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EVALUATION OF SOME IRAQI ROCKS AS CONSTRUCTION  
MATERIALS

THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES  
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FIRAS IBRAHIM YOUNUS YOUNUS

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FOR  
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IN  
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Approval of the Graduate School of Natural and Applied Sciences, Atılım University.

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## **ABSTRACT**

### **EVALUATION OF SOME IRAQI ROCKS AS CONSTRUCTION MATERIALS**

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Sedimentary rock discoveries constitute the vast majority of rock discoveries in Iraq, where these rocks are widely used in various construction works in the western regions of Iraq. The main objective of this study is to assess the properties of rocks in Iraq's western region and to expand their suitability for use as construction materials. Three different types of rock mass blocks were collected from three different quarries in Iraq's western desert. The rock samples collected from these quarries were named as type A, B, and C. Afterwards these samples were prepared in the laboratory for the tests. The testing program included determining the water content of the rocks, as well as their saturation period, physical and chemical properties, and characterization through the X-ray diffraction test (XRD), the scanning electron microscope test (SEM), and the polarized microscope test. Furthermore, the engineering properties of these rocks were also discovered through destructive and non-destructive tests. They are included the point load test, tensile strength (Brazilian) test, and uniaxial compressive strength test (UCS), which were conducted on the dry and fully saturated samples. The non-destructive test included the Schmidt hammer test.

The characterization results revealed that A and B type samples are limestones, which consist mainly of calcite  $\text{CaCO}_3$  and a small amount of quartz  $\text{SiO}_2$  in type sample B, while C type samples are dolostone and consists of dolomite  $\text{CaMg}(\text{CO}_3)_2$  as the main compound. The results of the engineering tests on the rocks samples in the dry state revealed that rock type C has the highest engineering strength values, followed by rock

type B and rock type A. For all types of rocks, the effect of saturation resulted in a decrease in engineering strength values. The rock groups are classified according to their strength, with "Very weak rock" for all groups based on uniaxial compressive strength test results, "Moderately strong" for all groups based on point load test strength index  $Is_{(50)}$  values, and "Very weak rock" for all groups based on results of rebound number values of Schmidt hammer tests. Engineering strength findings revealed that the rocks of studied quarries are suitable for diverse use in construction.

**Keywords:** limestone, dolostone, calcite, sedimentary rock, point load, uniaxial compressive strength, western desert of Iraq, Schmidt hammer, indirect (Brazilian) tensile stress

## ÖZ

### BAZI IRAK KAYALARININ İNŞAAT MALZEMESİ OLARAK DEĞERLENDİRİLMESİ

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Ocak 2022, 103 Sayfa

Irak'ın genel yapısını oluşturan ve Irak'ın batı bölgelerinde de bulunan tortul kayalar bu bölgedeki çeşitli inşaat işlerinde yaygın olarak kullanılmaktadır. Bu çalışmanın temel amacı Irak'ın batı bölgesindeki kayaların özelliklerini değerlendirmek ve inşaat malzemesi olarak kullanılmaya uygunluklarını ortaya koymaktır. Irak'ın batı çölündeki farklı üç taş ocağından farklı türde kaya kütlesi blokları toplanmıştır. Bu taş ocaklarından toplanmış olan kaya örnekleri tip A, B ve C olarak adlandırılmıştır. Sonrasında bu örneklerden testler için laboratuvarında numuneler hazırlanmıştır. Test programı; kayaların su içeriğinin yanı sıra bunların doyma süresini, X-ışını kırılması testi (XRD) dolayısıyla fiziksel ve kimyasal özelliklerinin ve karakterizasyonlarının tespit edilmesini, tarayıcı elektron mikroskobu (SEM) testlerini ve polarlamalı mikroskop testini kapsamaktadır. Ayrıca, tahribatlı ve tahribatsız testler ile bu kayaların mühendislik özellikleri de çalışılmıştır. Bunlar; kuru ve tamamen doymuş numuneler üzerinde gerçekleştirilmiş olan nokta yük testini, çekme dayanımı (Brezilya) testini ve tek eksenli basınç dayanımı (UCS) testini kapsamıştır. Tahribatsız test olarak Schmidt çekici testi yapılmıştır.

Karakterizasyon sonuçları; A ve B tipi kayaların temel olarak kalsitten  $\text{CaCO}_3$  ve B tip numunede de az miktarda kuvarstan  $\text{SiO}_2$  oluşan kireçtaşı olduklarını, bunun yanı sıra C tip numunelerin ise temel bileşen olarak  $\text{CaMg}(\text{CO}_3)_2$ 'den oluşan dolomit kayası olduğunu ortaya koymuştur. Kaya numuneleri üzerinde kuru durumda gerçekleştirilmiş olan mühendislik testlerinin sonuçları; C tip kayanın en yüksek

mühendislik dayanım değerlerine sahip olduğunu, bunun ardından B tip kayanın ve A tip kayanın geldiğini ortaya koymuştur. Suyu doygunluk durumunun tüm kaya tipleri için dayanım değerlerinde bir düşüşe neden olduğu görülmüştür. Kaya türleri dayanımlarına göre: tüm gruplar için tek eksenli basınç dayanımı testi sonuçlarına göre “Çok zayıf kaya”; tüm gruplar için nokta yük testi dayanım endeksi  $I_s(50)$  değerlerine göre “Orta derecede güçlü” ve tüm gruplar için Schmidt çekici dayanım testlerinin geri sıçrama sayısı değerlerinin sonuçlarına göre de "Çok zayıf kaya" sınıfına girdiği görülmüştür. Bu çalışmadan elde edilen mühendislik dayanımı bulgularına göre incelenen taşların farklı inşaat kullanımları için uygun olduğunu ortaya koymuştur.

**Anahtar Kelimeler:** kireçtaşı, dolomit kaya, kalsit, tortul kaya, nokta yükü, tek eksenli basınç dayanımı, Irak’ın batı çölü, Schmidt çekici, dolaylı çekme dayanımı

## DEDICATION

*To*

*My father, Prof. Dr. Ibrahim Younus Al-Rawi*

*My idol, my supporter, my motivator*

*To*

*My mother, Rabeah Hammadi Mustara*

*The heart that never stops loving and praying*

*To*

*My wife, Sumaya Yasir Younus*

*Love of my life*

*To*

*My children, Hamzah and Yasameen*

*The happiness of my life*

*To*

*My brothers*

*Aws Ibrahim Younus*

*Dr. Mohammed Ibrahim Younus*

*Ahmed Ibrahim Younus*

*Dr. Amenah Ibrahim Younus*

*To my friends*

*Nooruldeen Khalid*

*Mustafa Al-Ageedi*

*Haithem Al-Mashhadani*

*Ali Farooq Al-Salihi*

*Thank you for your support, your love, your patience, your prayers*

*You are all my world*

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## TABLE OF CONTENTS

|   |      |
|---|------|
| <b>ABSTRACT</b> .....   | iii  |
| <b>ÖZ</b> .....   | v    |
| <b>DEDICATION</b> .....   | vii  |
| <b>ACKNOWLEDGMENTS</b> .....  | viii |
| <b>TABLE OF CONTENTS</b> .....  | ix   |
| <b>LIST OF TABLES</b> .....   | xiii |
| <b>LIST OF FIGURES</b> .....  | xiv  |
| <b>CHAPTER 1 INTRODUCTION</b> .....                                     | 1    |
| 1.1 General .....   | 1    |
| 1.2 Problem Statement .....   | 1    |
| 1.3 The Aim of this Research .....                                      | 2    |
| 1.4 Content of the Thesis.....  | 3    |
| 1.4.1 Chapter I.....  | 3    |
| 1.4.2 Chapter II.....   | 3    |
| 1.4.3 Chapter III .....   | 3    |
| 1.4.4 Chapter IV .....  | 3    |
| 1.4.5 Chapter V .....   | 3    |
| <b>CHAPTER 2 LITERATURE REVIEW</b> .....                                | 4    |
| 2.1 Introduction .....  | 4    |
| 2.2 Geological Formation of Rocks .....                                 | 4    |
| 2.3 Rocks Used as a Constriction Materials.....                         | 5    |
| 2.4 Factors Affecting using the Rocks as a Construction Materials ..... | 6    |
| 2.5 Engineering and Mechanical Tests on Rocks .....                     | 7    |
| 2.5.1 Schmidt Hammer (SH).....  | 7    |
| 2.5.2 Physical and Mechanical Properties of Rocks .....                 | 10   |

|   |           |
|---|-----------|
| 2.5.2.1 Bulk Density ( $\rho$ ) .....                               | 10        |
| 2.5.2.2 Unit Weight ( $\gamma$ ).....                               | 10        |
| 2.5.2.3 Specific Gravity (G) .....                                  | 10        |
| 2.5.2.4 Void Ratio (e) .....  | 10        |
| 2.5.2.5 Compressive strength.....                                   | 10        |
| 2.5.2.6 Tensile strength.....                                       | 10        |
| 2.5.2.7 Shear strength .....  | 11        |
| 2.6 Using of Rocks and Aggregates as a construction Materials ..... | 11        |
| 2.6.1 Roofing and Facing Materials .....                            | 11        |
| 2.6.2 Armour stone.....   | 11        |
| 2.6.3 Crushed Rock .....  | 11        |
| 2.6.4 Road Aggregate.....   | 12        |
| 2.6.5 Gravels and Sands .....                                       | 12        |
| 2.6.5.1 Gravel .....  | 12        |
| 2.6.5.2 Sand .....  | 13        |
| 2.7 Rocks and Aggregates in Iraq .....                              | 13        |
| 2.7.1 Silica Sands (Glass Sands) .....                              | 14        |
| 2.7.2 Limestone for building purposes.....                          | 15        |
| 2.7.3 Marble .....  | 15        |
| 2.7.4 Sands and Gravel.....   | 15        |
| 2.7.5 Salinas .....   | 15        |
| 2.7.6 Clays .....   | 15        |
| 2.7.7 Flint clays .....   | 16        |
| 2.7.8 Porcellanite Rocks.....                                       | 16        |
| 2.7.9 Quartzite and Silicrete Rocks.....                            | 16        |
| 2.7.10 Bauxite .....  | 16        |
| 2.7.11 Chert .....  | 16        |
| <b>CHAPTER 3 METHODOLOGY .....</b>                                  | <b>17</b> |
| 3.1 General .....   | 17        |
| 3.2 Geological of study area.....                                   | 19        |
| 3.3 Selection of rock samples.....                                  | 23        |

|   |           |
|---|-----------|
| 3.3.1 Quarry One (Q1) .....                       | 25        |
| 3.3.2 Quarry Two (Q2).....                        | 26        |
| 3.3.3 Quarry three (Q3).....                      | 27        |
| 3.4 Preparing Rock Specimens.....                 | 28        |
| 3.5 Saturation of Specimens.....                  | 32        |
| 3.6 Physical Tests.....                           | 33        |
| 3.7 Chemical Tests .....                          | 33        |
| 3.8 Characterization of the Rocks .....           | 34        |
| 3.8.1 Polarized Microscope.....                   | 34        |
| 3.8.2 XRD Tests.....                              | 34        |
| 3.8.3 SEM Test.....                               | 35        |
| 3.9 Engineering Test .....                        | 36        |
| 3.9.1 Non-destructive Test .....                  | 36        |
| 3.9.1.1 Schmidt Hammer Test.....                  | 36        |
| 3.9.2 Destructive Tests .....                     | 37        |
| 3.9.2.1 Point Load Test.....                      | 37        |
| 3.9.2.2 Brazilian Test.....                       | 38        |
| 3.9.2.3 Uniaxial Compression Test.....            | 39        |
| 3.10 Test Program .....                           | 40        |
| <b>CHAPTER 4 TEST RESULTS AND DISCUSSION.....</b> | <b>41</b> |
| 4.1 General .....                                 | 41        |
| 4.2 Specimens Saturation Results .....            | 41        |
| 4.3 Physical Tests Results .....                  | 43        |
| 4.4 Chemical Tests Results .....                  | 43        |
| 4.5 Characterization of the Rocks .....           | 44        |
| 4.5.1 XRD Tests Results .....                     | 44        |
| 4.5.2 Polarized Microscope.....                   | 46        |
| 4.5.2.1 Sample A .....                            | 46        |
| 4.5.2.2 Sample B.....                             | 46        |

|  |           |
|--|-----------|
| 4.5.2.3 Sample C.....                                  | 47        |
| 4.5.3 Scanning Electron Microscope (SEM).....          | 48        |
| 4.6 Engineering Test Results.....                      | 51        |
| 4.6.1 Non-destructive Test Results .....               | 51        |
| 4.6.1.1 Schmidt Hammer Test Results .....              | 51        |
| 4.6.2 Destructive Tests Results .....                  | 52        |
| 4.6.2.1 Point load Test Results .....                  | 52        |
| 4.6.2.2 Brazilian Test Results .....                   | 57        |
| 4.6.2.3 Uniaxial Compression Test Results.....         | 61        |
| 4.7 Summary and Evaluation of Tests Results.....       | 65        |
| <b>CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS .....</b> | <b>68</b> |
| 5.1 Conclusions .....                                  | 68        |
| 5.2 Recommendations for Future Works .....             | 69        |
| <b>REFERENCES.....</b>                                 | <b>70</b> |
| <b>APPENDICES .....</b>                                | <b>73</b> |
| APPENDIX A.....  | 73        |
| APPENDIX B .....                                       | 78        |
| APPENDIX C .....                                       | 84        |

## LIST OF TABLES

|  |    |
|--|----|
| Table 2.1 Approximate strength classification of rocks [11].....   | 8  |
| Table 2.2 Correlation between Schmidt hammer rebound and uniaxial compressive strength and Young's modulus [8].....  | 9  |
| Table 3.1 Locations and coordinates of the study areas.....  | 23 |
| Table 3.2 Categories and numbers of specimens for each test of the three types of rocks that have been studied ..... | 31 |
| Table 3.3 Standard specifications for physical test.....   | 33 |
| Table 3.4 Standard specifications for chemical test.....   | 33 |
| Table 4.1 Physical test results .....  | 43 |
| Table 4.2 Chemical test results .....  | 43 |
| Table 4.3 Rebound number for rocks A, B, & C .....   | 51 |
| Table 4.4 Point load test results full dry .....   | 53 |
| Table 4.5 Point load test results full saturated .....   | 55 |
| Table 4.6 Brazilian tensile stress results full dry .....  | 58 |
| Table 4.7 Brazilian tensile stress results full saturated .....  | 59 |
| Table 4.8 Uniaxial compressive strength (UCS) full dry.....  | 62 |
| Table 4.9 Uniaxial compressive strength (UCS) full saturated.....  | 63 |
| Table 4.10 The approximate strength classification of the rock's samples .....                                       | 67 |
| Table 4.11 The recommendations for use of the three rocks types.....   | 67 |

## LIST OF FIGURES

|   |    |
|---|----|
| Figure 2.1 The rocks cycle formation in the nature [5].....   | 5  |
| Figure 2.2 The relationship between uniaxial compressive strength and the Schmidt Hammer Rebound (R) [11] ..... | 9  |
| Figure 3.1 Load-bearing walls .....   | 19 |
| Figure 3.2 Cladding stones for facades .....  | 19 |
| Figure 3.3 Cladding the banks of rivers and streams.....  | 19 |
| Figure 3.4 Retaining walls .....  | 19 |
| Figure 3.5 Iraq deserts.....  | 20 |
| Figure 3.6 Parts of the western desert .....  | 20 |
| Figure 3.7 Lithological map of Iraq [34] .....  | 21 |
| Figure 3.8 Location of study area .....   | 22 |
| Figure 3.9 Hydraulic crushing hammer attached to an excavator.....  | 23 |
| Figure 3.10 Collect and load rocks by an articulated loader.....  | 24 |
| Figure 3.11 Collecting large blocks of rock and crushing them manually by workers .....                         | 24 |
| Figure 3.12 Quarry one (Q1) produces rocks type A.....  | 25 |
| Figure 3.13 Quarry two (Q2) produces rocks type B.....  | 26 |
| Figure 3.14 C-type rock blocks.....   | 27 |
| Figure 3.15 Quarry three (Q3) produces rocks type C.....  | 27 |
| Figure 3.16 Extraction of cylindrical specimens from rock masses .....  | 28 |
| Figure 3.17 Extraction of cylindrical specimens from rock masses .....  | 28 |
| Figure 3.18 Modify the dimensions of the specimens for the first category.....                                  | 29 |
| Figure 3.19 Rock specimens of the second category .....   | 29 |
| Figure 3.20 Rock specimens of the third category.....   | 30 |
| Figure 3.21 Drying and weighing the rock specimens before immersing them in water.....                          | 32 |
| Figure 3.22 Immersion specimens in water for escalating periods of time and weighing each time .....            | 32 |
| Figure 3.23 X-ray diffraction test device .....   | 34 |
| Figure 3.24 Scanning electron microscope (SEM) test device .....  | 35 |

|   |    |
|---|----|
| Figure 3.25 Testing the rebound number (Schmidt hammer) of rock specimens.....  | 36 |
| Figure 3.26 Point Load Test Device .....  | 37 |
| Figure 3.27 Brazilian Test Device .....   | 38 |
| Figure 3.28 Uniaxial Compression Test device (Microcomputer Controlled<br>Electronic Universal testing machine) Model: WDW-200.....                                     | 39 |
| Figure 4.1 The relationship between water content and time of immersion (the lower<br>Figure shows the relationship for the first two hours out of the 406 hours) ..... | 42 |
| Figure 4.2 X-ray diffraction of sample A.....   | 44 |
| Figure 4.3 X-ray diffraction of sample B.....   | 45 |
| Figure 4.4 X-ray diffraction of sample C.....   | 45 |
| Figure 4.5 Reflect microscope images of rock specimens type ( A ) .....   | 46 |
| Figure 4.6 Reflect microscope images of rock specimens type ( B ).....  | 47 |
| Figure 4.7 Reflect microscope images of rock specimens type ( C ).....  | 47 |
| Figure 4.8 Scanning electron microscope images for sample A.....  | 48 |
| Figure 4.9 Scanning electron microscope images for sample B .....   | 49 |
| Figure 4.10 Scanning electron microscope images for sample C .....  | 50 |
| Figure 4.11 Rebound Number for the three rock samples .....   | 50 |
| Figure 4.12 Point load strength index $I_{S(50)}$ in dry and saturated conditions of the<br>three rock samples.....   | 56 |
| Figure 4.13 Failure modes of the rock samples (A, B, & C) under point load test ...   | 57 |
| Figure 4.14 The change in the tensile value in the dry and saturated state of the three<br>rock samples.....  | 60 |
| Figure 4.15 Failure modes in dry and saturated conditions of the rock samples A, B,<br>& C under Brazilian test.....  | 61 |
| Figure 4.16 Maximum stress in dry and saturated conditions of the three rock samples<br>in uniaxial compressive strength test .....                                     | 64 |
| Figure 4.17 Failure modes in dry and saturated conditions of the rock sample A<br>under uniaxial compressive strength.....  | 65 |
| Figure 4.18 Failure modes in dry and saturated conditions of the rock sample B under<br>uniaxial compressive strength.....  | 65 |

# CHAPTER 1

## INTRODUCTION

### 1.1 General

Despite the development of construction materials in the recent decades and years, the use of rocks in the field of construction is still used so far. Sedimentary rocks are among the essential natural resources that are used in the field of construction and industry and are also one of the most important sources of minerals globally. These rocks form a large part of the stratigraphic column in Iraq and are concentrated in the western and southwestern regions and cover about 104,000 km<sup>2</sup> of the country's area. Sedimentary rocks are used in several fields, such as building units in load-bearing walls and retaining walls, in facade covering works, internal and external cladding of walls and floors, in cladding the banks of rivers and streams, in road works as a base layer or under foundations, and in concrete as aggregate, in addition to the earthworks of railways, also used in the construction industries for example, limestone and gypsum rocks that are used in the production of cement, filler, and plaster. The multiple uses of rocks are due to the different conditions of their formation or deposition, which led to the difference in their mechanical and physical properties.

### 1.2 Problem Statement

Despite the vast area of the Iraqi Western Desert, there are few studies and research that classify and evaluate the rocks of these areas. Nevertheless, these areas were and still are a source of many natural resources in the field of construction, such as cement, filler, lime, and plaster. It is also an important and promising source in the field of mining and industry, such as sulfur, phosphates, glass sand, gas, and others. The use of stone blocks in construction is very common in the western regions of Iraq; through the field survey, three types of rocks used in the construction field were identified, where each type of rock is distinguished by its colour. These types of rocks are used indiscriminately as building materials such as cladding stones for facades, building load-bearing walls, partition walls, retaining walls and cladding the banks of rivers and streams. This has a significant impact on the life, cost, efficiency, and feasibility of the

facility. The characteristics and uses of each type of rock differ from the other, where one type is preferred over the other in terms of strength, mass, and interaction with water. These and other important characteristics have not been adequately studied. Finally, classifying and evaluating these types of rocks may dispense with the use of construction manufactured units, which has a significant positive impact on the climate.

### **1.3 The Aim of this Research**

In this study, the western region of Iraq is highlighted, near the border city of Al-Qaim with Syria. These regions are distinguished by their use of rock blocks in the building due to their abundance and the low value of their extraction, modifying and transferring them compared to the value and transportation of manufactured building blocks. In contrast, the nearest brick production factory is 300 kilometres away. Hence, the residents of these areas resort to developing methods for extracting and modifying stone for construction, it can be said that 95% of the government buildings and Residential houses in the western region of Iraq, which about 700,000 people inhabit, is built of rocks. This study will shed light on the type of rocks used in those regions building units. it will conduct several experiments on these rocks to find out their physical, chemical, and engineering properties and their suitability for use in construction.

## **1.4 Content of the Thesis**

### **1.4.1 Chapter I**

This chapter consists of the introduction, which is divided into a general introduction, problem statement, the aim of this research and finally, the structure of the research. This chapter explains a general idea about the use of rocks in the western region of Iraq, the reasons for choosing this region, and the statement of the great benefits of studying the rocks of these regions.

### **1.4.2 Chapter II**

It consists of a literature review. This chapter presents a review of previous studies conducted on different types of rocks and their classification and evaluation methods.

### **1.4.3 Chapter III**

This chapter shows the methods of collecting and preparing rock samples and a summary of the methods of conducting testing according to the technical specifications given for each test.

### **1.4.4 Chapter IV**

Display the results of the conducted tests, the equations, and the calculations with discussion. This chapter includes different presentations methods such as tables, figures, graphs, and pictures.

### **1.4.5 Chapter V**

Presents the conclusions derived from this study, such as classification and evaluation of the three types of rocks, as well as the main important recommendations for future studies.

## CHAPTER 2

### LITERATURE REVIEW

#### 2.1 Introduction

Since ancient times, people have used rocks as building materials. However, engineers used many types of rocks and aggregates in civil engineering applications, such as constructing roads, buildings, and other engineering projects. Rocks have been used as a construction material because of High bearing capacity, durability, local availability, low cost and energy for extraction and processing.

#### 2.2 Geological Formation of Rocks

Rocks are aggregates of one of the many types of minerals. The nature, type and properties of rocks are almost related to the mineral composition and type of formation. The main types of rocks can be classified into three types named [1], [2].

1. **Igneous rocks:** are formed from magma, which has originated well below the surface, has ascended towards the surface and has crystallized solid rock either on the surface or deep within the earth's crust as its temperature fell. Igneous rocks can be divided into two groups such as extrusive (volcanic) igneous rocks, which formed when "Lava" solidifies by rapid cooling at the surface, and intrusive (plutonic) igneous rocks, which formed when "Magma" solidifies by very slow cooling to the depth of many kilometres within the earth [3].
2. **Sedimentary rocks:** are formed by the accumulation and compaction of (a) fragments of pre-existing rocks that have been disintegrated by erosion; (b) organic debris such as shell fragments or dead plants; or (c) material dissolved in surface waters (rivers, oceans, etc.) or groundwater, which is precipitated in conditions of oversaturation [4].
3. **Metamorphic rocks:** are formed from pre-existing rocks of any type, which have been subjected to increases of temperature and/or pressure, such that the rocks undergo change. This change results in the metamorphic rock being different from the original parental material in appearance, texture and mineral composition. The rock cycle formation in nature can be shown in Figure 2.1 [5].

