PREDICTION OF MECHANICAL PROPERTY OF CARBONATE ROCKS FROM PHYSICAL, PETROGRAPHIC AND CMEMICAL PROPERTIES

Samerhkea Promma

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นางสาวเสมอแข พรมมา

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรมหาบัณฑิต

สาขาวิชาเทคโนโลยีธรณี

มหาวิทยาลัยเทคโนโลยีสุรนารี

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

Thesis Examining Committee

____

(Prof. Dr. Kittitep Fuenkajorn)

Chairperson

____

(Dr. Anisong Chitnarin)

Member (Thesis Advisor)

____

(Dr. Decho Phueakphum)

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เสมอแข พรมมา : การประเมินคุณสมบัติเชิงกลศาสตร์ของหินคาร์บอเนตจากคุณสมบัติทางกายภาพ ศิลาวิทยาและเคมี (PREDICTION OF MECHANICAL PROPERTY OF CARBONATE ROCKS FROM PHYSICAL, PETROGRAPHIC AND CHEMICAL PROPERTIES) อาจารย์ที่ปรึกษา : อาจารย์ ดร.อานิสงส์ จิตนารินทร์, 89 หน้า.

การศึกษาครั้งนี้มีวัตถุประสงค์เพื่อประเมินคุณสมบัติทางกลศาสตร์ของหินคาร์บอเนตจากคุณสมบัติทางกายภาพ (ค่าความหนาแน่น ความพรุนและความเร็วคลื่น)ลักษณะทางศิลาวิทยา และองค์ประกอบทางเคมีของหินโดยทำการทดสอบหินเพื่อหาคุณสมบัติกำลังรับแรงกดสูงสุดในแกนเดียว กำลังรับแรงดึงสูงสุด ค่าดัชนีความคงทน และค่าความต้านทานต่อการสึกร่อนของมวลหินหยาบ ลักษณะเนื้อหินคาร์บอเนตศึกษาโดยใช้กล้องจุลทรรศน์แสงโพลาไรซ์ การจำแนกหินปูนทำตามแบบของ Folk (1962) ปริมาณองค์ประกอบของหินปูนได้แก่มวลรวมคาร์บอเนต (allochem)เนื้อพื้น (mud matrix) และวัตถุประสานเนื้อแคลไซต์ (calcite cement)หาได้จากการเปรียบเทียบแผนภาพและวิธีการนับจุด โดยสามารถแยกหินปูนได้สองชนิดหลัก คือ หินปูน มิกไครท์ (Micrite limestone) และหินปูนสปาร์ไรท์ (Sparitic limestone)และได้คำนวณอัตราส่วนของมิกไครท์และ สปาร์ไรท์ ในการวิเคราะห์องค์ประกอบทางเคมีของตัวอย่างหิน ได้ใช้เทคนิคการเลี้ยวเบนของรังสีเอ็กซ์ ซึ่งพบว่าตัวอย่างหินที่ทดสอบมีแร่แคลไซต์เป็นองค์ประกอบหลัก (ร้อยละ 67.82ถึง ร้อยละ100) และในบางตัวอย่างมีแร่อื่น อาทิ ควอ ตซ์ (ร้อยละ0.10ถึงร้อยละ11.01) แร่ดินเหนียว (ร้อยละ0.59ถึงร้อยละ1.62)โดโลไมต์ (ร้อยละ0.14ถึงร้อยละ0.57) และแร่เหล็กที่มีปริมาณน้อยกว่าร้อยละ 1.00 ผลการทดสอบและวิเคราะห์ระบุว่า คุณสมบัติทางกายภาย ได้แก่ ความหนาแน่นและความเร็วคลื่นปฐมภูมิ มีอิทธิพลต่อคุณสมบัติเชิงกลศาสตร์บางชนิด โดยค่ากำลังรับแรงกดสูงสุดในแกนเดียว ค่าสัมประสิทธิ์ความยืดหยุ่น และค่ากำลังรับแรงดึงสูงสุด มีแนวโน้มขึ้นอยู่กับความหนาแน่นและความเร็วคลื่นปฐมภูมิ แต่ค่าสัมประสิทธิ์ความยืดหยุ่นไม่มีความสัมพันธ์ที่ชัดเจนกับความเร็วคลื่นปฐมภูมิ ส่วนค่าดัชนีความคงทนและค่าความต้านทานต่อการสึกร่อนของมวลหินหยาบไม่ขึ้นอยู่กับความหนาแน่นและความเร็วคลื่นปฐมภูมิ ความสัมพันธ์ระหว่างคุณสมบัติเชิงกลศาสตร์และอัตราส่วนของ มิกไครท์ต่อสปาร์ไรท์ แสดงให้เห็นว่าในหินตัวอย่างที่มีอัตราส่วน มิกไครท์ ต่อสปาร์ไรท์ สูง จะมีค่ากำลังรับแรงกดสูงสุดในแกนเดียว ค่าสัมประสิทธิ์ความยืดหยุ่น และค่ากำลังรับแรงดึงสูงสุดลดลง อย่างไรก็ตามความสัมพันธ์นี้ไม่มีความชัดเจนเชิงสถิติ เมื่อพิจารณาผลกระทบของแร่องค์ประกอบต่อคุณสมบัติเชิงกลศาสตร์ พบว่าแร่ควอตซ์ที่มีปริมาณน้อยกว่า ร้อยละ 1.00 จะไม่มีผลต่อคุณสมบัติทางกล ศาสตร์ของตัวอย่างหิน

ที่ทดสอบ แต่ในตัวอย่างหินปูนที่มีควอตซ์ร้อยละ 11.01พบว่าค่ากำลังรับแรงกดสูงสุดในแกนเดียว ค่าสัมประสิทธิ์ความยืดหยุ่น และค่ากำลังรับแรงดึงสูงสุดมีค่าสูงขึ้น การเพิ่มขึ้นของปริมาณแร่ดินเหนียวในหินปูนมีแนวโน้มที่จะทำให้ค่ากำลังรับแรงกดสูงสุดในแกนเดียว ค่าสัมประสิทธิ์ความยืดหยุ่น และค่ากำลังรับแรงดึงสูงสุดเพิ่มขึ้น สำหรับหินทราเวอทีนซึ่งมีความพรุนมาก และปริมาณ แร่ควอตซ์และแร่ดินเหนียวน้อย พบว่ามีความแข็ง มากกว่าหินปูนสปาร์ไรท์ หินอ่อนซึ่งประกอบด้วยผลึกแคลไซต์เป็นองค์ประกอบหลัก จะมีความหนาแน่นปานกลางและมีคุณสมบัติทางกลศาสตร์ในระดับปานกลางของกลุ่มตัวอย่าง

สาขาวิชาเทคโนโลยีธรณี ลายมือชื่อนักศึกษา ____________________

ปีการศึกษา2557 ลายมือชื่ออาจารย์ที่ปรึกษา________________

SAMERHKEA PROMMA: PREDICTION OF MECHANICAL PROPERTY OF CARBONATE ROCKS FROM PHYSICAL, PETROGRAPHIC AND CHEMICAL PROPERTIES.THESIS ADVISOR:ANISONG CHITNARIN, Ph.D.,89 PP.

CARBONATE ROCKS/ MECHANICAL PROPERTY/ PHYSICAL PROPERTY/ PETROGARPHY/MINERAL COMPOSITION

The objective of this study is to estimate the mechanical properties of carbonate rocks by using their physical properties (density, porosity and wave velocity) petrography and chemical composition. The mechanical tests of rocks are performed to determine uniaxial compressive strength, Brazillian tensile strength, slake durability index and Los Angeles abrasion and impaction. The limestone classification is based on Folk's scheme (Folk, 1962). Texture of the limestones is studied under a polarized light microscope. The quantification of limestone components such as allochem, mud matrix and calcite cement is based on comparison charts and point counting method. The limestone samples can be classified to two board types: Micritic limestone and Sparitic limestone. The sparite-to-micrite ratio of each sample is also calculated. The chemical composition of the rock samples is analyzed by X-ray diffraction technique. All specimens are composed of mainly calcite (about 67.82-100%). Some specimens contain quartz (about 0.10 to 11.01%), clay mineral (about 0.59 to 1.62%), dolomite (about 0.14 to 0.57%) and Fe-bearing minerals are detected in less than 1%.The results indicate that density and P-wavevelocity have some effects on the mechanical properties that is the

uniaxialcompressive strength, elastic modulus and Brazilian tensile strength tend to depend on

density and P-wave velocity. The elastic modulus also shows inconclusive tend with P-wave velocity. The slake durability index and Los Angeles abrasion and impaction test of the tested carbonate rocks tend to be independent of their density and P-wave velocity. The relationship between the mechanical properties and the sparite-to-micrite ratio indicates that the uniaxial compressive strength, elastic modulus, and tensile strength values decrease with increasing sparite-to-micrite ratio. However, this relationship is statistically unclear. For the mineral composition, quartz content of less than 1% has no significant effect on the mechanical properties of the tested rock specimens. However, the higher amount of quartz (in a sample contenting11.01%) results in the higher uniaxial compressive strength, elastic modulus and Brazilian tensile strength. The increase of clay mineral content of limestone tends to increase the uniaxial compressive strength, elastic modulus and Brazilian tensile strength. The tested travertine which has high porosity and small amounts of quartz and clay mineral content has the higher strength than the sparitic limestone. The marbles which consist of mainly calcite crystals have moderate density and their mechanical properties are in middle range of the tested carbonate rock specimens.

School of Geotechnology Student's Signature________________

Academic Year 2014 Advisor's Signature________________

ACKNOWLEDGMENTS

I wish to acknowledge the funding supported by Suranaree University of Technology (SUT).

I would like to express my sincere thanks to Dr. Anisong Chitnarin for her valuable guidance and efficient supervision. I appreciate her strong support, encouragement, suggestions and comments during the research period. My heartiness thanks to Prof. Dr. Kittitep Fuenkajorn and Dr. Decho Phueakphum for their constructive advice, valuable suggestions and comments on my research works as thesis committee members. Grateful thanks are given to all staffs of Geomechanics Research Unit, Institute of Engineering who supported my work.

Finally, I would like to thank beloved parents for their love, support and encouragement.

Samerhkea Promma

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SYMBOLS ANDABBREVIATIONS

σ_c	=	Uniaxial Compressive Strengths
P	=	Failure Load
A	=	Initial Cross-Sectional Area
E	=	Elastic Modulus
L	=	Thickness of Specimen
σ_B	=	Tensile Strengths
P_f	=	Applied Load at Failure
D	=	Diameter of Specimen
I_d	=	Slake Durability Index

CHAPTER I

INTRODUCTION

1.1 Background and rationale

Carbonate rocksare exposed in central Thailand. They are predominantly limestone with locally marble and are economically important as sources of raw materialsfor Portland cement and construction industries.The quality of carbonate rocksare determined by mineralogical characteristics and physic-mechanical properties. However, the significant geotechnical properties such as strength, durability, elasticity of limestone can be determined by sets of laboratory testing which are costly and time consuming.

Carbonate rockscompose mainly of calcium carbonate; howeverlimestone and marble are formed in different origins.Limestone can originate from skeletons and fragments of marine organisms, and usually compose of argillaceous sediments.Marble is formed by contact metamorphic process and composed of nearly 100 % calcite.Such various compositions result in different textures and chemical compositionswhich affect the mechanical properties of the rocks. Therefore study petrographic including texture and composition under microscope along with chemical analysis may reveal the effects of them on the mechanical properties of the carbonate rocks. Howeverknowledge of the relationship between physical, chemical and mechanical properties of carbonate rocks in Thailand is rare.

1.2 Research objective

The objective of this study is to estimate the mechanical properties of limestones,travertine and marbles by using physical, petrographical properties and chemical composition. The rock samples were prepared for slab thin sections and studied under polarized microscope. The mechanical tests such as uniaxial compressive strength, Brazillian tensile strength, Los Angeles abrasion, slake durability index were conducted. The physical properties such as density, porosity and wave velocity were conducted. Crushed samples were analyzed by XRD technique for chemical composition.

1.3 Scope and limitations

The scope and limitations of the research include as follows.

1. Carbonate rocks of the Saraburi Group exposed in Phetchabun, NakhonSawan, Lopburi, Saraburiprovinces are collected for this research.
2. Rock thin sections are prepared for petrographic study.
3. Chemical compositions of the carbonate rocks are obtained by X-ray Diffraction technique (XRD).
4. The rock specimens for mechanical tests are prepared following ASTM standard practices.
5. Mechanical tests in their study include uniaxial compressive strength test, Brazillian tensile strength test, slake durability index test, Los Angeles abrasion and impaction test.
6. The tests for physical properties includedensity, porosity and wave velocity.

1.4 Research methodology

The research methodology comprises of 6 steps including 1) literature review, 2) sample collection and preparation, 3) laboratory testing, chemical composition analysis and petrographic analysis, 4) data analysis, 5) discussions and conclusions and 6) thesis writing and presentation (Figure 1.1).

1.4.1 Literature review

Literature review is carried out in order to understandphysical and mechanical properties of sedimentary rocks especially, the carbonate type.These include the petrographical properties and chemical composition of sedimentary rocks and theeffects of mineralogical and textural characteristics on the mechanical properties of the carbonate rocks. Sources of information are text books, journals, technical reports and conference papers.

1.4.2 Sample preparation

Rock samples used in this research are the carbonate rocks of the Saraburi group collected from Phetchabun, NakhonSawan, Lopburi andSaraburi areas. The samples were prepared at the Geomechanics laboratory, Suranaree University of Technology for the physical and the mechanical tests, the petrographic study and the chemical analysis.

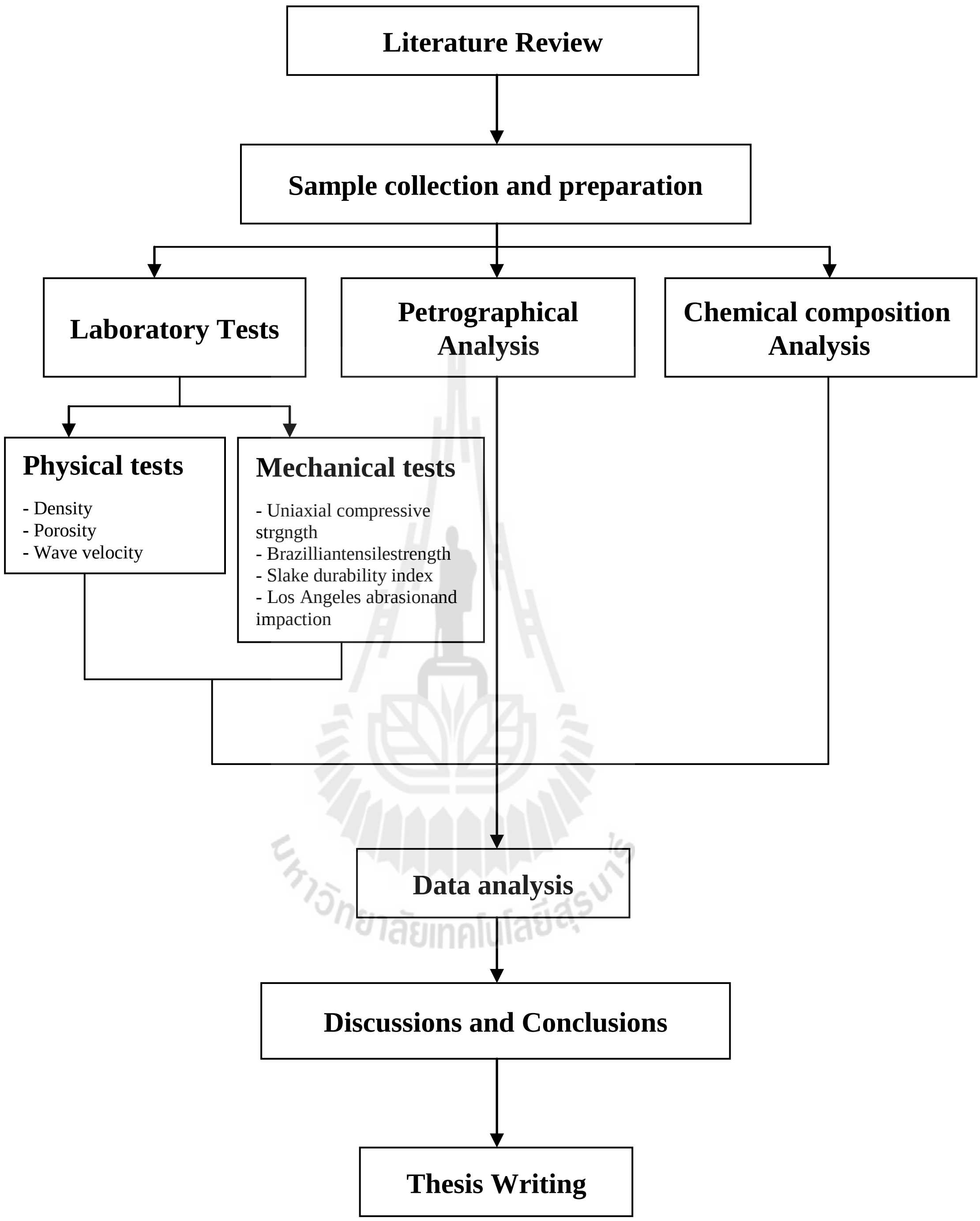


Figure 1.1 Research methodology.

1.4.3 Laboratory experiment

1) Physical testing

The physical testing included density and porosity (ASTM C97), wave velocity (ASTM D2845)of the carbonate rocks.

2) Mechanical testing

The mechanical testing include the uniaxial compressive strength (ASTM D7012), Brazilian tensile strength tests(ASTM D3967), the slake durability index (ASTM D4644) and Los Angeles abrasionand impaction test (ASTM C-131).

3) Chemical composition Analysis

Chemical analyses of the carbonate rocks are carried out by means of X-ray diffraction (XRD).

4) Petrographical Analysis

Petrographical study iscarried out by thin section analysis.Polished thin sections are prepared and examined undera polarized lightmicroscope.Petrologic parameters includedetermination of texture and classification of rock types.

1.4.4 Relationships between mechanical properties and physical, petrographical and chemical properties.

The results from laboratory areused to establish relationship between mechanical properties and physical,petrogarphical and chemicalproperties.

1.4.5 Discussions, conclusions and thesis writing.

All aspects of the studies mentioned are documented and incorporated into the thesis. The discussions on validity and potential applications of the results are also mentioned in this thesis. The research or findings are published in the conference proceedings or journals.

1.5 Thesis contents

This thesis is divided into seven chapters; 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 IVexplains the laboratory experiment, Chapter Vpresents the relationships between physic-mechanical properties and petrogarphic and chemical composition and Chapter VIpresentsthe discussions, the conclusions and recommendations for future studies.

CHAPTER II

LITERATURE REVIEW

Literatures related to the physical, chemical, petrographic and mechanical properties of the carbonate rocks have been reviewed in this research.

2.1 Classification of carbonate rocks

Perhaps, the most widely used classifications of limestone are those of Folk (1959, 1962) and Dunham (1962). Dunham's schemehas advantage over Folk's during a field investigation. Folk's scheme is much useful for polarizing microscopy. Both classifications subdivide limestones primarily on the basis of matrix content. Calcite mud (micrite) is microcrystalline calcite and grain size generally less than 4 μm. Micrites are susceptible to digenetic alteration and may be replaced by coarser mosaics of microsper (5-15 μm). Spary calcite is invariably precipitated after the fibrous calcite described earlier which is mostly a main cement. Carbonate particles can be divided allochemical. However, details of compositional and textural constituents of the carbonates that reflect the depositional and digenetic history of the carbonate rocks can be found in Flügel(1982), Moore (1989), Tucker (1991), Microfacies analysis according to Flügel which has different classification is aimed for specific objectives such as paleoenvironment and basin analysis. Dunham's classification and its modification by Embry and Klovan (1971) and James (1984) deal with depositional texture (Figure 2.1). For this reason, scheme may be better suited for rock descriptions that employ a hand specimen or thin section under thebinocular microscope.This subdivision is based on the particle fabic and on the kind of particle binding during sedimentation. In the former a distinction is made between mud-supported and grain-supported fabic. Dunham used names that combine the name of fabic types with the name of the grain type: mudstone (mud supported, <10% grain), wackestone (mud supported, > 10% grain), packstone (grain support), grainstone (lacks mud and grain support).

The system of classification suggested by Folk (Figure 2.1) is based upon the fact that, in principle, carbonate rocks are comparable to sandstone and shales, in regard to sedimentation. Based on the percentage of interstitial material, the rocks may be further subdivided into two groups: sparryallochemicallimestones(containing a sparry calcite cement of clear coarsely crystalline mosaic calcite crystals)and microcrystalline allochemical limestone(containing microcrystallincalcite mud, micrite, which is subtranslucent grayish or brownish particles less than about 5 microns in size).The names are formed by combining terms for matrix (micrite), cement (sparite) and particles (allchemical) (Figure 2.2).

Marble is metamorphic rock which composes of recrystallized carbonate minerals. It is generally refer to metamorphosed limestone.Metamorphism causes variable recrystallization of the original carbonate mineral grains. The resulting marble rock is typically composed of an interlocking of carbonate crystals. Primary sedimentary textures and structures of the original carbonate rock have typically been modified or destroyed.It comes in a vast range of colors from white, green, red to black and its veining generally contrasts with the base stone color (Chan, 1994).Marble texture is described based on number of grain components. A graincomponent is a primitive unit of morphology (Suresh et al., 2008).White and homogenous marble is the result of metamorphism of very pure limestone. When other material is involved in the marble formation process, the homogenous structure disappears and veins, spots show up as textures on marble (Ar and Akgul, 2008).

