smooth-surface fracture for marble.

$$y = -0.891x + 6.299 \quad (5.9)$$

The relationship between the number of fractures versus S-wave velocity (V_s) with the parallel direction and smooth-surface fracture for marble.

$$y = -0.401x + 3.334 \quad (5.10)$$

The relationship between the number of fractures versus P-wave velocity (V_p) with the parallel direction and rough-surface fracture for marble.

$$y = -0.789x + 6.336 \quad (5.11)$$

The relationship between the number of fractures versus S-wave velocity (V_s) with the parallel direction and rough-surface fracture for marble.

$$y = -0.351x + 3.354 \quad (5.12)$$

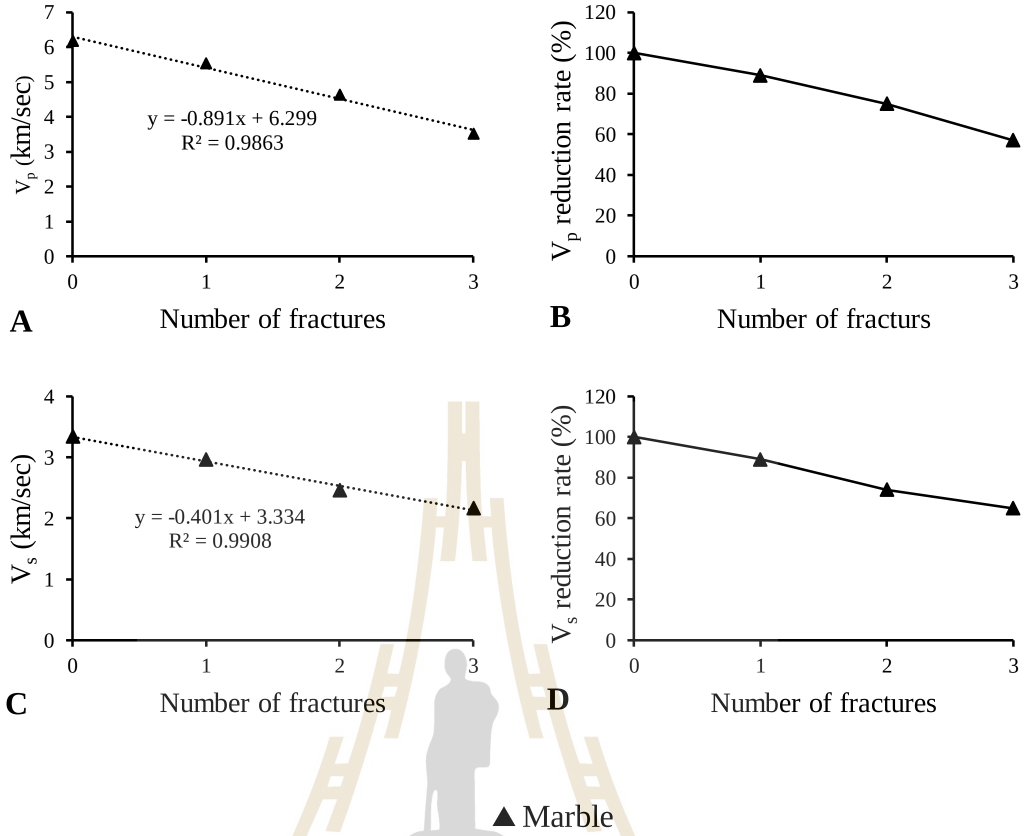


Figure 5.11 **A** number of fractures versus V_p, **B** V_p reduction rate versus number of fractures for parallel direction. **C** number of fractures versus V_s, **D** V_s reduction rate versus number of fractures for parallel direction (Smooth-surface fracture).