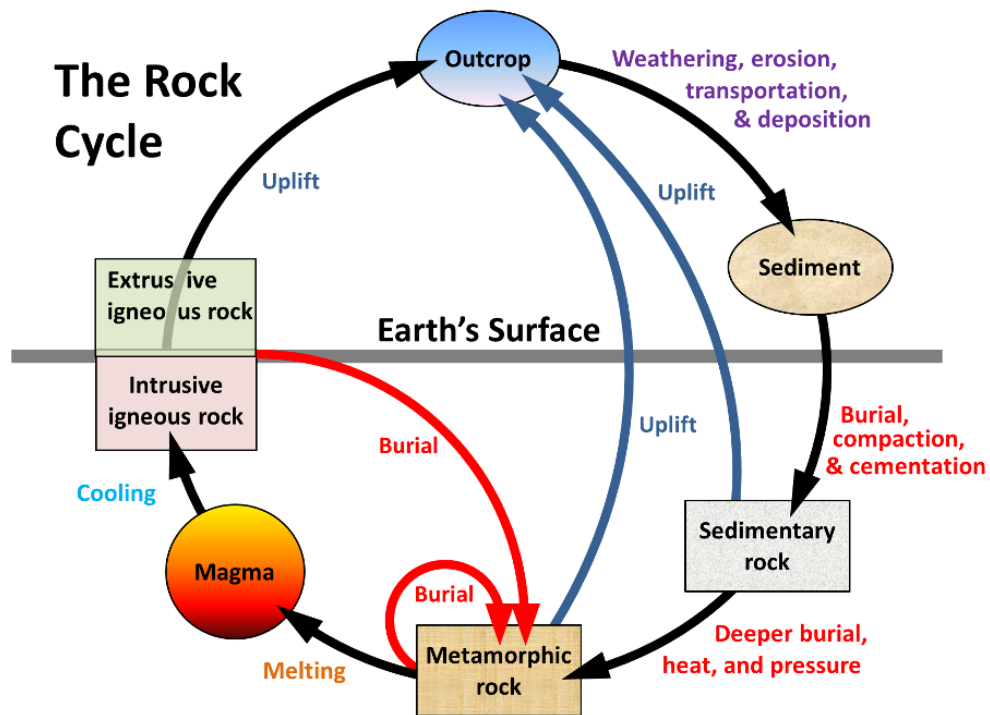


Figure 2.1 The rocks cycle formation in the nature [5].

### 2.3 Rocks Used as Construction Materials

Rocks that have been used as in construction materials as in their normal size or crushed into a smaller size were produced for a number of purposes, such as for concrete fabrics and road aggregate. Crushed aggregates have the following characteristics:

1. Angular rocks are better for road stone.
2. Impurities are easily removed by screening.
3. The main costs are blasting and crushing.
4. Selection often based on distance from quarry to site; transport costs [6].

## 2.4 Factors Affecting using the Rocks as a Construction Materials

Many factors can affect the engineer's decision whether to use the rocks in building construction. These factors are:

1. The volume of material that can be quarried: as far as volume is concerned, the life of the quarry should be at least 20 years. The amount of overburden that has to be removed also affects the economics of quarrying.
2. The ease with which it can be quarried: the ease with which a rock can be quarried depends on geological structures, notably the geometry of joints and bedding planes. Ideally, rock for building stone should be massive, certainly it must be free from closely spaced joints or other discontinuities as these control block size. In the case of sedimentary rocks, where beds dip steeply, quarrying has to take place along the strike. Steeply dipping rocks can also give rise to problems of slope stability when excavated. On the other hand, if beds of rock dip gently, it is advantageous to develop the quarry floor along the bedding planes. The massive nature of igneous rocks such as granite means that a quarry can be developed in any direction, within the constraints of planning permission.
3. The wastage due to quarrying: weathered rock represents waste; therefore, the ratio of fresh to weathered rock is another economic factor.
4. The cost of transportation.
5. Appearance: a uniform appearance is generally desirable in building stone. The appearance of a stone largely depends on its colour, texture, and mineral composition. Generally speaking, rocks of light colour are used as building stones.
6. Physical Properties such as:
  - a. Texture and porosity: the texture and porosity of a rock affect its ease of dressing and the amount of expansion.
  - b. Strength: for usual building purposes, uniaxial compressive strength of 35 MPa is satisfactory. In certain instances, tensile strength is important, which may be generated in a stone subjected to ground movements. The tensile strength of a rock is a fraction of its compressive strength. Hardness is a factor of small consequence, except where a stone is subjected to continual wear, such as in steps or paving.
  - c. Durability: The durability of a stone is a measure of its ability to resist weathering over an extensive period. It is one of the most important factors that determine whether or not a rock will be working for building stone. This test involves immersing specimens for 10 days in sulphuric acid. Stones that are unaffected by

the test are regarded as being resistant to attack by acidic rainwater. Those stones that fail are not recommended for external use in polluted environments [7].

## **2.5 Engineering and Mechanical Tests on Rocks**

There are several tests that can be carried out on the rocks in order to investigate their engineering and mechanical properties, such as:

### **2.5.1 Schmidt Hammer (SH)**

The Schmidt Hammer (SH), originally designed for testing the hardness of concrete in 1948, was first used in a geomorphological context in the 1960s. The SH has become the advantages and disadvantages of the device for measuring rock characteristics and has been used for an increasing range of purposes, including the study of various weathering phenomena a range. The Schmidt Hammer (SH) is an indexed method to determine uniaxial compressive strength.

The instrument measures the rebound distance of a controlled impact on a rock surface. There are now several versions of the hammer. The 'N' type can provide data on a range of rock types from weak to very strong, with compressive strengths ranging from 20 to 250 MPa. The 'L' type hammer has an impact stress time lower than the 'N' type, and the 'P' type is a pendulum hammer for testing materials of very low hardness, with compressive strength of less than 70 kPa. When the SH is pressed against a surface, its piston is automatically released onto the plunger. Part of the piston's impact energy is consumed by absorption and is transformed into heat and sound. The remaining energy represents the impact penetration resistance of the surface. This enables the piston to rebound. The distance travelled by the piston after it rebounds called the rebound value (R). Harder rocks have higher R values [8].

Rebound values are influenced by gravitational forces to varying degrees so that non-horizontal rebound values must be normalized with reference to the horizontal direction [9]. The R Value is shown by a pointer on a scale on the side of the instrument (range 10–100). Therefore, it is important that the Schmidt Hammer is used with care and properly calibrated [10].

A very substantial number of R values have been obtained from many different rock types in many parts of the world [8]. At one end of the scale, 'weak' rocks such as chalk, and marls have low compressive strength. At the other end, silicates, very hard

limestone, quartzite, and various igneous rocks have values exceeding 60, and very occasionally 70.

Selby and John [11] has divided rocks up into five classes Table 2.1. This provides a useful basis for classifying rocks and for giving a clear indication of a rock's character. Because of its speed, simplicity, portability, low cost and non-destructive, the SH has been used as a means of estimating other rock properties, such as compressive strength [12]. Various researchers have studied the relationship between rock compressive strength and SH R values, as shown in Table 2.2. The  $R^2$  value has ranged between 0.7 and 0.99 [13]. Nonetheless, Hack and Huisman [14] point out, a large number of tests in the field, using the SH, will tend to give a better estimate of the intact rock strength at various locations than a limited number of more complex test.

Table 2.1: Approximate strength classification of rocks [11]

| Description  | Uniaxial compressive strength, MPa | Point load strength $I_{s(50)}$ , MPa | Schmidt Hammer N-Type, 'R' | Characteristic rocks  |
|--|------------------------------------|---------------------------------------|----------------------------|---|
| Very weak rock – Crumbles under shrap blows with geological pick point, can be cut with pocket knife.                        | 1-25                               | 0.04-1.0                              | 10-35                      | Weathered weakly Compacted sedimentary rocks-chalk, rock salt                           |
| Weak rock – shallow Cuts or scraping with pocket knife with difficulty, pick point indents deeply with firm blow             | 25-50                              | 1.0-1.5                               | 35-40                      | Weakly cemented Sedimentary rocks – coal siltstone, also schist                         |
| Moderately strong rock – knife cannot be used to scrape or peel surface, shallow indentation under firm blow from pick point | 50-100                             | 1.5-4.0                               | 40-50                      | Competent sedimentary Rocks – sandstone shale, slate                                    |
| Strong rock – hand-held sample breaks with one m firm blow from hammer end of geological pick                                | 100-200                            | 4.0-10.0                              | 50-60                      | Competent igneous and Metamorphic rocks – marble, granite, gneiss                       |
| Very strong rock – requires many blows a from geological pick to break intact sample   | >200                               | >10                                   | >60                        | Dense fine-grained igneous and metamorphic rocks – quartzite, dolerite, gabbro, basalt. |

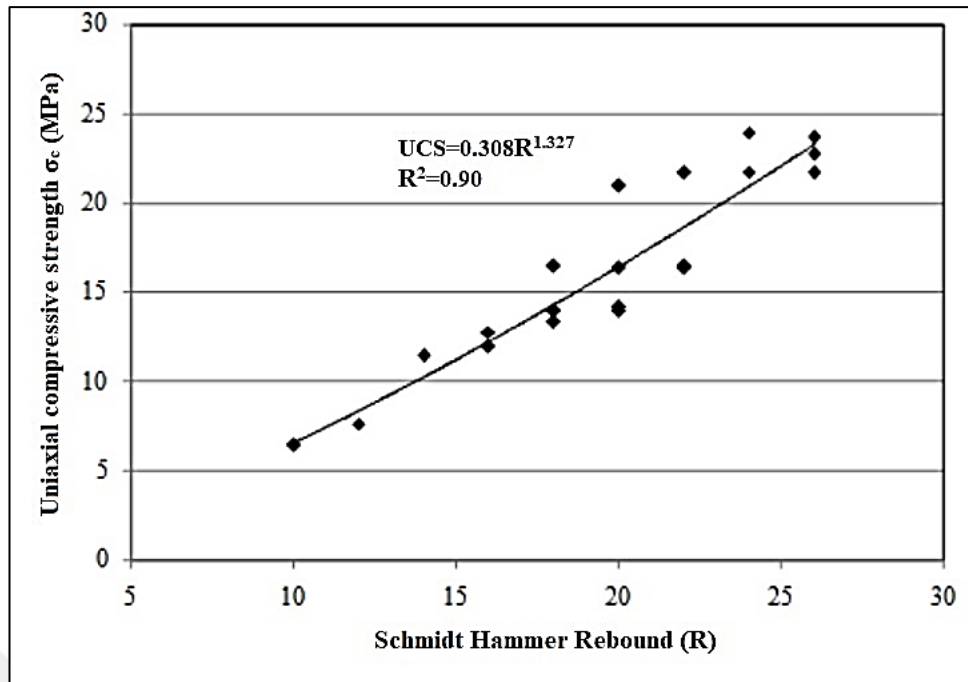


Figure 2.2 The relationship between uniaxial compressive strength and the Schmidt Hammer Rebound (R) [11]

Table 2.2: Correlation between Schmidt hammer rebound and uniaxial compressive strength and Young's modulus [8]

| Equation   | R <sup>2</sup> | Researcher                 | Lithology                |
|--|----------------|----------------------------|--------------------------|
| UCS  |                |                            |                          |
| $UCS = 6.9 \times 10^{(0.0087\gamma R + 0.16)}$    | 0.94           | Deere and Miller (1966)    | varied                   |
| $UCS = 6.9 \times 10^{(1.348\gamma R - 1.325)}$    | -              | Aufmuth (1973)             | varied                   |
| $UCS = 0.447\exp(0.045(R + 3.5) + \gamma)$         | -              | Kidybinski (1980)          | Coal, Shale, mudstone    |
| $UCS = 2R$   | 0.72           | Singh et al. (1983)        | Sandstone, siltstone     |
| $UCS = 0.4RLM - 3.6$                               | 0.94           | Sheorey et al. (1984)      | Coal                     |
| $UCS = 0.994R - 0.383$                             | 0.70           | Haramy and De Marco (1985) | Coal                     |
| $UCS = 702R - 1104$                                | 0.77           | O'Rourke (1989)            | Sandstone                |
| $UCS = 2.208e^{0.067R}$                            | 0.96           | Katz et al. (2000)         | Limestone, sandstone     |
| $UCS = \exp(0.818 + 0.059R)$                       | 0.98           | Yilmaz and Sendir (2002)   | Gypsum                   |
| $UCS = 2.75R - 36.83$                              | -              | Dincer et al (2004)        | Andesite, basalts, tuffs |
| $UCS = 2.22R - 47.67$                              | -              | Aggistalls et al (1996)    | Gabbros, basalts         |
| E  |                |                            |                          |
| $E = 6.95\gamma^2 R - 1.14 \times 106$             | 0.88           | Deere and Miller (1966)    | Varied                   |
| $E = 6.9 \times 10^{(1.06 \log(\gamma R) + 1.86)}$ | -              | Aufmuth (1973)             | varied                   |
| $E = 0.00013R^{3.09074}$                           | 0.99           | Katz et al. (2000)         | Syenite, granite         |
| $E = \exp(1.146 + 0.054R)$                         | 0.91           | Yimaz and Sendir (2002)    | gypsum                   |

UCS = Uniaxial compressive strength (MPa), E = Young's modulus (MPa), R = Schmidt hammer rebound number,  $\gamma$  = rock density ( $g/cm^3$ )

## **2.5.2 Physical and Mechanical Properties of Rocks**

According to Das [15] and Zumberge [16], the physical and mechanical properties of rocks are as follows:

### **2.5.2.1 Bulk Density ( $\rho$ )**

It is the ratio between weight of grains and its volume, which is the average density and its units are  $\text{g/cm}^3$ . For most rocks near the earth surface have average densities between  $(1.5 - 3) \text{ g/cm}^3$ .

### **2.5.2.2 Unit Weight ( $\gamma$ )**

It is the ratio of rock weight to its volume and its unit is  $\text{N/m}^3$ .

### **2.5.2.3 Specific Gravity (G)**

It is an essential property in engineering projects, represents the ratio of rock density (or its unit weight) to water density (or its unit weight) so that G has no units.

### **2.5.2.4 Void Ratio (e)**

It is the ratio of volume of voids to the volume of solid.

### **2.5.2.5 Compressive strength**

It is the stresses that result from compressive forces causing contraction in the volume of rocks. There are two types:

- a- Unconfined (Uniaxial) Compressive Strength: It is the most frequently used strength test for rocks in which a load on the rock acts in one direction only.
- b- Confined (Triaxial) Compressive Strength: Rocks in nature are seldom subjected to stresses in one direction but subjected to stresses from three directions.

### **2.5.2.6 Tensile strength**

It is the maximum tensile stress, which a material is capable of developing. In nature, the rock mass is rarely subjected to direct tension, but it is subjected to tensile stresses. In the roofs and domes of underground openings, tension develops in the tensile zone of the rock mass. Tensile stresses are also developed on the underside of a rock slab or a beam subjected to bending; hence the knowledge of a tensile strength of the rock mass is also necessary. Rocks are weak in tension. It has been found that rocks possess a tensile strength which is about 10 % of its compressive strength. Because it is

difficult to prepare rock samples for direct tensile tests, so the tensile strength of rock samples is determined indirectly by other methods (Brazilian and bending tests).

#### **2.5.2.7 Shear strength**

It is the capacity of a rock mass to take shear stress or the maximum resistance to deformation due to shear displacement caused by shear stress. Shear strength in a rock mass is derived from the surface frictional resistance along the sliding plane, interlocking between the individual rock grains and cohesion in the sliding surface of the rock.

### **2.6 Using of Rocks and Aggregates as a construction Materials**

#### **2.6.1 Roofing and Facing Materials**

Rocks used for facing stones should have high tensile strength in order to resist cracking. Rocks used for roofing purposes must split into thin slabs, in addition to being durable and impermeable. Consequently, slate is one of the best roofing materials available and has been used extensively.

#### **2.6.2 Armour stone**

Armour stone refers to large blocks of rock that are used to protect civil engineering structures. Large blocks of rock, which may be single-size or, more frequently, widely graded (rip-rap), are used. Usually, armour stone is specified by weight, a median weight of between 1 and 10 tons normally being required. Blocks up to 20 tons, however, may be required for breakwaters that will be subjected to large waves. They are used to:

- a. Protect the upstream face of dams against wave action.
- b. In the construction of riverbank and bed protection and stabilization,
- c. In coastal engineering for the construction breakwaters, embankments,
- d. Protection of sea walls, and for rubble rock grains [17].

#### **2.6.3 Crushed Rock**

Crushed rock is produced for a number of purposes, the chief of which are concrete and road aggregate. Approximately 75% of the volume of concrete consists of aggregates; therefore, its properties have a significant influence on the engineering behaviour of concrete. Aggregate is divided into coarse (4-40 mm) and fine types (less than 4 mm in size). The amount of overburden that has to be removed is an important

factor in quarrying operations, for if this increase and is not used, then a time comes when quarrying operations become uneconomic [17].

#### **2.6.4 Road Aggregate**

Aggregate constitutes the basic material for road construction and is quarried in the same way as aggregate for concrete. One of the most important parameters of road aggregate is the polished stone value (PSV) test, which influences skid resistance because it forms the greater part of a road surface; rock aggregate used as road metal must be:

- a. Fresh with high strength, to bear the main stresses imposed by traffic.
- b. High resistance to impact and abrasion, polishing and skidding, and frost action.
- c. It must also be impermeable,
- d. Chemically inert and
- e. Possess a low coefficient of expansion [17].

#### **2.6.5 Gravels and Sands**

##### **2.6.5.1 Gravel**

Gravel deposits usually represent local accumulations, for example, channel fillings. A gravel deposit consists of a framework of pebbles between which are voids. The voids are rarely empty, being occupied by sand, silt, or clay material. The shape and surface texture of the pebbles in a gravel deposit is influenced by the agency responsible for its transportation and the length of time taken in transport, although the shape is also dependent on the initial shape of the fragment, which in turn is controlled by the fracture pattern within the parent rock. Gravel particles can be classified as rounded, irregular, angular, flaky and elongated in shape. The composition of a gravel deposit reflects not only the type of rocks in the source area but is also influenced by the agents responsible for its formation and the climatic regime in which it was or is being deposited [17].

### **2.6.5.2 Sand**

The shape of sand grains, however, is not greatly influenced by the length of transport. Sands used for building purposes should have the following characteristics:

1. Sands are used for building purposes to give bulk to concrete, mortars, and plasters.
2. Sand consisting of a range of grade sizes gives a lower proportion of voids than one in which the grains are of uniform size.
3. Sands used for building purposes are usually siliceous in composition
4. Sand should be as free from impurities as possible.
5. Ideally, they should contain less than 3%, by weight, of silt or clay, since they need a high-water content to produce a workable concrete mix. High water content leads to shrinkage and cracking in concrete drying.
6. The presence of feldspars in sands used in concrete has occasionally caused cracking.
7. Mica and particles of shale adversely affect the strength of concrete.
8. If iron pyrite occurs in the sand, it gives rise to unsightly rust stains when used in concrete [17].

### **2.7 Rocks and Aggregates in Iraq**

Iraqi's rocks are one of the most important sources for different types of minerals that are used for construction and industries, especially Northern region and the Western desert. The Northern Region (Kurdistan Region) has an enormous number of different carbonate rock units, which vary widely in their geological age and sedimentary depositional environment. Limestone quarried from the exposures has a wide range of usages and applications, such as dimension stone, crushed stone, building stone and paving stones. Since antiquity, limestone was used as building materials in areas where they were naturally available and abundant. Little work has been done to indicate the physical and mechanical properties of the limestone, especially under humid environment [18].

The Western Desert of Iraq is one of the most interesting physiographic provinces in the region. Many important industries in Iraq are based on the mineral resources of the Western Desert. The phosphate fertilizer industry is based on Akashat phosphoresces deposit. Refractories and ceramic industries are based on Dwuekhla kaolinitic claystone deposit and the Hussainiyat bauxite and flint clay deposits; the glass industry use quartz-sand from Rutbah [19]. The cement industry uses many limestone and clay

deposits and ironstones from the South Hussainiyat deposit and montmorillonite clay stones from the Safra mine, which are used as drilling mud. Subsurface potential for mineral deposits is still not explored, and the possibility of finding new mineral deposits is still valid in view of the geological history of the Western Desert and the diversity of its lithostratigraphic units [20]. Fluvial and fluviomarine deposits of quartz-sand are characteristic features of the Rutbah Formation (Cenomanian) [21]. Many industries are developed using the natural resource of the Western Desert, but there is more that can be proved, tested and applied. Generally, the landscape of the Western Desert of Iraq is not complex but is characterized by varied forms; the study area is hilly to the semi-flat area. The lithology and hardness of rocks have played a role in the development of different landforms; for example, the hard rocks give the desert a plateau form. Interbedded rocks of variable hardness have accelerated the dissection of the plateau into steps or minor plateaus. The soluble rocks have led in forming of cost units and features. Finally, the soft rocks contributed in the development of eolian units. The Western Desert of Iraq is covered by various geological formations ranging from Paleozoic (Pre-Carboniferous) to Cenozoic in age. This study includes Maaddud Formations, which was recognized in the Iraqi Western Desert for the first time by Al-Mubarak and Amin [22]. It represents the upper part of the first sedimentary cycle of the Cretaceous. It is exposed east of Rutbah town by 11 Km and extends eastwards till about 70 Km, near Jabal Arainbah and extends north-eastwards till Faidhat Tlaihah. There, it disappears due to tectonic reasons and appears again north of Faidhat Tlaihah and extends northwards for about 45 Km as dissected segments by NW - SE trending faults [23]. The following is a summary of Iraqi Geological Materials:

### **2.7.1 Silica Sands (Glass Sands)**

Silica sand is mainly located in The Ardhumma quarry west of Rutba in the Western Desert to produce glass sand and supply some of the Ramadi Glass Factory, as raw materials for silica brick industry, in addition to the foundry factory. Glass sands must have a silica content of over 95%. The amount of iron oxides present in glass sands must be very low [24].

### **2.7.2 Limestone for building purposes**

In many parts of Iraq, limestone suitable for building is available. Extracting and quarrying these rocks needs some requirements such as freedom from fissure and fractures as well as the relative softness of the rock. One of these quarries is Jalla in Anbar Governorate for the rock blocks, which are then transferred to a factory where they are cut into the required sizes by means of saws and diamond vibrators. Other three projects have been implemented and distributed on Sarchanar and Sinjar north of Iraq and Haklan in Anbar Governorate [24].

### **2.7.3 Marble**

Considerably large quantities of marble are available in different colours and kinds, which are distributed in various districts north of the country. Marble blocks started in production quarries of Salahuddin, Rayat, Darbandikhan and Panjawin [24].

### **2.7.4 Sands and Gravel**

There are many quarries of sands and gravels and constructing factories together with their washing and sorting in various districts of Iraq and large quantities. These include Nabai centre, Sinam centre, Tieb centre, gravel centre in Mosul-Hammam Alil, gravel centre in Qaim-Akashat [24].

### **2.7.5 Salinas**

To cover the requirements of mankind and animal consumption, all necessary investigations were made on internal Salinas Sea Salinas in Fao. In order to produce refined salts suitable for human and animal consumption, as well as for industrial purposes, steps are taken to develop some of the internal Salinas in order to produce natural sodium sulphate and secondary chemical compounds for bromide and magnesium compounds in later stages [24].