<table>
<tr><td colspan="6">Allochthonous Limestone
Original components not organically bound during deposition</td><td colspan="3">Allochthonous Limestone
Original components organically bound during deposition</td></tr>
<tr><td colspan="4">Less than 10% > 2 mm component</td><td colspan="2">Greater than 10% > 2 mm components</td><td rowspan="3">By organisms that build a rigid framework</td><td rowspan="3">By organisms that encrust and bind</td><td rowspan="3">By organis ms that act as baffles</td></tr>
<tr><td colspan="3">Contains lime mud (< 0.03 mm)</td><td>No lime mud</td><td rowspan="3">Mud-supported</td><td rowspan="3">Supported by grain components coarser than 2 mm</td></tr>
<tr><td colspan="2">Mud-supported</td><td colspan="2" rowspan="2">Grain-supported</td></tr>
<tr><td>Less than 10% grains (> 0.03 mm < 2 mm)</td><td>Greater than 10% grains</td><td colspan="3">Boundstone</td></tr>
<tr><td>Mudstone</td><td>Wackstone</td><td>Packstone</td><td>Grainstone</td><td>Floatstone</td><td>Rudstone</td><td>Framestone</td><td>Bindstone</td><td>Bafflestone</td></tr>
</table>

Figure 2.1 Dunham’s classification of carbonate rocks (Tucker,1991)

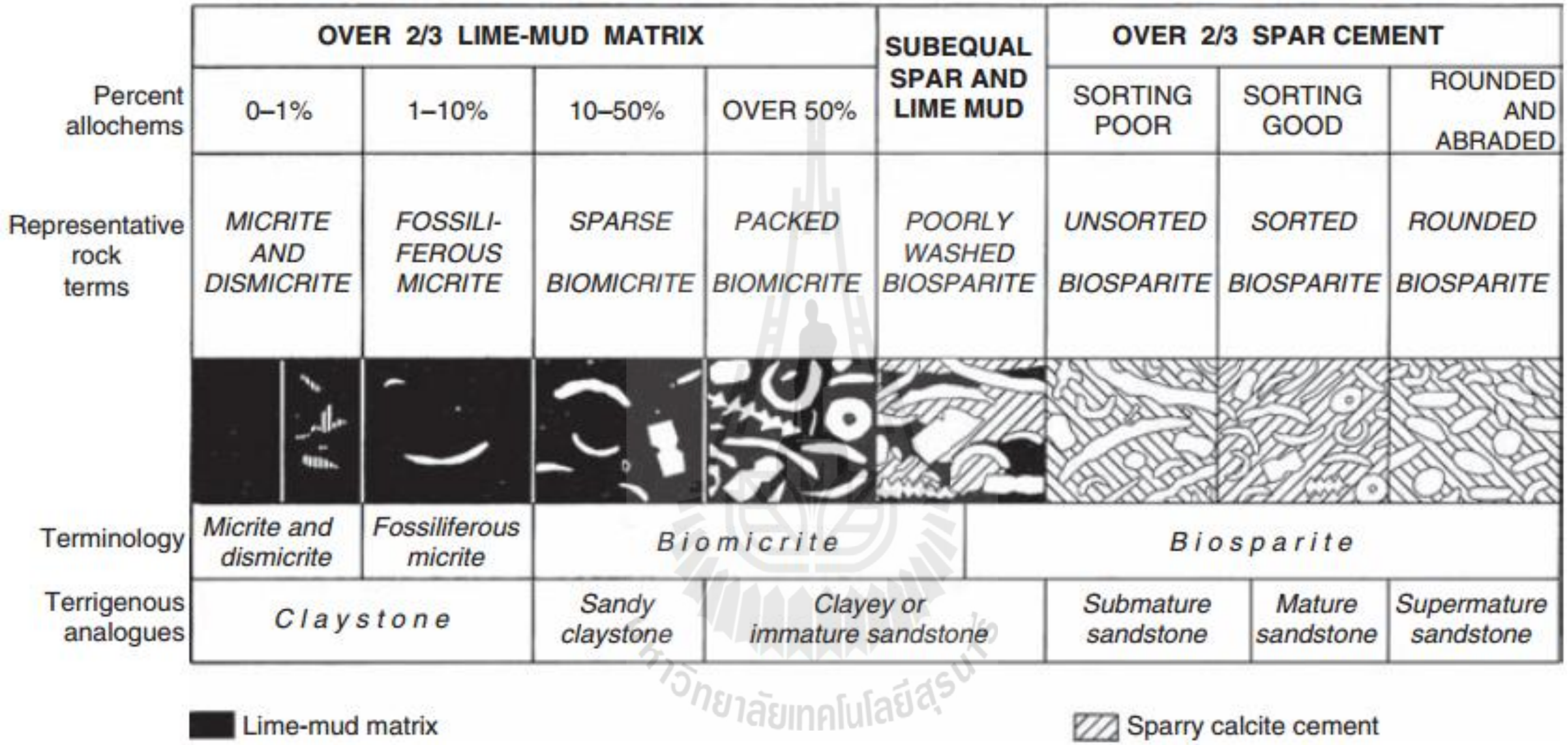


Figure 2.2 Folk's classification of carbonate rocks (Boggs, 2009)

2.2 Physical, chemical and mechanical properties of carbonate rocks

Several researchers have studied and gathered the relevant information on physical, mechanical and chemical properties of the carbonate rocks. The common physical properties are density; porosity and wave velocity. The mechanical properties include uniaxial compressive strength; tensile strength; slake durability index test and Los Angles abrasion and impaction. The chemical properties involvemineral composition of the limestones and marbles.

Tourenq and Archimbaud (1976) found that mineralogy, structure, and porosity were fundamental parameters for characterization of carbonate rocks. The porosity was considered to be the paramount important. The clay mineral content was stressed as a relevant component of the mineralogy. They presented correlation between physical and mechanical properties to enable characterization of pure carbonate (without clay mineral) by three parameters: (1) porosity, ultrasonic velocity and Young's modulus(2) ultimate compression strength, tensile strength and hardness and(3) drillability, abrasion loss and dynamic fragmentation.

Rodrigues (1988) proposed that the carbonate rocks were composed predominantly of calcite ($CaCO_3$) with variable amounts of accessory minerals, among which quartz and clay minerals were the most relevant from the geotechnical point of view. A smaller proportion was composed predominantly of dolomite considerably their geotechnical properties.

The most probable quartz and clay minerals occurred in large range of percent composition. The differences in geotechnical behavior produced by the access minerals when coupled with their variation influence strikingly the geotechnical properties of carbonate rocks. The influence of quartz and clay mineral on the properties of carbonate rocks was clearly dissimilar. Quartz was chemically and mechanically more resistant than calcite. Its occurrence in carbonate rocks might be beneficial for some geotechnical properties. Clay mineral, on the other hand, due to their peculiar crystal structure and properties always contributed to the degradation of the geotechnical behavior of the carbonate rocks.

Hatzor and Palchik (1998) investigated the influence of physical properties such as porosity, mean grain size on compressive strength of heterogeneous dolomites. Theyconcluded that previous workers who had reported exceptionally good correlation between mean grain size and compressive strength must had tested extremely homogeneous samples, in which the only textural variable was the mean grain size. In heterogeneous rock, however, voids, which might function as stress concentrators and as nucleation sites, must be considered. They developed a new model for the compressive strength of the brittle, heterogeneous Aminadav dolomites, based upon porosity, mean grain size, and elastic modulus. In their model, peak axial stress is inversely related to the square root of mean grain size, and to porosity, and was directly related to the elastic modulus and confining pressure.

Yasar and Erdogan (2004) determined the mechanical and physical properties of carbonate rocks using P-wave velocity.Ultrasonic techniques are known as non-destructive and easy to apply, both for site and laboratory conditions. In rock engineering, sound velocity (SV) techniques have increasingly been used to determine the dynamic properties of rocks. The SV of a rock mass is closely related to the intact rock properties and measuring the velocity in rock masses interrogates the rock structure and texture. In their experiment,the important influencing factors were rock type, mineralogical composition, rock texture and structure, grain size and shape, density, porosity, anisotropy, porewater, confining pressure, temperature, weathering and alteration zones, bedding planes, and joint properties.The samples of rocks were tested in the Mining Engineering laboratory of Cukurova University for determination of statistical relations with the mechanical and physical properties. The three different rock types of the carbonate rocks were texted. The SV values of the rocks were correlated with the uniaxial compressive strength (σ_c); Young's modulus (E) anddensity (ρ) for each rock type.The results of regression equations and the correlation coefficients were given in graphs of the mean values of the test results between SV index and uniaxial compressive strength; Young's modulus and density were shown in Figure 2.3

In conduction, results indicated that the uniaxial compressive strength (σ_c); Young's modulus (E) and density (ρ) of various carbonate rock types could be estimated from their SV values by using simple linear mathematical relations.

Ugur et al. (2009) established empirical relations between the Los Angeles abrasion and impact resistance (LAAI) for 100 and 500 revolutions and physical properties of rock samples collected from many locations in Turkey. The Los Angeles and impact test is a measurement of degradation of mineral aggregates of standard grading resulting from a combination of actions including abrasion or attrition, impact, and grinding in a rotating steel drum containing a specified number of steel spheres.

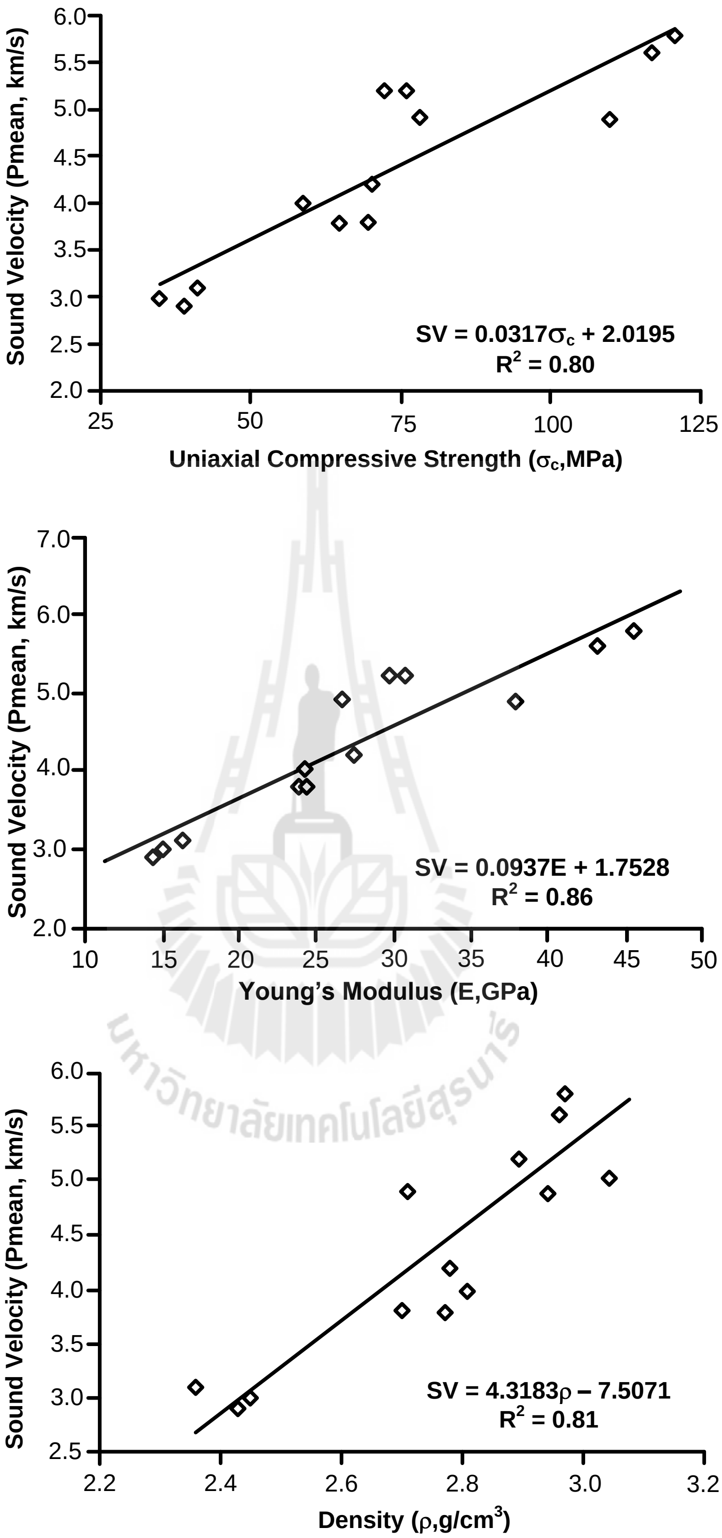


Figure 2.3 Correlation of sound velocity and rock properties (Yasar and Erdogan 2004)

The LAAI test is widely used as an indicator of the relative quality or competence of mineral aggregates and is one of mechanical properties of a aggregate The samples tested included ignous rock of volcanic origin as well as both metamorphic and sedimentary rocks. The volcanic igneous rock was andesite while the metamorphic rocks were mainly marbles and the sedimentary samples were limestones and travertines of different grain sizes. The samples were initially tested for their physical and mechanical properties such as bulk density, P-wave velocity, Schmidt and shore hardness, uniaxial compressive strength, indirect tensile strength and point load index and then the fresh rock samples were crushed and tested for LAAI value.

In an attempt to establish a more meaningful relationship, LAAI values were divided by P-wave velocity (Vp) values since it was strongly dependent on the porosity, density, mineral composition, size and frequency of fractures in the rock structure and indicated weakness of rocks to abrasion. The LAAI value was inversely related to measured properties and decreases with an increase in each different rock property. Among the large number of functions, the following logarithmic function found to be providing the best correlation to data. Among the tested rocks, andesite and limestones were more resistant to abrasion than marbles and travertines. Rock properties had certain influence on the abrasion of rocks and could be used to predict LAAI value of rocks. Dependence of abrasion characteristics on each rock property investigated by regression analysis showed that high correlations exist.

Yagiz (2009) investigated the relationship between the physical properties and modulus of elasticity, uniaxial compressive strength and index properties of nine types of rock including travertine, limestone, dolomitic limestone and schist. The samples of four types of travertines, two types of limestone, dolomitic limestone and two types of schist were collected from different quarries around the cities of Denizli and Antalya in western Turkey.The results of the study indicated the physical properties rebound values had a reliable relationship with the uniaxial compressive strength of rock. The study suggests that, as the Schmidt hammer test was easy to use and non-destructive, the proposed equations to estimate rock parameters from the Schmidt hammer rebound number might be valuable at the preliminary stage of design. However, comparison with previous research indicated they should be used with caution and for the specified rock types only.

Rajabzadeh et al. (2012) determined the physical of rock classes and porosity on the relationship between uniaxial compressive strength (σ_c) and some other properties of carbonate rocks with different genesis (sedimentary, diagenetic, and metamorphic). Studied properties included density (γ), Young's modulus (E), and tensile strength (σ_t). The samples were collected in different parts of Iran. The samples were taken of sedimentary limestones,dolomitic limestones and marbles. They used statistical analysis and regression modeling to investigate the role of porosity on the mechanical properties.Dry uniaxlai compressive strength (σ_{cd}) and saturated uniaxlai compressive strength (σ_{cs}) were considered as dependent. The ratios of different properties to porosity (γ/n; E/n; and σ_t/n) were regarded as independentvariables insedimentary limestones and marbles. It was found that, in diagenetic dolomitic limestones utilizing porosity did not yield any significant improvement of correlation coefficients between different variables and uniaxial compressive strength.

2.3 Petrographic and mechanical properties of carbonate rocks

Tarawneh et al. (2007) characterized the limestone rocks in Ma'an area, south Jordan and studieddetailed geological, petrographic and physico-mechanical tests of limestone. The limestones understudy was purity and quite homogenous in internal texture and structure. The results of petrographic studies indicated that fossils formed 50-80 % of the limestone. The representative sample were tested and used to investigate the physical and mechanical properties of the limestone such as uniaxial unconfined compressive stress values (CS), water absorption percentage (WA), surface abrasion (SA), seismic velocity (SV) and specific gravity (SG). Different tests in this study indicated almost similar results for different limestone types except the uniaxial unconfined test.The results revealed that the controlling factor in the classification process was the uniaxial unconfined compressive stress test which was an expression of the ultimate compression stress that could be sustained by the given specimen before failure under unconfined condition.Limestone could be classified into their categories as show in Table 2.1.

Table 2.1 Classification of different types of building limestone(Tarawneh et al.,2007).

	Class A	Class B	Class C
SA, mm	<33	33-37	37-44
CS, N/mm^2	>55	28-55	12-28
WA, %	<3	3-4.2	4.2-7.5
SV, m/s	2500-6000 for limestone rocks		

Sabatakakis et al. (2008) investigated the influence of composition content and microstructure on strength and especially on mi values of intact sedimentary rocks (marlstone, sandstone and limestone). Physical properties petrography and the strength under uniaxial and triaxial compression were determined. The material constant (m_i) which constitutes an input parameter for Hoek and Brown failure criterion, was estimated by analyzing the results from triaxial compression tests. From the statistical analysis of the data, regression equations were established among rock material parameters, while conversion factors relating index properties and strength were also determined. The sampling locations were widely distributed around Greek. In this study limestone samples were generally dark grey colored. Calcite content was generally more than 95% and other constituents were opaque minerals. According to Folk's (1962) classification scheme, the limestone samples were mainly sparse biomicrite, poorly-washed biosparite and unsorted biosparite.The m_i value of limestones was strongly related to the ratio of sparitic to micritic material percentage and it decreased according to a power expression with the increase of composition percentage of sparitic material. The mean value of m_i for biosparite is about 15 and for biomicrite 22. The textural characteristics appeared to be more important than mineral composition to the mechanical properties variation of limestones. The sparitic textures grain sizes were typically large and the packing was not very dense resulted in lower strength as it was expressed via the mi values.

Gajic et al. (2010) determined lithologocal, structure, texture properties and depositional processes and their link with physical and mechanical properties in order to examine the quality of the Struganik limestone in Vardar zone, western Serbia. The Struganik limestone was qualified by its petrological and physical and mechanical properties coupled with statistical analysis.According to the observed petrographic of the limestone sample were classified by Folk (1959) to two types, micrite limestone and allochemical limestone.The micrite limestone was mainly composed of microcrystalline calcite-micrite. Non-carbonaceous compounds were clay minerals, organic matter and subordinated silty material. According to the calcite content, micrite limestone referred to pure limestone, clayey limestone and marlstone. The micritelimestones were defined by the amount of biogenic component, either as micrite and fossiliferousmicrite or as biomicrite (Figure 2.4). The allochemical and orthochemical types, the bio-intraspar varieties were the commonest. Among the sparry varieties, intrasparrudite, biosparrudite, intrabiosparrudite, biosparite and intrabiosparite may be distinguished(Figure 2.5).

The values of physic-mechanical properties, such as density, porosity, water absorption and strength, were statistically analyzed and the obtained data were used to assess the rock quality in the quarry. The relationship among the quantified properties was described by regression analyses and the equations of the best-fit line.Themechanical properties of the limestone pointed to variable quality, which was in accordance with the petrogarphical heterogeneity of the rocks. The samples of rocks were strong to moderately strong regarding the unconfined compressive strength. The micritelimestones had highest values of strength but the allochemical (biointar-spar) have lower strength values. The reasons for variable technical properties might be during variable layer thickness, lamination, stylolite and other texture forms.

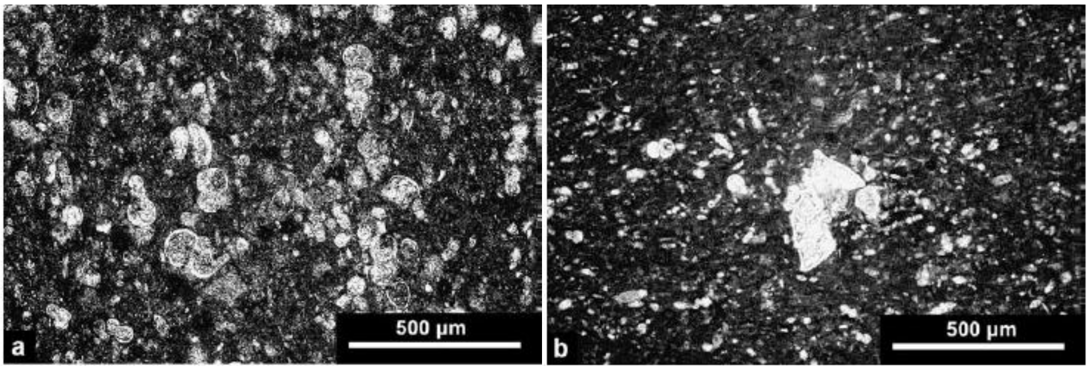


Figure 2.4 Photomicrographs of the micrite limestone: (a)Biomicrite and (b) Fossiliferousmicrite with globotruncana in the middle(Gajic et al., 2010)

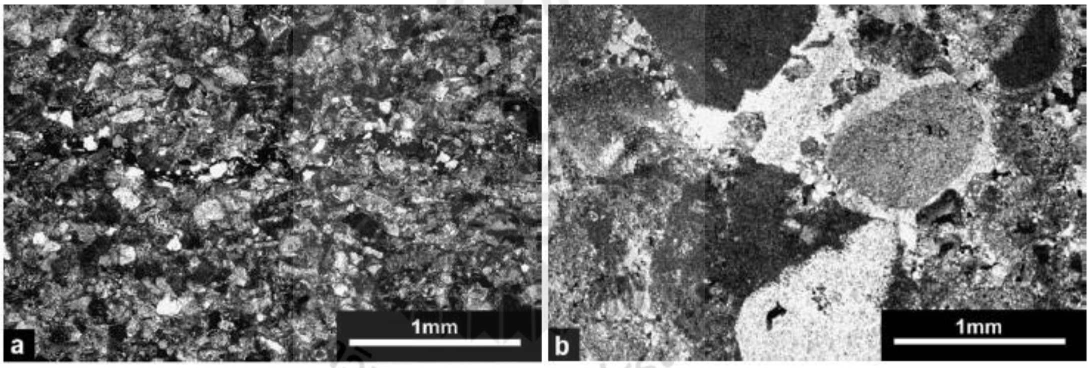


Figure 2.5 Photomicrographs of the allochemical limestone: (a) Fine-grained intrabiosparite and (b) Coarse-grained biosparite(Gajic et al., 2010)

Ozcelik et al. (2013) analyzed selected limestones and marbles and to determine the relationship between petrographical characteristics, engineering index properties and mechanical properties. Data belonging to limestone and marble rock samples were also subjected to regression analyses to obtain best curve fits. The empirical equationsemploying microscopic data including mineralogical and petrographical properties, which were statistically significant and correlated with mechanical properties to provide estimators of engineering properties involved in correlation. In their case the rock fabric and compositional properties of rock samples were correlated with five engineering properties using regression analysis.The engineering propertiesinclude uniaxial compressive strength, tensile strength, elastic modulus, unit volume weight and apparent porosity. The empirical equations were developed to predict physical and mechanical properties of limestone and marble rock samples from microscopic data. The physical and mechanical properties of limestone and marble rock samples from microscopic data could be more easily predicted by using a simple linear regression. The equationswere developed for the prediction of strength of the limestone by using a stepwise linear multiple regression. They found out that smaller grain size was a primary reasonfor the higher uniaxial compressive strength of limestone and marble type rocks. Quartz content was positively correlated with uniaxial compressive strength ofthe limestone, calcite content in limestone and marble rock types was negatively correlated with uniaxial compressive strength.