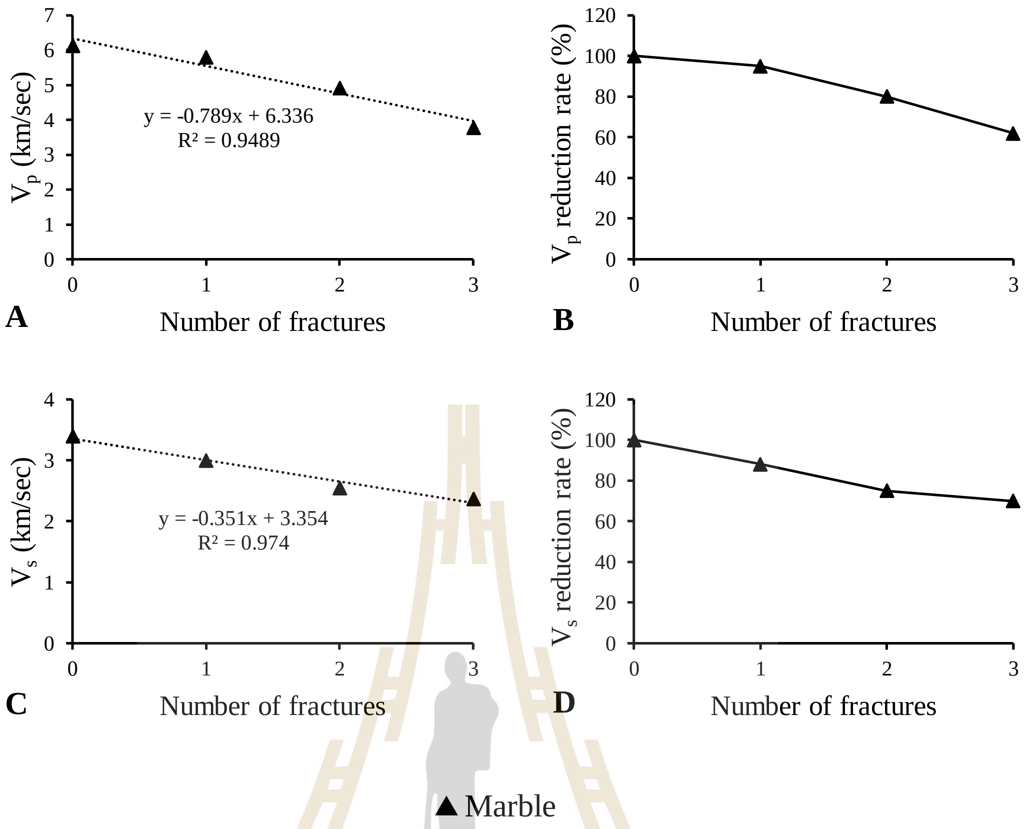


Figure 5.12 **A** number of fractures versus V_p, **B** V_p reduction rate versus number of fractures for parallel direction. **C** Number of fractures versus V_s, **D** V_s reduction rate versus number of fractures for parallel direction (Rough-surface fracture).

The linear relation is represented by a dash line for marble with R^2=0.9986 for the number of fractures versus V_p and V_s (R^2=0.9817) for non-parallel direction and smooth-surface fracture (Figure 5.13). The number of fractures versus V_p (R^2=0.9872) and V_s (R^2=0.9982) for non-parallel direction and rough-surface fracture (Figure 5.14).Thus, it is proposed here that a high correlation was found between the number of fractures and P-wave and S-wave velocity within the tested specimens. The following equation defines this relationship:

The relationship between the number of fractures versus P-wave velocity (V_p) with the non-parallel direction and smooth-surface fracture for marble.

$$y = -0.920x + 6.145 \quad (5.13)$$

The relationship between the number of fractures versus S-wave velocity (V_s) with the non-parallel direction and smooth-surface fracture for marble.

$$y = -0.457x + 3.328 \quad (5.14)$$

The relationship between the number of fractures versus P-wave velocity (V_p) with the non-parallel direction and rough-surface fracture for marble.

$$y = -0.878x + 6.272 \quad (5.15)$$

The relationship between the number of fractures versus S-wave velocity (V_s) with the non-parallel direction and rough-surface fracture for marble.