### **2.7.6 Clays**

a. Ceramic Clays: They are composed mainly of kaolinite and quartz with some alumina content and iron oxides. There are many quarries of kaolin clays (white and coloured) in Koua district, Duekhla quarry and Hussainiyat valley in the western desert suitable for the manufacture of some ceramic products utilizing one of the sites to supply ceramic factory in Ramadi and white cement factory in Falluja. In addition, they are used for coloured roof tiles and many construction industries.

b. Bentonite

Clays; Bentonite clays are composed mainly of montmorillonite minerals. Bentonite clays are widespread in Qara Tappa and Zurluk in Kirkuk. These clays have been used in civil engineering, such as driving piles, excavation works (digging of wells), purification and treatment work as well as metallurgic works (sand casting) [24].

#### **2.7.7 Flint clays**

These clays are available in Hussainiyat valley in the western desert. They consist of kaolinite and quartz with alumina 35-41% and silica 38-46%. They are used for the manufacture of white cement and ceramic materials [24].

#### **2.7.8 Porcellanite Rocks**

These rocks are of high porosity consists mainly of silica 85% and alumina 10%. They are widespread in the western desert of Iraq. They were deposited in the marine depositional environment with the accumulation of great quantities of diatoms rich in silica. It is used in many construction materials and as an abrasive material [24].

#### **2.7.9 Quartzite and Silcrete Rocks**

Quartzite rocks are one of the main siliceous deposits that are widely spread in the Western Desert of Iraq. These deposits are with high hardness and are suitable for high-quality silica refractories (silica bricks) due to their high silica content reaching 97% with low alumina ( $Al_2O_3$ ) (<1.5%).

Silcrete rocks are a type of quartzite siliceous deposits widespread in the western desert. Silcrete rocks consist mainly of quartz in the range of 95-99% with some iron oxide and carbonate as a cementing material. It is used mainly for manufacturing acidic refractories (silica bricks) [24].

#### **2.7.10 Bauxite**

It is hydrous alumina available in Hussainiyat valley in the western desert, Iraq. It consists of kaolinite, quartz, alumina (47-62%), and silica (14-40%). It is used for cement manufacture, abrasive material and refractories and many other chemical industries [24].

#### **2.7.11 Chert**

These rocks are strong rocks with high content of silica reaching 94% with a low amount of oxides of calcium, magnesium and iron. They are widespread in Akashat in the western desert [24].

## CHAPTER 3

### METHODOLOGY

#### 3.1 General

In this chapter, the rock mass samples and intact rock specimens which were used in this study will be discussed, Rock mass samples were collected from three different quarries, for three types of rocks commonly used in construction in that region, which are used in several construction fields such as cladding stones for facades, building load-bearing walls, retaining walls, cladding the banks of rivers and streams, foundation and construction works below ground level, road works as a base layer or under foundations, earthworks of railways see Figures 3.1, 3.2, 3.3, & 3.4. The methods of extracting rock masses and the process of preparing rock specimens will also be presented. Also, the saturation time for each type of rock will be found. This chapter also discusses the tests that have been carried out according to the testing program that was prepared during the preliminary stages of research preparation,, namely engineering tests, which include non-destructive and destructive test, the former includes Schmidt Hammer test, while the latter was carried out in the dry and saturated conditions, including Point Load, Brazilian and uniaxial compression test, Also rock characterization experiments were conducted and included XRD test, polarized microscope test and SEM test, as well as physical test, which include specific gravity, unit weight and water content. Also, chemical tests include organic, gypsum, total soluble salt (TSS), and sulphate  $SO_3$ .



Figure 3.1 Load-bearing walls



Figure 3.2 Cladding stones for facades



Figure 3.3 Cladding the banks of rivers and streams



Figure 3.4 Retaining walls

### 3.2 Geology of study area

The Iraqi Western Desert makes up more than one-third of the country's area, covering about 104000 km<sup>2</sup>. It extends from the Iraqi - Syrian border and Euphrates River, in the north and east to the Iraqi-Saudi and Iraqi- Jordanian borders, in the south and west, respectively. This desert is divided into two parts, the western and southern deserts, called the Southern Badia and the Western Badia Figure 3.5 [23].

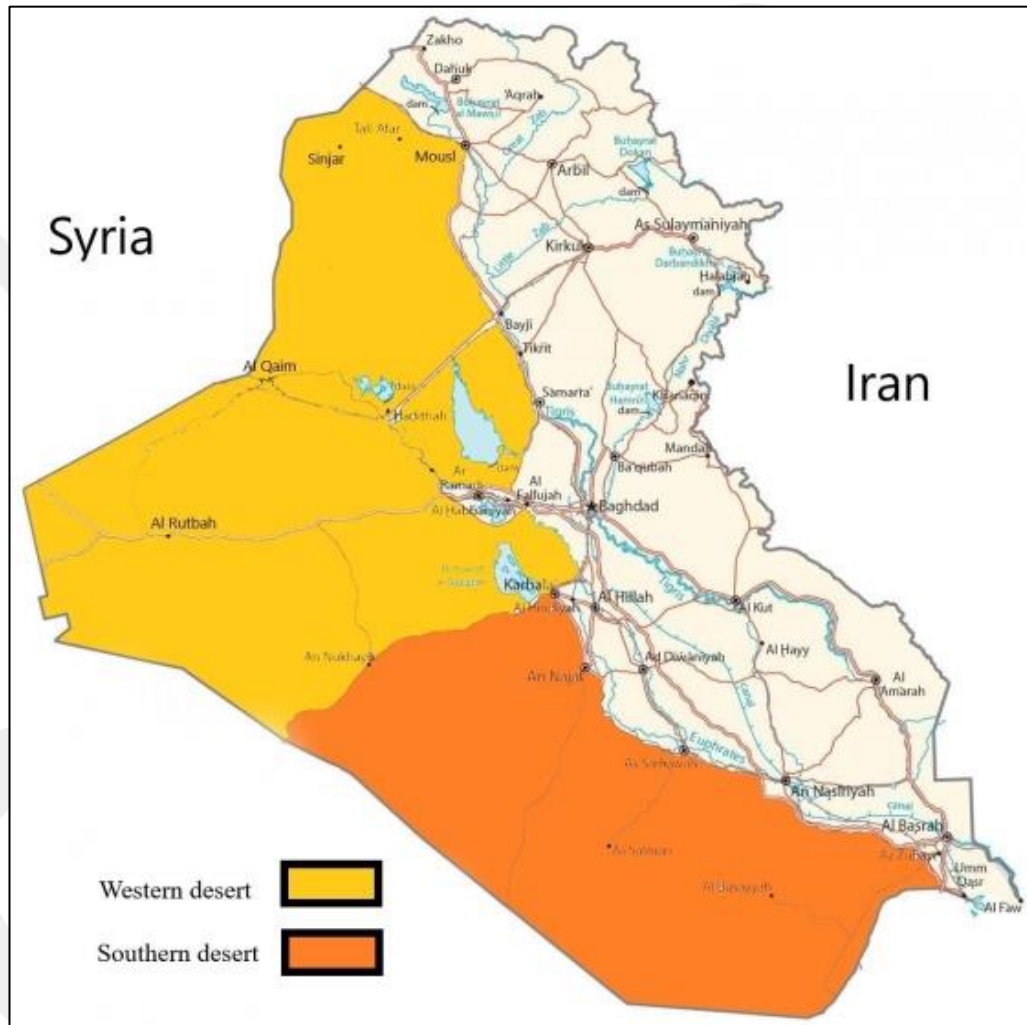


Figure 3.5 Iraq deserts

The western desert is characterized by the diversity of the topographical nature, where three basic topographical forms can be distinguished depending on the type and thickness of the surface rock layer, which is: The western part, The middle part, and the eastern part Figure 3.6 [23].

The middle part, which pertains to our study, extends from the Euphrates River in the northeast to the Iraqi-Saudi border in the southwest. These areas consist of deep and dense valleys that flow into the Euphrates River. The range of exposed rocks is Pleistocene, and the oldest exposed rocks are Permian in age Figure 3.7 [23].

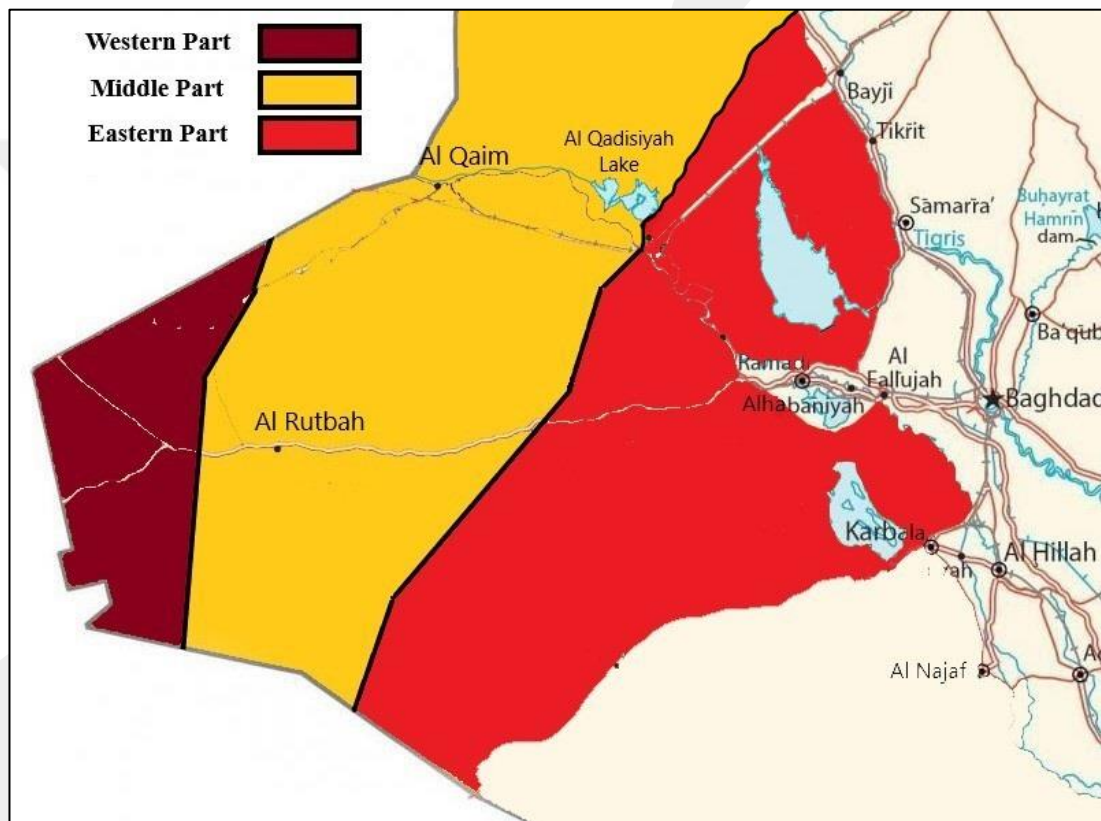


Figure 3.6 Parts of the western desert

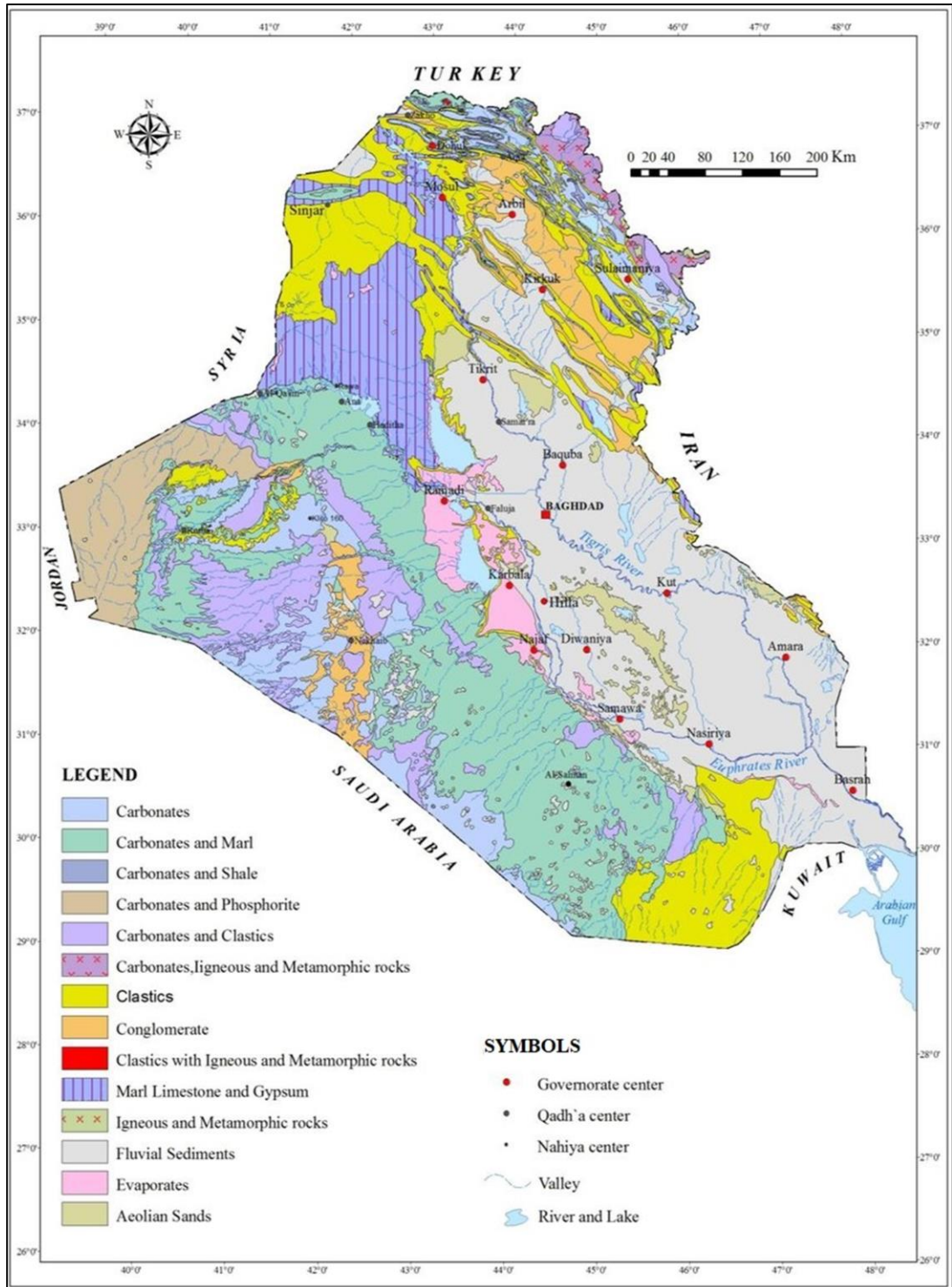


Figure 3.7 Lithological map of Iraq [34]

Three stone quarries were identified for selecting samples from them Q1, Q2, and Q3 as shown in Figure 3.8. These sites were chosen because they produce three types of rocks that are widely used. These three quarries are located in the Al-Anbar Governorate, and the locational information of the quarries are presented in the Table 3.1.

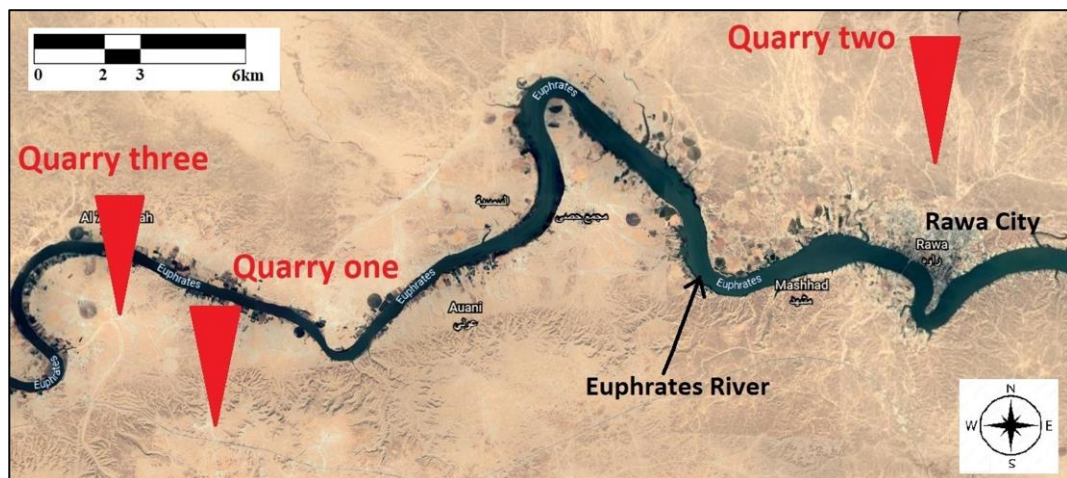


Figure 3.8 Locations of study areas

Table 3.1 Locations and coordinates of the study areas

| Description                              | quarry symbol | rock symbol | Location    |             | Elevation (m) |
|--|---------------|-------------|-------------|-------------|---------------|
|  |               |             | Longitude E | Latitude N  |               |
| Limestone yellowish in color             | Q1            | A           | 41°40'51.2" | 34°25'26.5" | 288           |
| Limestone tend to brown and maroon color | Q2            | B           | 41°54'06.2" | 34°31'05.1" | 182           |
| White dolostone                          | Q3            | C           | 41°40'58.9" | 34°25'02.9" | 293           |

### 3.3 Selection of rock samples

Through the on-site detection of rock quarries for how the rocks are extracted, at first the surface soil layer, which usually ranges in thickness (1 - 2 m), is lifted by an articulated loader or bulldozer until it reaches the rocky layer, then the process of crushing the rocky layer begins by a hydraulic crushing hammer attached to an excavator as shown in the Figure 3.9. The bulldozer collects them, and the crushing of large blocks is done manually as shown in the Figures 3.10, 3.11, then they are loaded and transported to construction sites. The thickness and depth of the rock layers vary from one type to another and from one quarry to another.



Figure 3.9 Hydraulic crushing hammer attached to an excavator



Figure 3.10 Collect and load rocks by an articulated loader



Figure 3.11 Collecting large blocks of rock and crushing them manually by workers

### 3.3.1 Quarry One (Q1)

This quarry is located near the Euphrates River, on the road that connects the city of Rawa and the border city of Al-Qaim, as shown in Figure 3.8 and Table 3.1. It produces rocks type A that is yellow in colour, at a depth of (1-2 m), the thickness of the rock layer of this type about (0.5-1 m) as shown in Figure 3.12, and it is one of the preferred types in building due to its ease of formation with the required dimensions and low mass compared with other types, this type of rock is usually used in the construction of load-bearing walls, in addition, walls can be built with a minimum thickness of 30 cm.



Figure 3.12 Quarry one (Q1) produces rocks type A

### 3.3.2 Quarry Two (Q2)

This quarry is located near the city of Rawa, as shown in Figure 3.8 and Table 3.1. This quarry produces B-type rocks that are brown in colour, as shown in Figure 3.13, which is located above the surface of the earth or at a small depth and are usually exposed to various weathering factors; also, this type of rock is characterized by its hardness and high density.



Figure 3.13 Quarry two (Q2) produces rocks type B

### 3.3.3 Quarry three (Q3)

This quarry produces rock type C, which is identified by its white appearance, as shown in Figure 3.14. This type of rock is the most widespread in the Western Desert of Iraq and is widely employed in the building industry. This type of rock can be extracted after the extraction of the type A rocks layer. The thickness of the rock layer of this type is higher than other types of rocks, reaching five meters. The hardness of this type of rock increases with its depth. The upper layers are extracted, which can be easily fractured and formed see Figure 3.15. Further, this type of rock is widely used in building load-bearing walls and in various fields of industry, such as the production of cement, plaster, fertilizers, and others.



Figure 3.14 C-type rock blocks



Figure 3.15 Quarry three (Q3) produces rocks type C

### 3.4 Preparing Rock Specimens

After preparing the rock blocks, they were transferred to a workshop in Rawa city, cylindrical specimens of each type of rock were taken, by using a 54mm diameter core drilling machine for two categories see Figures 3.16, 3.17, In addition to the third category of irregularly shaped specimens with small dimensions for petrographic tests.



Figure 3.16 Extraction of cylindrical specimens from rock masses



Figure 3.17 Extraction of cylindrical specimens from rock masses

The first category cylinder shape with 54mm diameter, length to diameter ratio (2-3) and 15cm length were prepared for uniaxial compressive strength and Schmidt hammer test respectively, see Figure 3.18.



Figure 3.18 Modify the dimensions of the specimens for the first category

The second category disc shape with 54mm diameter and length to dimension ratio ( $t/d$ ) of (0.20–0.75) and ( $0.3d < L < d$ ) were prepared for Brazilian test and point load test, respectively, were  $t$ =thickness of the disc,  $d$ = diameter 54mm see Figure 3.19.



Figure 3.19 Rock specimens of the second category

The third category was irregularly shaped with flat surfaces; this category of specimens was used in physical test, chemical test and characterization of rocks tests; irregular and different sized pieces of rock were used for each type of rock in physical and chemical tests. Also, cross-area dimensions about (1\*2cm) for XRD and less dimensions for SEM test, see Figure 3.20. Table 3.2 summarizes the categories of specimens.



Figure 3.20 Rock specimens of the third category

Table 3.2 Categories and numbers of specimens for each test of the three types of rocks that have been studied

| No  | Tests                     | Dimensions                           |               | Categories   | No. of specimens |        |        |                     |        |        | Total number of specimens |
|-----|---------------------------|--------------------------------------|---------------|--------------|------------------|--------|--------|---------------------|--------|--------|---------------------------|
|     |                           |                                      |               |              | Dry Condition    |        |        | Saturated Condition |        |        |                           |
|     |                           | Length (mm)                          | Diameter (mm) |              | type A           | type B | type C | type A              | type B | type C |                           |
| 1   | Uniaxial Compression Test | L/D =2-3                             | 54            | Category (1) | 5                | 5      | 5      | 5                   | 5      | 5      | 30                        |
| 2   | Schmidt Hammer Test       | 150                                  | 54            |              | 5                | 5      | 5      |                     |        |        | 15                        |
| 3   | Point load Test           | $0.3D < L < D$                       | 54            | Category (2) | 10               | 10     | 10     | 10                  | 10     | 10     | 60                        |
| 4   | Brazilian Test            | L/D =0.2-0.75                        | 54            |              | 10               | 10     | 10     | 10                  | 10     | 10     | 60                        |
| 5   | Water Content             | L/D =0.2-0.75                        | 54            |              | 10               | 10     | 10     |                     |        |        | 30                        |
| 6   | XRD Tests                 | Irregular shapes and different sizes |               | Category (3) | 1                | 1      | 1      |                     |        |        | 3                         |
| 7   | SEM Test                  |                                      |               |              | 1                | 1      | 1      |                     |        |        | 3                         |
| 8   | Polarized microscope      |                                      |               |              | 1                | 1      | 1      |                     |        |        | 3                         |
| 9   | Physical Tests            |                                      |               |              | 1                | 1      | 1      |                     |        |        | 3                         |
| 10  | Chemical Tests            |                                      |               |              | 1                | 1      | 1      |                     |        |        | 3                         |
| 210 |                           |                                      |               |              |                  |        |        |                     |        |        |                           |

### 3.5 Saturation of Specimens

Natural water contents of each type of rock must be determined for use when conducting tests in dry conditions and saturated conditions, to determine the impact of water saturation on a physical characteristic of rocks, the specimens were weighed and then dried for 24 hours at 106° C and weighed, then immersed in water see Figures 3.21 & 3.22. The specimens were then removed, weighed, and returned to the basin multiple times as shown in Appendix A and for escalating periods of time until the specimens are fully saturated such that their weights are steady. By observing the change in the weight of the specimens with the increase in the immersion period, we deduce the time required to saturate each type of rock. The duration of immersion of the specimens in water until saturation is used to compare the Engineering properties of the three types of rocks in the dry and saturated conditions.