Arman et al. (2014) studied on the petrographical aspects and relationship between geomechanical properties, uniaxial compressive strength, point load index, indirect tensile strength, Schmidt hardness value, P-wave velocity and unit weight, of the limestonesof the Lower Oligocene Asmari Formation in Al Ain city area. They described the effects of the rock properties on their geomechanical behavior as local bedrock. The core samples for the required rock mechanical tests were obtained from each of these blocks. Fragments from the samples used for coring were set aside for sectioning for petrographic and textural analysis. The mineral composition of the examined limestone rock samples are composed mainly of calcite, in addition to minor percentages of dolomite and quartz. The rocks samples had three microfacies types (Figure 2.6). Packstonemade up of skeletal and non-skeletal grains embedded in a partially recrystallized micritic groundmass. Wackestone contained a smaller percent of skeletal grains embedded in micritic groundmass. Grainstone had a low content of skeletal grains embedded in a sparry groundmass. The most common of these processes were dissolution and dolomitization resulting in vuggy and moldic porosity within the skeletal grains and groundmass.They found that the fossils and cavities had heterogonous distribution may affected the geomechanical properties. In case studied, the result illustrated very weak correlation and highly scattered data. This result might be due to the present of inconspicuous microfracture and their cementing material.

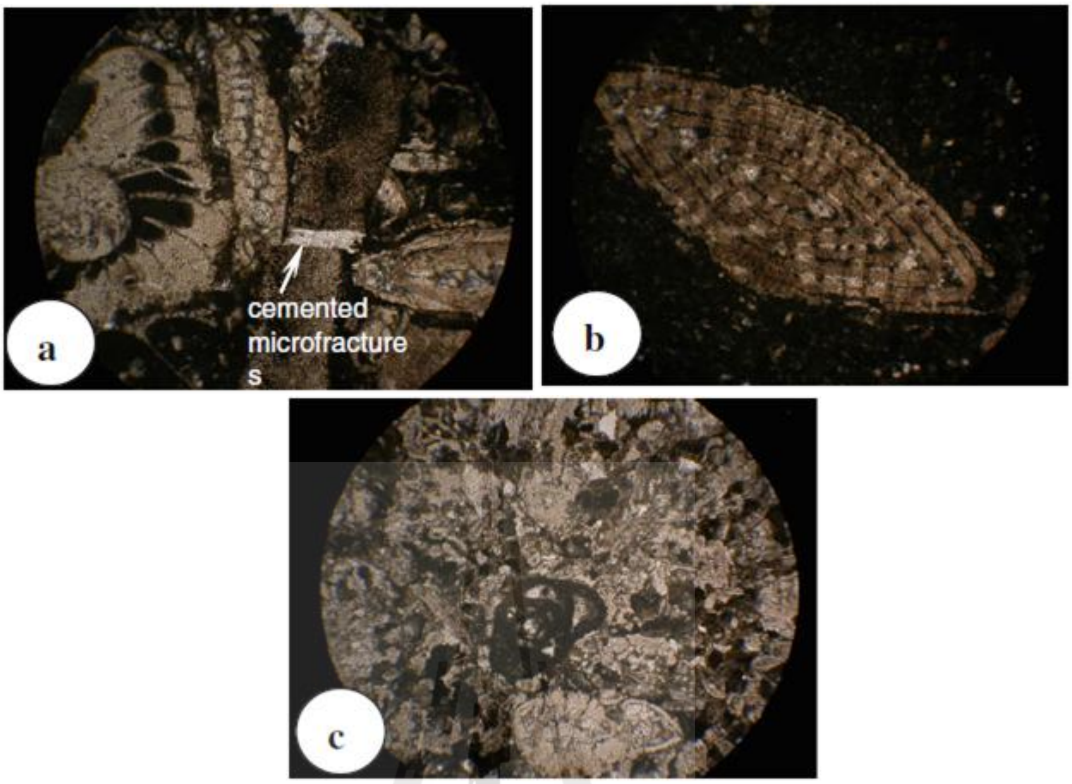


Figure 2.6 The obtained microfacies types: (a) Packstone,(b)Wackstone, and (c)Grainstone.(Arman et al., 2014)

Table 2.2 Summary of mechanical properties, physical properties and mineralogical composition of carbonate rocks

Rock type	Mechanics properties				Physical properties				Mineral composition				Sources
	Compressive strength (MPa)	Tensile strength (MPa)	Slake durability index (%)	Los Angles abrasion (%)	Elastic modulus (GPa)	Density (g/cm3)	Porosity (%)	Wave velocity (km/s)	Calcite (%)	Quartz (%)	Clay minerals (%)	Other minerals (%)	
Limestone	46.60	13.80	-	-	7.27	2.67	1.822	-	-	-	-	-	Rajabzadeh et al. (2012)
	28.60	5.00	-	-	7.23	2.69	0.867	-	-	-	-	-	
	-	-	-	-	-	2.69	2.279	-	-	-	-	-	
	93.50	7.80	-	-	12.27	2.71	0.274	-	-	-	-	-	
	34.00	10.80	-	-	13.27	2.71	1.926	-	-	-	-	-	
	22.10	5.30	-	-	8.01	2.56	9.764	-	-	-	-	-	
	-	-	-	-	-	2.60	8.607	-	-	-	-	-	
	39.40	6.60	-	-	10.53	2.71	0.444	-	-	-	-	-	
Dolomite	54.27	9.67	-	-	11.58	2.72	0.432	-	-	-	-	-	
	35.20	6.60	-	-	12.97	2.71	0.333	-	-	-	-	-	
	36.30	7.07	-	-	11.57	2.71	0.403	-	-	-	-	-	
Marble	67.80	7.25	-	-	11.87	2.69	0.529	-	-	-	-	-	
Limestone	55.30	4.65	-	-	22.83	2.68	0.530	-	81.20	1.30	-	-	Ozcelik et al. (2013)
	65.80	4.04	-	-	25.24	2.68	0.890	-	80.00	3.40	-	-	
	59.77	4.03	-	-	17.43	2.68	0.590	-	76.60	2.00	-	-	
	56.76	5.01	-	-	20.35	2.69	0.600	-	72.30	3.70	-	-	
	105.48	8.50	-	-	20.25	2.69	0.350	-	55.40	27.40	-	-	
	110.77	7.68	-	-	17.94	2.69	0.320	-	59.00	23.00	-	-	
Marble	52.26	7.55	-	-	17.02	2.70	0.440	-	90.00	-	-	-	
	79.00	8.25	-	-	17.50	2.69	0.340	-	90.00	-	-	-	
	63.49	6.84	-	-	21.14	2.69	0.200	-	90.00	-	-	-	
	74.51	6.39	-	-	21.43	2.70	0.290	-	92.00	-	-	-	
	49.02	5.96	-	-	13.07	2.69	0.430	-	92.00	-	-	-	

Table 2.2 Summary of mechanical properties, physical properties and mineralogical composition of carbonate rocks (cont.)

Rock type	Mechanics properties				Physical properties				Mineral composition				Sources
	Compressive strength (MPa)	Tensile strength (MPa)	Slake durability index (%)	Los Angles abrasion (%)	Elastic modulus (GPa)	Density (g/cm3)	Porosity (%)	Wave velocity (km/s)	Calcite (%)	Quartz (%)	Clay minerals (%)	Other minerals (%)	
Marble	45.57	5.09	-	-	15.72	2.70	0.430	-	90.00	-	-	-	Ozcelik et al. (2013)
	51.84	6.47	-	-	15.96	2.69	0.390	-	93.00	-	-	-	
	28.68	7.73	-	-	12.74	2.74	0.830	-	95.00	-	-	-	
	30.00	3.10	-	-	9.86	2.69	0.610	-	95.00	-	-	-	
Limestone	32.59	5.14	97.64	-	-	2.37		8.31	-	-	-	-	Arman et al. (2014)
	40.66	3.88	97.75	-	-	2.38		6.68	-	-	-	-	
	57.80	5.33	95.83	-	-	2.38		5.50	-	-	-	-	
	30.91	4.30	96.66	-	-	2.22		8.21	-	-	-	-	
	31.27	4.07	97.9	-	-	2.25		6.60	-	-	-	-	
	34.78	8.11	95.57	-	-	2.46		10.01	-	-	-	-	
	34.45	6.33	97.91	-	-	2.47		7.82	-	-	-	-	
	20.39	7.60	94.86	-	-	2.19		9.27	-	-	-	-	
	50.06	8.08	98.11	-	-	2.49		9.40	-	-	-	-	

CHAPTER III

SAMPLES PREPARATION

3.1 Sample collection

Rock samples used in this research are the carbonate rocks of the Saraburi Group which exposed in Phetchabun, NakhonSawan, Lopburi, Saraburi areas. Blocks of eight types of the carbonate rocks were collected includinga travertine, two marbles and five limestones. Classification of limestones in the field followed Dunham’s scheme (Dunham, 1992) are shown on Figure 3.1 and description of the limestones are summarized in Table 3.1. Marble are classified by their color and texture.

3.2 Sample preparation

Specimens were prepared for four different laboratory tests: physical andmechanical properties, petrogarphic analysis and chemical analysis.

3.2.1 Physical and mechanical tests

The physical and mechanical properties of the carbonate rocks were determined by a variety of laboratory tests. The specimens were prepared and tested generally in accordance with the procedures suggested by ISRM (1981). The specimens were drilled from the blocks of each rock type.The blocks were cored to give cylindrical specimens.The ends of specimens were trimmed as required and further smoothen by a saw cut machine in order to avoid end effects.

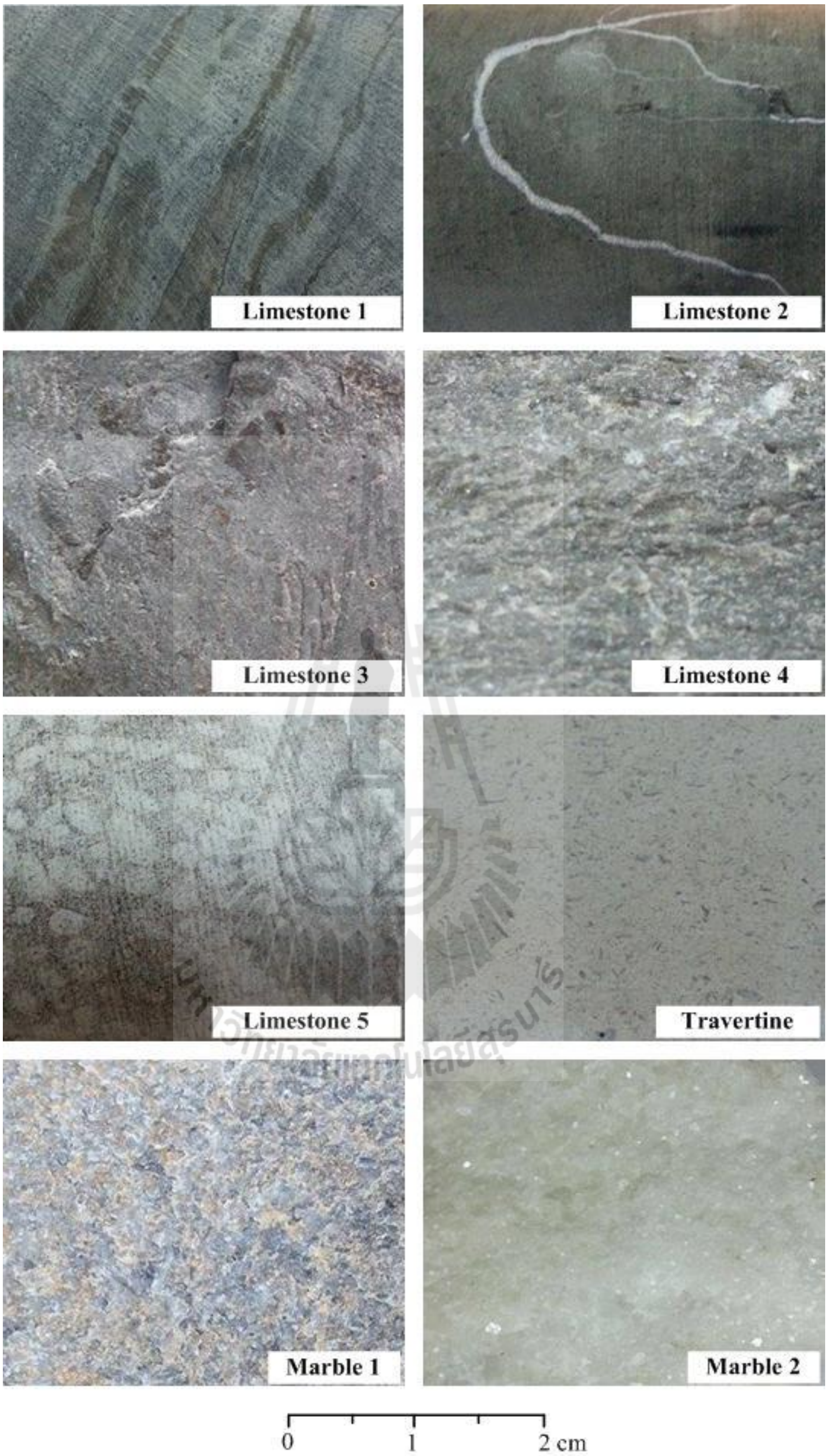


Figure 3.1 Texture of eight different types of the carbonate rocks as classified in the field

Table 3.1 Initial classification of the carbonate rocks in this study.

Rock type	Code	Classification (Dunham, 1962)	Sample description
Limestone 1	L1	Mudstone	Thick bedded, dark grey to greenish grey, with clay and calcite laminations and intraclasts
Limestone 2	L2	Mudstone	Thick bedded, very dark grey, with small bioclasts (<2 mm)
Limestone 3	L3	Wackstone	Thick bedded, grey, with frequent non-linear calcite veins
Limestone 4	L4	Wackstone	Thick bedded, grey, with bioclasts
Limestone 5	L5	Packstone	Thick bedded, grey, with large fusulines(> 0.2 mm)
Travertine	T	Packstone	Thick bedded, light gray, colorless, with bioclasts greater than 10%, small bioclasts (<2 mm)
Marble 1	MB1	Brownish grey marble	Inequigranular, fine to medium crystalline marble (≥ 2 mm), brown and light grey in color
Marble 2	MB2	White marble	Inequigranular, fine to medium crystalline (≥ 0.1 mm), white marble

The specimens prepared for physical and mechanical properties such as density, porosity, wave velocity and uniaxial compressive strength tests are of cylindrical shape with 54 mm in diameter and 108 mm in length (L/D=2)(Figure 3.2).Brazilian tensile strength was determined on the cylindrical shape samples with 54 mm in diameter and 27 mm in length (L/D=0.5)(Figure 3.3).

The cylindrical specimens were tested, and after failure they becomerock fragment. There rocks fragments were broken into the properties for slake durability index and Los Angeles abrasion and impaction test. Rock fragments of more than 5,000 g and 500 g of each type were prepared for Los Angeles abrasion and impaction test and slake durability index test, respectively(Figure 3.4). Specimen coding and number of tested specimens are shown in Table 3.2.

Table 3.2 Specimen code used in this study

Type \ Experiments	Density, Porosity, Wave velocity	Uniaxial compressive strength	Brazilian tensile strength	Slake durability index	Los Angles abrasion and impaction
Limestone 1	LS-01-P01 to P03	LS-01-UCS01 to UCS03	LS-01-BZ01 to BZ03	LS-01-SDI01	-
Limestone 2	LS-02-P01 to P03	LS-02-UCS01 to UCS03	LS-02-BZ01 to BZ05	LS-02-SDI01	-
Limestone 3	LS-03-P01 to P05	LS-03-UCS01 to UCS05	LS-03-BZ01 to BZ05	LS-03-SDI 01	LS-03-LAAI01
Limestone 4	LS-04-P01 to P05	LS-04-UCS01 to UCS05	LS-04-BZ01 to BZ05	LS-04-SDI01	LS-04-LAAI01
Limestone 5	LS-05-P01 to P05	LS-05-UCS01 to UCS05	LS-05-BZ01 to BZ05	LS-05-SDI01	LS-05-LAAI01
Travertine	T-01-P01 to P03	T-01-UCS01 to UCS03	T-01-BZ01 to BZ05	T-01-SDI01	-
Marble 1	MB-01-P01 to P03	MB-01-UCS01 to UCS03	MB-01-BZ01 to BZ05	MB-01-SDI01	-
Marble 2	MB-02-P01 to P05	MB-02-UCS01 to UCS05	MB-02-BZ01 to BZ05	MB-02-SDI01	MB-02-LAAI01
Number of samples	29	29	40	10	4
Total samples					112

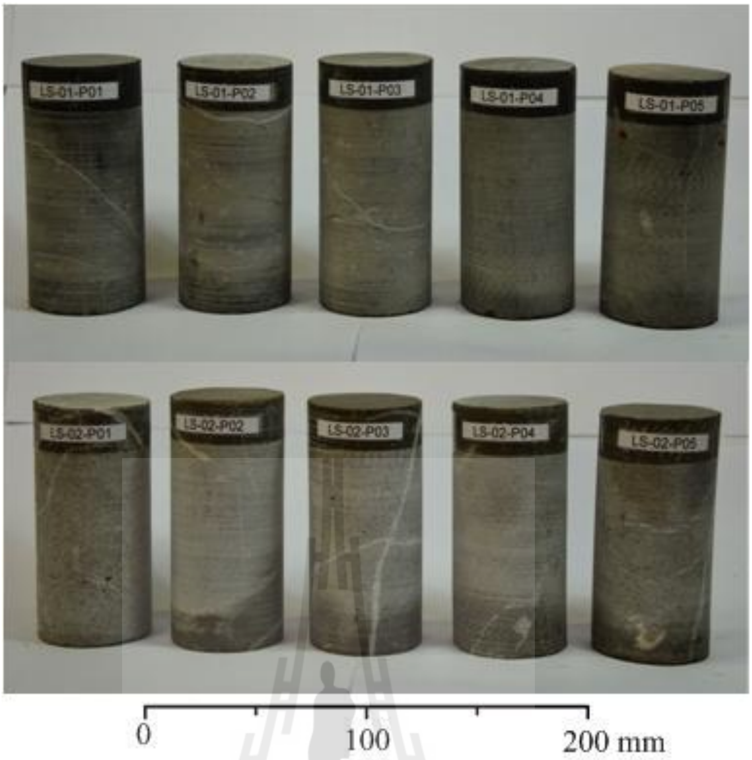


Figure 3.2 Examples of cylindrical specimens prepared for measurement of density, porosity, wave velocity and uniaxial compressive strength test

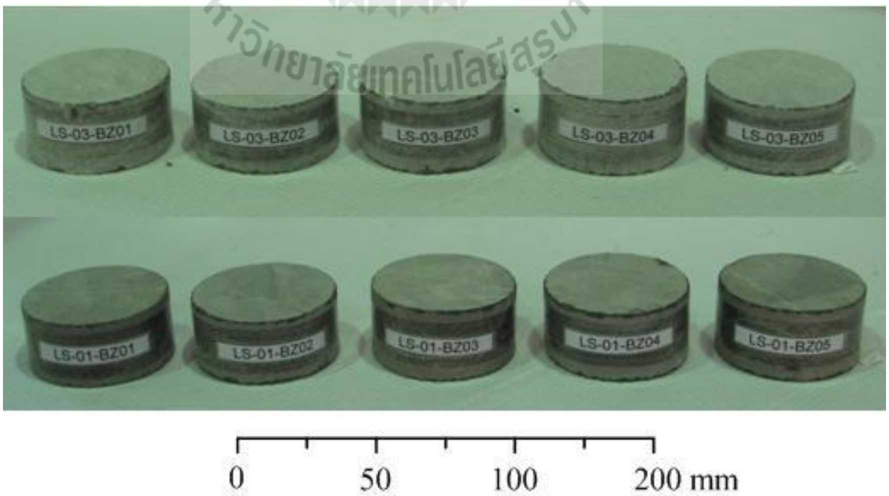


Figure 3.3 Examples of shot cylindrical specimens prepared for Brazillian tensile strength test

Figure 3.4 Examples of irregular shape specimens prepared for slake durability index test and Los Angeles abrasion and impaction test

3.2.2 Petrographic analysis

Three slaps of each rock type were prepared to have a size of about 80×30 mm which can be trimmed to fit a size of glass (Figure 3.5). The specimen was cut by a diamond saw to obtain a flat surface and the required size. A flat surface was polished to eliminate the traces of cutting and to obtain a smooth flat surface.The polished surface was stuck onto a glass slide with a colorless and isotropic cementing agent. After the slap was stuck to the slide, it was cut to obtain the thinnest slice possible, until if reached a final thickness of about 0.03 mm.The slide was cleaned and covered with a slide cover, which was attached with a similar cement to the one used to stick the sample to the slide.The thin section were studied under the polarizing microscope is also called the petrographic microscope because it is used in the study of rocks. In examine thin section of rocks, the texture is brought out and mineral composition be determined.Point counting is a statistical technique. Point counting is a means of describing rock in an unbiased and quantitative way.It involves looking at a large number of points on the photomicrographs, recording exactly what is seen at each point and then assembling a description from all the photomicrographs recorded. In order to be a statistically valid representation, the number of points described is typically 100.