$$y = -0.377x + 3.318 \quad (5.16)$$

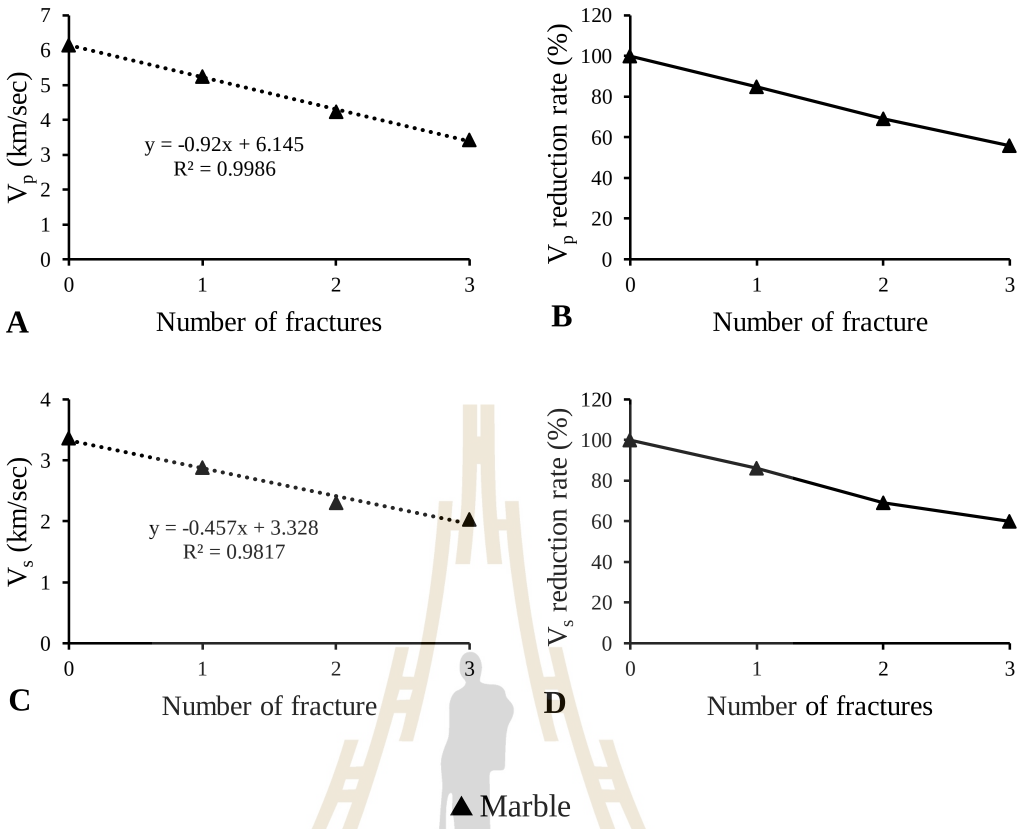


Figure 5.13 **A** number of fractures versus V_p, **B** V_p reduction rate versus number of fractures for non-parallel direction. **C** Number of fractures versus V_s, **D** V_s reduction rate versus number of fractures for non-parallel direction (Smooth-surface fracture).