Figure 3.21 Drying and weighing the rock specimens before immersing them in water



Figure 3.22 Immersion specimens in water for escalating periods of time and weighing each time

### 3.6 Physical Tests

Three specimens were prepared for each type of rock. The specimens were delivered and tested at the University of Technology - Scientific and Engineering Consultation Bureau - Construction Materials Laboratory, Accreditation Code (TL036), the Specific Gravity, Unit Weight, and Porosity values were found. The test was done according to the Standard specifications, as shown in Table 3.3.

Table 3.3 Standard specifications for physical test

| Type           | Test             | Standard    |
|----------------|------------------|-------------|
| Physical Tests | Specific Gravity | ASTM D-854  |
|                | Unit Weight      | ASTM D-7263 |
|                | Porosity         | ASTM D-4525 |

### 3.7 Chemical Tests

Three specimens were prepared for each type of rock. The specimens were delivered and tested at the University of Technology - Scientific and Engineering Consultation Bureau - Construction Materials Laboratory, Accreditation Code (TL036), the proportion of sulfur salts  $SO_3$ , total soluble salts (TSS), gypsum content, and content of organic matter values were found. The test was done according to the Standard specifications, as shown in Table 3.4.

Table 3.4 Standard specifications for chemical test

| Type          | Test                                 | Standard             |
|---------------|--------------------------------------|----------------------|
| Chemical Test | Organic content                      | BS 1377: 1990 Part 3 |
|               | Gypsum Content (%)                   |                      |
|               | Total Soluble Salt (TSS) Content (%) |                      |
|               | Sulphate ( $SO_3$ ) Content (%)      |                      |

## 3.8 Characterization of the Rocks

### 3.8.1 Polarized Microscope

The purpose of the examination is the naming and determining of the rock type through knowing the elements that make it. The examination was carried out in the Iraqi Geological Survey institute. Slides were taken from three types of rocks A, B and C. The slides were examined with a 2500x polarizing microscope.

### 3.8.2 XRD Tests

X-ray diffraction is an important instrument in analysing specimens and extracting information about the physical properties, structure, crystalline composition, and chemical composition of materials. Tests were conducted for the three rocks specimen in the University of Technology, Nanotechnology and Advanced Materials Research Centre - Advanced Measurements Lab. The model of the device that was used is XRD-6000; the rock specimen was used is irregularly shaped with flat surfaces; the cross-area dimensions about (1-1.5 cm) see Figure 3.23.



Figure 3.23 X-ray diffraction test device

### 3.8.3 SEM Test

A scanning electron microscope is used to examine, analyse and identify the chemical elements of the specimen surfaces. This microscope uses a narrow electron beam that scans the specimen's surfaces, which causes reflecting the secondary electrons; from this reflection, a three-dimensional image of the sample surface can be produced. Tests were conducted for the three rock specimens in the University of Technology, Nanotechnology and Advanced Materials Research Centre - Advanced Measurements Lab. The rock specimen was used is an irregular shape with flat surfaces, the cross-area dimension about (0.5-1 cm). See Figure 3.24.



Figure 3.24 scanning electron microscope (SEM) test device

### **3.9 Engineering Tests**

Engineering tests are divided into two parts, non-destructive test and destructive test.

#### **3.9.1 Non-destructive Test**

There are many non-destructive tests for rocks, mainly divided into two methods, mechanical methods and electrical methods, mechanical methods are divided into seismic, ultrasonic and hammer methods. In this study, one of the hammer methods was carried out, which is the Schmidt hammer test.

##### **3.9.1.1 Schmidt Hammer Test**

The Schmidt hammer is used to set the rebound number, where the work of the device depends on the strength of the rebound of an elastic mass from the surface to be tested. This rebound number is used to guide the approximate value of the compressive strength of concrete, rocks, manufactured building blocks, one of the advantages of this device are that it can be used on site easily and get immediate results, and it is easy to calibrate it from time to time. The test was conducted according to the American standard specifications ASTM [25] see Figure 3.25.



Figure 3.25 Testing the rebound number (Schmidt hammer) of rock specimens

### 3.9.2 Destructive Tests

There are many destructive tests for rocks. In this study, three destructive tests were performed on the three types of rocks in the dry and fully saturated state.

#### 3.9.2.1 Point Load Test

The point load test is one of the tests that can be done in the field in addition to the laboratory. It is used to classify solid samples, such as concrete, rock, to give an initial evaluation. It is also used to predict other parameters of resistance, such as tensile strength, compressive strength. This test is done by applying uniaxial pressure to one specific point in the rock specimens. The test was done according to the American standard specifications ASTM [26]. Ten specimens were used for each type of rock. The specimens were also tested in saturated and dry conditions see Figure 3.26.



Figure 3.26 Point Load Test Device

### 3.9.2.2 Brazilian Test

It is one of the destructive tests and is also considered one of the indicative tests for tensile strength and compressive strength. In this test, the tensile strength is measured by placing the cylindrical specimen on its side and applying a distributed load on its side to determine the maximum load that the specimen can bear before it breaks. The tensile stress is found from the laws of elasticity theory. The test was conducted according to the following standard specifications ASTM [27]. Ten specimens were used for each type of rock with dimensions 54 mm diameter and  $L/D=0.2-0.75$ . The specimens were also tested in saturated and dry conditions see Figure 3.27.



Figure 3.27 Brazilian Test Device

### 3.9.2.3 Uniaxial Compression Test

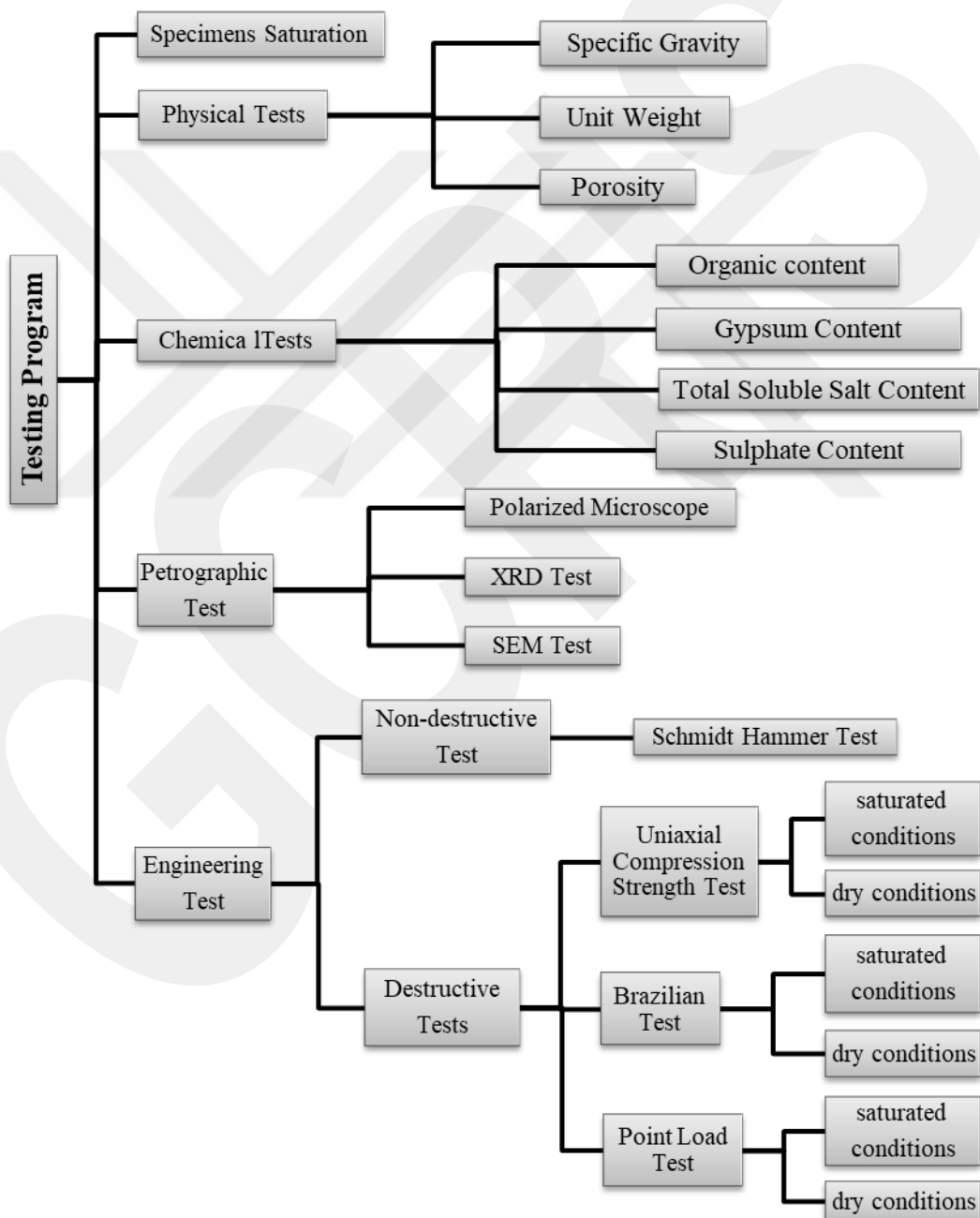
The purpose of this test is to determine the uniaxial compressive strength when loading on a certain area of the specimen's ends, where the test was conducted on the cylindrical specimen. One of the advantages of the device that was used is that it gives all the pressure values from the beginning to the end of the test in tables. The specimen was also tested in saturated and dry conditions. The specimen's dimensions are 150mm length and 54mm Diameter. The test was conducted in Iraq - University of Technology - Department of Production Engineering and Metallurgy - Structural Laboratory with a device (Microcomputer Controlled Electronic Universal testing machine) see Figure 3.28. The test was done according to ASTM [28].



Figure 3.28 Uniaxial Compression Test device (Microcomputer Controlled Electronic Universal testing machine) Model: WDW-200.

### 3.10 Testing Program

The program test was divided into five main sections, which included: Finding the water content and period of full saturation with water, the chemical and physical properties also included the characterization of the three rocks through petrographic test and also finding the engineering properties. Two hundred and ten specimens with different dimensions and shapes were used according to the requirements of the specifications used in each experiment.



## CHAPTER 4

### TEST RESULTS AND DISCUSSION

#### 4.1 General

This chapter explains test results, calculations, corrections, and the equations used in experimental tests. More than 210 samples were used in these experiments to understand the behaviour of these rocks. The rock specimens were examined in the dry and saturated conditions to find out the effects of water content on the results of each of the point load index tests, Brazilian indirect tensile strength test, and uniaxial compressive strength test.

#### 4.2 Specimens Saturation Results

Ten samples were used for each type of rock to find the full saturation period for the three types of rocks. By observing the change in the weight of the samples during immersion, after 406 hours of immersion, the change in weights of the samples came to a standstill. The test obtained based on ASTM [29], the following equations were used to find the percentage of water content as follows:

$$W_w = W_{sat} - W_{dry}$$

$$WC = \frac{W_w}{W_{dry}} \times 100\%$$

Where WC is Water Content,  $W_{dry}$  = Dry sample weight (g),  $W_{sat}$  = Weight of sample saturated with water (g),  $W_w$  = Weight of the Water in the sample (g).

Figure 4.1 shows the relationship between water content and time of immersion for all types of samples according to the technique that referred in Chapter Three.

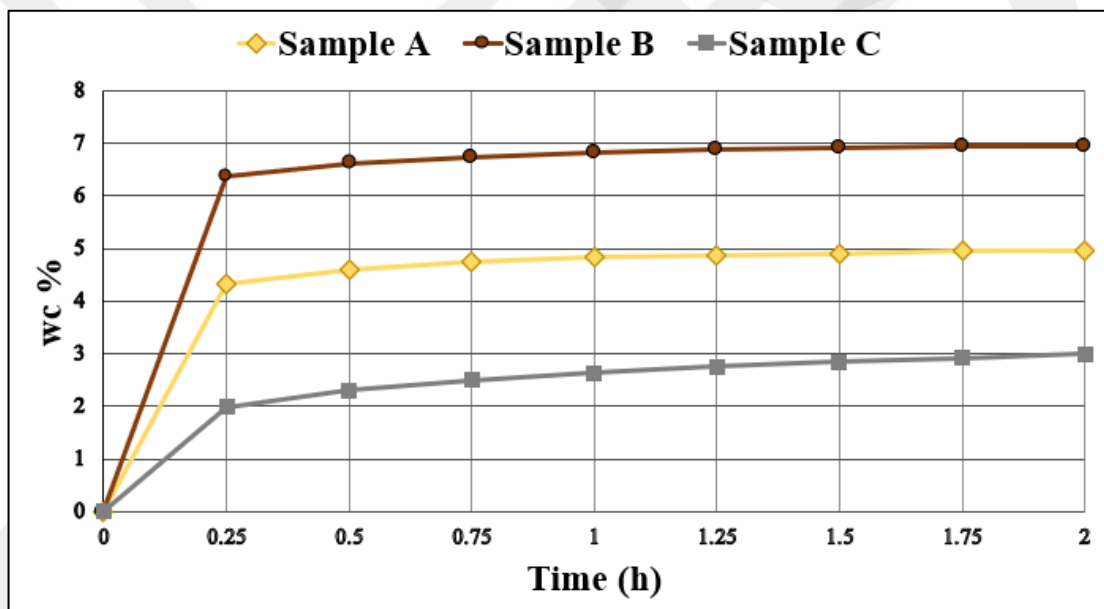
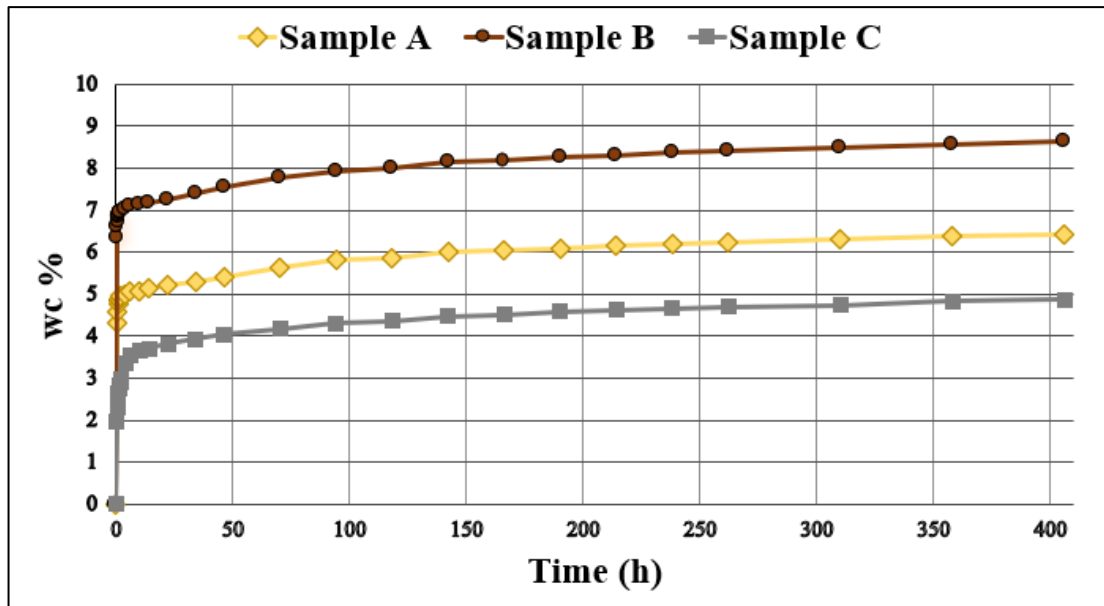


Figure 4.1 The relationship between water content and time of immersion (the lower figure shows the relationship for the first two hours out of the 406 hours)

From Figure 4.1 shows that the water content increased sharply up to 67% for type A and 73% for type B, while it reached 23% for type C during the first 15 minutes. It is also noted that type B has the highest value in water content, reaching 8.6% after 406 hours of immersion in water, which is almost twice the value of type C 4.8% for the same immersion period. While type A reached up to 6.4%. The results of water content calculation for all types of rocks are given in Appendix A.

### 4.3 Physical Tests Results

Physical tests were carried out, which included finding the specific gravity, dry density and porosity according to the requirements of ASTM [30], ASTM [31], and ASTM [32], respectively, of the three rock samples A, B, and C, the tests were conducted in the Scientific and Engineering Consultation Bureau of the University of Technology, The results in Table 4.1 shows that the specific gravity and dry density of rock type A are the highest, also note that the highest value for porosity is for rock type B, and this explains why it obtained the highest value for water content.

Table 4.1 Physical test results

| No. | Physical Requirements                 | Result   |          |          |
|-----|---------------------------------------|----------|----------|----------|
|     |                                       | sample A | sample B | sample C |
| 1   | Specific Gravity                      | 2.04     | 1.77     | 2.14     |
| 2   | Dry density (kg/m <sup>3</sup> )      | 2042.63  | 1770.28  | 2141.67  |
| 3   | Porosity (%)                          | 16.09    | 17.33    | 8.67     |
| 4   | Original density (kg/m <sup>3</sup> ) | 2429.76  | 2495.94  | 2507.89  |
| 5   | Original water content (%)            | 2.6%     | 5.6%     | 3.4%     |

### 4.4 Chemical Tests Results

Table 4.2 shows the results of the chemical tests of the three rock samples A, B, and C these tests include the proportion of sulfur salts, total dissolved salts, gypsum content and content of organic matter according to the requirements of British Standards BS [33], the tests was conducted in the Scientific and Engineering Consultation Bureau of the University of Technology.

Table 4.2 Chemical test results

| No. | Chemical Requirements                               | Result   |          |          |
|-----|---|----------|----------|----------|
|     |   | sample A | sample B | sample C |
| 1   | The proportion of sulfur salts<br>SO <sub>3</sub> % | 0.19     | 0.12     | 0.14     |
| 2   | Total dissolved salts (TSS)%                        | 1.6      | 1.6      | 0.2      |
| 3   | Gypsum content (Gpy.)%                              | 0.41     | 0.26     | 0.3      |
| 4   | Content of organic matter<br>(OM)%                  | 0.04     | 0.04     | 0.03     |

## 4.5 Characterization of the Rocks

### 4.5.1 XRD Tests Results

X-Ray Diffraction (XRD): samples are identified by using X-ray diffraction technique type XRD 6000 Diffractometer using an X-ray tube as follows: Cu (1.54060Å), Voltage: 40 kV and Current: 30 mA. The analysis is carried out in the University of Technology Nanotechnology and Advanced Materials Research Centre - Advanced Measurements Lab. XRD analysis shows that limestone is the main lithology of samples A and B composed mainly of calcite  $\text{CaCO}_3$  with a little amount of quartz  $\text{SiO}_2$  in sample B. On the other hand, sample C is dolostone and consists of dolomite  $\text{CaMg}(\text{CO}_3)_2$  with calcite minerals. X-Ray diffraction results are given in Appendix B.

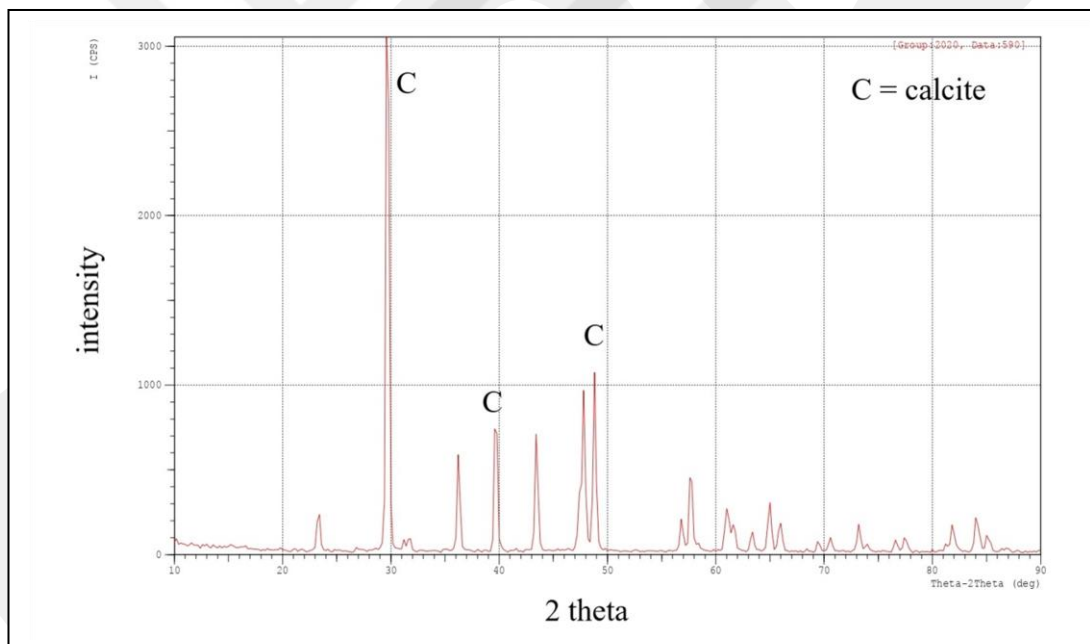


Figure 4.2 X-ray diffraction of sample A

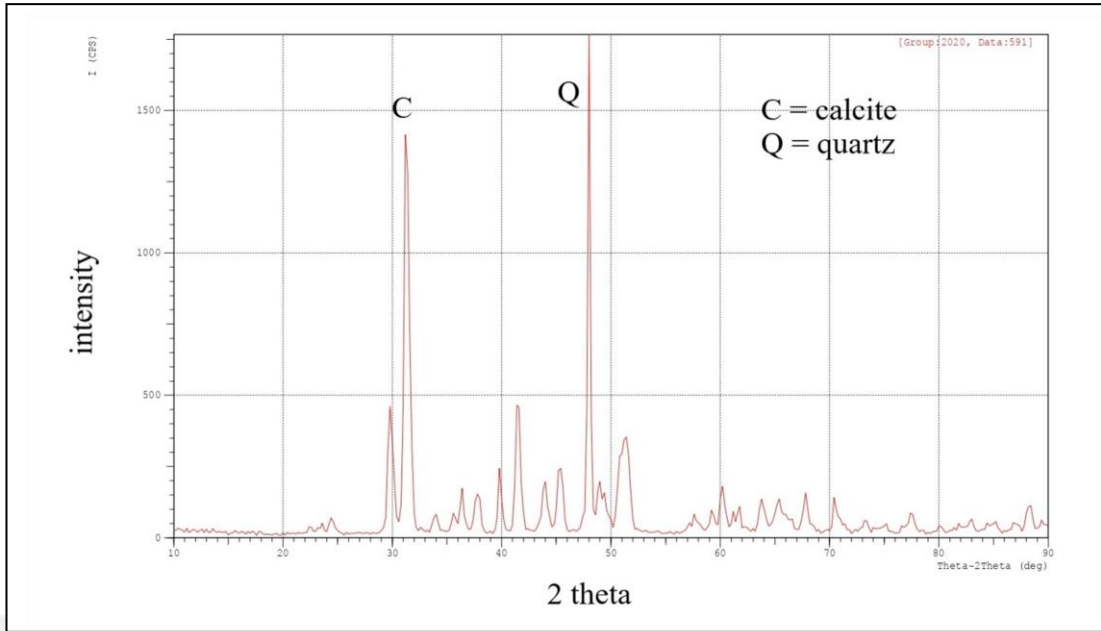


Figure 4.3 X-ray diffraction of sample B

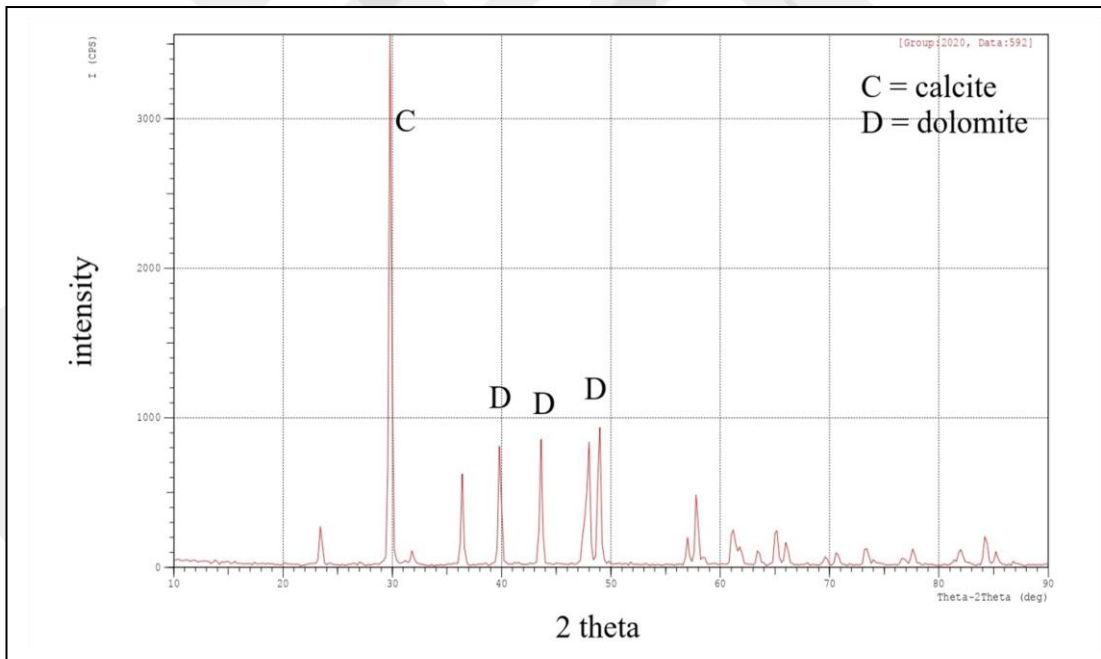


Figure 4.4 X-ray diffraction of sample C

#### 4.5.2 Polarized Microscope

Figures 4.5, 4.6 & 4.7 show polarized images of samples A, B and C by reflect microscope (type 2500x). The Samples were prepared and examined at the Iraqi Geological Survey Institute.