3.2.3 Chemical analysis

Representatives of each carbonate rocks type are grinded into rock powder (Figure 3.7) (with less than 2 µm in size) for the XRD analysis which powder is then spread uniformly over the surface of a glass slid, using a small amount of adhesive binder. The instrument is so constricted that this slide, when clamped in place, rotates in the path of collimated X-ray beam while a counting tube, mounted on an arm, rotates about is to pick up the reflected X-ray beam. The samples were analyzed at The Center of Scientific and Technological Equipment, Suranaree University of Technology.

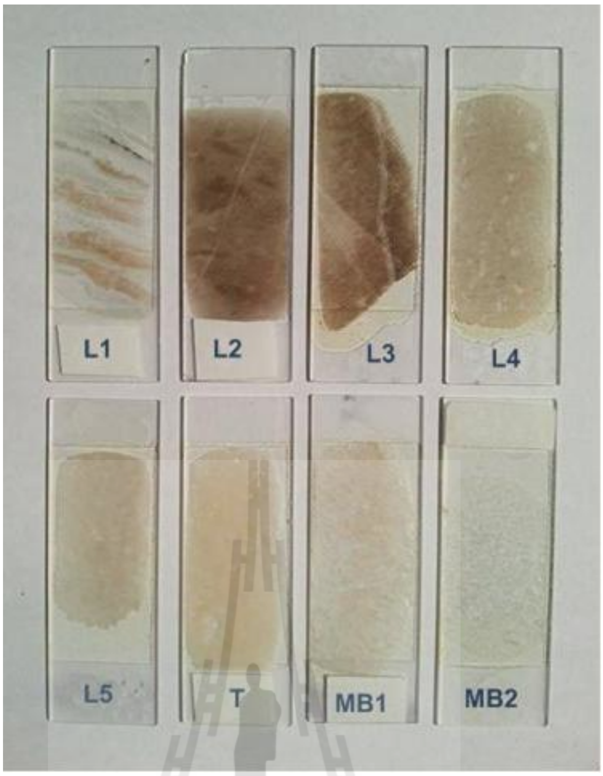


Figure 3.5 Thin sections prepared for petrographic analysis used under polarizing microscope

Figure 3.6 Rock powder prepared for XRD analysis

CHAPTER IV

LABORATORY EXPERIMENT

The laboratory experiment preformed can be divided into four main types: physical and mechanical property determinations, petrography analysis and chemical composition. All experiments are 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.

4.1 Physical property testing

4.1.1 Density and porosity measurement

Saturation buoyancy is a common method for measuring the porosity and density (ASTM-C 97-88). The measurement of porosity was conducted under dry and fully saturated conditions. Under the dry condition, the specimens were oven dried for 48 hours before the test, under the saturated condition the specimens were submerged under water in a pressure vacuum chamber for 48 hours before the measurement (Figure 4.1). Weights were measured using a digital balance (with ±0.1 g accuracy).As a result, the porosity ranges between 0.00 to 3.60% and the mean density changes from 2.50 to 2.72% (Table 4.1).

4.1.2 Wave velocity measurement

Wave velocity measurement was performed on the cylindrical shaped specimens with L/D=2.0 (see Chapter 3). Sonic viewer 170 (Model 5338) was used(Figure 4.2). The direct transmission method was conducted for measuring of P-wave, S-wave velocities of sample. The faces of the specimens wereflattenedand smooth to provide tight contacts of transducers with the faces of each specimen. The application of ultrasonic compression wave pulses to the sample was carried out in accordance with American Society of Testing Materials (ASTM D2845) test designation.Wave velocity through the specimen was calculated from the travel time from the generator to the receiver at the opposite end.The results are showninTable 4.1. The P-wave velocity of the carbonate rocks ranges from 6.37 to 6.96 km/s and S-wave velocity ranges from 2.35 to 3.83 km/s. The wave velocities of the carbonate rocks are similar to the ranges of other for example studies Siegesmund and Dürrast(2011).

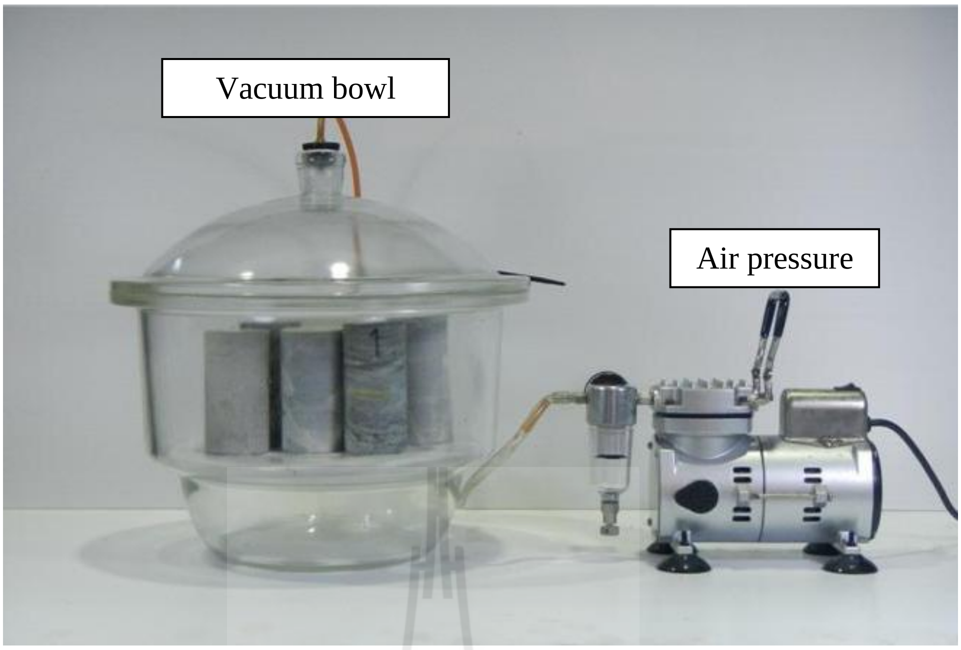


Figure 4.1 Porosity measurement device

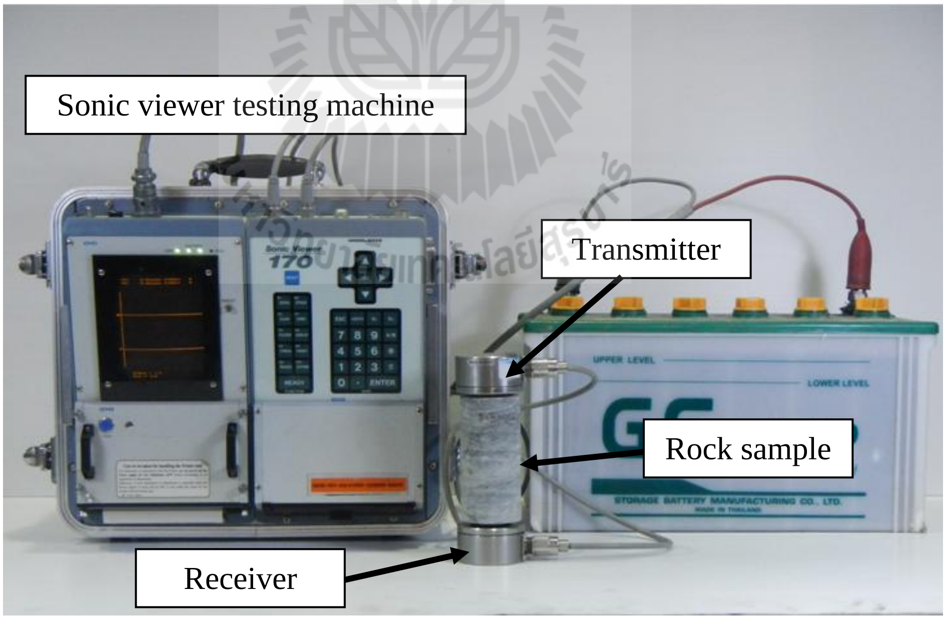


Figure 4.2 Wave velocity measurementsdevice

Table 4.1 Physical properties of the specimens

Rock types	Specimen No.	Density (g/cm^3)	Porosity (%)	Wave velocity (km/s)	
				P-wave	S-wave
Limestone 1	LS-01-P01	2.69	0.00	6.85	3.84
	LS-01-P02	2.70	0.00	7.68	3.40
	LS-01-P03	2.75	0.00	6.35	3.24
	Average	2.71 ± 0.03	0.00 ± 0.00	6.96 ± 0.67	3.49 ± 0.31
Limestone 2	LS-02-P01	2.70	0.00	6.47	3.39
	LS-02-P02	2.69	0.00	6.89	3.12
	LS-02-P03	2.70	0.00	5.74	3.78
	Average	2.70 ± 0.01	0.00 ± 0.00	6.37 ± 0.58	3.43 ± 0.33
Limestone 3	LS-03-P01	2.68	0.22	7.71	4.08
	LS-03-P02	2.67	0.22	5.21	2.81
	LS-03-P03	2.68	0.28	6.79	3.50
	LS-03-P04	2.70	0.24	6.30	4.64
	LS-03-P05	2.68	0.19	7.34	4.10
	Average	2.68 ± 0.01	0.23 ± 0.03	6.67 ± 0.98	3.83 ± 0.70
Limestone 4	LS-04-P01	2.69	0.32	7.72	3.97
	LS-04-P02	2.69	0.31	5.62	2.74
	LS-04-P03	2.69	0.34	5.52	2.87
	LS-04-P04	2.67	0.35	6.74	3.78
	LS-04-P05	2.69	0.32	6.50	2.51
	Average	2.69 ± 0.01	0.33 ± 0.02	6.42 ± 0.09	3.17 ± 0.66
Limestone 5	LS-05-P01	2.67	0.23	5.80	2.25
	LS-05-P02	2.69	0.31	6.35	4.14
	LS-05-P03	2.63	0.31	6.89	2.39
	LS-05-P04	2.68	0.35	6.18	2.59
	LS-05-P05	2.65	0.35	6.96	2.31
	Average	2.66 ± 0.02	0.31 ± 0.05	6.44 ± 0.49	2.74 ± 0.80
Travertine	T-01-P01	2.50	2.03	5.72	2.37
	T-01-P02	2.51	3.75	6.64	2.34
	T-01-P03	2.49	5.03	6.18	2.35
	Average	2.50 ± 0.01	3.60 ± 1.51	6.18 ± 0.46	2.35 ± 0.02
Marble 1	MB-01-P01	2.71	0.78	6.21	3.90
	MB-01-P02	2.73	0.99	7.76	3.18
	MB-01-P03	2.70	0.99	5.86	3.18
	Average	2.71 ± 0.02	0.92 ± 0.12	6.61 ± 1.01	3.42 ± 0.42

Table 4.1 Physical properties of the specimen (cont.)

Rock types	Specimen No.	Density (g/cm^3)	Porosity (%)	Wave velocity (km/s)	
				P-wave	S-wave
Marble 2	MB-02-P01	2.71	1.07	6.74	3.41
	MB-02-P02	2.70	1.47	6.80	4.06
	MB-02-P03	2.71	0.69	5.91	3.70
	MB-02-P04	2.75	0.71	6.52	3.80
	MB-02-P05	2.72	1.73	7.75	3.42
	Average	2.72 ± 0.02	1.13 ± 0.46	6.74 ± 0.66	3.68 ± 0.27

4.2 Mechanical property testing

4.2.1 Uniaxial compressive strength test

The uniaxial compressive strength (UCS) or the rock strength is required for applications of strength in each type of carbonate rocks. Test procedure for the laboratory determination of the UCS strictly follows the American Society for Testing and Materials standard (ASTM D7012) and suggested method by ISRM (International Society of Rock Mechanics Brown, 1981). In this study the cylindrical specimens with a nominal diameter of 54 mm and length to diameter ratio of 2.0 were axially loaded to failure. The UCS of eachspecimen was calculating by dividing the maximum load by the original cross sectional area.The compression load frame was used. The laboratory arrangement is shown inFigure 4.3. The strength (σ_c) was calculated from the applied axial load. The following equation is used:

$$\sigma_c = P/A \tag{4.1}$$

where Pis the failure load and A is the initial cross-sectional area.The elastic modulus (E) is 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 4.2. The test resultsshow that the mean UCS ranges between 41.2 MPa and 72.0 MPa, all samples can be classified to medium strength rock according to Arman et al. (2014). The extension failure mode is observed in photograph of selected failed specimens (Figure 4.4).

Figure 4.3 Uniaxial compressive strength test device

Figure 4.4 Example of the rock sampleswith failed under loading from uniaxial compressive strength testing

Table 4.2 Test results from the uniaxial compressive strength testing

Rock types	Specimen No.	σ_c (MPa)	E (GPa)	Poisson's ratio
Limestone 1	LS-01-UCS01	75.81	16.73	0.25
	LS-01-UCS02	54.62	15.48	0.19
	LS-01-UCS03	85.84	18.29	0.27
	Average	72.09 ± 15.94	16.83 ± 1.41	0.24 ± 0.04
Limestone 2	LS-02-UCS01	63.11	10.25	0.21
	LS-02-UCS02	65.00	14.28	0.23
	LS-02-UCS03	68.42	17.45	0.2
	Average	65.51 ± 2.69	13.99 ± 3.61	0.21 ± 0.02
Limestone 3	LS-03-UCS01	58.54	7.47	0.14
	LS-03-UCS02	49.96	6.13	0.12
	LS-03-UCS03	73.99	8.15	0.12
	LS-03-UCS04	66.49	8.85	0.14
	LS-03-UCS05	44.53	5.14	0.11
	Average	58.70 ± 11.95	7.15 ± 1.51	0.13 ± 0.01
Limestone 4	LS-04-UCS01	45.90	4.33	0.13
	LS-04-UCS02	50.05	6.55	0.13
	LS-04-UCS03	34.50	4.8	0.19
	LS-04-UCS04	54.31	8.4	0.15
	LS-04-UCS05	41.21	4.33	0.13
	Average	45.19 ± 7.70	5.68 ± 1.77	0.15 ± 0.03
Limestone 5	LS-05-UCS01	61.68	8.19	0.12
	LS-05-UCS02	52.13	9.29	0.17
	LS-05-UCS03	57.78	8.51	0.14
	LS-05-UCS04	59.19	8.51	0.15
	LS-05-UCS05	51.04	6.65	0.13
	Average	56.36 ± 4.60	8.23 ± 0.97	0.14 ± 0.02
Travertine	T-01-UCS01	44.83	8.02	0.28
	T-01-UCS02	52.54	8.25	0.33
	T-01-UCS03	43.52	8.08	0.31
	Average	46.96 ± 4.87	8.12 ± 0.12	0.31 ± 0.03
Marble 1	MB-01-UCS01	50.21	8.84	0.2
	MB-01-UCS02	49.00	10.9	0.24
	MB-01-UCS03	52.20	19.67	0.26
	Average	50.47 ± 1.61	13.14 ± 5.75	0.23 ± 0.03

Table 4.2 Test results from the uniaxial compressive strength testing (cont.)

Rock type	Specimen No.	σ_c (MPa)	E (GPa)	Poisson's Ratio
Marble 2	MB-02-UCS01	54.25	11.38	0.13
	MB-02-UCS02	41.08	7.36	0.16
	MB-02-UCS03	56.40	12.54	0.16
	MB-02-UCS04	56.34	11.96	0.17
	MB-02-UCS05	49.90	8.79	0.16
	Average	51.59 ±6.44	10.41 ± 2.23	0.16 ± 0.02

4.2.2 Brazilian Tensile strength test

The Brazilian tensile strength test (BZ) was conducted to determine the indirect tensile strength of the specimens. The test was performed in accordance with the ASTM standard (ASTM D3967) and the ISRM suggested methods (Bieniawski and Hawkes, 1978). Five specimens type of the carbonate rocks were tested. The compression load frame is used (Figure 4.5). The diametrical load was applied to the specimen. The cylindrical surfaces were free from obvious tool marks and any irregularities across the thickness of the specimen. The constant stress rate was maintained about 0.1 MPa/second. The load was applied until failure which normally occurs under 2 minutes. The Brazilian tensile strength (σ_B) was calculated from the applied axial load. The following equation is used:

$$\sigma_B = 2P_f/\pi LD \qquad (4.2)$$

where P_f is the applied load at failure indicated by the testing machine, L is the thickness of specimen, and Dis the diameter of specimen.The results from this test are given in Table 4.3.Photograph of selected failed specimens is given in Figure 4.6.

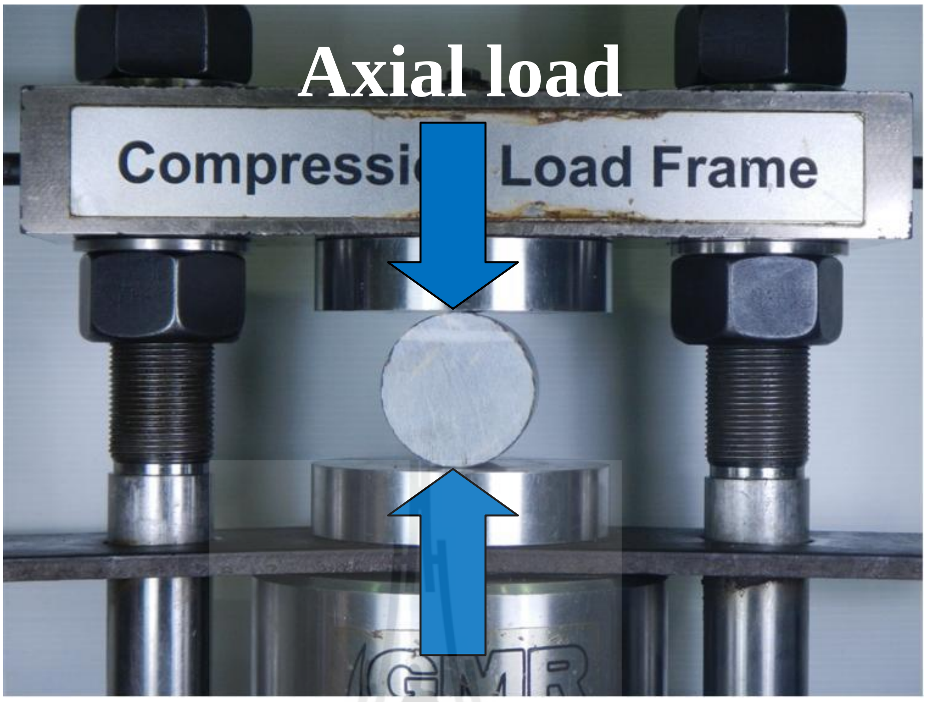


Figure 4.5 Brazilian tensile strength test, device showing that the specimen is loaded diametrically with compression load frame

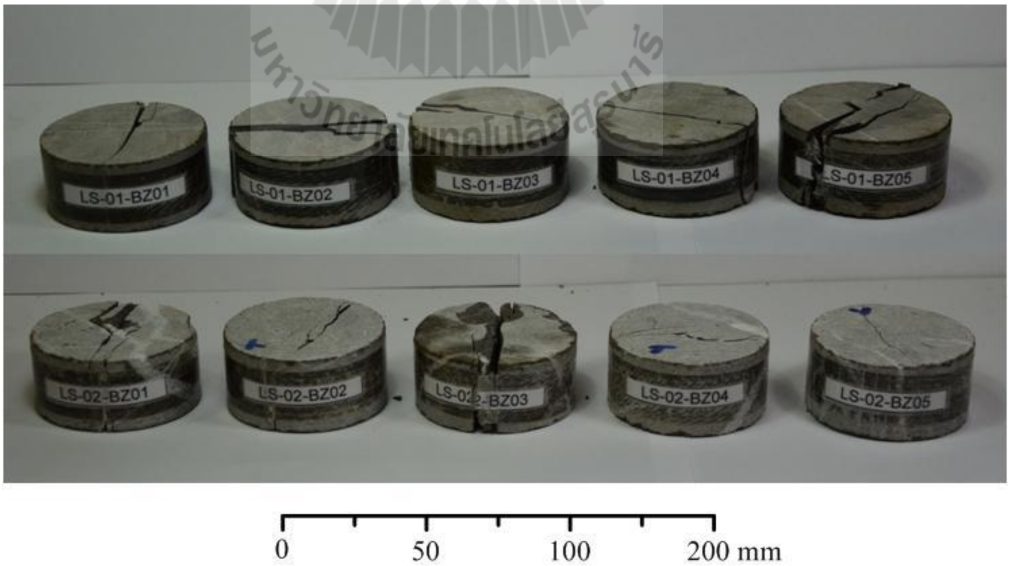


Figure 4.6 Examples of the post-tested specimens after from Brazilian tensile strength tests

Table 4.3 Test results from the Brazilian tensile strength testing.