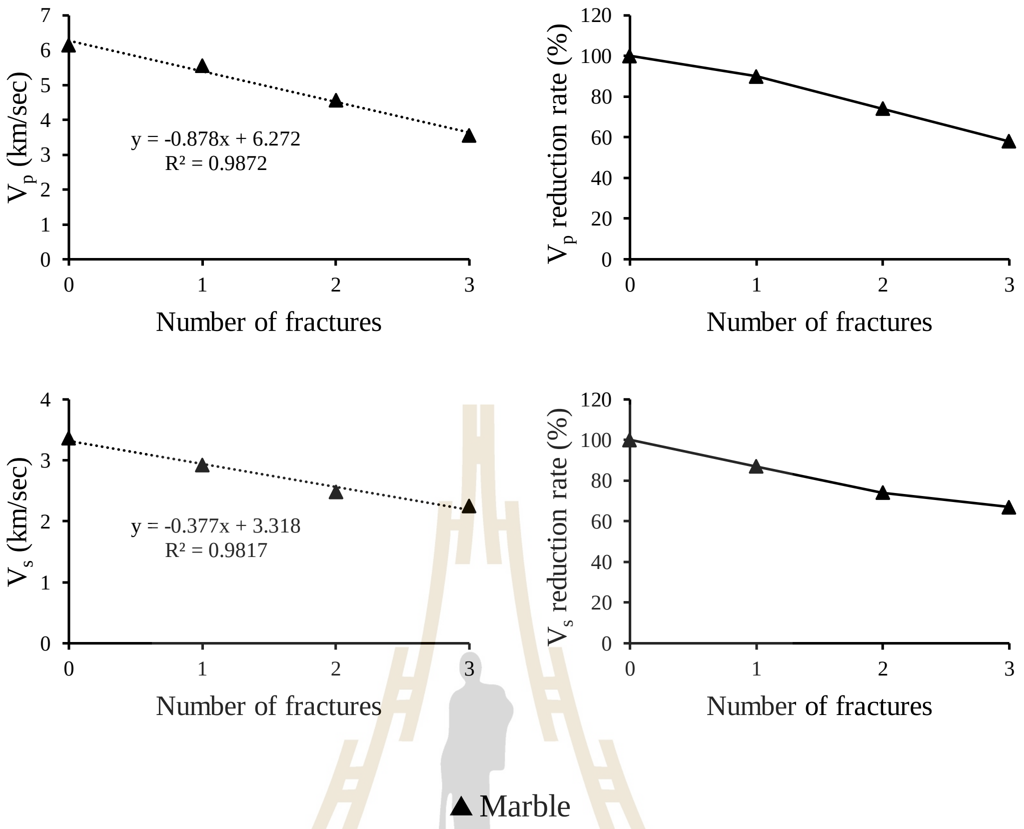


Figure 5.14 **A** number of fractures versus V_p, **B** V_p reduction rate versus number of fractures for non-parallel direction. **C** Number of fractures versus V_s, **D** V_s reduction rate versus number of fractures for non-parallel direction (Rough-surface fracture).

5.4 Relationship between wave velocity and mechanical properties

Mechanical properties include uniaxial compressive strength, Elastic modulus and Poisson's ratio. The uniaxial compressive strength of the samples ranges from 45.58 to 83.53 MPa (Jaeger et al. 2007). The elastic modulus and Poisson's ratio is calculated from the stress-strain curves at 50% of the maximum stress level. The elastic modulus varies from 8.07 to 13.54 GPa and Poisson's ratio ranges from 0.13 to 0.32.

The regression analysis of linear shows relationship between UCS, E and ν and wave velocity (V_p and V_s).

The linear relation is represented by a dash line with R^2=0.8831 for relation P-wave velocity and UCS (Figure 5.15) and R^2=0.8293 for relation S-wave velocity and UCS (Figure 5.16). Thus, it is proposed here that a high correlation was found between the UCS and P-wave and S-wave velocity within the tested specimens. The following equation defines this relationship:

The relationship between uniaxial compressive strength and P-wave velocity.

$$UCS = 57.532V_p - 229.65 \quad (5.17)$$

The relationship between uniaxial compressive strength and S-wave velocity.

$$UCS = 90.085V_s - 208.03 \quad (5.18)$$

Where UCS is in MPa.