##### 4.5.2.1 Sample A

Figure 4.5 shows that calcite mineral is abundant with some dolomite grains scattered in the sample. Calcite grains are embedded in a matrix consisting of micrite and microsparite carbonate (calcite or dolomite), also abundant fossils such as pelecypods, echinoids, algae, and gastropod. Dissolution such as biomolds and intercrystalline resulting during diagenesis process.

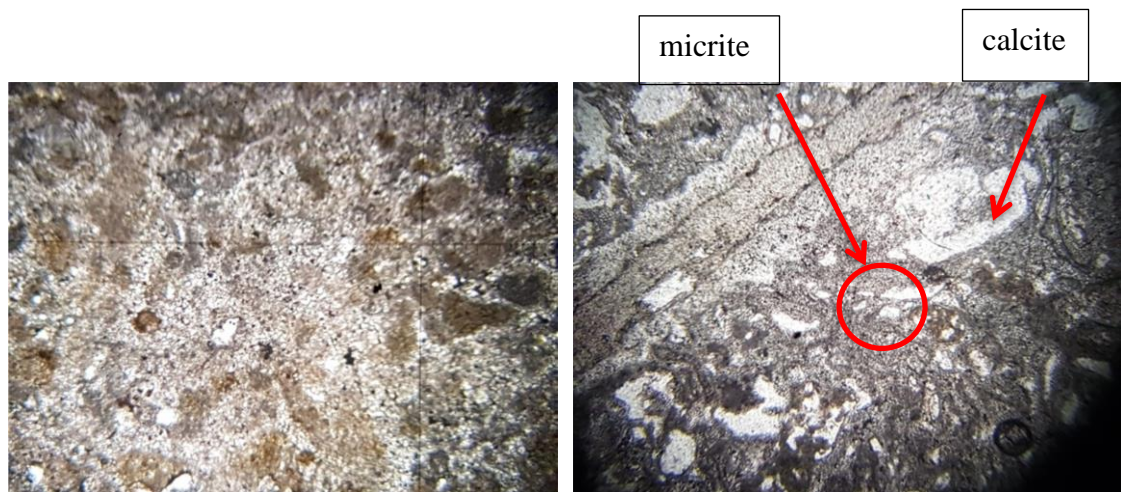


Figure 4.5 Reflect microscope images of rock specimens type ( A )

##### 4.5.2.2 Sample B

The polarized microscope images of sample B, as shown in Figure 4.6, show that rock is composed of fine to medium grains of calcite mineral with a lot of fine quartz grains. Also, the rock contains intraclasts (Fragments) of earlier formed limestone. Most are intraclasts, originating within the basin of deposition. The matrix of rock consists of fine grains of calcite crystals called microsparite formed during diagenesis. Dissolution and void spaces development, such as intercrystalline recrystallization, affect groundmass during the diagenesis process.

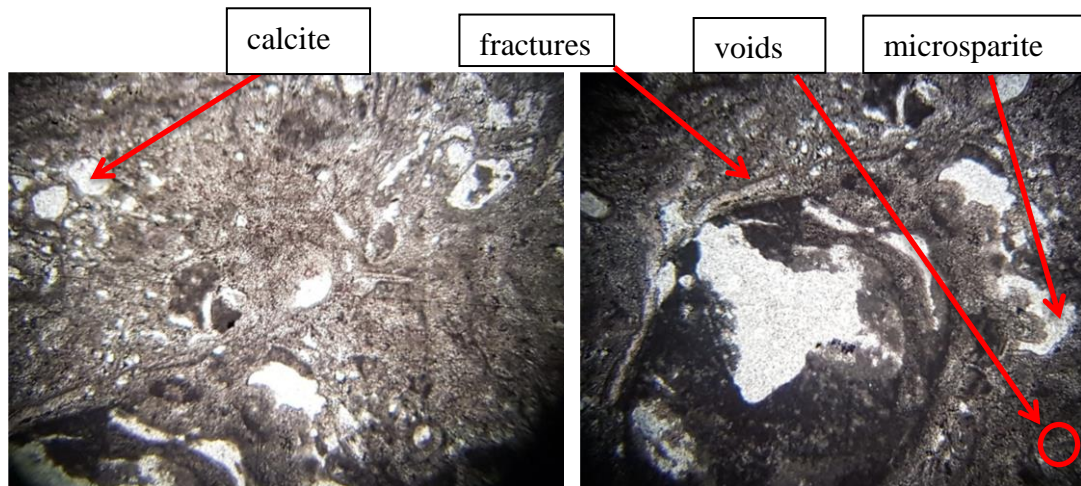


Figure 4.6 Reflect microscope images of rock specimens type ( B )

#### 4.5.2.3 Sample C

Fine crystalline dolostone lithotype was originally dolomitized limestone and then replaced completely by fine crystalline dolostone. The dolomite crystals are mostly rhombohedral to slightly euhedral in shape Figure 4.7. The rock consists mainly of micrite as groundmass with fossils. Also, sample show dissolution effects such as intercrystalline resulting from the diagenesis process. Dolostone is a carbonate rock composed almost entirely of dolomite,  $\text{CaMg}(\text{CO}_3)_2$ . Most dolostones appear to result from the diagenetic conversion of calcite or high-Mg calcite to dolomite after primary deposition of the original calcium carbonate-bearing minerals.



Figure 4.7 Reflect microscope images of rock specimens type ( C )

### 4.5.3 Scanning Electron Microscope (SEM)

A scanning electron microscope (SEM) is a type of electron microscope that produces images of a sample by scanning the surface with a focused beam of electrons. Model SU7000. The tests were carried out on the three rock samples in the University of Technology, Nanotechnology and Advanced Materials Research Centre -Advanced Measurements Lab. The SEM image of sample A Figure 4.8 shows that calcite and dolomite have a smooth surface with few micro fractures and voids. The SEM image of sample B Figure 4.9 shows that calcite and microsparite. The sample contains many pores and voids as well as many microfractures compared to limestone sample A. In the dolomite rock, Figure 4.10. The crystals are mainly fine crystals with intercrystalline pores and, the crystal plane was flat, which are mostly tightly mosaicked to each other with rare dissolution.

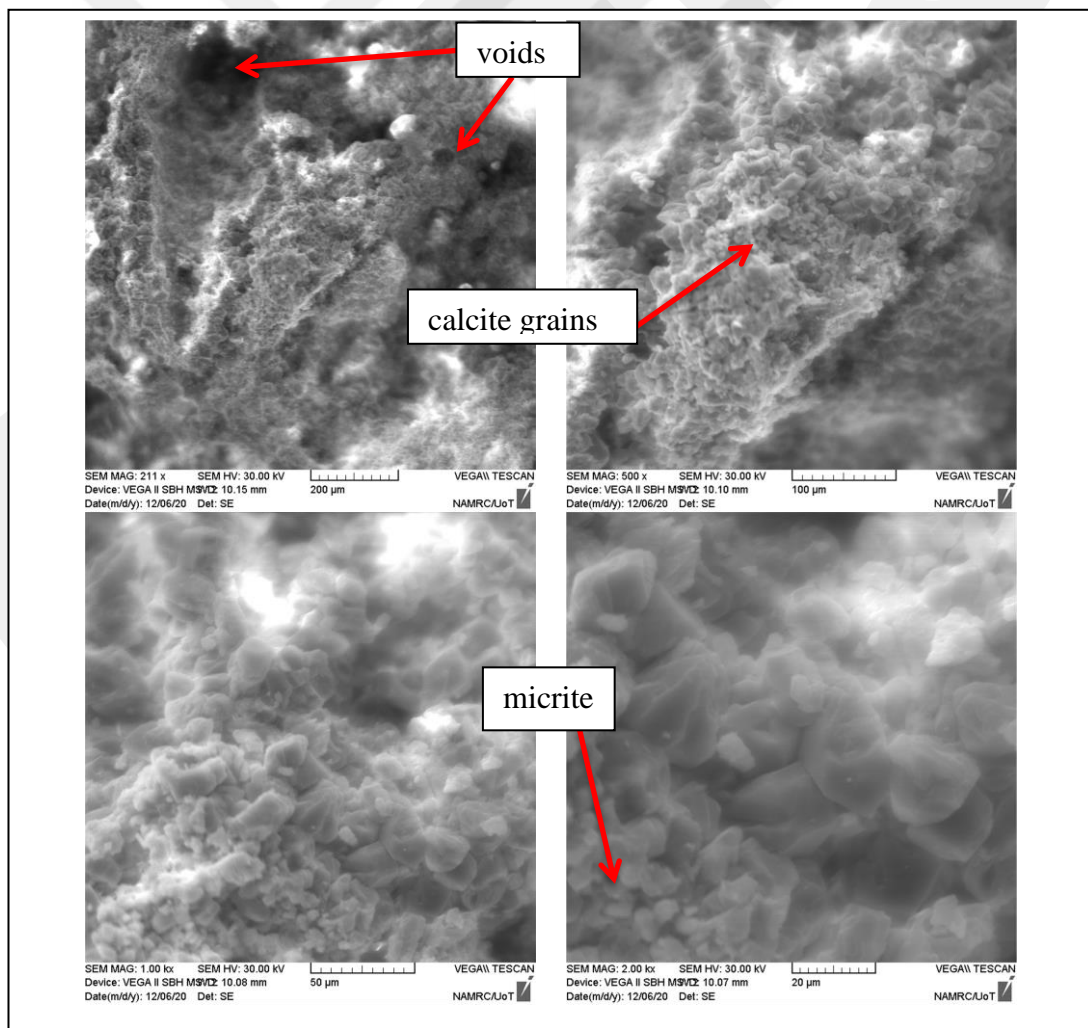


Figure 4.8 Scanning electron microscope images for sample A

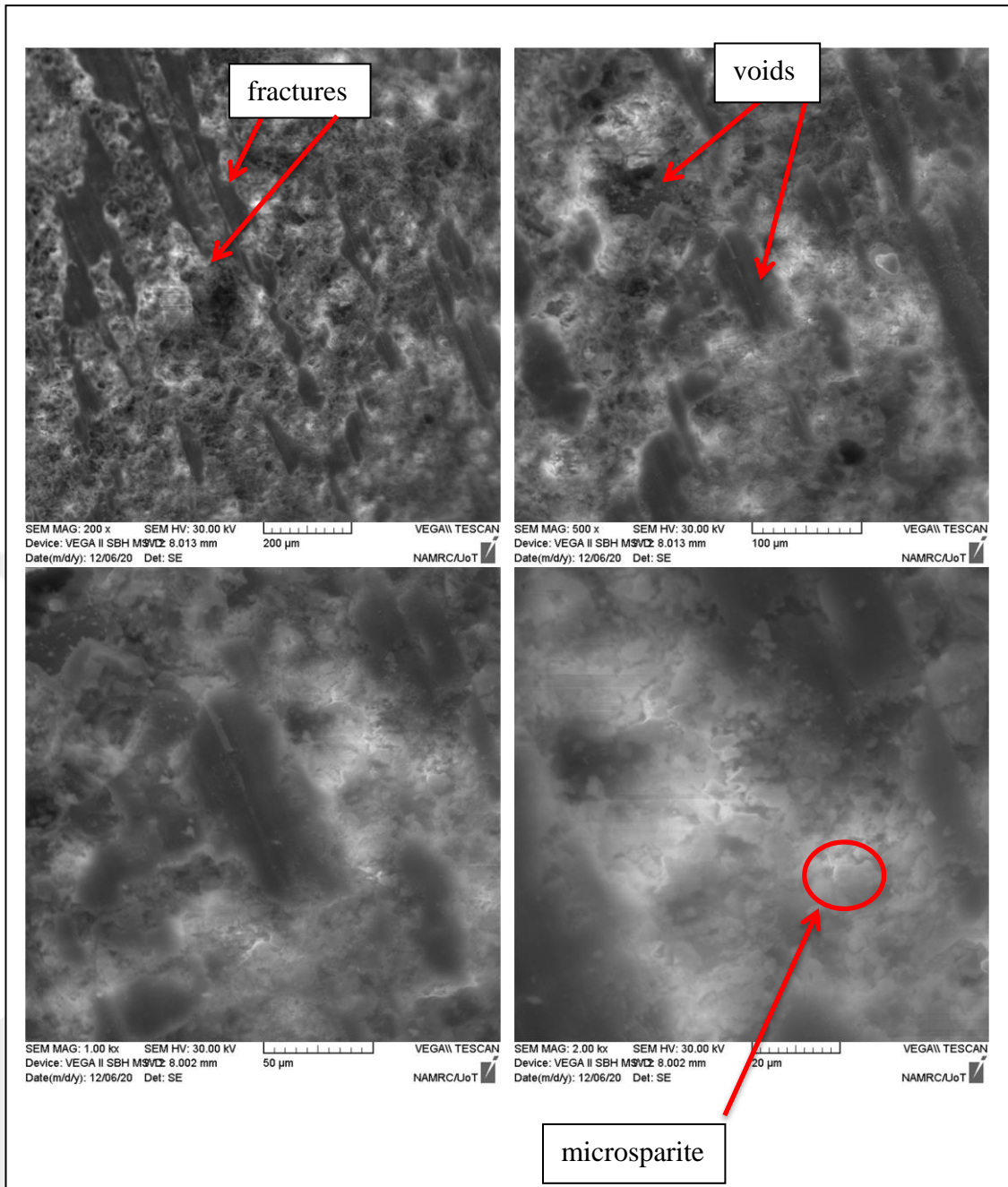


Figure 4.9 Scanning electron microscope images for sample B

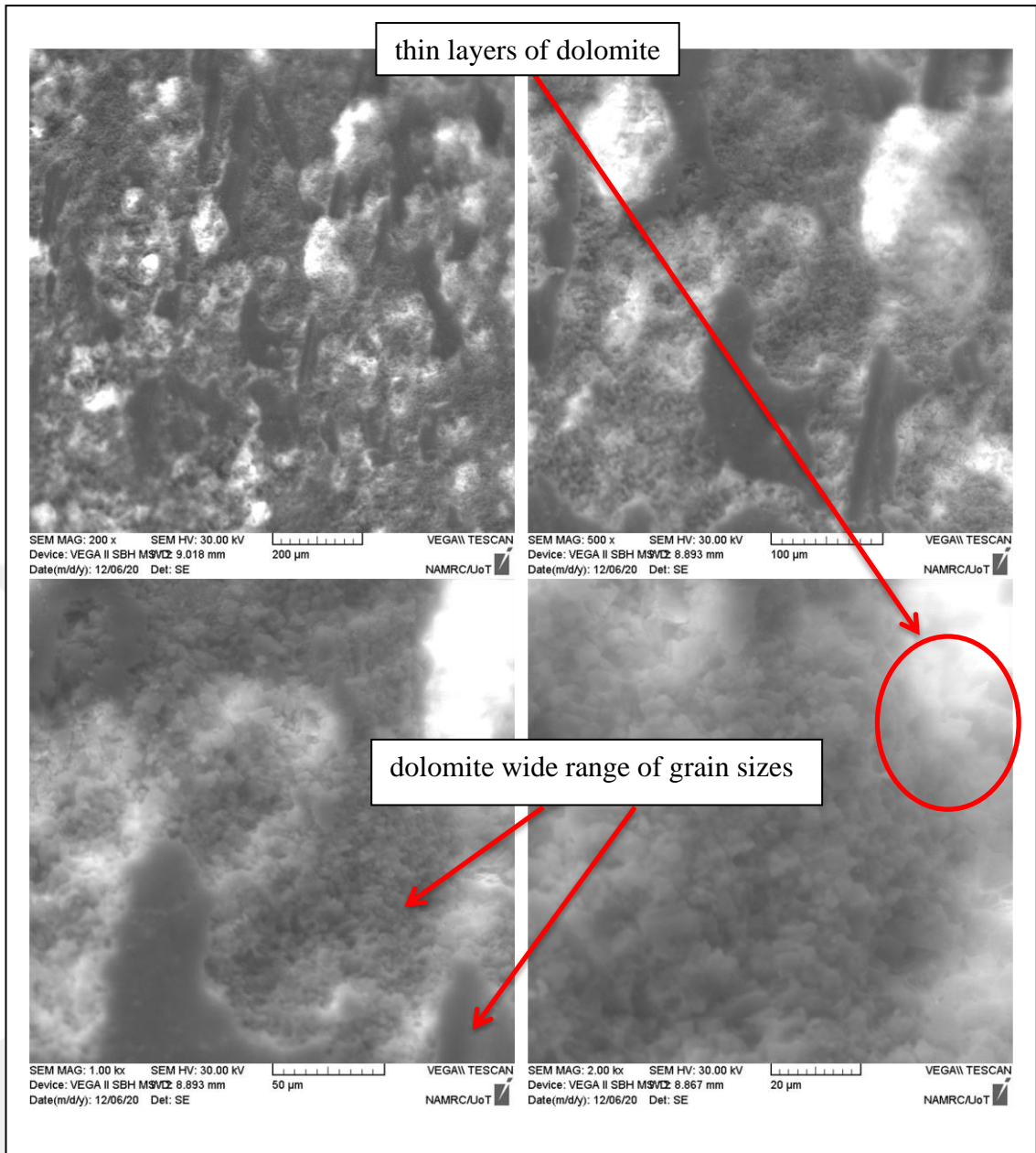


Figure 4.10 Scanning electron microscope images for sample C

## 4.6 Engineering Test Results

Four engineering tests were carried out, which were divided into non-destructive and destructive tests

### 4.6.1 Non-destructive Test Results

This type of test was carried out using one of the hammer methods, which is the Schmidt hammer test

#### 4.6.1.1 Schmidt Hammer Test Results

In this test, fifteen rock specimens (five for each type) were examined using a Schmidt hammer; Cylindrical specimens with a diameter of NX 54mm and a length of 15cm were tested. The experiment was carried out with a Schmidt Hammer L-type with an impact energy of 0.735. The test conducted vertically downwards on horizontal surfaces. The rebound value that exceeds or decreases more than 7 than the average was ignored, and the average of the rest of the readings was taken, the test was performed according to ASTM [25], The results show that the highest value of the rebound number is the rock type C, which reached 26, then type B 22, and finally the type A 16.5, The Table 4.3, and the Figure 4.11 show the Rebound number for all rocks types.

Table 4.3 Rebound number for rocks A, B, & C

| Sample No | Rebound Value |    |    |    |    |    |    |    |    |    | Average of Ten Readings Value | Average of Five Samples |
|-----------|---------------|----|----|----|----|----|----|----|----|----|-------------------------------|-------------------------|
| A1        | 17            | 13 | 14 | 15 | 18 | 17 | 15 | 13 | 13 | 14 | 15                            | 16.5                    |
| A2        | 18            | 16 | 17 | 17 | 18 | 18 | 18 | 16 | 16 | 16 | 17                            |                         |
| A3        | 15            | 16 | 14 | 16 | 15 | 15 | 15 | 14 | 16 | 15 | 15                            |                         |
| A4        | 18            | 17 | 19 | 21 | 22 | 18 | 16 | 21 | 23 | 18 | 19                            |                         |
| A5        | 12            | 11 | 13 | 13 | 15 | 14 | 11 | 14 | X  |    | 13                            |                         |
| B1        | 23            | 19 | 25 | 28 | 20 | 20 | 23 | 19 | 19 | 24 | 22                            | 22                      |
| B2        | 22            | 31 | 34 | 34 | 33 | 27 | 25 | 30 | 32 | 34 | 31                            |                         |
| B3        | 27            | 19 | 18 | 20 | 26 | 22 | 25 | 24 | 26 | 23 | 23                            |                         |
| B4        | 19            | 20 | 23 | 17 | 18 | 19 | 21 | 16 | 22 | 22 | 20                            |                         |
| B5        | 12            | 16 | 15 | 17 | 15 | 11 | 16 | 14 | 13 | 11 | 14                            |                         |
| C1        | 14            | 17 | 12 | 15 | 11 | 14 | 15 | 15 | 12 | 11 | 14                            | 26                      |
| C2        | 32            | 33 | 29 | 32 | 36 | 33 | 36 | 32 | 35 | 30 | 33                            |                         |
| C3        | 37            | 31 | 32 | 31 | 28 | 34 | 36 | 31 | 30 | 29 | 32                            |                         |
| C4        | 19            | 21 | 18 | 22 | 25 | 22 | 19 | 17 | 17 | 18 | 20                            |                         |
| C5        | 32            | 31 | 34 | 30 | 28 | 35 | 31 | 33 | 30 | 28 | 31                            |                         |

discarding value

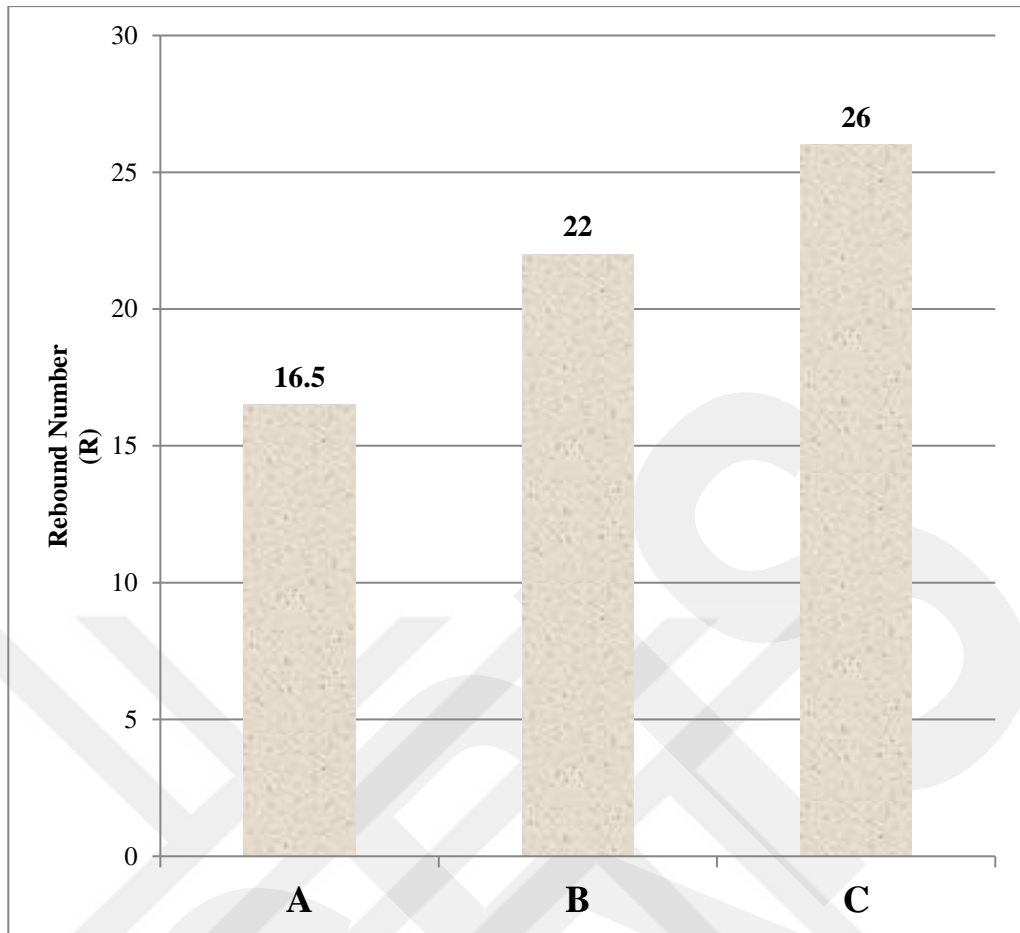


Figure 4.11 Rebound Number for the three rock samples

#### 4.6.2 Destructive Tests Results

Three destructive tests were carried out. The results of these tests in fully dry and saturated conditions are presented below.