Rock types	Specimen No.	σ_B (MPa)
Limestone 1	LS-01-BZ01	17.49
	LS-01-BZ02	13.84
	LS-01-BZ03	19.03
	LS-01-BZ04	18.51
	LS-01-BZ05	16.69
	Average	17.11 ± 2.04
Limestone 2	LS-02-BZ01	15.68
	LS-02-BZ02	12.62
	LS-02-BZ03	13.68
	LS-02-BZ04	11.19
	LS-02-BZ05	12.79
	Average	13.19 ± 1.65
Limestone 3	LS-03-BZ01	8.85
	LS-03-BZ02	9.85
	LS-03-BZ03	9.2
	LS-03-BZ04	10.48
	LS-03-BZ05	9.63
	Average	9.60 ± 0.62
Limestone 4	LS-04-BZ01	7.68
	LS-04-BZ02	7.47
	LS-04-BZ03	10.23
	LS-04-BZ04	8.05
	LS-04-BZ05	7.97
	Average	8.28 ± 1.11
Limestone 5	LS-05-BZ01	10.85
	LS-05-BZ02	7.82
	LS-05-BZ03	8.02
	LS-05-BZ04	8.88
	LS-05-BZ05	9.43
	Average	9.00 ± 1.22
Travertine	T-01-BZ01	7.11
	T-01-BZ02	7.63
	T-01-BZ03	7.74
	T-01-BZ04	9.17
	T-01-BZ05	8.18
	Average	7.97 ± 0.77

Table 4.3 Test results from the Brazilian tensile strength testing (cont.).

Rock types	Specimen No.	σ_B (MPa)
Marble 1	MB-01-BZ01	11.32
	MB -01-BZ02	12.42
	MB -01-BZ03	11.06
	MB -01-BZ04	11.42
	MB -01-BZ05	7.34
	Average	10.71 ± 1.95
Marble 2	MB-02-BZ01	15.68
	MB-02-BZ02	11.09
	MB-02-BZ03	17.77
	MB-02-BZ04	11.15
	MB-02-BZ05	7.34
	Average	12.61 ± 4.13

4.2.3 Slake durability index test

The test of the slake durability index (SDI) was aimed to determine durability of the rock specimens. The specimens had same in size and weight of 50 g. Ten specimens for eachtype of carbonate rock were prepared. A sample was placed into a drum and was rotated for a specified of speed of 20 rpm for 10 min. The sample was dried at 110˚C for 12 hours. Figure 4.7 shows apparatus and data reduction was similar to that of the standard practice (ASTM D4644) standard.The slake durability index was calculated as the percentage ratio of final to initial dry weights of rock in the drum after the drying and wetting cycles.The results of slake durability index (I_d) isgiven in Table 4.4.

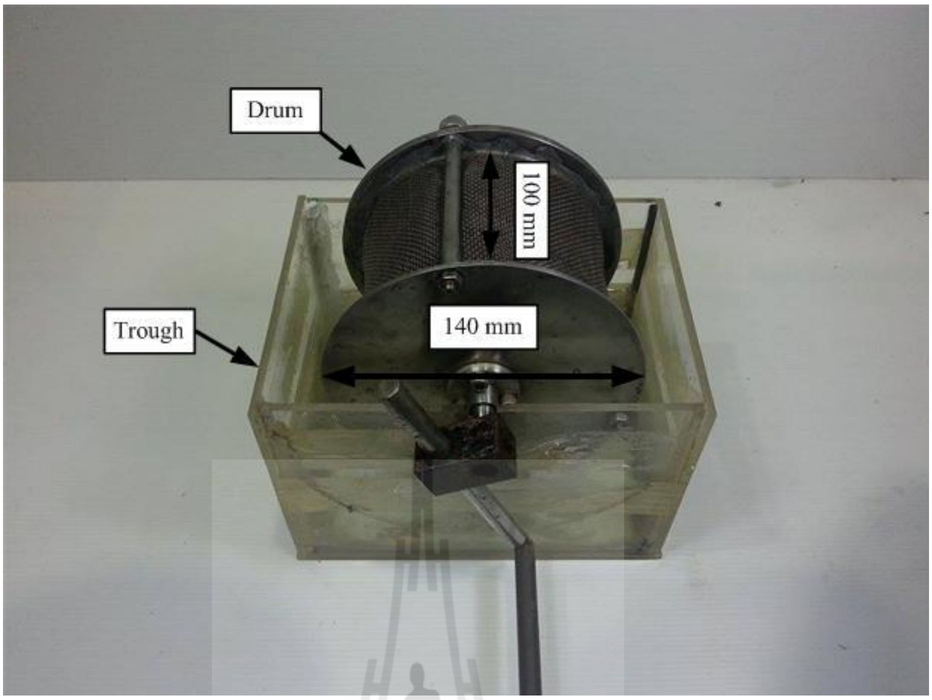


Figure 4.7 Slake durability index testing apparatus

Figure 4.8 Examples of the post-tested specimensfrom slake durability index test

4.2.4 Los Angeles abrasion and impaction test

The Los Angeles abrasionand impaction test (LAAI) is a measure of degradation of mineral aggregates of standard grinding resulting from a combination of actions including abrasion or attrition, impact, and grinding in a rotating steel drum contain a specified number of steel spheres.Los Angeles abrasion testwas performed following the ASTM (C-131:Resistance to Degradation of Small-Size Coarse).The Los Angeles and impact testing machine consists of a hollow steel cylinder, closed at both ends,having an inside diameter of 710±5mm and an inside length of 508±5 mm (Figure 4.9). A rock fragments specimenswere placed into this cylinder with a charge consisting of steel spheres and was rotated for a specified number of revolutions from 100 to 500. The interior of the cylinder had a shelf that picks up the sample and charge during each rotation and drops them on the opposite side of the cylinder, subjecting the sample to abrasion or attrition. The cylinder rotated at 30 to 33 rpm and after the prescribed number of revolutions, the machine was automatically be stopped by a counter switch. The test consisted of placingrock fragments specimens in a steel drum along with 6–12 steel spheres weighing approximately 420 g each and having a diameter of 47 mm.The tests were carried out on 8 different rock types of the carbonate rocks. The abrasion values are given in Table 4.3.

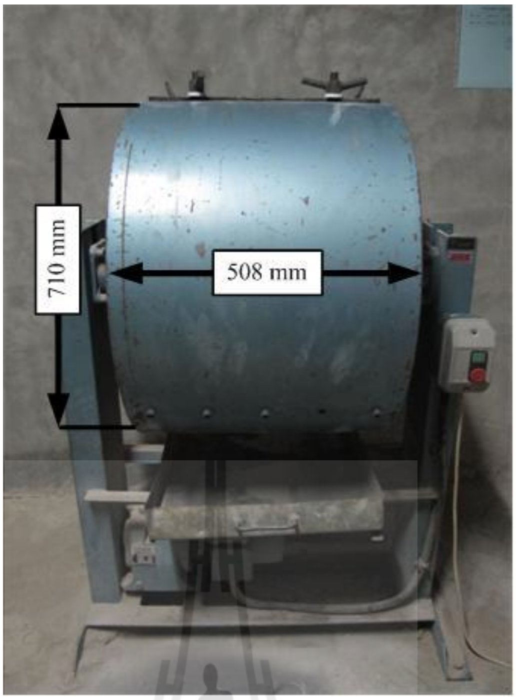


Figure 4.9 Los Angeles abrasion and impaction testing machine

Figure 4.10 Examples of the specimens after testing of Los Angeles abrasion and impaction test

Table 4.4 Test results from the slake durability index testing andLos Angeles abrasion and impact testing.

Rock types	Specimen No.	Id (%)	Specimen No.	LAAI (%)
Limestone 1	LS-01-SDI01	99.24	-	-
Limestone 2	LS-02-SDI01	99.38	-	-
Limestone 3	LS-03-SDI01	99.24	LS-03-LAAI01	20.60
Limestone 4	LS-04-SDI01	99.31	LS-04-LAAI01	18.12
Limestone 5	LS-05-SDI01	99.28	LS-05-LAAI01	20.73
Travertine	T-01-SDI01	99.33	-	-
Marble 1	MB-01-SDI01	99.58	-	-
Marble 2	MB-01-SDI01	99.58	MB-02-LAAI01	21.11

4.3 Petrographic analysis

The petrographic characteristics of the travertine, marbles and limestoneswere carried out under a polarized light microscope. The rock thin sections (see Chapter 3) were examined for the petrographic description and were classified according to their mud matrix (micrite), calcite cement (sparite) and texture. The quantification of limestone components such as allochem, mud matrix and calcite cement was based on comparison charts and point counting method (Flügel, 2004). Sparite to micrite ratio of all sample were also determined. The results are given in Table 4.5. The limestone samples were classified according to Folk's (1962) classification scheme. The samples can be assigned as Micrite, Sparse biomicrite, Rounded pelsparite and Packed biomicrite types. The texture of limestone can be classified in two broad categories, micritic limestone and sparitic limestone.Selected microphotographs showing the characteristics of each type are shown in Figures 4.10 to4.15.Micritic texture of limestones are the fine grained calcite muds. These have again often been microspars and sometimes have been affected by clay mineral (Figure 4.11).Biomicrite texture consists mainly of mud matrix and allochem component is represented argillaceous and organic materials (in Figures 4.12 - 4.13 and Figures 4.15 – 4.16). Rounded pelsparite consists mainly of cemented by sparitic or microspars (Figures 4.14). The marbles were classified by grain size and color (Figure 4.17- 4.18) two types: brownish gray marble and white marble. The contents of calcite were distinguished for each thin section.

Table 4.5 Petrographic characteristic asproperties of the carbonate rocks samples

Rock type	Classification Folk, 1962	Component (%)			Sparite/Micrite ratio	Microscopic notes (matrix alteration, allochem, microfracture and vein)
		Allochem	Micrite	Sparite		
Limestone 1	Micrite	0.10	60.03	39.87	0.66	Matrix completely altered to microspars (<0.1 mm crystal size),partly replaced by calcite (<2 mm), clay minerals
Limestone 2	Sparse biomicrite	15.28	60.25	24.47	0.41	Matrix and allochem mostly altered to microspars, argillaceous and organic materials present
Limestone 3	Sparse biomicrite	17.50	76.36	6.14	0.35	Mud matrix, rarely altered
Limestone 4	Rounded pelsparite	58.33	10.72	30.95	2.89	Allochem partly altered to microspars, matrix mostly replaced by sparry calcite
Limestone 5	Packed biomicrite	57.68	30.56	11.76	0.38	Allochem partly altered to microspars, matrix altered to microspars and partly replaced by sparry calcite
Travertine	Sparse biomicrite	10.08	85.12	4.80	0.06	Matrix and allochem mostly altered to microspars,Mud matrix, rarely altered
Marble 1	Brownish gray marble	N/A	N/A	N/A	N/A	Inequigranular, fine to medium crystalline marble, brown and light grey, granoblastic, anhedral, bending twin lamellae
Marble 2	White marble	N/A	N/A	N/A	N/A	Inequigranular, fine to medium crystalline marble, white, granoblastic, anhedral