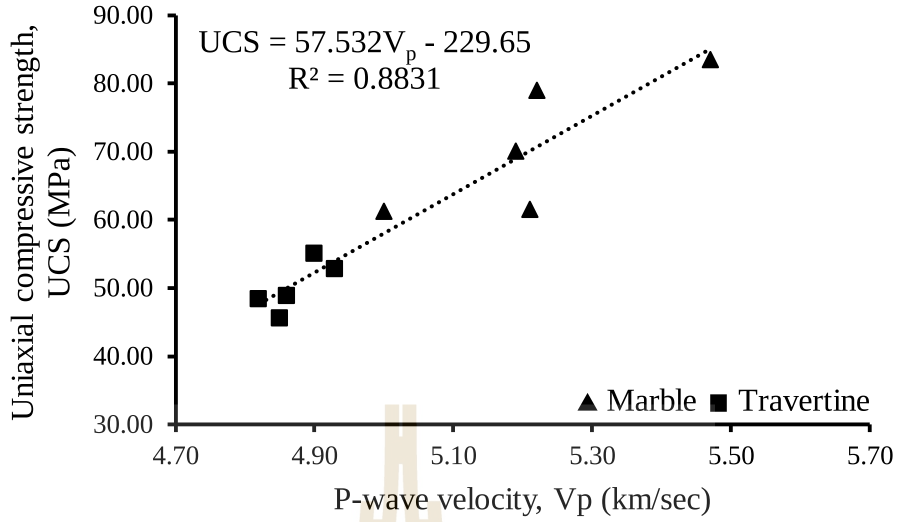


Figure 5.15 Relationship between the P-wave velocity and uniaxial compressive strength.

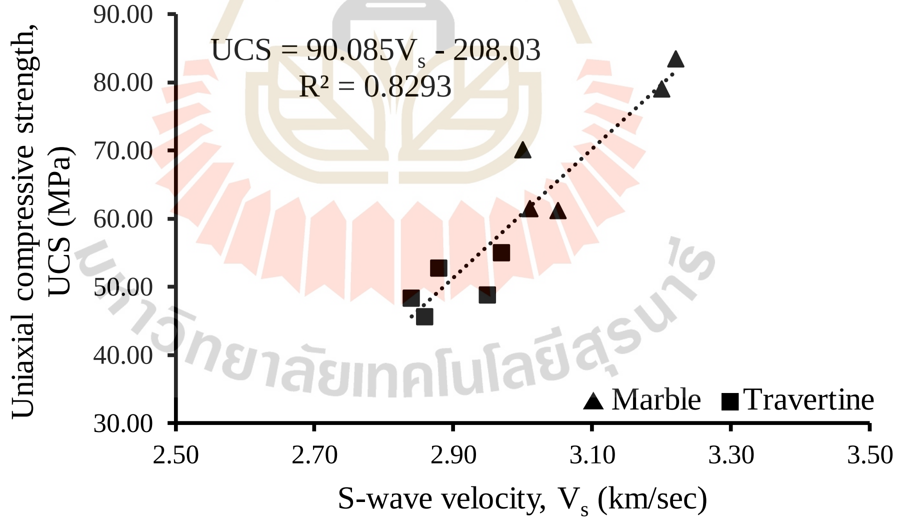


Figure 5.16 Relationship between the S-wave velocity and uniaxial compressive strength.

The linear relation is represented by a dash line with R^2=0.8290 for relation P-wave velocity and E (Figure 5.17) and R^2=0.8764 for relation S-wave velocity and E (Figure 5.18). Thus, it is proposed here that a high correlation was found between the E and P-wave and S-wave velocity within the tested specimens. The following equation defines this relationship:

The relationship between elastic modulus and P-wave velocity.

$$E = 9.0509V_p - 35.579 \quad (5.19)$$

The relationship between elastic modulus and S-wave velocity.

$$E = 14.041V_s - 32.246 \quad (5.20)$$

Where E is in GPa.