##### 4.6.2.1 Point load Test Results

Test performed on the disc specimen with (NX core) 54 mm in diameter and length of (0,3 to 1 of diameter) by axial test for ten specimens in the dry condition and ten specimens in the saturated condition for each type of rock A, B, and C. According to ASTM [26], an axial load was subjected to the specimens until the point of failure, and the highest failure load and the duration of the load until failure was recorded for each

specimen; the uncorrected point load strength index  $I_s$  was calculated by the following equation

$$I_s = \frac{P}{De}$$

Where P is Failure load, De is the equivalent diameter of the specimen was computed as

$$De = \sqrt{\frac{4WD}{\pi}}$$

Where W is the Width (thickness) of the specimen, D is the Diameter of a specimen  
The size-corrected point load strength index  $I_{s(50)}$  was computed from the following equation

$$I_{s(50)} = I_s \times \left(\frac{De}{50}\right)^{0.45}$$

Through the results gave in the Tables 4.4, & 4.5 it can notice that the rock type C has the highest value of point load strength index  $I_{s(50)}$ , and the  $I_{s(50)}$  for all types of rocks has decreased after saturation by 28% and 36% for rocks type A and B respectively, while it decreased by 50% for rock type C. See Figure 4.12.

Table 4.4 Point load test results full dry

| Samples | Dimensions (mm) |               | Failure time (Sec) | Applied load (kg) | Applied load (N) | De             | Is (MPa) | Is(50) (Mpa) |
|---------|-----------------|---------------|--------------------|-------------------|------------------|----------------|----------|--------------|
|         | Diameter (W)    | Thickness (D) |                    |                   |                  |                |          |              |
| A1      | 54              | 33            | 17                 | 609               | 5972             | 47.65          | 2.63     | 2.57         |
| A2      | 55              | 33            | 38                 | 390               | 3825             | 48.08          | 1.65     | 1.63         |
| A3      | 55              | 33            | 21                 | 619               | 6070             | 48.08          | 2.63     | 2.58         |
| A4      | 55              | 32            | 23                 | 447               | 4384             | 47.35          | 1.96     | 1.91         |
| A5      | 54              | 33            | 45                 | 532               | 5217             | 47.65          | 2.30     | 2.25         |
| A6      | 54              | 32            | 12                 | 610               | 5982             | 46.92          | 2.72     | 2.64         |
| A7      | 54              | 33            | 15                 | 488               | 4786             | 47.65          | 2.11     | 2.06         |
| A8      | 54              | 33            | 16                 | 397               | 3893             | 47.65          | 1.72     | 1.68         |
| A9      | 54              | 31            | 19                 | 412               | 4040             | 46.18          | 1.89     | 1.83         |
| A10     | 54              | 33            | 43                 | 423               | 4148             | 47.65          | 1.83     | 1.79         |
|         |                 |               |                    |                   |                  | Is(50) average |          | 2.09         |
| B1      | 54              | 33            | 18                 | 663               | 6502             | 47.65          | 2.86     | 2.80         |
| B2      | 55              | 33            | 11                 | 432               | 4236             | 48.08          | 1.83     | 1.80         |
| B3      | 54              | 32            | 14                 | 429               | 4207             | 46.92          | 1.91     | 1.86         |
| B4      | 54              | 33            | 15                 | 781               | 7659             | 47.65          | 3.37     | 3.30         |
| B5      | 54              | 31            | 19                 | 612               | 6002             | 46.18          | 2.81     | 2.72         |
| B6      | 55              | 33            | 22                 | 598               | 5864             | 48.08          | 2.54     | 2.49         |
| B7      | 54              | 33            | 18                 | 718               | 7041             | 47.65          | 3.10     | 3.04         |
| B8      | 55              | 32            | 19                 | 792               | 7767             | 47.35          | 3.46     | 3.38         |
| B9      | 55              | 33            | 13                 | 689               | 6757             | 48.08          | 2.92     | 2.87         |
| B10     | 54              | 33            | 16                 | 598               | 5864             | 47.65          | 2.58     | 2.53         |
|         |                 |               |                    |                   |                  | Is(50) average |          | 2.68         |
| C1      | 54              | 33            | 18                 | 859               | 8424             | 47.65          | 3.71     | 3.63         |
| C2      | 54              | 33            | 15                 | 590               | 5786             | 47.65          | 2.55     | 2.49         |
| C3      | 54              | 32            | 11                 | 426               | 4178             | 46.92          | 1.90     | 1.84         |
| C4      | 55              | 33            | 13                 | 765               | 7502             | 48.08          | 3.24     | 3.19         |
| C5      | 54              | 33            | 12                 | 1126              | 11042            | 47.65          | 4.86     | 4.76         |
| C6      | 54              | 33            | 13                 | 1004              | 9846             | 47.65          | 4.34     | 4.24         |
| C7      | 54              | 33            | 10                 | 931               | 9130             | 47.65          | 4.02     | 3.94         |
| C8      | 55              | 32            | 11                 | 1006              | 9865             | 47.35          | 4.40     | 4.29         |
| C9      | 55              | 31            | 13                 | 892               | 8748             | 46.60          | 4.03     | 3.90         |
| C10     | 54              | 31            | 16                 | 812               | 7963             | 46.18          | 3.73     | 3.60         |
|         |                 |               |                    |                   |                  | Is(50) average |          | 3.59         |

Table 4.5 Point load test results full saturated

| Samples | Dimensions (mm) |               | Failure time (Sec) | Applied load (kg) | Applied load (N) | De             | Is (MPa) | Is(50) (Mpa) |
|---------|-----------------|---------------|--------------------|-------------------|------------------|----------------|----------|--------------|
|         | Diameter (W)    | Thickness (D) |                    |                   |                  |                |          |              |
| A1      | 54              | 31            | 18                 | 356               | 3491             | 46.18          | 1.64     | 1.58         |
| A2      | 54              | 31            | 33                 | 390               | 3825             | 46.18          | 1.79     | 1.73         |
| A3      | 54              | 30            | 22                 | 367               | 3599             | 45.43          | 1.74     | 1.67         |
| A4      | 54              | 32            | 29                 | 410               | 4021             | 46.92          | 1.83     | 1.77         |
| A5      | 54              | 32            | 33                 | 309               | 3030             | 46.92          | 1.38     | 1.34         |
| A6      | 54              | 34            | 19                 | 344               | 3373             | 48.36          | 1.44     | 1.42         |
| A7      | 54              | 33            | 29                 | 388               | 3805             | 47.65          | 1.68     | 1.64         |
| A8      | 54              | 32            | 19                 | 298               | 2922             | 46.92          | 1.33     | 1.29         |
| A9      | 54              | 31            | 23                 | 312               | 3060             | 46.18          | 1.43     | 1.38         |
| A10     | 54              | 30            | 36                 | 234               | 2295             | 45.43          | 1.11     | 1.07         |
|         |                 |               |                    |                   |                  | Is(50) average |          | 1.49         |
| B1      | 54              | 33            | 43                 | 412               | 4040             | 47.65          | 1.78     | 1.74         |
| B2      | 54              | 32            | 19                 | 398               | 3903             | 44.66          | 1.96     | 1.86         |
| B3      | 54              | 34            | 76                 | 418               | 4099             | 48.36          | 1.75     | 1.73         |
| B4      | 54              | 32            | 34                 | 389               | 3815             | 46.92          | 1.73     | 1.68         |
| B5      | 54              | 31            | 36                 | 320               | 3138             | 46.18          | 1.47     | 1.42         |
| B6      | 54              | 33            | 23                 | 398               | 3903             | 47.65          | 1.72     | 1.68         |
| B7      | 54              | 33            | 17                 | 423               | 4148             | 47.65          | 1.83     | 1.79         |
| B8      | 54              | 32            | 19                 | 327               | 3207             | 46.92          | 1.46     | 1.42         |
| B9      | 54              | 31            | 34                 | 412               | 4040             | 46.18          | 1.89     | 1.83         |
| B10     | 54              | 34            | 39                 | 433               | 4246             | 48.36          | 1.82     | 1.79         |
|         |                 |               |                    |                   |                  | Is(50) average |          | 1.69         |
| C1      | 54              | 31            | 43                 | 312               | 3060             | 46.18          | 1.43     | 1.38         |
| C2      | 54              | 34            | 19                 | 418               | 4099             | 48.36          | 1.75     | 1.73         |
| C3      | 54              | 33            | 76                 | 498               | 4884             | 47.65          | 2.15     | 2.11         |
| C4      | 54              | 31            | 34                 | 387               | 3795             | 46.18          | 1.78     | 1.72         |
| C5      | 54              | 31            | 36                 | 466               | 4570             | 46.18          | 2.14     | 2.07         |
| C6      | 54              | 31            | 23                 | 398               | 3903             | 46.18          | 1.83     | 1.77         |
| C7      | 54              | 32            | 17                 | 412               | 4040             | 46.92          | 1.84     | 1.78         |
| C8      | 54              | 34            | 19                 | 432               | 4236             | 48.36          | 1.81     | 1.78         |
| C9      | 54              | 32            | 34                 | 410               | 4021             | 46.92          | 1.83     | 1.77         |
| C10     | 54              | 33            | 39                 | 490               | 4805             | 47.65          | 2.12     | 2.07         |
|         |                 |               |                    |                   |                  | Is(50) average |          | 1.82         |

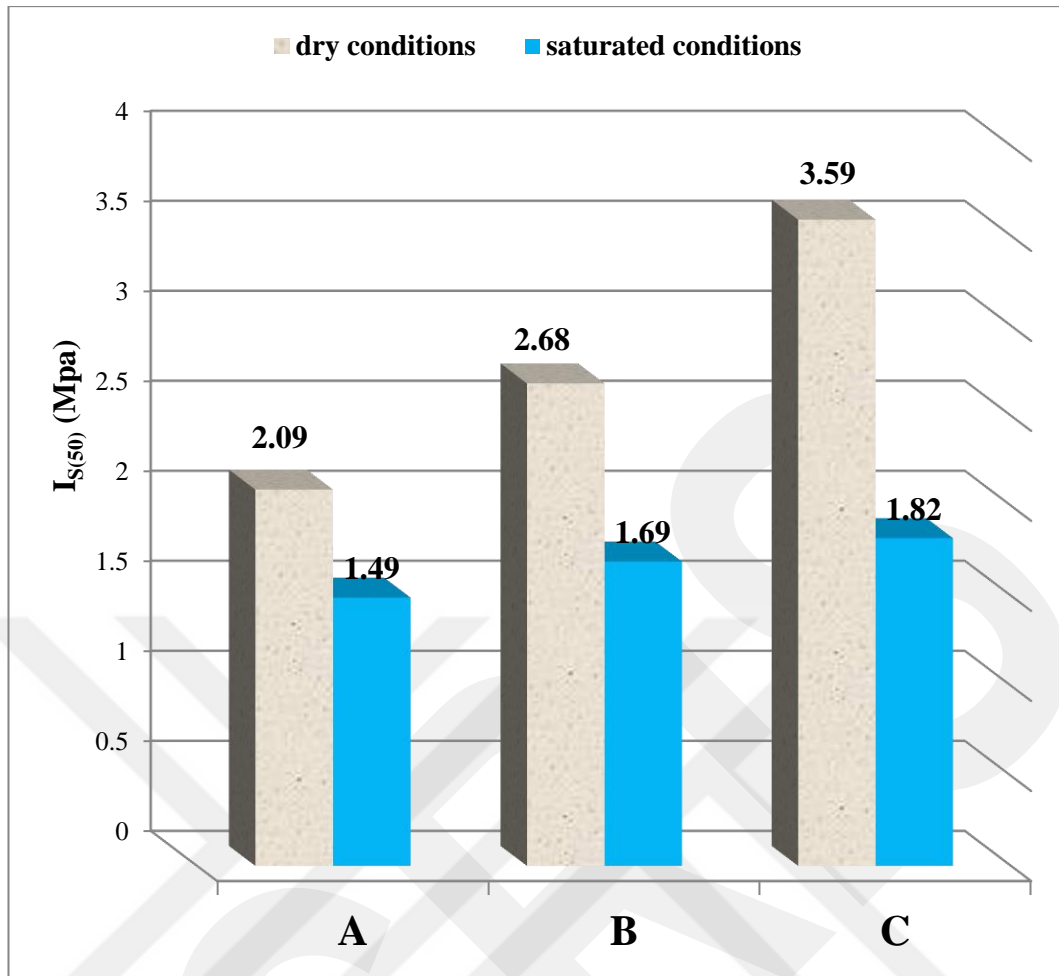


Figure 4.12 Point load strength index  $I_{S(50)}$  in dry and saturated conditions of the three rock samples

#### 4.6.2.1.1 Failure Modes for Point Load Test

By examining the failure patterns of the point load test for the three rock types A, B, and C see Figure 4.13 in the dry and saturated conditions, we see that the failure patterns are typical and almost similar for the three types of rocks. Where we see that the specimens were divided into two types of failure, the first type is the diagonal failure, where the specimens are divided into two halves, while in the second failure, the specimens are divided into three pieces. Also, it seems that the second failure is prevalent, and no difference in failure was observed after testing the specimen in the saturated condition, although water contributed to the weakening of all specimens, as shown in the results.

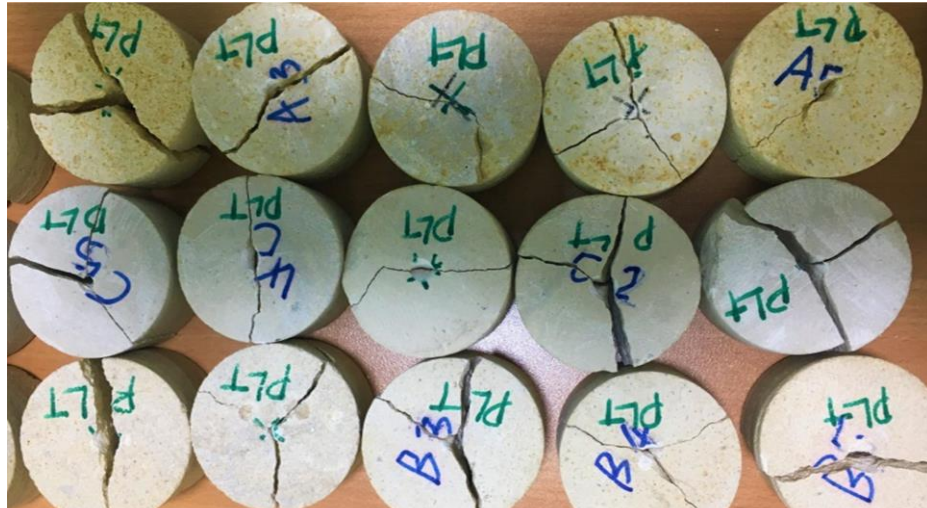


Figure 4.13 Failure modes of the rock samples (A, B, & C) under point load test

#### 4.6.2.2 Brazilian Test Results

Test performed on the cylindrical core with (NX core) 54 mm in diameter and length t/d ratio of (0.20–0.75) according to ASTM [27], ten specimens in the dry condition and ten specimens in the saturated condition for each type of rock A, B, and C are subjected to a load that is evenly distributed across the disc's thickness, with a uniform vertical line load applied diametrically. The highest failure load was recorded; the tensile strength ( $\sigma_t$ ) for each specimen is calculated using the equation.

$$\sigma_t = \frac{2P}{\pi dt}$$

Where P is Failure load, d = Specimen diameter, t = Thickness of specimen.

Tables 4.6, & 4.7, show the results obtained for the three rock samples A, B, and C for the saturated dry conditions. It is noted that sample C has the highest tensile strength value in the dry condition, followed by samples B and then A, While the tensile strength value of the C sample decreases significantly by 65 %, the C sample has the lowest tensile strength value of all the samples in the saturated condition., Sample B, on the other hand, is the lowest effected by water, with a decrease of 18% see Figure 4.14.

Table 4.6 Brazilian tensile stress results full dry

| Samples | Dimensions (mm) |               | Applied load (kg)        | Applied load (N) | Max tensile strength $\sigma_t$ (MPa) |
|---------|-----------------|---------------|--------------------------|------------------|---------------------------------------|
|         | Diameter (D)    | Thickness (t) |                          |                  |                                       |
| A1      | 55              | 33            | 1987                     | 19486.5          | 6.84                                  |
| A2      | 54              | 36            | 1080                     | 10591.6          | 3.47                                  |
| A3      | 55              | 36            | 934                      | 9159.7           | 2.95                                  |
| A4      | 54              | 35            | 1320                     | 12945.2          | 4.36                                  |
| A5      | 55              | 36            | 1102                     | 10807.3          | 3.48                                  |
| A6      | 55              | 35            | 890                      | 8728.2           | 2.89                                  |
| A7      | 55              | 35            | 864                      | 8473.2           | 2.80                                  |
| A8      | 55              | 36            | 989                      | 9699.1           | 3.12                                  |
| A9      | 54              | 36            | 1003                     | 9836.4           | 3.22                                  |
| A10     | 54              | 35            | 680                      | 6668.8           | 2.25                                  |
|         |                 |               | Average $\sigma_t$ (MPa) |                  | 3.3                                   |
| B1      | 55              | 33            | 1207                     | 11837.0          | 4.15                                  |
| B2      | 55              | 36            | 740                      | 7257.2           | 2.33                                  |
| B3      | 53              | 36            | 1214                     | 11905.7          | 3.97                                  |
| B4      | 55              | 34            | 1062                     | 10415.0          | 3.55                                  |
| B5      | 54              | 35            | 974                      | 9552.0           | 3.22                                  |
| B6      | 55              | 35            | 1004                     | 9846.2           | 3.26                                  |
| B7      | 54              | 34            | 1370                     | 13435.6          | 4.66                                  |
| B8      | 54              | 36            | 1170                     | 11474.2          | 3.76                                  |
| B9      | 55              | 36            | 1430                     | 14024.0          | 4.51                                  |
| B10     | 55              | 35            | 1103                     | 10817.1          | 3.58                                  |
|         |                 |               | Average $\sigma_t$ (MPa) |                  | 3.8                                   |
| C1      | 55              | 33            | 1087                     | 10660.2          | 3.74                                  |
| C2      | 54              | 34            | 573                      | 5619.4           | 1.95                                  |
| C3      | 55              | 34            | 1511                     | 14818.4          | 5.05                                  |
| C4      | 56              | 35            | 1927                     | 18898.1          | 6.14                                  |
| C5      | 53              | 34            | 1405                     | 13778.8          | 4.87                                  |
| C6      | 54              | 35            | 1720                     | 16868.0          | 5.68                                  |
| C7      | 55              | 36            | 1514                     | 14847.8          | 4.78                                  |
| C8      | 56              | 36            | 2142                     | 21006.6          | 6.64                                  |
| C9      | 56              | 36            | 1344                     | 13180.6          | 4.16                                  |
| C10     | 55              | 34            | 1818                     | 17829.1          | 6.07                                  |
|         |                 |               | Average $\sigma_t$ (MPa) |                  | 5.1                                   |

highest value (ignored)

lowest value (ignored)

Table 4.7 Brazilian tensile stress results full saturated

| Samples | Dimensions (mm) |               | Applied load (kg)        | Applied load (N) | Max tensile strength $\sigma_t$ (MPa) |
|---------|-----------------|---------------|--------------------------|------------------|---------------------------------------|
|         | Diameter (D)    | Thickness (t) |                          |                  |                                       |
| A1      | 53              | 34            | 544                      | 5335.0           | 1.89                                  |
| A2      | 54              | 34            | 876                      | 8590.9           | 2.98                                  |
| A3      | 53              | 33            | 651                      | 6384.4           | 2.33                                  |
| A4      | 55              | 32            | 1748                     | 17142.6          | 6.20                                  |
| A5      | 56              | 34            | 634                      | 6217.6           | 2.08                                  |
| A6      | 56              | 34            | 739                      | 7247.4           | 2.42                                  |
| A7      | 57              | 36            | 610                      | 5982.3           | 1.86                                  |
| A8      | 56              | 35            | 1014                     | 9944.3           | 3.23                                  |
| A9      | 56              | 35            | 817                      | 8012.3           | 2.60                                  |
| A10     | 55              | 36            | 583                      | 5717.5           | 1.84                                  |
|         |                 |               | Average $\sigma_t$ (MPa) |                  | 2.4                                   |
| B1      | 54              | 32            | 925                      | 9071.5           | 3.34                                  |
| B2      | 52              | 33            | 919                      | 9012.6           | 3.35                                  |
| B3      | 55              | 34            | 1531                     | 15014.5          | 5.11                                  |
| B4      | 55              | 32            | 1111                     | 10895.6          | 3.94                                  |
| B5      | 56              | 33            | 800                      | 7845.6           | 2.70                                  |
| B6      | 55              | 34            | 776                      | 7610.2           | 2.59                                  |
| B7      | 54              | 36            | 709                      | 6953.2           | 2.28                                  |
| B8      | 56              | 35            | 514                      | 5040.8           | 1.64                                  |
| B9      | 55              | 34            | 897                      | 8796.9           | 3.00                                  |
| B10     | 55              | 36            | 1045                     | 10248.3          | 3.30                                  |
|         |                 |               | Average $\sigma_t$ (MPa) |                  | 3.1                                   |
| C1      | 53              | 34            | 625                      | 6129.4           | 2.17                                  |
| C2      | 53              | 36            | 991                      | 9718.7           | 3.24                                  |
| C3      | 54              | 34            | 509                      | 4991.8           | 1.73                                  |
| C4      | 54              | 32            | 527                      | 5168.3           | 1.91                                  |
| C5      | 55              | 35            | 416                      | 4079.7           | 1.35                                  |
| C6      | 55              | 35            | 287                      | 2814.6           | 0.93                                  |
| C7      | 54              | 34            | 486                      | 4766.2           | 1.65                                  |
| C8      | 55              | 36            | 612                      | 6001.9           | 1.93                                  |
| C9      | 56              | 37            | 473                      | 4638.7           | 1.43                                  |
| C10     | 55              | 34            | 563                      | 5521.3           | 1.88                                  |
|         |                 |               | Average $\sigma_t$ (MPa) |                  | 1.8                                   |

highest value (ignored)

lowest value (ignored)