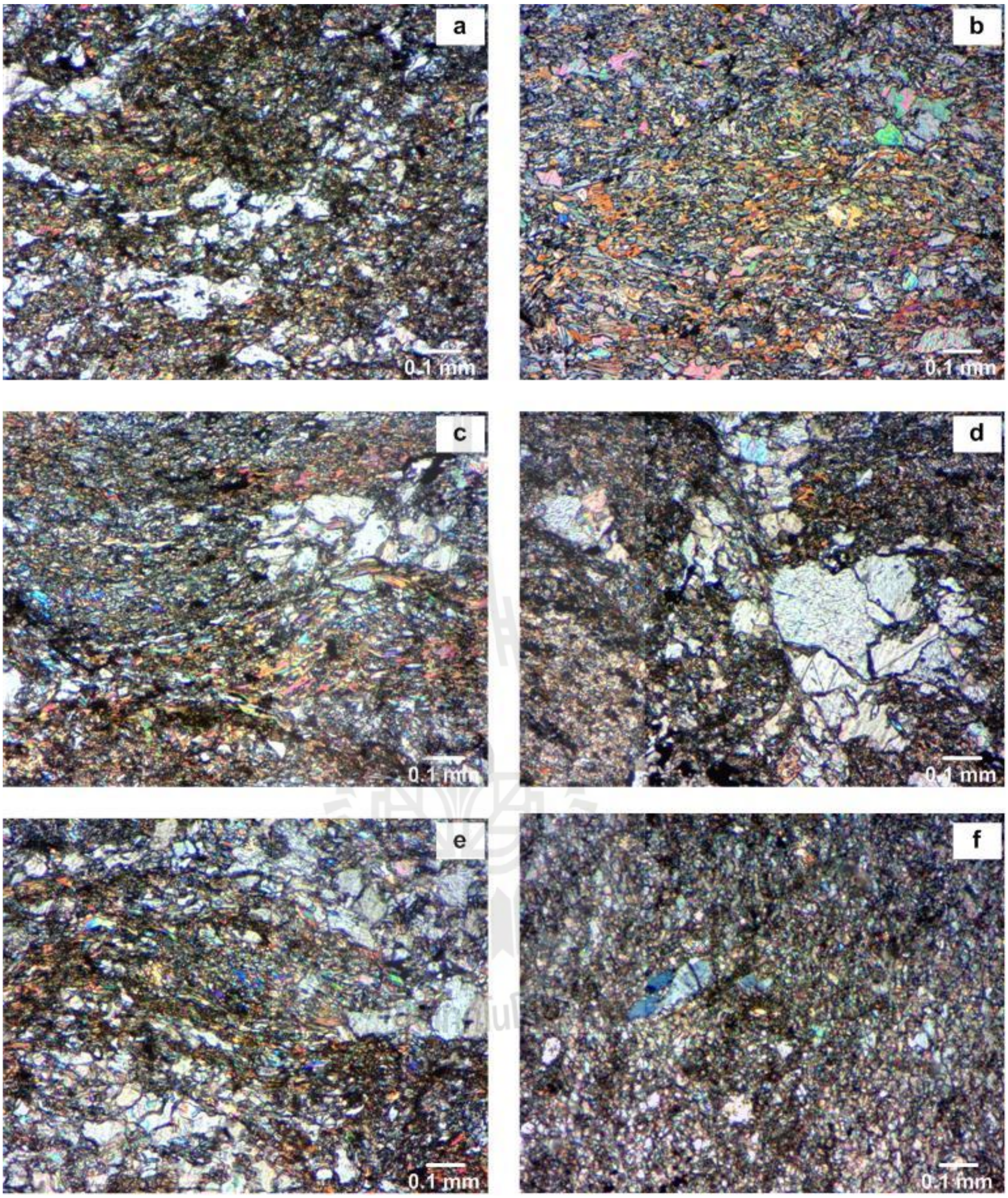


Figure 4.11 Representative photomicrographsof limestone1:Micrite

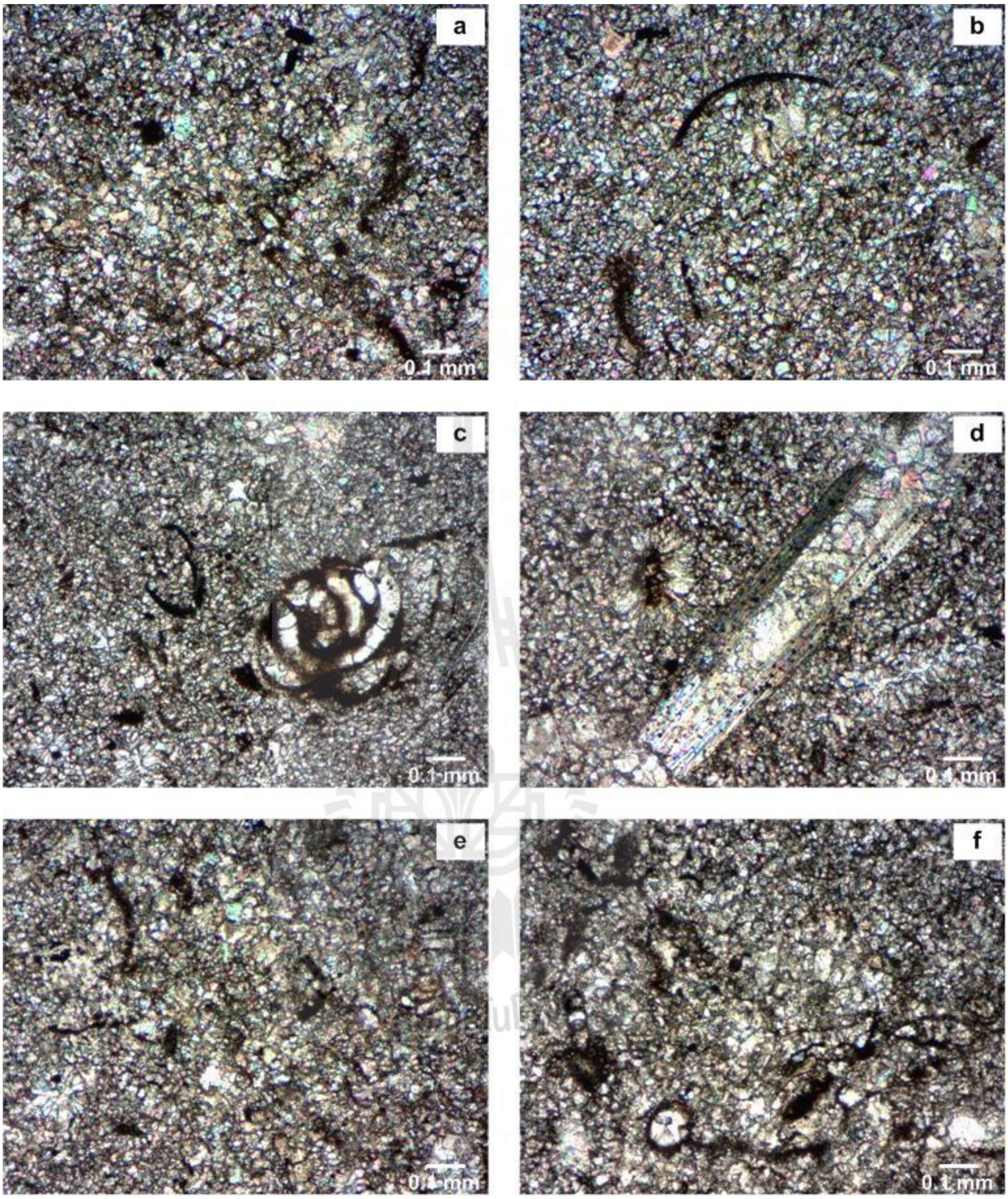


Figure 4.12 Representative photomicrographs of limestone2: Sparse biomicrite

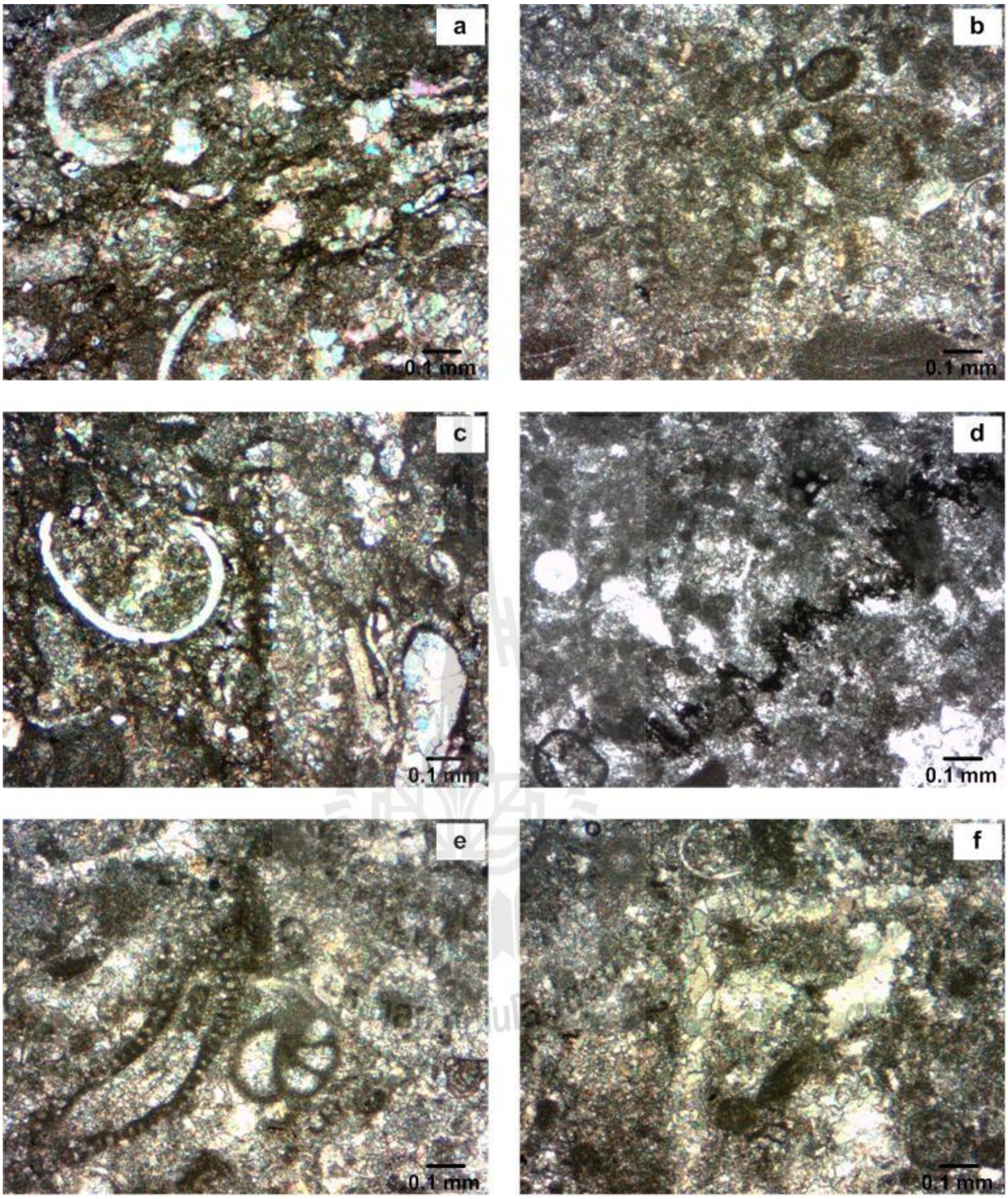


Figure 4.13 Representative photomicrographs of limestone3: Sparse biomicrite

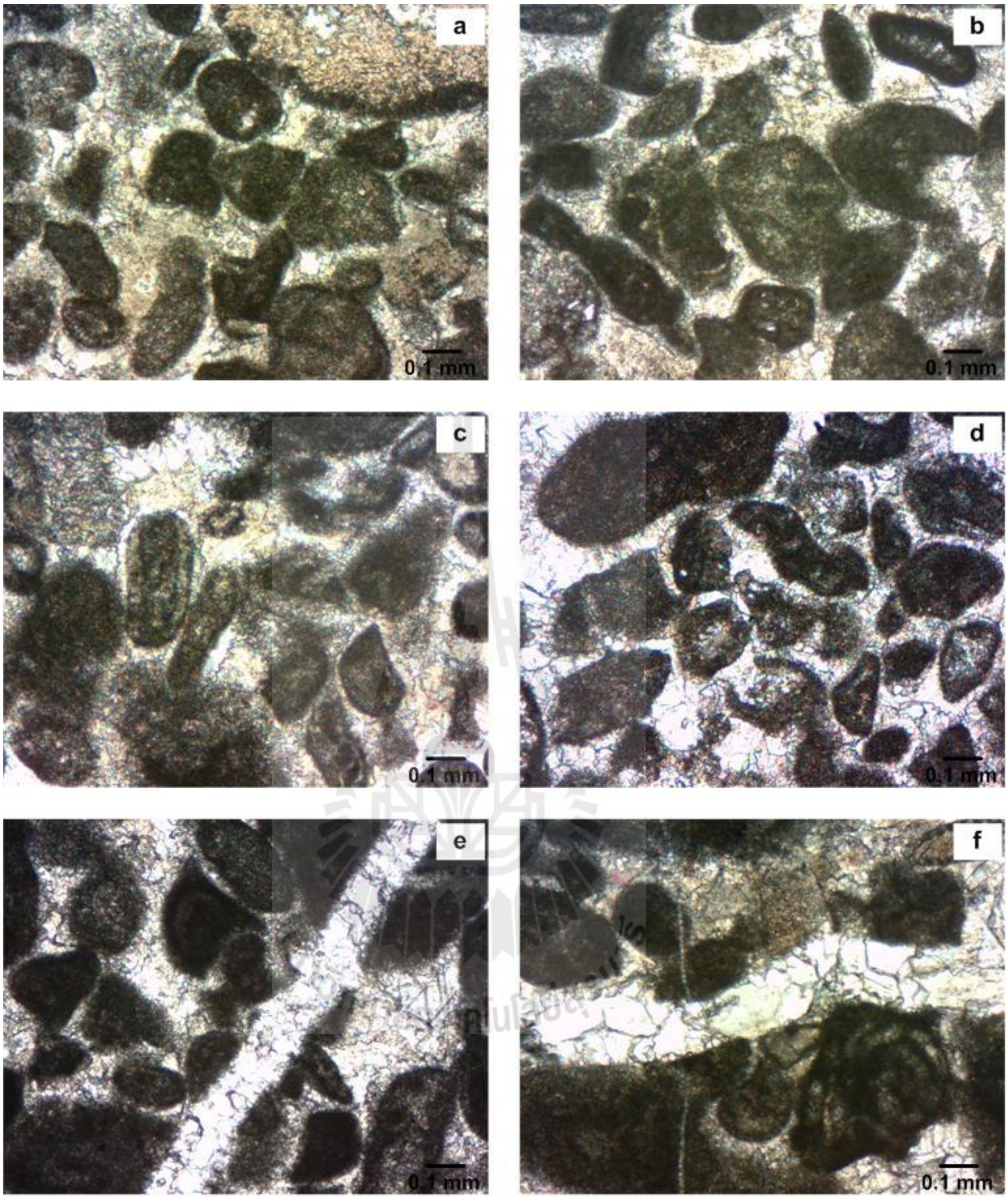


Figure 4.14 Representative thin section micrographs of limestone4: Rounded pelsparite

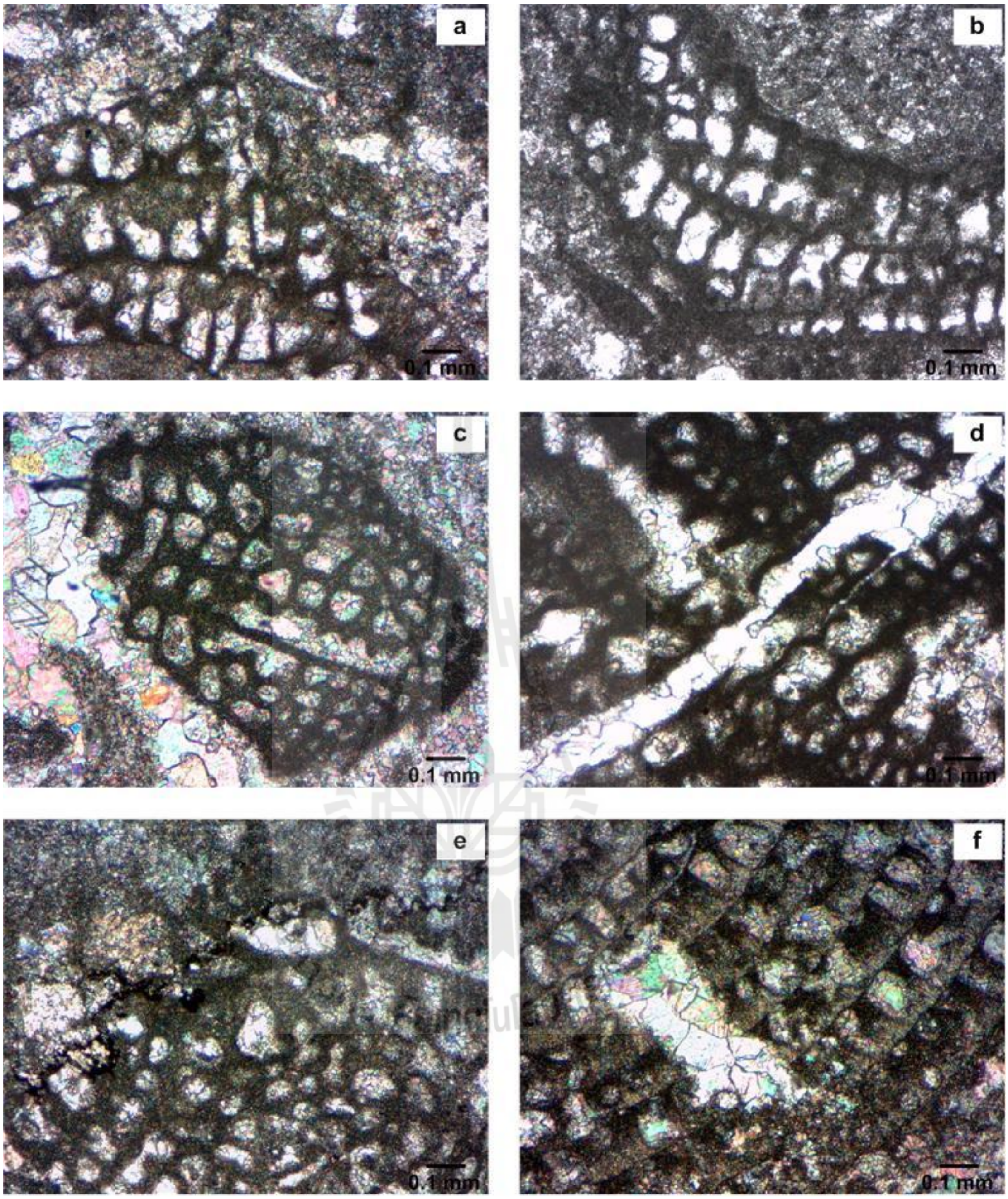


Figure 4.15 Representative photomicrographs of limestone5: Packed biomicrite

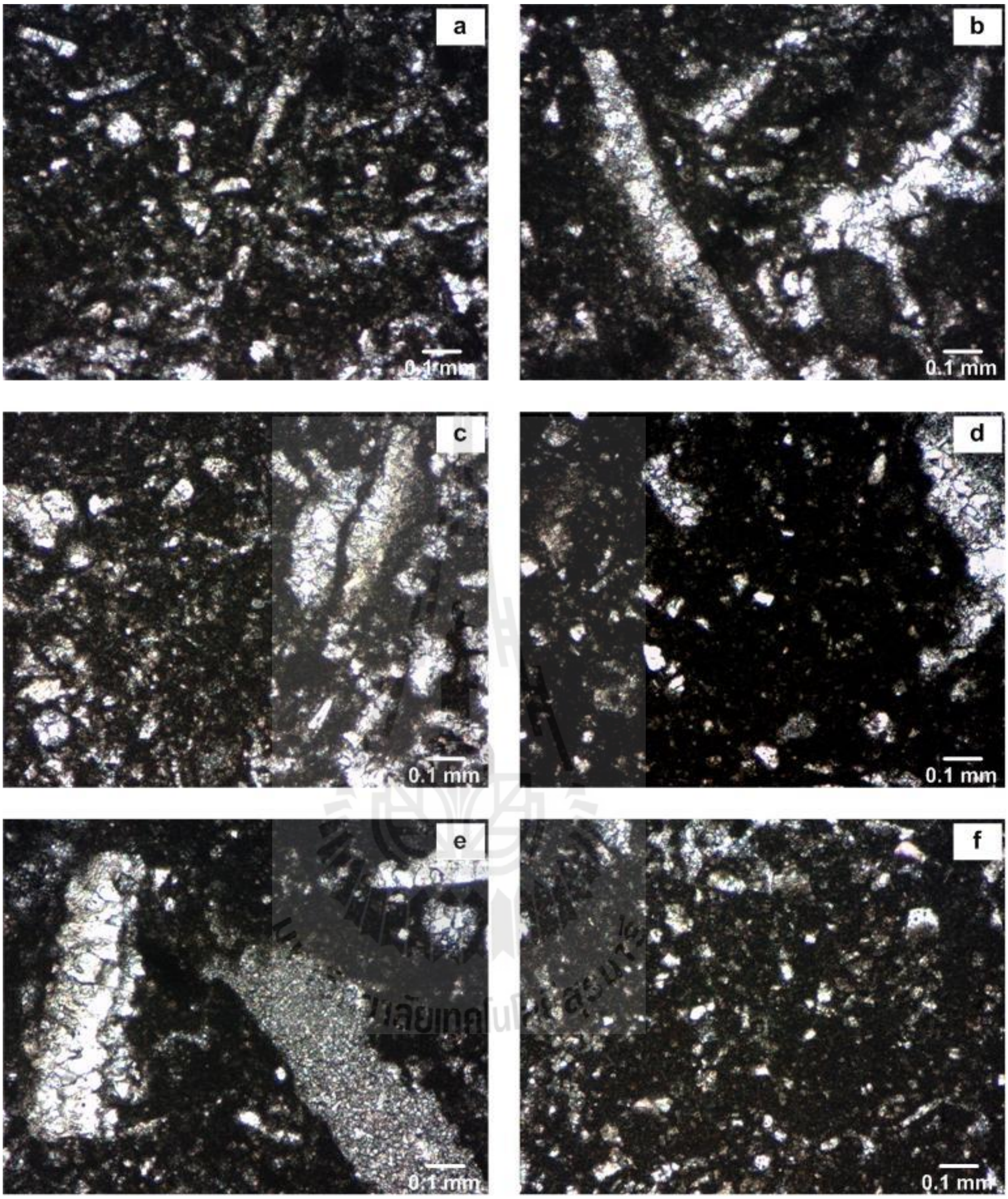


Figure 4.16 Representative photomicrographsof travertine : Sparse biomicrite

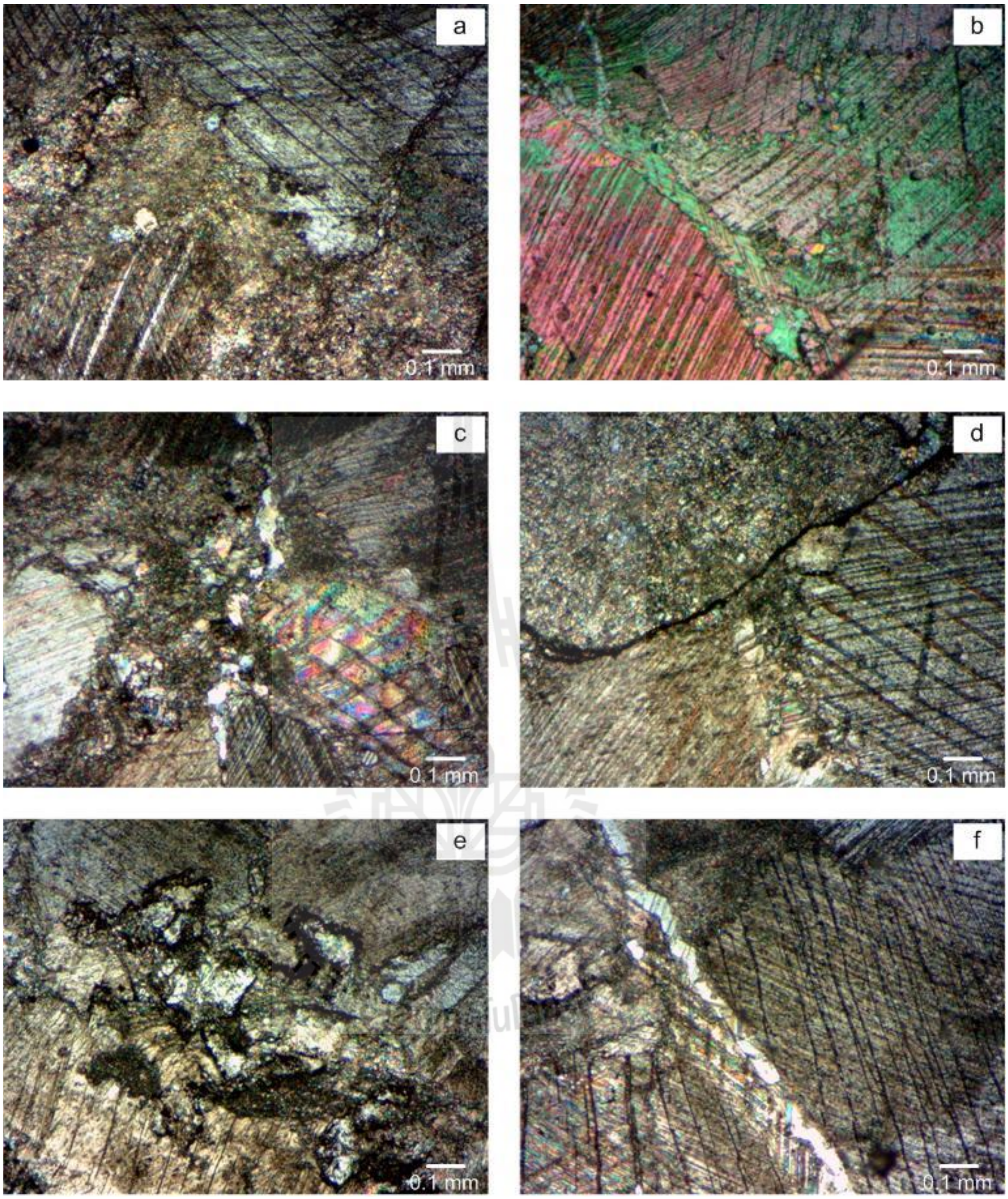


Figure 4.17 Representative photomicrographsof marble1 : Brownish gray marble

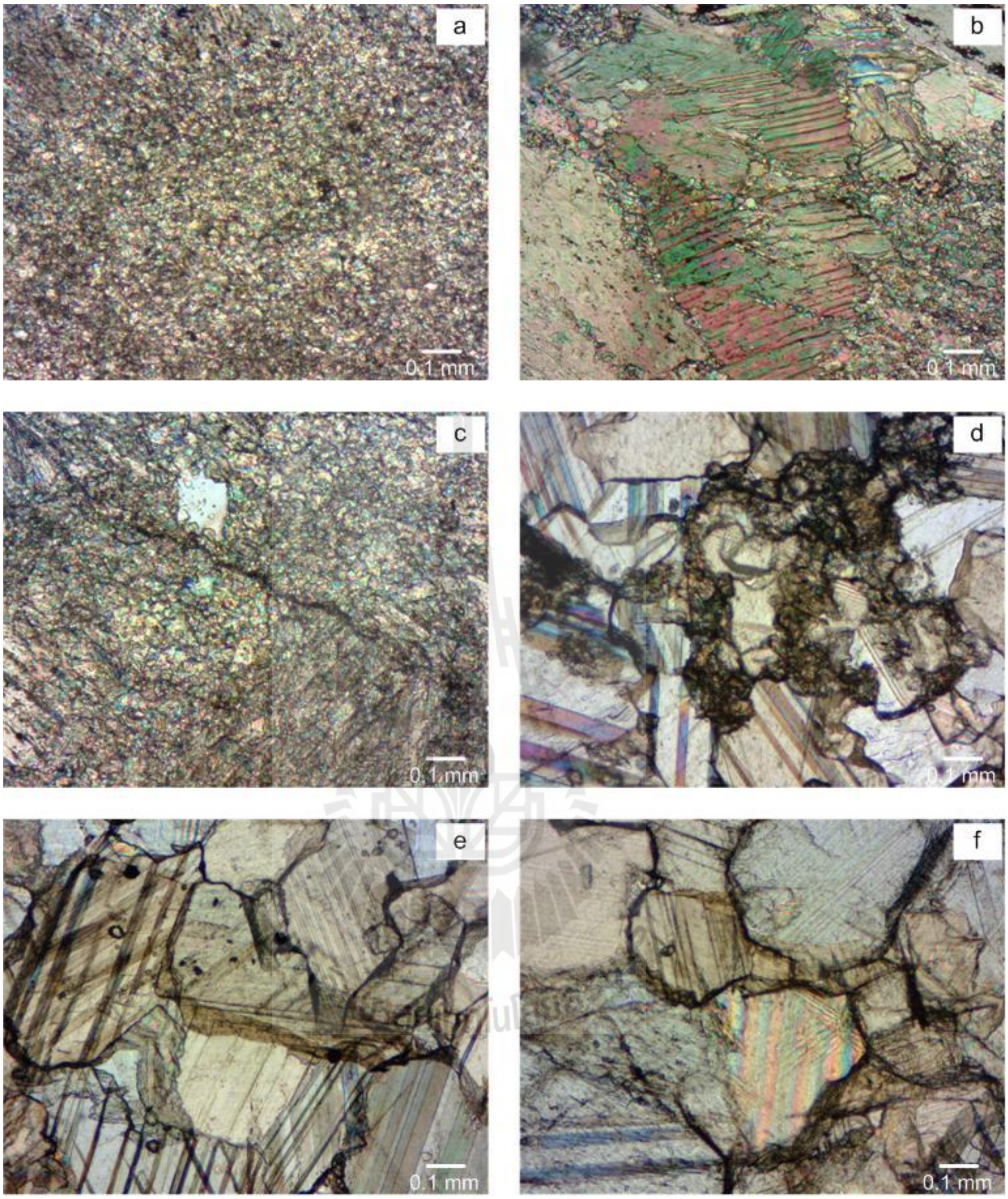


Figure 4.18 Representative photomicrographsof marble 2 : White marble

4.4 Chemical analysis

Chemical composition of the carbonate rocks were analyzed by X-ray diffraction technique (XRD). The results show that the mineralogical compositions are consisted mainly of calcite and secondly dominated by quartz. Calcite content ranges from 67.82 to 100 %. The samples containing quartz content ranges from 0.00 to 11.01 %Quartz content is generally less than 1% except for L1 (11.01%) and L2 (1.36). The dolomite content less than 1% and clay mineral content less than 1%, except for L1 and L2 had content more than 1%. Rock samples studied; there are also other minerals such as Orthoclase, Actinolite, Fe-bearing minerals. The results are shown in Table 4.7and the diffraction pattern of the carbonate rock specimens is shown in Figures 4.19 -4.22.