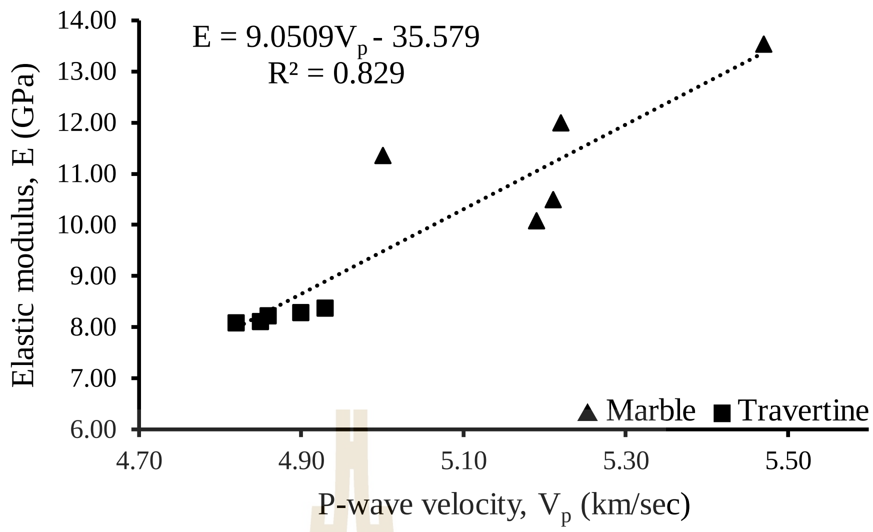


Figure 5.17 Relationship between the P-wave velocity and elastic modulus.

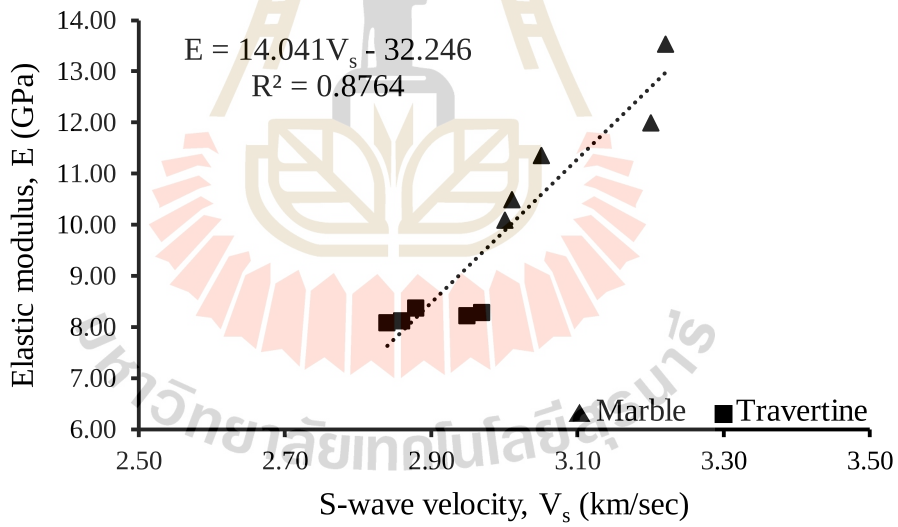


Figure 5.18 Relationship between the S-wave velocity and elastic modulus.

The relationship between wave velocity and Poisson's ratio. In statistical terms, the result is unclear. However, it can be divided into two groups according to different density ranges (Figure 5.19-5.20). The marble has the lower Poisson's ratio but the high density and P-wave and S-wave velocity. The travertine has the higher Poisson's ratio but the low density and P-wave and S-wave velocity. This is similar to the result of Promma (2014).