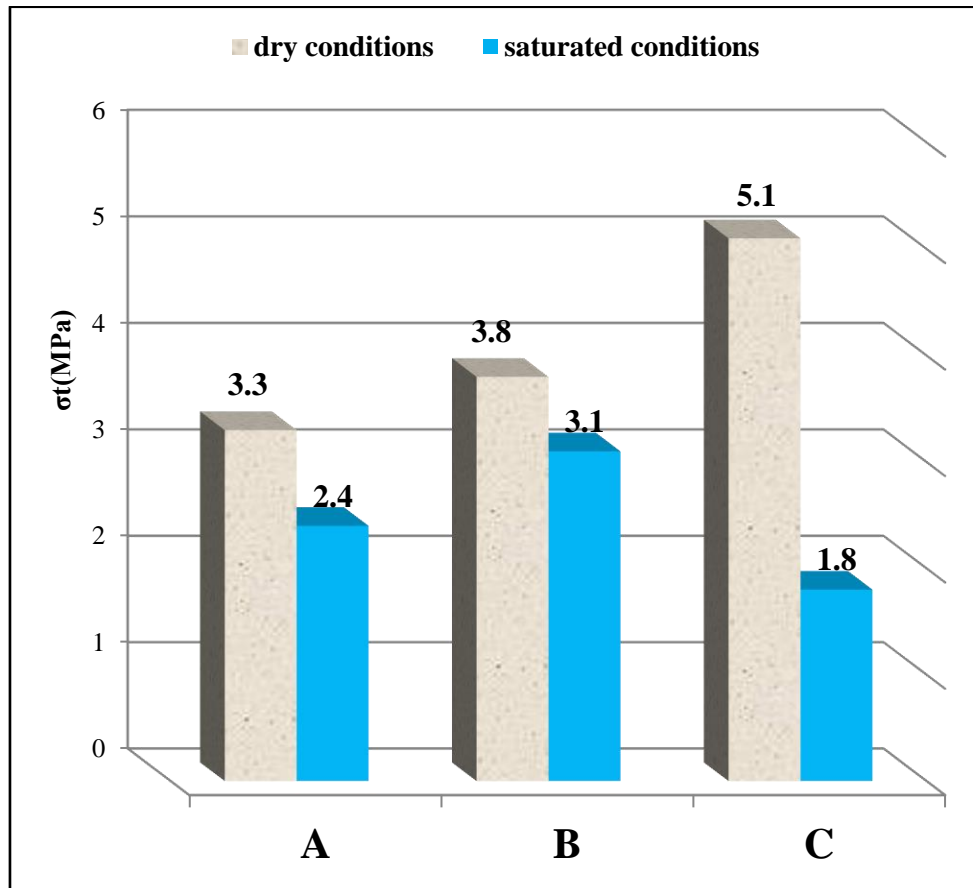


Figure 4.14 The change in the tensile value in the dry and saturated state of the three rock samples

#### 4.6.2.2.1 Failure Modes for Brazilian Test

By examining the failure patterns of 60 samples that were tested for tensile strength test (Brazilian test), it is noted that the method of failure of the three types of rocks A, B, and C in the dry and saturated state is a central failure that cuts the specimen into two halves with an axial diagonal slit, and this is prevalent in the dry and saturated conditions see Figure 4.15, as well. It is also noted that there is another type of failure that appears in the saturation condition failure, especially rock type A, which is a non-central failure where two vertical slits appear on both sides of the diagonal axis, and it is further noted that the edges of the saturated specimens are crushed in the contact area of the upper and lower jaws of the testing device.



Figure 4.15 Failure modes in dry and saturated conditions of the rock samples A, B, & C under Brazilian test

#### 4.6.2.3 Uniaxial Compression Test Results

Five specimens were tested in saturated and five more in dry conditions for each type of rock in the structural laboratory of the Department of Production Engineering and Minerals at the University of Technology. The test was carried out according to the ASTM [28] on an MTS universal testing machine with an axial load capacity of 1000 kN, which is controlled by a computer. A cylindrical core with (NX core) 54 mm in diameter and length/diameter ratio of 2.0–3.0 subjected to an axial load with a stress rate in the range of 0.5–1.0 MPa/s until the point of failure. From the results obtained, the optimum value of the highest failure load was found for each specimen by using the intersection method. Also, a stress-strain plot was generated, from which young's modulus could be computed for each sample. The Tables 4.8, & 4.9, show the uniaxial compressive strength (UCS) for all rock types. It is noted from the results obtained that the highest value for maximum stress in the dry conditions is for type C and its value decreased sharply by 36% after saturation, also the value of maximum stress for type B decreased by 3%, while the value of maximum stress decreased for type A by 26 % after saturation, which is the minimum value of the three types in the dry and saturated conditions The Figure 4.16 shows the highest values of maximum stress in the dry and saturated conditions of the three rock samples. Graphs of stress-strain and load-deformation relationships at dry and saturated states for all types of rocks are given in Appendix C.

Table 4.8 Uniaxial compressive strength tests results (UCS) full dry

| Sample | Dimensions (mm) |             | Area (mm) <sup>2</sup> | Total Test time (Sec) | Ultimate load applied (N) | Deformation (mm) | Max strain $\epsilon$ | Max stress $\sigma$ (MPa) |
|--------|-----------------|-------------|------------------------|-----------------------|---------------------------|------------------|-----------------------|---------------------------|
|        | Diameter (mm)   | Length (mm) |                        |                       |                           |                  |                       |                           |
| A1     | 55              | 111         | 2376                   | 182.4                 | 19940                     | 1.278            | 0.0115                | 8.4                       |
| A2     | 54              | 111         | 2290                   | 159.0                 | 28600                     | 1.319            | 0.0119                | 12.5                      |
| A3     | 55              | 110         | 2376                   | 161.0                 | 22720                     | 1.345            | 0.0122                | 9.6                       |
| A4     | 55              | 112         | 2376                   | 516.5                 | 29920                     | 1.919            | 0.0171                | 12.6                      |
| A5     | 55              | 112         | 2376                   | 244.3                 | 18070                     | 1.266            | 0.0113                | 7.6                       |
|        |                 |             |                        |                       |                           | Average          | 0.0128                | 10.14                     |
| B1     | 54              | 112         | 2290                   | 212.9                 | 25800                     | 1.424            | 0.0127                | 11.3                      |
| B2     | 54              | 110         | 2290                   | 272.5                 | 38040                     | 1.815            | 0.0165                | 16.6                      |
| B3     | 55              | 110         | 2376                   | 294.1                 | 37240                     | 1.956            | 0.0178                | 15.7                      |
| B4     | 55              | 112         | 2376                   | 158.0                 | 19760                     | 1.053            | 0.0094                | 8.3                       |
| B5     | 55              | 112         | 2376                   | 171.1                 | 13880                     | 1.131            | 0.0101                | 5.8                       |
|        |                 |             |                        |                       |                           | Average          | 0.0133                | 11.54                     |
| C1     | 54              | 112         | 2290                   | 238.555               | 21920                     | 1.600            | 0.0143                | 9.57                      |
| C2     | 54              | 112         | 2290                   | 199.795               | 35040                     | 1.664            | 0.0149                | 15.30                     |
| C3     | 55              | 110         | 2376                   | 257.395               | 33000                     | 4.285            | 0.0390                | 13.89                     |
| C4     | 55              | 113         | 2376                   | 190.915               | 31480                     | 1.595            | 0.0141                | 13.25                     |
| C5     | 55              | 110         | 2376                   | 225.235               | 31600                     | 1.499            | 0.0136                | 13.30                     |
|        |                 |             |                        |                       |                           | Average          | 0.01918               | 13.06                     |

Table 4.9 Uniaxial compressive strength tests results (UCS) full saturated

| Sample | Dimensions (mm) |             | Area (mm) <sup>2</sup> | Total Test time (Sec) | Ultimate load applied (N) | Deformation (mm) | Max strain $\epsilon$ | Max stress $\sigma_c$ (MPa) |
|--------|-----------------|-------------|------------------------|-----------------------|---------------------------|------------------|-----------------------|-----------------------------|
|        | Diameter (mm)   | Length (mm) |                        |                       |                           |                  |                       |                             |
| A1     | 55              | 112         | 2206                   | 217.8                 | 13200                     | 1.446            | 0.0129                | 6.0                         |
| A2     | 54              | 111         | 2290                   | 365.8                 | 18800                     | 2.425            | 0.0218                | 8.2                         |
| A3     | 54              | 112         | 2290                   | 230.5                 | 16120                     | 1.525            | 0.0136                | 7.0                         |
| A4     | 54              | 113         | 2043                   | 240.9                 | 21080                     | 1.613            | 0.0143                | 10.3                        |
| A5     | 55              | 111         | 2376                   | 239.4                 | 13440                     | 1.584            | 0.0143                | 5.7                         |
|        |                 |             |                        |                       |                           | Average          | 0.0153                | 7.44                        |
| B1     | 55              | 109         | 2376                   | 234.1                 | 26440                     | 1.563            | 0.0143                | 11.1                        |
| B2     | 55              | 112         | 2376                   | 264.1                 | 32960                     | 1.750            | 0.0156                | 13.9                        |
| B3     | 55              | 110         | 2376                   | 331.5                 | 27080                     | 2.193            | 0.0199                | 11.4                        |
| B4     | 54              | 113         | 2290                   | 239.5                 | 25160                     | 1.608            | 0.0142                | 11.0                        |
| B5     | 54              | 112         | 2290                   | 232.1                 | 19800                     | 1.553            | 0.0139                | 8.6                         |
|        |                 |             |                        |                       |                           | Average          | 0.0155                | 11.2                        |
| C1     | 54              | 109         | 2290                   | 231.9                 | 12640                     | 1.535            | 0.0141                | 5.5                         |
| C2     | 54              | 112         | 2290                   | 285.4                 | 26600                     | 1.910            | 0.0171                | 11.6                        |
| C3     | 55              | 113         | 2376                   | 359.6                 | 24720                     | 2.381            | 0.0211                | 10.4                        |
| C4     | 55              | 110         | 2376                   | 216.7                 | 16800                     | 1.445            | 0.0131                | 7.1                         |
| C5     | 55              | 113         | 2376                   | 309.8                 | 17080                     | 2.060            | 0.0182                | 7.2                         |
|        |                 |             |                        |                       |                           | Average          | 0.01672               | 8.36                        |

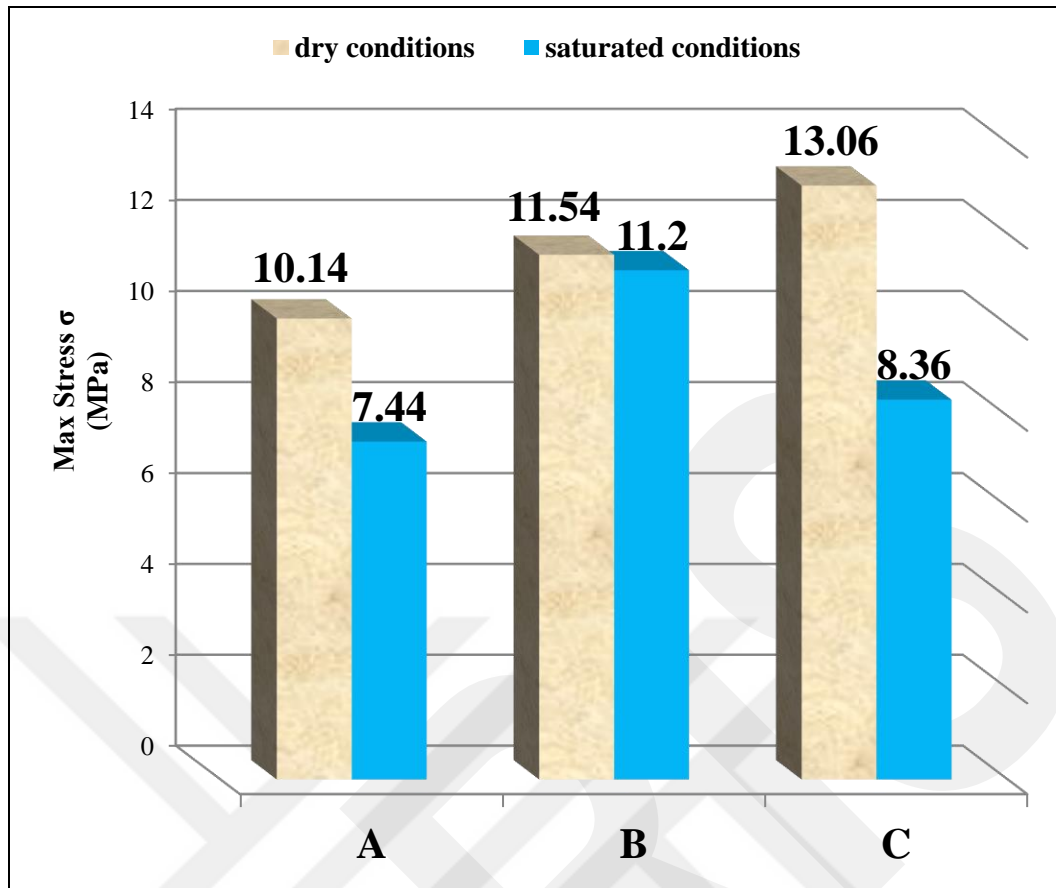


Figure 4.16 Maximum stress in dry and saturated conditions of the three rock samples in uniaxial compressive strength test

#### 4.6.2.3.1 Failure Modes for Uniaxial Compressive Strength (UCS)

By examining the tested rock specimens A, B, and C see Figures 4.17, 4.18, & 4.19 in the dry and saturated conditions and after examining 30 specimens, it is made clear that the sample failures are almost the same. The cracks of the dry specimens produce fragments near the lower and upper edges, while the saturated samples have a higher displacement and external and internal crushing. Generally, the failure can be diagnosed in two forms, the first form is the failure of the axial separation, and the second is the failure of the shearing along with single plane failure. The form of failure depends on the spread of microscopic cracks in a specific rotation axis, as well as the voids within the rock composition and the microstructure that allow the cracks to merge and pass to form one clear crack.



Figure 4.17 Failure modes in dry and saturated conditions of the rock sample A under uniaxial compressive strength



Figure 4.18 Failure modes in dry and saturated conditions of the rock sample B under uniaxial compressive strength

#### 4.7 Summary and Evaluation of Tests Results

Through the results obtained from the tests, the results are summarized and evaluated in the following points: -

1. The results of XRD analysis show that limestone is the main lithology for A and B rock samples composed mainly of calcite  $\text{CaCO}_3$  with a little amount of quartz  $\text{SiO}_2$  in sample B. On the other hand, sample C is dolostone and consists of dolomite  $\text{CaMg}(\text{CO}_3)_2$  with calcite minerals.
2. The reflection microscope images indicate that calcite grains are embedded in a matrix consisting of micrite and microsparite carbonate in rock sample A, the rock

sample B is composed of fine to medium grains of calcite mineral with a lot of fine quartz grains, the matrix of this rock type consists of fine grains of calcite crystals called microsparite, also notes in this type that dissolution and void space development during the diagnosis process. The rock sample C is a carbonate rock composed almost entirely of dolomite; the rock consists mainly of micrite as groundmass with fossils. Also, samples show dissolution effects resulting from the diagnosis process.

3. From the SEM image of sample A, it appears that calcite and dolomite have a smooth surface with micro fractures and voids. It also shows calcite, microsparite and many pores and voids as well as many microfracture in sample B. The dolomite granules are shown in mainly fine crystals with intercrystalline pores and the crystal plane was flat in sample C.
4. The fully saturated water content was observed for three rock samples after 406 hours of soaking time.
5. Samples A and B gained about 67% and 73% respectively from maximum saturated water content at the first 15 minutes of soaking time, while sample C gained about 23% from maximum saturated content at the same time.
6. The maximum saturated water content was observed in sample B, which reached to 8.6%, while the maximum saturated water content was 6.4%, and 4.8% for samples A and C, respectively.
7. Through the engineering tests of the rock samples in the dry condition, it appears clearly that the rock type C (Dolostone) showed the highest resistance and hardness, followed by the rock type B (Limestone), while type A (Limestone) has shown the lowest resistance and hardness of the three types of rocks.
8. The effect of saturating the rock samples with water showed a clear decrease in the engineering strength values for all types of rocks. This effect can be clearly observed in sample C, where the point load strength index value, tensile strength value, and stress value in uniaxial compressive strength test decreased by 50%, 65%, and 36% respectively for sample C, 36%, 18%, and 3% for sample B, 29%, 27%, and 26% for sample A, it is also noted that sample B is the least affected by water saturation.
9. Table 4.10 shows the approximate strength classification of the rocks samples through the results obtained from the engineering tests according to Table 2.1.

10. Table 4.11 shows the types of rocks and recommendations for the use of each type according to the results obtained from this study.

Table 4.10 The approximate strength classification of the rock's samples

| No | Test  | Rock Type   | Engineering Strength Values | Description       |
|----|---|-------------|-----------------------------|-------------------|
| 1  | The average of maximum stress values of uniaxial compressive strength (UCS) | Rock type A | 10.14                       | Very weak rock    |
|    |   | Rock type B | 11.54                       | Very weak rock    |
|    |   | Rock type C | 13.06                       | Very weak rock    |
| 2  | The average of strength index $Is_{(50)}$ values of point load test         | Rock type A | 2.09                        | Moderately strong |
|    |   | Rock type B | 2.68                        | Moderately strong |
|    |   | Rock type C | 3.59                        | Moderately strong |
| 3  | The average of rebound number values of Schmidt hammer test                 | Rock type A | 16.5                        | Very weak rock    |
|    |   | Rock type B | 22                          | Very weak rock    |
|    |   | Rock type C | 26                          | Very weak rock    |

Table 4.11 The recommendations for use of the three rocks types

| No | Rock use applications                                | Rock type A | Rock type B | Rock type C |
|----|--|-------------|-------------|-------------|
| 1  | Cladding stones for facades                          | ✓           | ✓           | ✓           |
| 2  | Building load-bearing walls                          |             | ✓           | ✓           |
| 3  | Partition walls                                      | ✓           | ✓           | ✓           |
| 4  | Retaining walls                                      |             | ✓           |             |
| 5  | Cladding the banks of rivers and streams             |             | ✓           |             |
| 6  | Foundation and construction works below ground level |             | ✓           |             |
| 7  | Road works as a base layer or under foundations      |             | ✓           |             |
| 8  | Earthworks of railways                               | ✓           | ✓           |             |

## CHAPTER 5

### CONCLUSIONS AND RECOMMENDATIONS

#### 5.1 Conclusions

The following conclusions were obtained from the evaluation of the test results of this study:

- 1- The fully saturated water content was observed for three rock samples after 406 hours of soaking time. where the water content after this period reached 6.4%, 8.6% and 4.8% for A, B and C respectively.
- 2- Rock type A is limestone and its main component is calcite, rock type B is limestone as well, with a small amount of quartz, while rock type C is dolostone and its main component is dolomite. The matrix of rocks consists of fine grains of calcite crystals called microsparite, also the samples show dissolution and void space development during the diagnosis process.
- 3- the engineering tests of the rock samples showed that rock type C has the highest engineering strength values, followed by rock type B, while rock type A has shown the lowest engineering strength values of the three types of rocks in the dry condition. On the other hand, the effect of saturating the rock samples with water showed a clear decrease in the engineering strength values for all types of rocks. that can be clearly observed in sample C, which has the highest decrease in engineering strength values after saturation, while sample B has the least decrease in engineering strength values after saturation.
- 4- Preferably not to use rocks type C in foundation and construction works below ground level, retaining walls, and cladding the banks of rivers and streams.
- 5- Rocks type B is preferred for use in foundation and construction works below ground level, retaining walls, and cladding the banks of rivers and streams.

6- Rocks type C is preferred among the three types of rocks in the construction of load-bearing walls and several floors, but it is necessary to isolate them in some way from exposure to weathering.

7- Type A rocks are the least resistant to stress, so it is recommended to use them in the construction of non-load bearing walls such as fences and partitions in structural facilities, as well as in buildings that consist of one floor.

## **5.2 Recommendations for Future Works**

Following recommendations are given for future works:

1. Study effect of wetting drying cycle on mechanical properties of the same type of rocks.
2. Study the effect of salt water on physical and mechanical properties of limestone of the Western desert of Iraq.
3. Study the effect of weathering Geotechnical properties of limestone.
4. Take the same study to another form of rock, such as gypsum formation.
5. Studying the efficiency of rock walls in thermal insulation of the same types of rocks.
6. Studying the engineering and physical properties of rock walls as a mass and comparing them with brick walls, concrete blocks and clay blocks of the same types of rocks.
7. Studying the effect of earthquakes on walls built from these rocks and comparing them with walls built of bricks, concrete blocks and mud blocks.

## REFERENCES

- [1] Means, Winthrop Dickinson, and Paul Frederick Williams. *An outline of structural geology*. New York: John Wiley & Sons, 1976.
- [2] Milligan, Julie Ann, "A geophysical study of Rangitoto volcano." PhD diss, University of Auckland, United State of America, 1977.
- [3] Goodman, Richard E, *Introduction to rock mechanics*. Vol. 2 New York: Wiley, 1989.
- [4] Folk, Robert L, *Petrology of sedimentary rocks*. Austin: Hemphill publishing company, 1980.
- [5] Earle, Steven., "Physical geology," *BCcampus Open Education*, 2019.
- [6] Tarbuck, Edward J, Frederick K. Lutgens, and Dennis Tasa, *Earth science*. New Jersey: Prentice Hall, 1997.
- [7] Archer, J. W., et al., "Measurement and correlation of acoustic emissions and pressure stimulated voltages in rock using an electric potential sensor.," *International Journal of Rock Mechanics and Mining Sciences*, pp. 26-33, 2016.
- [8] Goudie, Andrew S., "The Schmidt Hammer in geomorphological research.," *Progress in Physical Geography* 30.6: 703-718.,2006.
- [9] Day, M. J., "Field assessment of rock hardness using the Schmidt test hammer.," *British Geomorphological Research Group Technical Bulletin* 18: 19-29.,1977.
- [10] McCarroll, Danny., "Potential and limitations of the Schmidt hammer for relative-age dating: field tests on Neoglacial moraines, Jotunheimen, southern Norway". *Arctic and Alpine Research* 21.3: 268-275.,1989.
- [11] Selby, Michael John., *Hillslope materials and processes*.UK, Oxford University Press, 1982.
- [12] Yılmaz, Işık, and Hüseyin Sendır., "Correlation of Schmidt hardness with unconfined compressive strength and Young's modulus in gypsum from Sivas (Turkey)". *Engineering Geology* 66.3-4: 211-219., 2002.
- [13] Yaşar, E., and Y. Erdoğan., *Estimation of rock physicommechanical properties using hardness methods*. *Engineering Geology* 71.3-4: 281-288., 2004.