Table 4.6XRD analysis of the studied carbonate rocks (analyzed bycenter of Scientific and Technological Equipment, Suranaree University of Technology)

Rock type	Specimen No	Chemical composition (%)					
		Calcite	Dolomite	Quartz	Clays	Siderite and Pyrite	Other mineral
Limestone 1	L1	67.82	0.39	11.01	1.62	0.00	19.16
Limestone 2	L2	96.90	0.39	1.36	1.02	0.32	0.01
Limestone 3	L3	98.08	0.31	0.73	0.86	0.02	0.00
Limestone 4	L4	97.86	0.57	0.94	0.59	0.01	0.03
Limestone 5	L5	98.38	0.33	0.27	0.95	0.07	0.00
Travertine	T	98.70	0.14	0.21	0.95	0.00	0.00
Marble 1	MB1	98.48	0.31	0.10	0.67	0.12	0.32
Marble 2	MB2	100.00	0.00	0.00	0.00	0.00	0.00

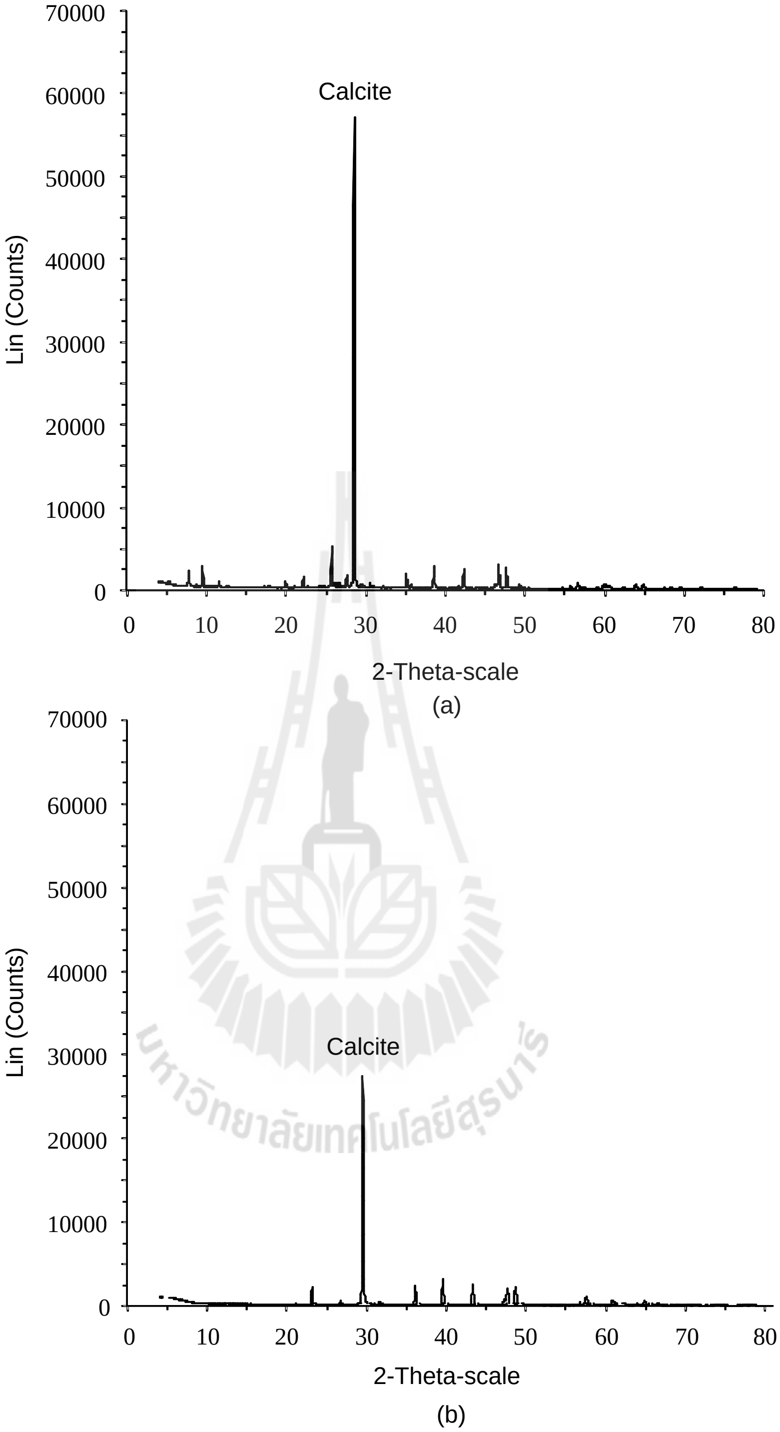
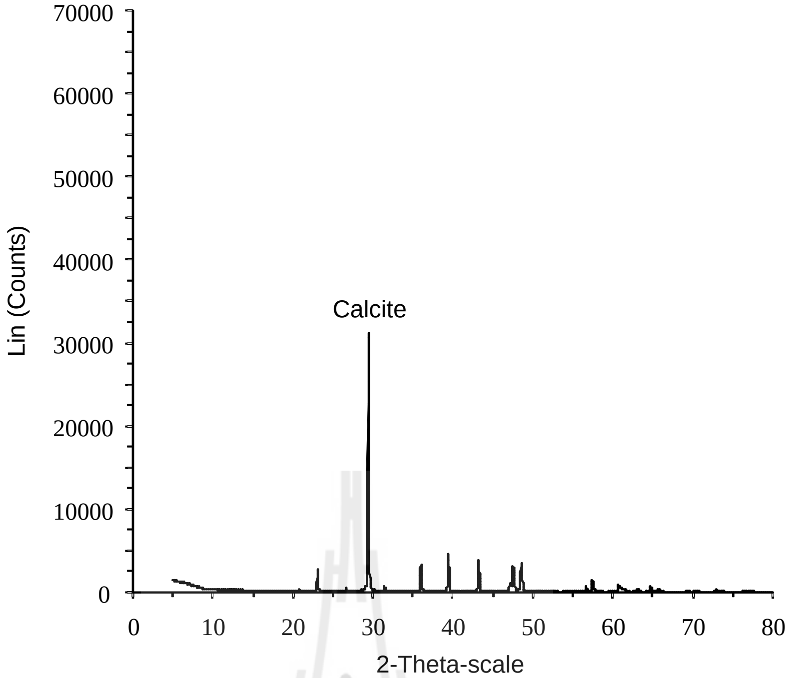


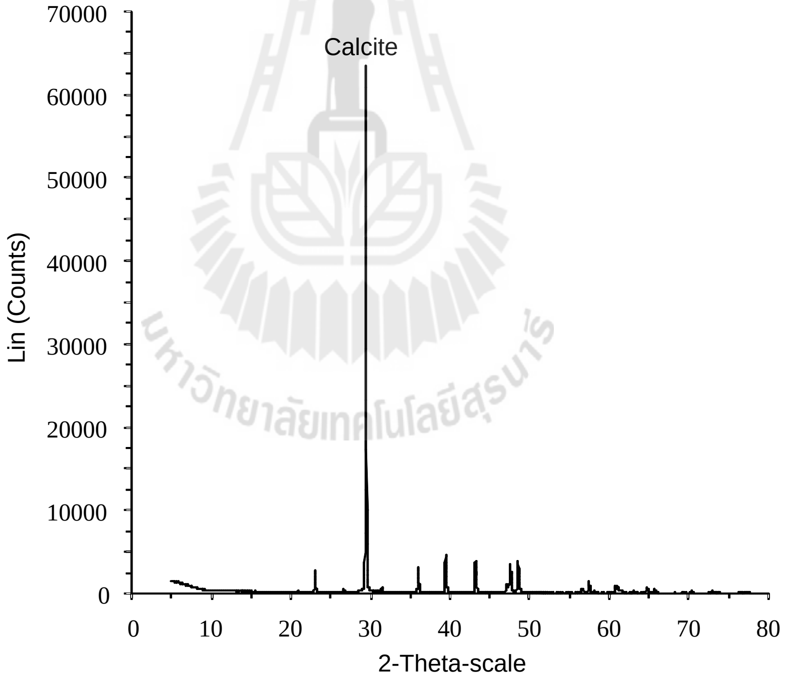
Figure 4.19 X-ray diffractgrams of powder from carbonate rocks specimens:

(a) Limestone 1 (L1)

(b) Limestone 2 (L2)



(a)



(b)

Figure 4.20 X-ray diffractgrams of powder from carbonate rocks specimens:

(a) Limestone 3 (L3)

(b) Limestone 4 (L4)

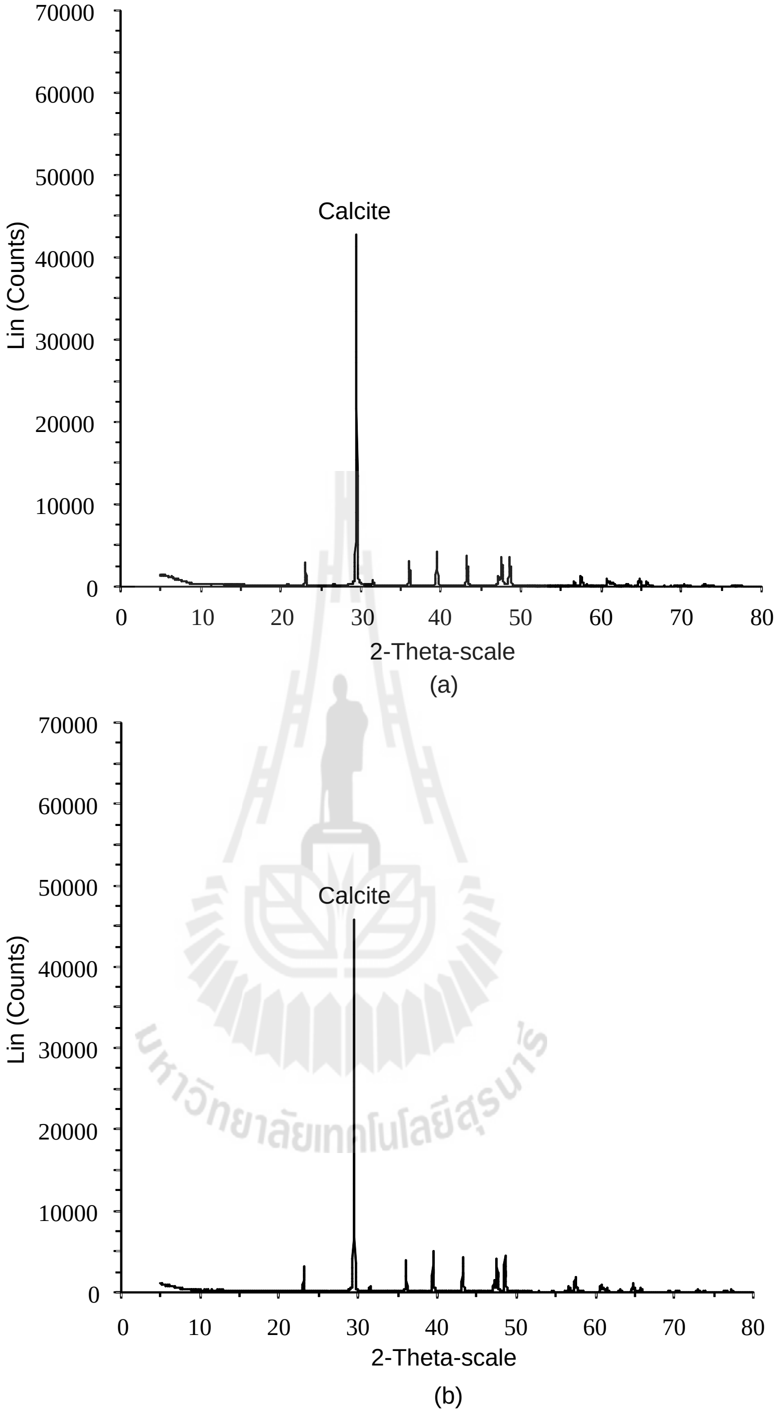


Figure 4.21 X-ray diffractgrams of powder from carbonate rocks specimens:

(a) Limestone 5 (L5)

(b) Travertine (T)

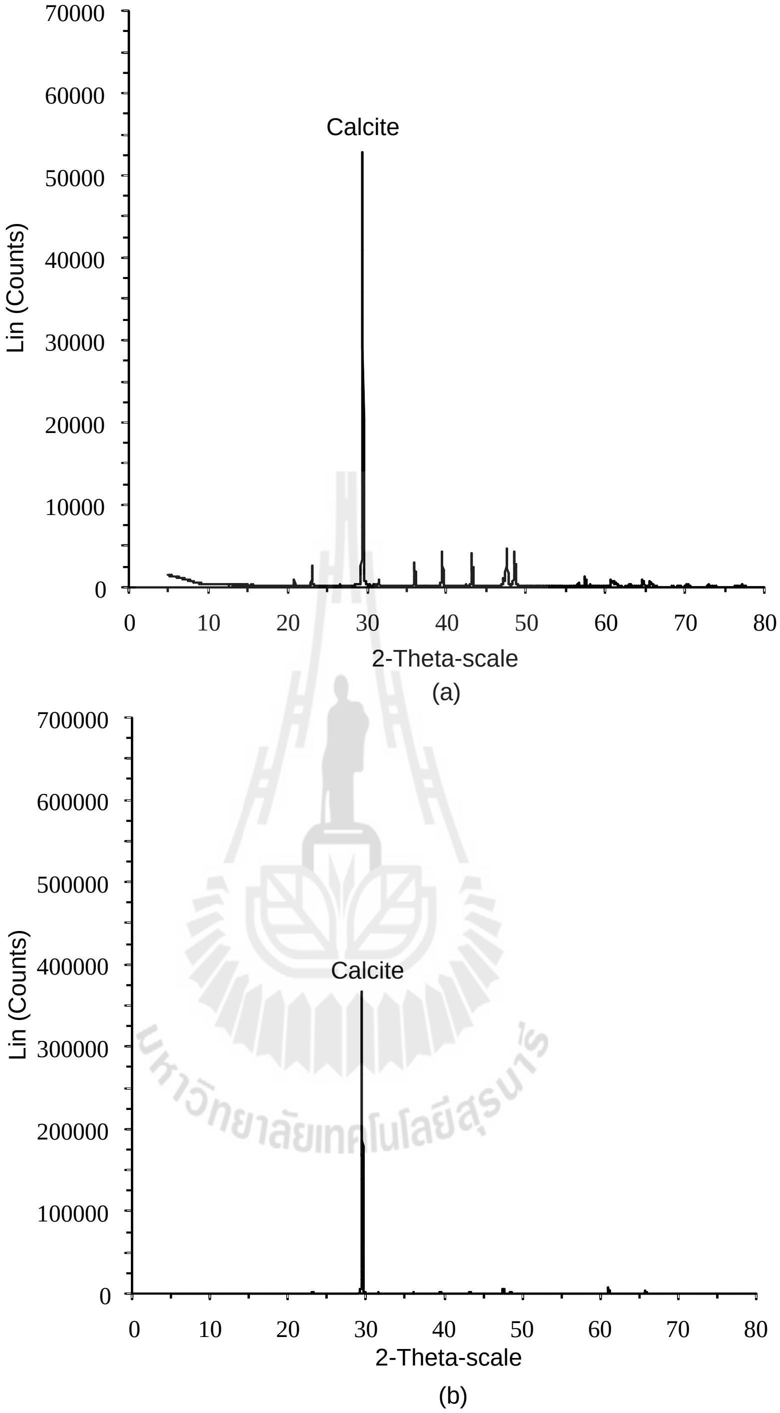


Figure 4.22 X-ray diffractgrams of powder from carbonate rocks specimens:

(a) Marble 1 (MB1)

(b) Marble 2 (MB2)

CHAPTER V

RELATIONSHIPS BETWEEN MECHANICAL, PHYSICAL, PETROGRAPHIC AND CHEMICAL PROPERTIES

The objective of this chapter is to estimate the relationships between the mechanical properties and physical, petrographic, and chemical properties of the studied rock specimens. Physical properties include density, porosity and wave velocity. The petrographic properties were considered here as sparite to micrite ratio. The mineral compositions are considered here involved percentage of quartz and clay mineral contents.

5.1 Relationship between mechanicalandphysical properties

The effects of physical properties such as density and P-wave velocity on the mechanical properties (uniaxial compressive strength, elastic modulus and Brazilian tensile strength, slake durability index and Los Angles abrasion and impaction) are determined. The uniaxial compressive strength of the carbonate rocks ranges from 45.19 to 72.09 MPa. The marble strengths are in the middle range of the carbonate rocks samples in test results (50.47 to 51.59 MPa). The elastic modulus of the rocks can be determined from the stress and strainrelations (Jaeger et al., 2007). The elasticmodulus varies from 5.68 to 16.83GPa. The slake durability index values are higher than 99% (ranges from 99.24 to 99.58%).The Los Angles abrasion and impactionvalues ranges from 18.12 to 21.11 %.

The results indicate that the uniaxial compressive strength, elastic modulus and Brazilian tensile strength tend to increase with increasing density, while the change of slake durability index are not significant (Figure 5.1). The results obtained from uniaxial compressive strength and Brazilian tensile strength test agree with the conclusion drawn by Arman et al. (2014).

The change of the uniaxial compressive strength and Brazilian tensile strength as a function of P-wave velocityare shown in Figures 5.2a and 5.2c. Increasing of P-wave velocity increases the uniaxial compressive and Brazilian tensile strengths. Figure 5.2b presents the change of the elastic modulus as a function of P-wave velocity. It is noted that the results are scatted. The elastic modulus shows inconclusive trend with increasing P-wave velocity. The durability index of the tested carbonate rocks tends to be independent of their density and P-wave velocity. This may be due to that all limestone tested here are highly durability based on the characteristic by Rintrawilai et al.(2011) and cannot be distinguish by the two cycles of the slake durability index testing.

The results obtained were suggested that the density is closely related to the mechanical properties of the test rocks which agree with theconclusiondrawn by Rajabzadeh et al.(2012).