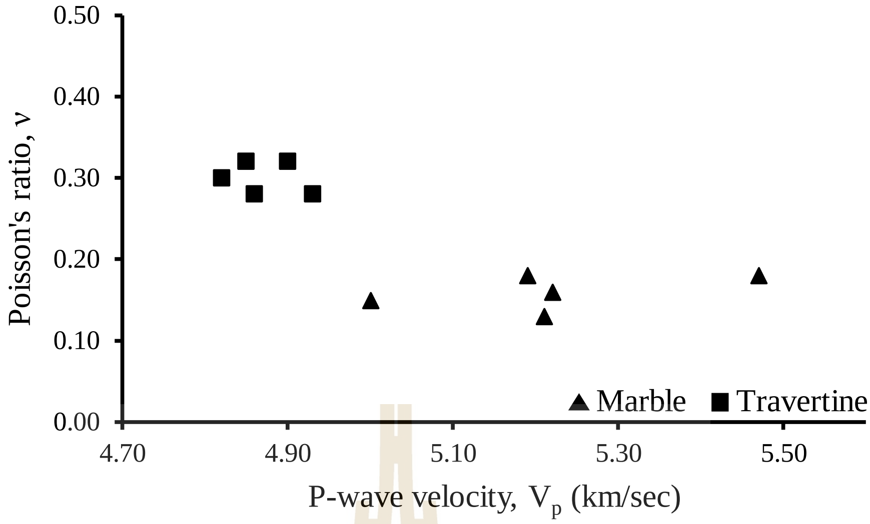


Figure 5.19 Relationship between the P-wave velocity and Poisson's ratio.

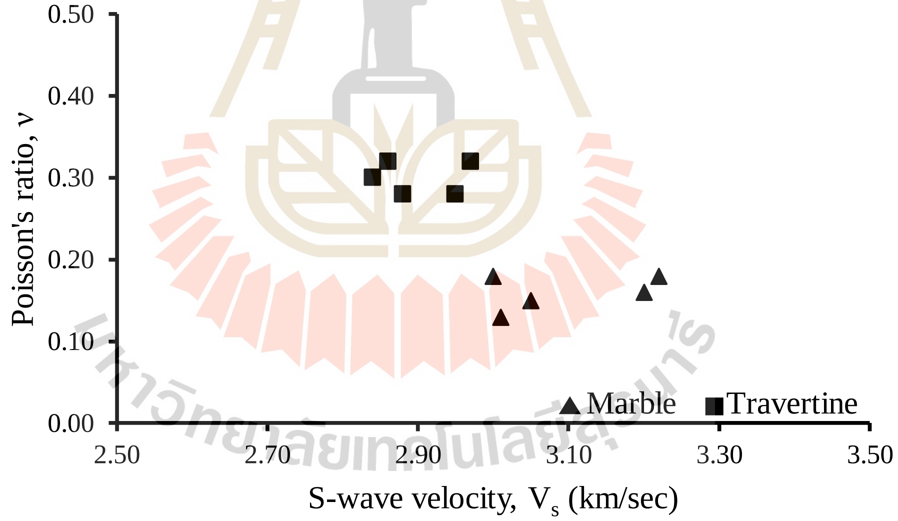


Figure 5.20 Relationship between the S-wave velocity and Poisson's ration.

The results show relationship between uniaxial compressive strength and P-wave and S-wave velocity; that is, the uniaxial compressive strength and elastic modulus seems to increase with increase of the P-wave and S-wave velocity. The results obtained from uniaxial compressive strength and agree with the conclusion drawn by Yaser and Erdogan (2014), Soroush et al. (2011), Altindag (2012), Khandelwal (2013), Arman et al. (2014), Promma (2014), Madhubabu et al. (2016) and Jaroenklang et al. (2017). Poisson's ratio can classify five categories (i.e. very low, low, medium, high and very high) for marble is high and travertine is low (Gercek 2007).

CHAPTER VI

DISCUSSIONS AND CONCLUSIONS

6.1 Discussions and conclusions

The study presented has mainly been focused on the influence of the fracture roughness, number of fractures and mechanical properties (Uniaxial compressive strength, elastic modulus and Poisson's ratio) of the investigated basic Saraburi marble and travertine on the wave velocity (P-wave and S-wave velocity) by using ultrasonic measurement. All objectives and requirements of this study have been met. The results of the laboratory testing and analyses can be concluded as follows.

The densities of the tested rocks range in normal value of carbonate rocks (Manger, 1963; Rafferty, 2012). The density of the tested samples can be recognized clearly by P-wave and S-wave velocity. The travertine has low density and low P-wave and S-wave velocity, on contrary, the marble has the higher density and the high P-wave and S-wave velocity. The wave velocity commonly depends on density of the rock.