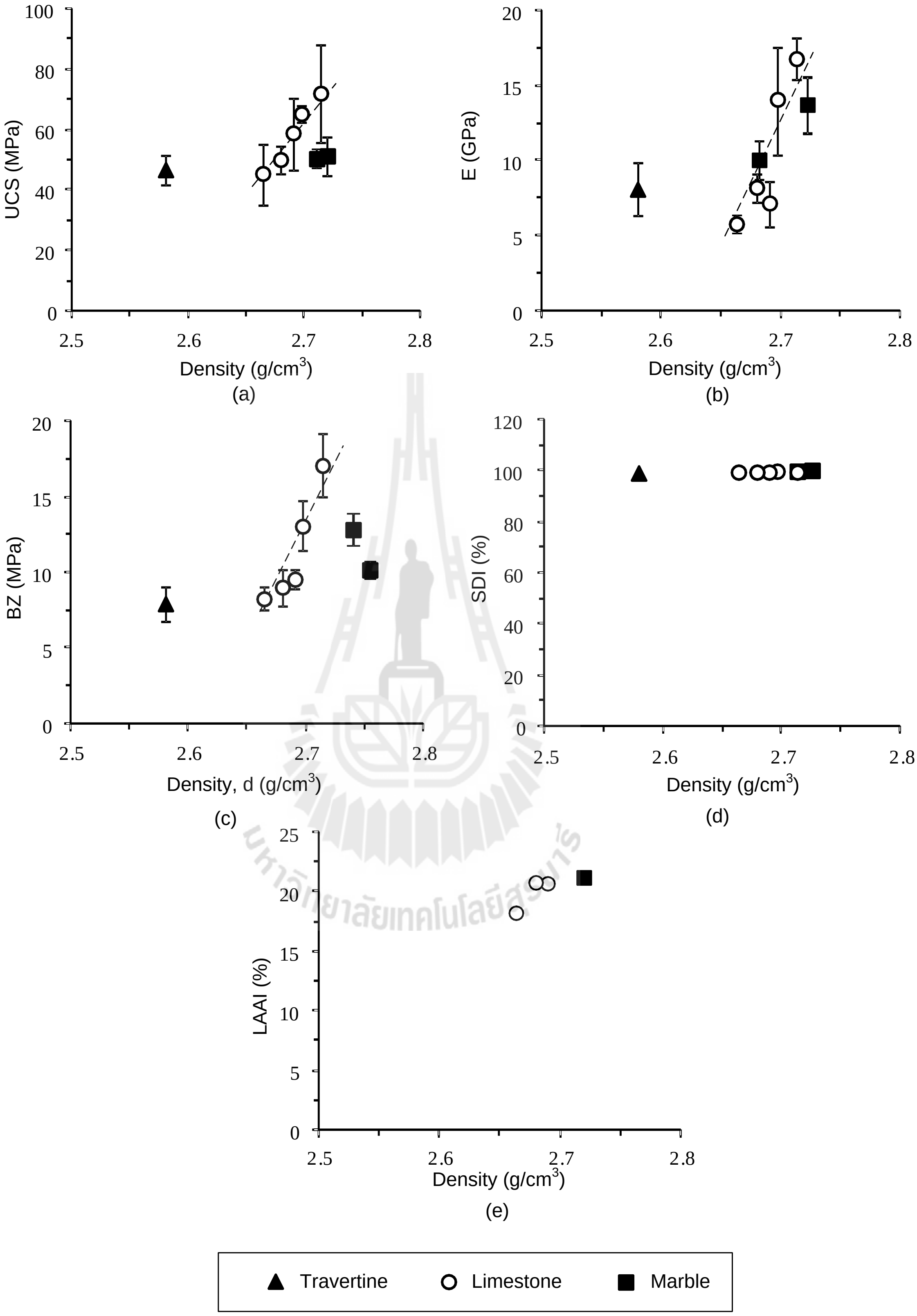


Figure 5.1 Relationship between the mechanical properties and density

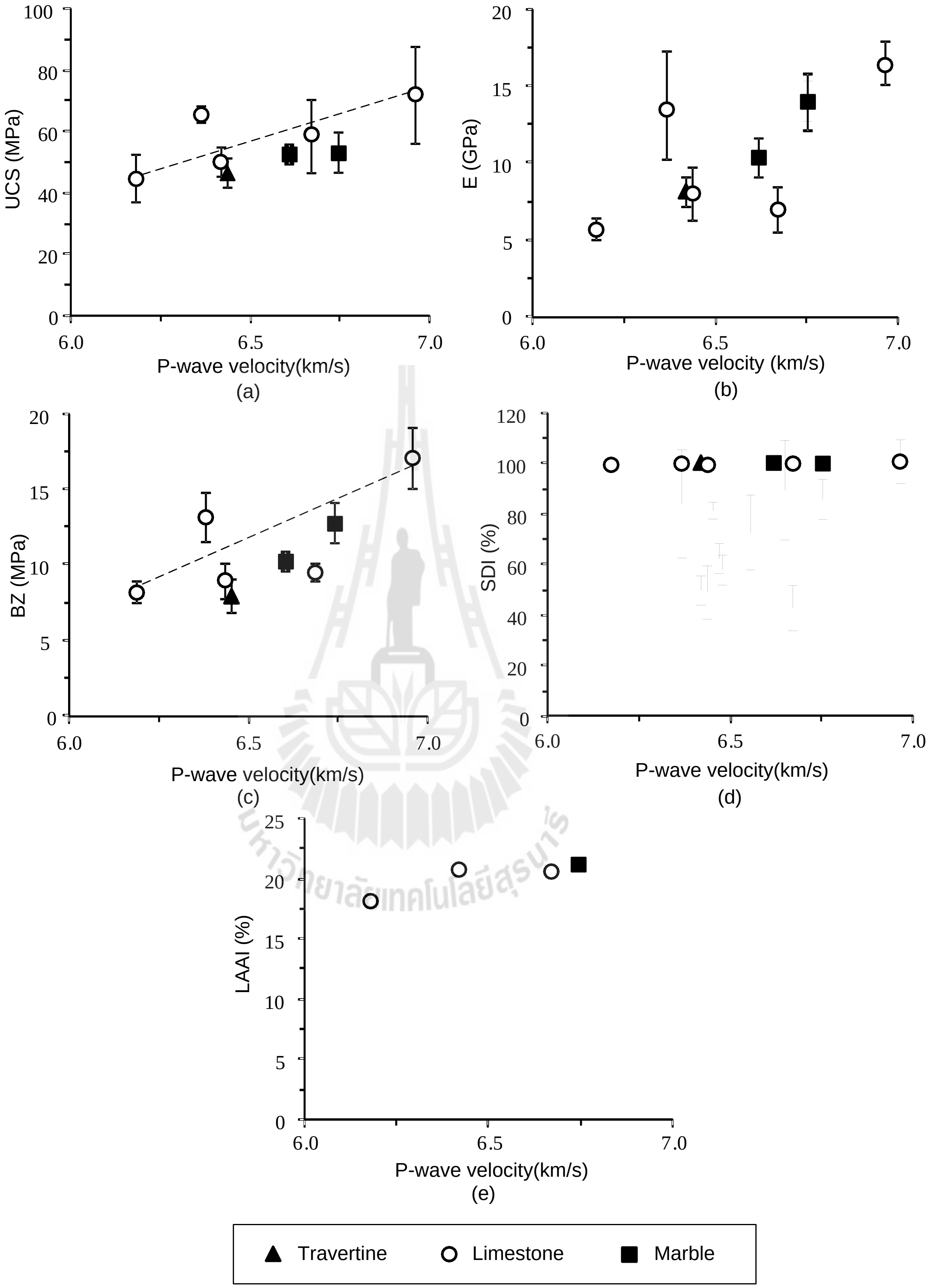


Figure 5.2 Relationship between the mechanical properties and P-wave velocity

5.2 Relationship between mechanical properties and petrographic property

The relationship between the mechanical properties and the sparite-to- micrite ratio of the limestone is shown in Figure 5.3.The results indicate that the uniaxial compressive strength, elastic modulus, and tensile strength values decrease with increasing the sparite-to-micrite ratio. These results can be found in the limestone 4 (L4). However, this relationship is statistically unclear. The strength of the tested limestones may not be controlled only by the sparite-to-micrite ratio. Similar conclusions are drawn by Tugrul and Zarif (2000). The limestone strength is probably controlled by depositional fabric, post depositional processes (Andriani and Walsh, 2002; Gajić et al., 2011) and grain size of texture (Hatzor and Plachik, 1997, 1998).The slake durability index and Los Angles abrasion and impaction test plotted against sparite-to-micrite ratio is shown in Figure 5.3d and Figure 5.3e which indicated that durability of the carbonate rocks seem to be independence of the limestone texture.

5.3 Relationship between mechanical properties and mineral composition

Figure 5.4 plots the mechanical properties (uniaxial compressive strength, elastic modulus and Brazilian tensile strength) againstthe quartz content from 0% to 11.01%. The resultsreveal that quartz of less than 1% has no significant effect on the mechanical properties of the carbonate rocks specimens. However, a higher amount of quartz contenting11.01% results in a higher uniaxial compressive strength, elastic

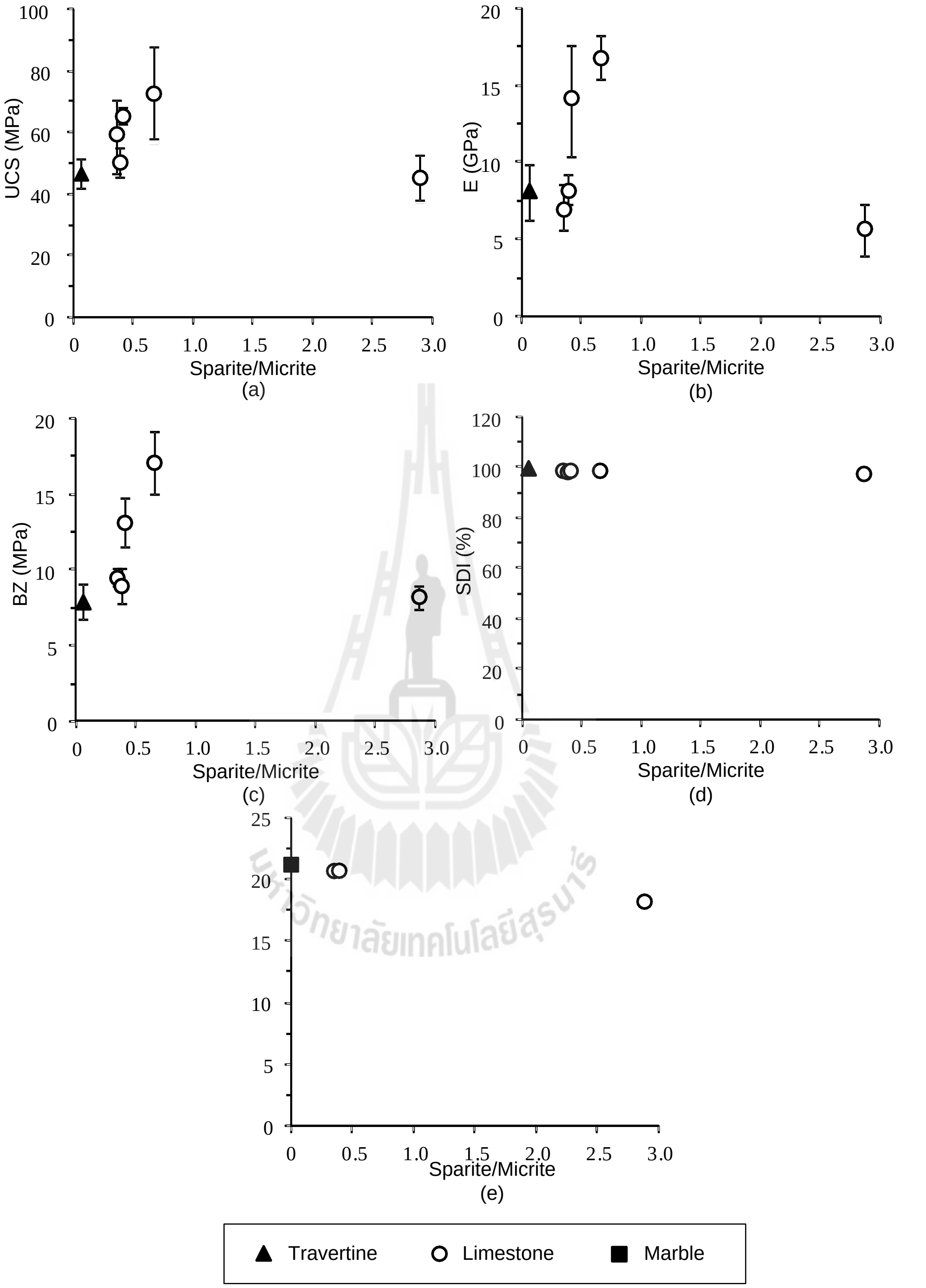


Figure 5.3 Relationship between the mechanical properties and sparite to micriteratio

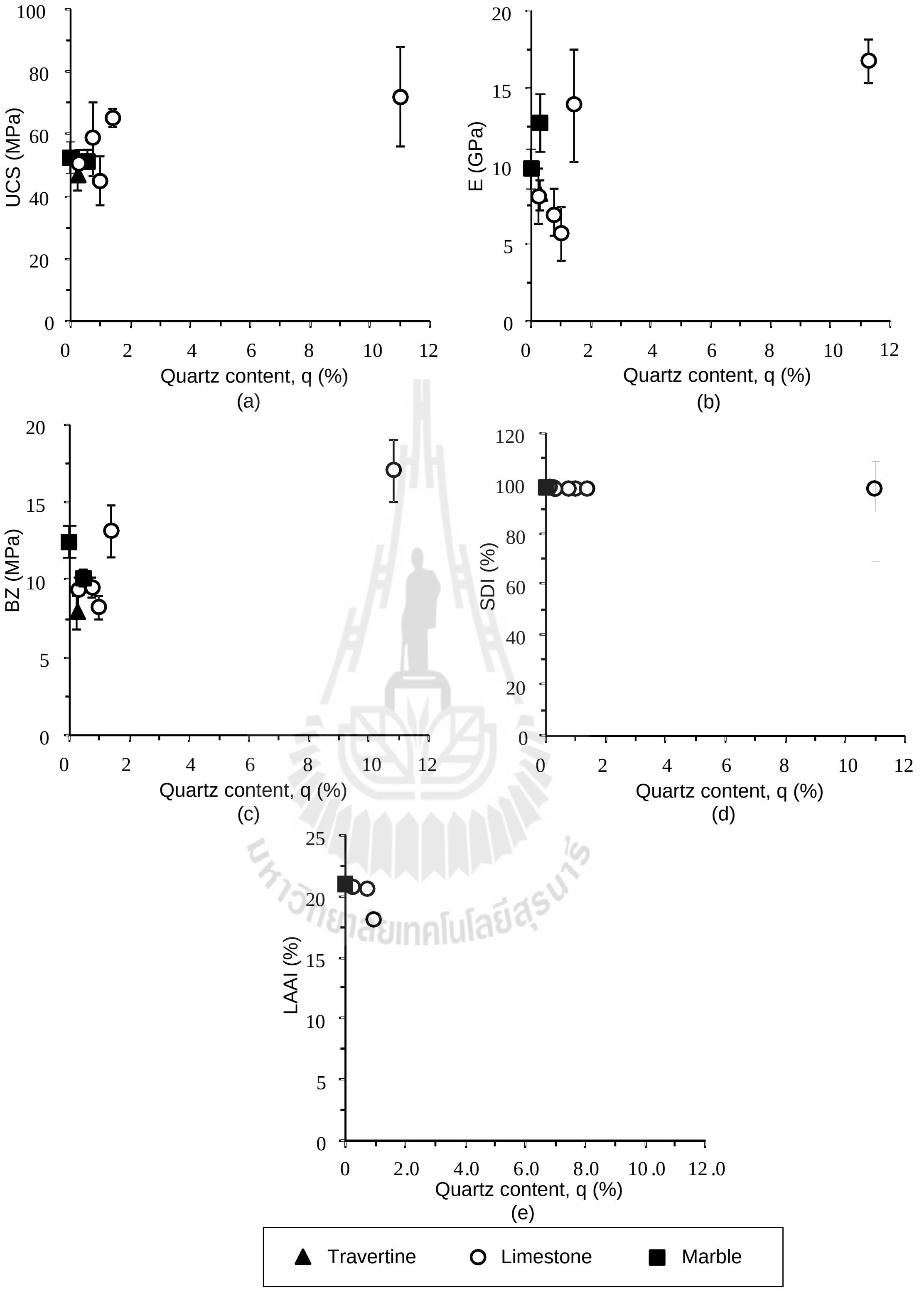


Figure 5.4 Relationship between the mechanical properties and quartz content

modulus and Brazilian tensile strength. This is supported by the conclusion drawn by Ozcelik et al. (2013) that the limestone strength increases with increasing percentage of quartz content. The slake durability index and Los Angles abrasion and impaction test plotted against quartz content of carbonate rocks are shown in Figure 5.4d and Figure 5.4e indicating the values durability index seems to be independent of quartz content. This is different from the conclusions drawn by Dhakal et al. (2002), who found that the slake durability index of rocks is closely related to mineralogical composition. This may be due to the fact that the mineral compositions of all carbonate rock specimens tested here are very similar. The calcite content for all rock types are from 67.82% to 100.00 % by weight. This suggests that the mineral of rocks tested has an insignificant effect on the slake durability index.

Figure 5.5 shows the mechanical properties of carbonate rocks as a function of clay mineral content, from 0 % to 1.62 %. It shows that the clay mineral content of the limestone may increase on the mechanical properties. The increase of clay mineral content tends to be increase the uniaxial compressive strength, elastic modulus and Brazilian tensile strength. For travertine and marbles, the small amounts of clay mineral content seem to have no effect on the mechanical properties of carbonate specimens. In Figure 5.5d the slake durability indexand Los Angles abrasion and impaction test is plotted against the clay mineral content. The diagram indicates that the clay mineral content has no effect on the slake durability indexand Los Angles abrasion and impaction test.

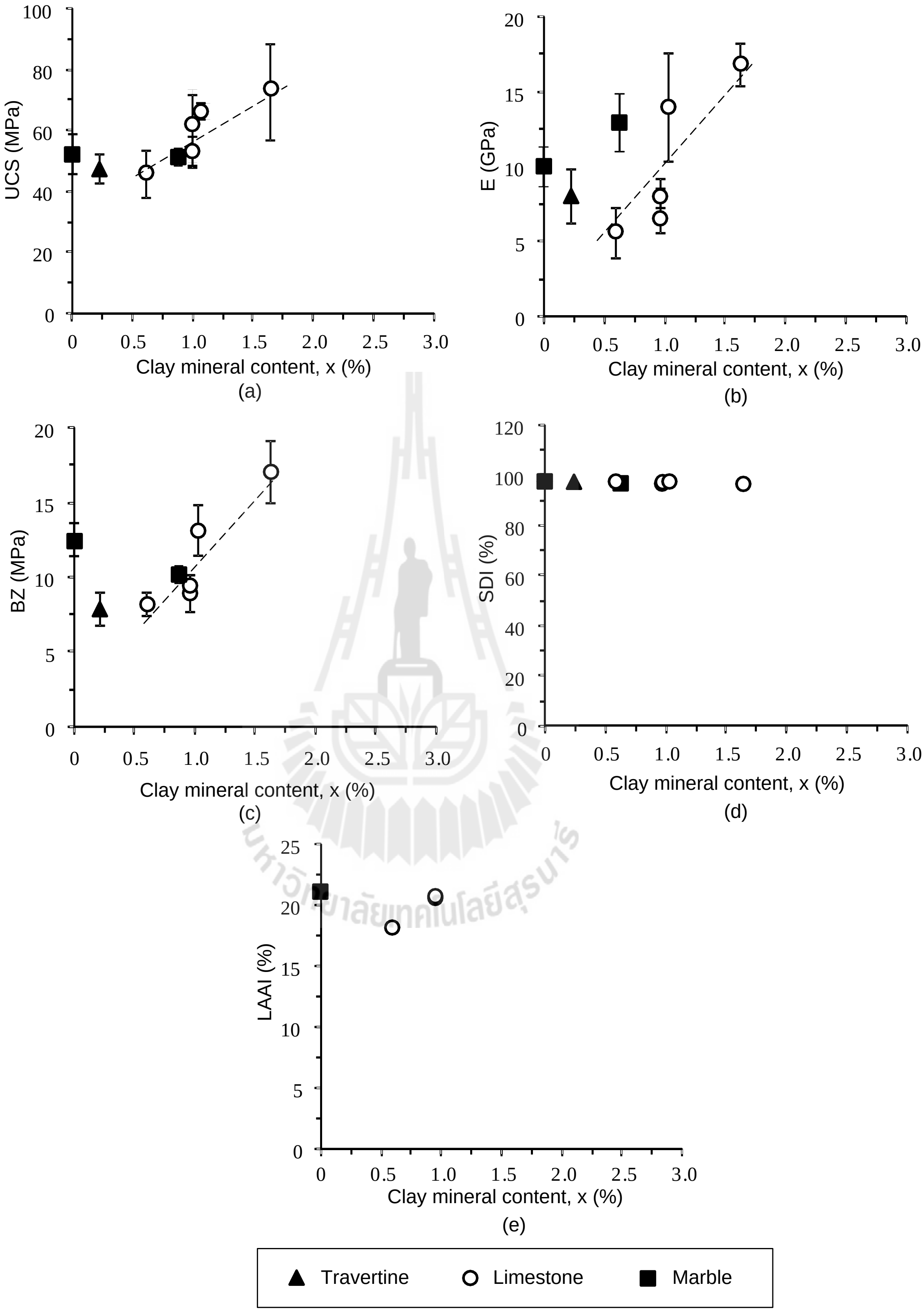


Figure 5.5 Relationship between the mechanical properties and clay mineral content

CHAPTER VI

DISCUSSIONS AND CONCLUSIONS

6.1 Discussions and conclusions

The study presented has mainly been focused on the influence of the physical properties, petrographic characteristics and mineral compositions of the investigated basic carbonate rocks on the mechanical properties. The mechanical properties testing in this study are divided into four groups: uniaxial compression strength test, Brazillian tensile strength test, slake durability index test and Los Angeles abrasion and impaction test. The physical properties considered here include the density, porosity and wave velocity. The point count method is used to estimate the petrographic characteristics. Additionally, textural description is carried out by using polarizing microscope. X-ray diffraction (XRD) is used to determine the mineral compositions of the carbonate rocks.

The results of this study indicate that the uniaxial compressive strength, elastic modulus and Brazilian tensile strength tend to depending on density and P-wave velocity. The elastic modulus also shows inconclusive trend with increasing P-wave velocity. The slake durability index and Los Angeles abrasion and impaction testof the tested carbonate rocks tend to be independent of their density and P-wave velocity, this may be due to the high durability of the tested limestone which cannot be distinguish by the two cycles of the slake durability index testing.

The relationship between the mechanical properties and the sparite-to-micrite ratio indicates that the uniaxial compressive strength, elastic modulus, and tensile strength values decrease with increasing the sparite-to-micrite ratio. However, the number of specimen with sparite used here are few. The strength of the tested limestones may not be controlled by the sparite content only but it may be controlled by other factors such as type of fabric, size of grains (fabrics), and post depositional processes. The slake durability index and Los Angeles abrasion and impaction test of the carbonate rocks seem to be independence of the texture.

The effects of mineral composition on mechanical properties reveal that quartz of less than 1% has no significant effect on the mechanical properties of the tested carbonate rock specimens. The limestone strength increases with increasing percentage of quartz content. The increase of clay mineral content of limestone tends to increase the uniaxial compressive strength, elastic modulus and Brazilian tensile strength. For travertine and marbles, the small amounts of clay mineral content have no effect on the mechanical properties. The values of slake durability index and Los Angeles abrasion and impaction test do not show relationship with quartz and clay mineral content. However, the mineral compositions of all tested carbonate rock specimens are very similar so that they do not significantly affect the durability index.

The porosity value are obtained from the proposed method in this study cannot indicate the invalid porosity because the pore space in the carbonate rocks are formed by the inter-crystalline boundaries.

The results from this study suggest a good trend to estimate the relationshipbetween the mechanical and physical, chemical and petrographic propertiesof 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.The numbers of the testedrock samples are insufficient to develop the mathematical relationship between the mechanical and physical, and petrographic propertiesof rocks. More testing is also desirable to confirm or verity that the petrography can predict the mechanical properties of rocks. This also suggests thatthe variety of rocks with different mineral compositions should be obtained.

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BIOGRAPHY

Miss. Samerhkea Promma was born on March16, 1990 in Chiang Rai province, Thailand. She received her Bachelor's Degree in Engineering (Geotechnology) from Suranaree University of Technology in 2012. For her post-graduate, she continued to study with a Master's degree in the Geological Engineering Program, Institute of Engineering, Suranaree university of Technology. During graduation, 2013-2014, she was a part time worker in position of research assistant at the Geomechanics Research Unit, Institute of Engineering, Suranaree University of Technology.