The results show the relationship between wave velocity and samples shape (Block and cylindrical shape). The comparing the average values of P-wave and S-wave velocity obtained in the specimens with block shape and cylinder shape slightly differences and the standard deviation is low indicating that the variance of the wave velocity is low. Therefore, the difference in shape does not affect the wave velocity. The results obtained from the relationship wave velocity and samples shape agree with the conclusion drawn by Vasconcelos et al. (2008).

The results show the relationship between wave velocity and fracture roughness. In the case of fracture roughness, the two forms are the smooth-surface fracture and rough-surface fracture. The wave propagation through the rough-surface fracture is higher than the smooth-surface fracture. Both in marble and travertine samples. Due to the rough surface fracture has a joint roughness coefficient (JRC) range from 7-10. When testing the wave velocity, the gap is less than the smooth surface fracture. Because the surface on both sides of the fracture to fit together, resulting in less gap. In general, the wave velocity moves through the air slower than solid. This is the reason that the rock mechanical properties from the calculation would be error.

The effect of the number of fracture on wave velocities was investigated on Saraburi marble and travertine associated with fracture was created varied from 0, 1, 2, and 3. The results show relationship between number of fractures and P-wave and S-wave velocity. The experiments confirm that P-wave and S-wave velocity decreases with an increase in the number of fractures in rocks, agreeing with the results obtained by Kahraman (2001), Altindag and Guney (2005), Leucci and De Giorgi (2006), Kurtukus et al. (2011), El Azhari et al. (2013) and Fathollahy et al. (2017). Furthermore, there is a good correlation between the number of fractures and the reduction rates in V_p and V_s (%) indicating that P-wave and S-wave velocities are attenuated rapidly as the number of fracture increases.

The waves move slightly slower when fractures are non-parallel; thus, physical characteristics of the rock samples are more significant than the direction of fractures.

The wave velocities have good correlation with uniaxial compressive strength and elastic modulus of marble and travertine. The results show relationship between uniaxial compressive strength and elastic modulus tend to depend on P-wave and S-wave velocity; that is, the uniaxial compressive strength and elastic modulus seems to increase with increase of the P-wave and S-wave velocity (Yasar and Erdogan, 2004; Altindag, 2012; Khanderlwal, 2013; Jaroenklang et al., 2017). The travertine had the lowest uniaxial compressive strength and elastic modulus and the lowest P-wave and S-wave velocity. The marble had the higher uniaxial compressive strength and elastic modulus and P-wave and S-wave velocity than the travertine, on contrary, the marble has the lower Poisson's ratio but the high P-wave and S-wave velocity. The travertine has the higher Poisson's ratio but the low P-wave and S-wave velocity. This is similar to the result of Promma (2014) who reported the lower uniaxial compressive strength and elastic modulus of travertine than those of marble. It is concluded here that the P-wave and S-wave velocity can be used to estimate the uniaxial compressive strength, elastic modulus and Poisson's ratio of the tested Saraburi marble and travertine.

The results from this study suggest a good trend to estimate the relationship between the wave velocity, fracture roughness, number of fracture and mechanical properties of carbonate rocks. Nevertheless, in order to further confirm the results obtained from this study, more testing should be performed with the higher number of specimens. It is quite clear the there are several profound factors which influence the mechanical properties of the carbonate rocks, therefore; a large group of rock samples should be adequate for mathematical analysis.

6.2 Recommendations for future studies

The uncertainties of the studied investigation and results discussed above lead to the recommendations for further studies. More testing is required on a variety of specimens with different rock type contents. Increasing the number of the specimens would statistically enhance the reliability of the test results. The numbers of the tested rock samples are insufficient to develop the mathematical relationship between the non-parallel direction and rock types. However, other factors such as texture and mineral composition may also play a role on physical and mechanical property of the rocks.

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