- [14] Hack, Robert, and Marco Huisman., "Estimating the intact rock strength of a rock mass by simple means.," *9th Congr. of the Int. Ass. Engin. Geol.*, 2002.
- [15] Das, Sarat Kumar, and Prabir Kumar Basudhar., "Comparison study of parameter estimation techniques for rock failure criterion models.," *Canadian geotechnical journal* 43.7: 764-771., 2006.
- [16] Nooner, Scott L., et al., "Structure of oceanic core complexes: Constraints from seafloor gravity measurements made at the Atlantis Massif.," *Geophysical research letters* 30.8, 2003.
- [17] Bell, Frederic Gladstone. *Engineering geology and geotechnics*. London: Elsevier, 2013.
- [18] Mirza, Tola A., and Saman Gh Rashid., "Mineralogy, Fluid inclusions and stable isotopes study constraints on genesis of sulfide ore mineral, Qaladiza area Qandil Series, Iraqi Kurdistan Region.," *Arabian Journal of Geosciences* 11.7: 1-15., 2018.
- [19] Awadh, Salih Muhammad, and Linaz Anis Fadhil., "Assessment of Carbonate Rocks, Western Desert of Iraq as dimension stones for building.," *Arab Journal of Science and Research Publishing* 17.3999: 1-17., 2016.
- [20] Al-Bassam, Khaldoun S., and Munaf A. Yousif., "Geochemical distribution and background values of some minor and trace elements in Iraqi soils and recent sediments.," *Iraqi Bulletin of Geology and Mining* 10.2: 109-156., 2014.
- [21] Al-Azzawi, Souad N., "Engineering geology of eastern portions of the Cherry Creek Basin, Colorado.," PhD diss., Colorado School of Mines, Minneapolis, MN 1986.
- [22] Al-Mubarak, M., and R. M. Amin., "Report on the regional geological mapping of the eastern part of the Western Desert and western part of the Southern Desert" *GEOSURV*, int. rep 1380, 1983.
- [23] Sissakian, Varoujan K., and Buthaina S. Mohammed., "Stratigraphy" *Iraqi Bulletin of Geology and Mining* 1: 51-124., 2007.
- [24] Hussein Hameed Karim, Oday Al-Taie, "Manufacturing refractory silica bricks from silica sand", University of Technology, January 2012.
- [25] ASTM (2014), "Standard test method for determination of rock hardness by rebound hammer method"
- [26] ASTM (2016), "Standard Test Method for Determination of the Point Load Strength Index of Rock and Application to Rock Strength Classifications"
- [27] ASTM (2016), "Standard Test Method for Splitting Tensile Strength (Brazilian Test) of Intact Rock Core Specimens"

- [28] ASTM (2002), "Standard Test Method for Uniaxial Compressive Strength of Intact Rock Core Specimens"
- [29] ASTM (2005), "Standard test methods for laboratory determination of water (moisture) content of soil and rock by mass"
- [30] ASTM (2015), "Standard Test Method for Specific Gravity and Absorption of Rock"
- [31] ASTM (2009), "Standard test methods for laboratory determination of density (unit weight) of soil specimens"
- [32] ASTM (2018), "Standard Test Method for Permeability of Rocks by Flowing Air"
- [33] Bsi, B. "Methods of test for soils for civil engineering purposes." British Standards Institution, Milton Keynes, UK. Vol. BS: 1377-3, 1990.
- [34] Sissakian, Varoujan K., and Zahra B. Saeed., "Lithological map of Iraq, compiled using GIS techniques.," *Iraqi Bulletin of Geology and Mining* 8.3: 1-13, 2012.
- [35] Al-Salih, Ali Farooq Mohammed Salih., "Effect of water content on the strength properties of Kufa limestone quarry, ". MS thesis. Atilim University Fen Bilimleri Enstitüsü, Turkey:Ankara, 2019.
- [36] Omar, Hemn M., and Nawzat R. Ismail., "The Suitability of Limestone from Pilaspi Formation (Middle-Late Eocene) for Building Stone in Koya Area, NE Iraq.," *ARO-THE SCIENTIFIC JOURNAL OF KOYA UNIVERSITY* 3.2: 18-23, 2015.
- [37] Awadh, Salih Muhammad, and Linaz Anis Fadhil., "Assessment of Carbonate Rocks, Western Desert of Iraq as dimension stones for building.," *Arab Journal of Science and Research Publishing* 17.3999: 1-17, 2016.
- [38] Agustawijaya, D. S., "The uniaxial compressive strength of soft rock.," *Civil Engineering Dimension* 9.1: 9-14, 2007.

## APPENDICES

### APPENDIX A

. The change in the weight of the samples during immersion

| Step 1 | the weight after sampling (g)                            |        |        | Step 3 | the weight after flooding the samples in water for 15min |        |        |
|--------|--|--------|--------|--------|--|--------|--------|
| No     | A  | B      | C      | No     | A  | B      | C      |
| 1      | 154.53   | 172.87 | 179.19 | 1      | 163.4  | 182.9  | 180.24 |
| 2      | 191.97   | 158.66 | 147.71 | 2      | 195.49   | 172.21 | 157.76 |
| 3      | 190.25   | 165.89 | 146.04 | 3      | 193.13   | 178.14 | 158.45 |
| 4      | 154.49   | 181.24 | 173.09 | 4      | 163.65   | 190.34 | 175.22 |
| 5      | 164.64   | 173.25 | 182.87 | 5      |  | 182.12 | 184.03 |
| 6      | 174.08   | 174.83 | 182.02 | 6      | 179.78   | 184.32 | 183.06 |
| 7      | 156.65   | 170.53 | 169.6  | 7      |  | 178.99 | 171.58 |
| 8      | 138.55   | 190.65 | 182.82 | 8      | 148.99   | 192.62 | 184.51 |
| 9      | 187.69   | 166.2  | 189.27 | 9      | 191.11   | 179.33 | 189.6  |
| 10     | 156.56   | 160.76 | 170.48 | 10     | 165.81   | 172.8  | 174.91 |
| Step 2 | after 24h in oven at 106c                                |        |        | Step 4 | the weight after flooding the samples in water for 30min |        |        |
| No     | A  | B      | C      | No     | A  | B      | C      |
| 1      | 154.37   | 172.76 | 178.98 | 1      | 163.62   | 183.43 | 180.56 |
| 2      | 191.88   | 158.57 | 147.62 | 2      | 196.21   | 172.5  | 158.2  |
| 3      | 190.17   | 165.75 | 145.96 | 3      | 193.77   | 178.36 | 158.5  |
| 4      | 154.45   | 181.13 | 172.96 | 4      | 163.74   | 191    | 175.87 |
| 5      | 164.56   | 173.15 | 182.67 | 5      |  | 182.37 | 184.49 |
| 6      | 174.04   | 174.73 | 181.78 | 6      | 180.57   | 184.52 | 183.48 |
| 7      | 156.58   | 170.48 | 169.46 | 7      |  | 180.17 | 172.12 |
| 8      | 138.49   | 190.54 | 182.62 | 8      | 149.24   | 193.25 | 185.03 |
| 9      | 187.64   | 166.12 | 188.93 | 9      | 191.78   | 179.48 | 190.03 |
| 10     | 156.5  | 160.69 | 170.37 | 10     | 166.09   | 172.96 | 175.91 |
| Step 5 | the weight after flooding the samples in water for 45min |        |        |        |  |        |        |
| No     | A  | B      | C      |        |  |        |        |
| 1      | 163.7  | 183.53 | 180.82 |        |  |        |        |
| 2      | 196.58   | 172.66 | 158.32 |        |  |        |        |
| 3      | 194.07   | 178.53 | 158.61 |        |  |        |        |
| 4      | 164.12   | 191.2  | 176.35 |        |  |        |        |
| 5      |  | 182.46 | 184.8  |        |  |        |        |
| 6      | 181.02   | 184.58 | 183.76 |        |  |        |        |
| 7      |  | 181.18 | 172.51 |        |  |        |        |
| 8      | 149.24   | 193.78 | 185.39 |        |  |        |        |
| 9      | 192.17   | 179.62 | 190.31 |        |  |        |        |
| 10     | 166.22   | 173.02 | 176.42 |        |  |        |        |

APPENDIX A (Continue)

| Step 6 | the weight after flooding the samples in water for 60min |        |        |
|--------|--|--------|--------|
| 1      | 163.74   | 183.61 | 181.07 |
| 2      | 196.85   | 172.78 | 158.48 |
| 3      | 194.32   | 178.63 | 158.64 |
| 4      | 164.13   | 191.25 | 176.73 |
| 5      |  | 182.55 | 185.07 |
| 6      | 181.1  | 184.62 | 184    |
| 7      |  | 181.95 | 172.69 |
| 8      | 149.35   | 193.9  | 185.55 |
| 9      | 192.49   | 179.6  | 190.51 |
| 10     | 166.38   | 173.11 | 176.8  |
| Step 7 | the weight after flooding the samples in water for 75min |        |        |
| 1      | 163.84   | 183.67 | 181.35 |
| 2      | 197  | 172.85 | 158.47 |
| 3      | 194.49   | 178.77 | 158.7  |
| 4      | 164.22   | 191.3  | 176.95 |
| 5      |  | 182.58 | 185.28 |
| 6      | 181.07   | 184.64 | 184.17 |
| 7      |  | 182.37 | 172.88 |
| 8      | 149.52   | 194.17 | 185.8  |
| 9      | 192.59   | 179.69 | 190.74 |
| 10     | 166.3  | 173.16 | 177.07 |
| Step 8 | the weight after flooding the samples in water for 90min |        |        |
| 1      | 163.92   | 183.66 | 181.39 |
| 2      | 197.05   | 172.88 | 158.48 |
| 3      | 194.57   | 178.85 | 158.77 |
| 4      | 164.16   | 191.34 | 177.19 |
| 5      |  | 182.71 | 185.51 |
| 6      | 181.18   | 184.71 | 184.34 |
| 7      |  | 182.5  | 173.12 |
| 8      | 149.55   | 194.23 | 185.98 |
| 9      | 192.78   | 179.74 | 190.85 |
| 10     | 166.33   | 173.13 | 177.2  |

| Step 9  | the weight after flooding the samples in water for 105min |        |        |
|---------|---|--------|--------|
| 1       | 163.97  | 183.69 | 181.56 |
| 2       | 197.14  | 172.95 | 158.54 |
| 3       | 194.68  | 178.92 | 158.79 |
| 4       | 164.22  | 191.32 | 177.36 |
| 5       |   | 182.69 | 185.63 |
| 6       | 181.14  | 184.79 | 184.49 |
| 7       |   | 182.46 | 173.2  |
| 8       | 149.52  | 194.37 | 186.14 |
| 9       | 192.91  | 179.81 | 190.99 |
| 10      | 166.46  | 173.16 | 177.36 |
| Step 10 | the weight after flooding the samples in water for 2h     |        |        |
| 1       | 164   | 183.72 | 181.65 |
| 2       | 197.18  | 173.03 | 158.68 |
| 3       | 194.75  | 178.94 | 158.8  |
| 4       | 164.23  | 191.36 | 177.5  |
| 5       |   | 182.72 | 185.77 |
| 6       | 181.23  | 184.75 | 184.61 |
| 7       |   | 182.48 | 173.4  |
| 8       | 149.6   | 194.45 | 186.24 |
| 9       | 192.87  | 179.85 | 191.07 |
| 10      | 166.42  | 173.18 | 177.48 |
| Step 11 | the weight after flooding the samples in water for 4h     |        |        |
| 1       | 164.72  | 184    | 182.54 |
| 2       | 197.53  | 173.61 | 159    |
| 3       | 194.98  | 179.63 | 159.21 |
| 4       | 164.62  | 191.63 | 178.37 |
| 5       |   | 183    | 186.58 |
| 6       | 181.38  | 185.24 | 185.44 |
| 7       |   | 182.68 | 174.3  |
| 8       | 149.99  | 194.9  | 187.31 |
| 9       | 193.22  | 180.17 | 192.49 |
| 10      | 166.66  | 173.7  | 178.01 |

APPENDIX A (Continue)

| Step 12 | the weight after flooding the samples in water for 6h  |        |        |
|---------|--|--------|--------|
| 1       | 164.81   | 184.23 | 182.96 |
| 2       | 197.58   | 173.88 | 159.16 |
| 3       | 195.03   | 179.78 | 159.48 |
| 4       | 164.79   | 191.69 | 178.6  |
| 5       |  | 183.15 | 186.95 |
| 6       | 181.6  | 185.37 | 185.86 |
| 7       |  | 182.85 | 174.71 |
| 8       | 150.25   | 195.06 | 187.67 |
| 9       | 193.29   | 180.25 | 192.85 |
| 10      | 166.78   | 173.77 | 178.19 |
| Step 13 | the weight after flooding the samples in water for 10h |        |        |
| 1       | 164.82   | 184.32 | 183.36 |
| 2       | 197.62   | 173.97 | 159.17 |
| 3       | 195.05   | 179.85 | 159.48 |
| 4       | 164.83   | 191.72 | 178.73 |
| 5       |  | 183.18 | 187.35 |
| 6       | 181.65   | 185.41 | 186.2  |
| 7       |  | 182.95 | 174.89 |
| 8       | 150.26   | 195.14 | 188.01 |
| 9       | 193.3  | 180.4  | 193.14 |
| 10      | 166.85   | 173.79 | 178.19 |
| Step 14 | the weight after flooding the samples in water for 14h |        |        |
| 1       | 164.89   | 184.32 | 183.56 |
| 2       | 197.78   | 174.19 | 159.18 |
| 3       | 195.06   | 180.01 | 159.62 |
| 4       | 165.1  | 191.86 | 178.77 |
| 5       |  | 183.2  | 187.44 |
| 6       | 181.72   | 185.42 | 186.33 |
| 7       |  | 182.99 | 174.94 |
| 8       | 150.44   | 195.17 | 188.05 |
| 9       | 193.35   | 180.61 | 193.3  |
| 10      | 167.03   | 173.86 | 178.23 |

| Step 15 | the weight after flooding the samples in water for 22h |        |        |
|---------|--|--------|--------|
| 1       | 164.96   | 184.48 | 183.86 |
| 2       | 197.86   | 174.4  | 159.3  |
| 3       | 195.14   | 180.26 | 159.73 |
| 4       | 165.24   | 191.92 | 178.88 |
| 5       |  | 183.36 | 187.66 |
| 6       | 181.73   | 185.44 | 186.58 |
| 7       |  | 183.03 | 175.02 |
| 8       | 150.62   | 195.24 | 188.31 |
| 9       | 193.43   | 180.72 | 193.53 |
| 10      | 167.21   | 173.97 | 178.27 |
| Step 16 | the weight after flooding the samples in water for 34h |        |        |
| 1       | 165.13   | 184.69 | 184.06 |
| 2       | 197.89   | 174.86 | 159.51 |
| 3       | 195.14   | 180.7  | 160.21 |
| 4       | 165.43   | 192.14 | 179.06 |
| 5       |  | 183.51 | 187.89 |
| 6       | 181.91   | 185.66 | 186.78 |
| 7       |  | 183.33 | 175.26 |
| 8       | 150.86   | 195.29 | 188.49 |
| 9       | 193.49   | 181.04 | 193.7  |
| 10      | 167.44   | 174.25 | 178.5  |
| Step 17 | the weight after flooding the samples in water for 46h |        |        |
| 1       | 165.37   | 184.92 | 184.16 |
| 2       | 197.93   | 175.3  | 159.96 |
| 3       | 195.14   | 181.05 | 160.73 |
| 4       | 165.57   | 192.3  | 179.24 |
| 5       |  | 183.66 | 187.97 |
| 6       | 182.1  | 185.83 | 186.92 |
| 7       |  | 183.43 | 175.39 |
| 8       | 151.28   | 195.32 | 188.62 |
| 9       | 193.61   | 181.32 | 193.84 |
| 10      | 167.59   | 174.64 | 178.74 |

APPENDIX A (Continue)

| Step 18 | the weight after flooding the samples in water for 70h  |        |        |
|---------|---|--------|--------|
| 1       | 166.03  | 185.29 | 184.32 |
| 2       | 198.11  | 175.91 | 160.59 |
| 3       | 195.27  | 181.63 | 161.34 |
| 4       | 166.05  | 192.69 | 179.44 |
| 5       |   | 184.1  | 188.02 |
| 6       | 182.4   | 186.15 | 187.03 |
| 7       |   | 183.79 | 175.62 |
| 8       | 151.79  | 195.4  | 188.76 |
| 9       | 193.77  | 181.76 | 193.84 |
| 10      | 168.21  | 175    | 179.06 |
| Step 19 | the weight after flooding the samples in water for 94h  |        |        |
| 1       | 166.32  | 185.52 | 184.39 |
| 2       | 198.26  | 176.23 | 161.03 |
| 3       | 195.33  | 181.96 | 161.88 |
| 4       | 166.48  | 192.91 | 179.67 |
| 5       |   | 184.33 | 188.2  |
| 6       | 182.63  | 186.26 | 187.16 |
| 7       |   | 184.08 | 175.84 |
| 8       | 152.26  | 195.41 | 188.9  |
| 9       | 193.83  | 182.06 | 193.9  |
| 10      | 168.64  | 175.15 | 179.34 |
| Step 20 | the weight after flooding the samples in water for 118h |        |        |
| 1       | 166.46  | 185.7  | 184.48 |
| 2       | 198.26  | 176.38 | 161.17 |
| 3       | 195.36  | 182.12 | 162.12 |
| 4       | 166.58  | 193.1  | 179.76 |
| 5       |   | 184.49 | 188.25 |
| 6       | 182.68  | 186.38 | 187.25 |
| 7       |   | 184.28 | 175.91 |
| 8       | 152.48  | 195.46 | 188.99 |
| 9       | 193.92  | 182.25 | 193.92 |
| 10      | 168.84  | 175.29 | 179.45 |

| Step 21 | the weight after flooding the samples in water for 142h |        |        |
|---------|---|--------|--------|
| 1       | 166.75  | 185.91 | 184.59 |
| 2       | 198.34  | 176.57 | 161.5  |
| 3       | 195.4   | 182.34 | 162.5  |
| 4       | 166.91  | 193.29 | 179.97 |
| 5       |   | 184.71 | 188.33 |
| 6       | 182.93  | 186.4  | 187.29 |
| 7       |   | 184.63 | 176.12 |
| 8       | 152.76  | 195.5  | 189.2  |
| 9       | 194.1   | 182.49 | 194.01 |
| 10      | 169.15  | 175.54 | 179.72 |
| Step 22 | the weight after flooding the samples in water for 166h |        |        |
| 1       | 166.89  | 185.98 | 184.64 |
| 2       | 198.36  | 176.74 | 161.67 |
| 3       | 195.4   | 182.4  | 162.79 |
| 4       | 167.01  | 193.4  | 180.07 |
| 5       |   | 184.72 | 188.41 |
| 6       | 182.93  | 186.46 | 187.36 |
| 7       |   | 184.74 | 176.17 |
| 8       | 152.84  | 195.5  | 189.24 |
| 9       | 194.1   | 182.62 | 194.01 |
| 10      | 169.21  | 175.69 | 179.87 |
| Step 23 | the weight after flooding the samples in water for 190h |        |        |
| 1       | 166.92  | 186.14 | 184.71 |
| 2       | 198.4   | 176.84 | 161.84 |
| 3       | 195.45  | 182.62 | 162.95 |
| 4       | 167.08  | 193.49 | 180.19 |
| 5       |   | 184.83 | 188.47 |
| 6       | 183.04  | 186.52 | 187.43 |
| 7       |   | 184.92 | 176.29 |
| 8       | 153.07  | 195.57 | 189.34 |
| 9       | 194.16  | 182.68 | 194.05 |
| 10      | 169.35  | 175.69 | 180.01 |

APPENDIX A (Continue)

| Step 24 | the weight after flooding the samples in water for 214h |        |        |
|---------|---|--------|--------|
| 1       | 167.17  | 186.31 | 184.79 |
| 2       | 198.47  | 176.99 | 161.95 |
| 3       | 195.5   | 182.78 | 163.11 |
| 4       | 167.24  | 193.57 | 180.21 |
| 5       |   | 184.89 | 188.53 |
| 6       | 183.05  | 186.6  | 187.46 |
| 7       |   | 185.01 | 176.33 |
| 8       | 153.15  | 195.72 | 189.41 |
| 9       | 194.16  | 182.9  | 194.07 |
| 10      | 169.5   | 175.74 | 180.07 |
| Step 25 | the weight after flooding the samples in water for 238h |        |        |
| 1       | 167.24  | 186.39 | 184.79 |
| 2       | 198.47  | 177.03 | 162.07 |
| 3       | 195.51  | 182.91 | 163.28 |
| 4       | 167.33  | 193.7  | 180.25 |
| 5       |   | 184.96 | 188.59 |
| 6       | 183.11  | 186.72 | 187.53 |
| 7       |   | 185.1  | 176.39 |
| 8       | 153.3   | 195.72 | 189.5  |
| 9       | 194.27  | 182.9  | 194.08 |
| 10      | 169.5   | 175.89 | 180.16 |
| Step 26 | the weight after flooding the samples in water for 262h |        |        |
| 1       | 167.31  | 186.46 | 184.88 |
| 2       | 198.47  | 177.18 | 162.23 |
| 3       | 195.54  | 182.91 | 163.41 |
| 4       | 167.35  | 193.77 | 180.39 |
| 5       |   | 185.01 | 188.63 |
| 6       | 183.18  | 186.72 | 187.53 |
| 7       |   | 185.26 | 176.45 |
| 8       | 153.33  | 195.72 | 189.51 |
| 9       | 194.29  | 182.94 | 194.08 |
| 10      | 169.6   | 175.89 | 180.22 |

| Step 27 | the weight after flooding the samples in water for 310h |        |        |
|---------|---|--------|--------|
| 1       | 167.47  | 186.6  | 184.91 |
| 2       | 198.61  | 177.42 | 162.32 |
| 3       | 195.58  | 183.17 | 163.59 |
| 4       | 167.5   | 193.97 | 180.44 |
| 5       |   | 185.12 | 188.68 |
| 6       | 183.27  | 186.8  | 187.6  |
| 7       |   | 185.42 | 176.55 |
| 8       | 153.4   | 195.64 | 189.58 |
| 9       | 194.35  | 183.16 | 194.05 |
| 10      | 169.75  | 176.01 | 180.34 |
| Step 28 | the weight after flooding the samples in water for 358h |        |        |
| 1       | 167.71  | 186.75 | 185    |
| 2       | 198.72  | 177.45 | 162.47 |
| 3       | 195.66  | 183.28 | 163.8  |
| 4       | 167.68  | 194.08 | 180.65 |
| 5       |   | 185.32 | 188.79 |
| 6       | 183.39  | 186.92 | 187.78 |
| 7       |   | 185.44 | 176.61 |
| 8       | 153.63  | 195.67 | 189.66 |
| 9       | 194.4   | 183.33 | 194.15 |
| 10      | 170   | 176.12 | 180.61 |
| Step 29 | the weight after flooding the samples in water for 406h |        |        |
| 1       | 167.7   | 186.83 | 185.07 |
| 2       | 198.69  | 177.63 | 162.61 |
| 3       | 195.69  | 183.43 | 163.98 |
| 4       | 167.78  | 194.15 | 180.73 |
| 5       |   | 185.35 | 188.83 |
| 6       | 183.46  | 186.99 | 187.75 |
| 7       |   | 185.66 | 176.74 |
| 8       | 153.69  | 195.74 | 189.77 |
| 9       | 194.42  | 183.46 | 194.13 |
| 10      | 169.97  | 176.24 | 180.67 |

## APPENDIX B

### X-Ray Diffraction (XRD) Results

#### Rock Sample A

```

*** Basic Data Process ***

Group      : 2020
Data       : 590

# Strongest 3 peaks
no. peak  2Theta      d          I/I1    FWHM      Intensity  Integrated Int
   no.      (deg)         (A)          (deg)    (Counts)  (Counts)
  1  2      29.7191     3.00370    100     0.49680    1550    4102
  2  7      48.8055     1.86446     31     0.47650     488    1181
  3  6      47.7469     1.90330     28     0.59910     438    1397

# Peak Data List
peak      2Theta      d          I/I1    FWHM      Intensity  Integrated Int
no.       (deg)         (A)          (deg)    (Counts)  (Counts)
  1      23.3611     3.80480     7      0.51530     103     292
  2      29.7191     3.00370    100     0.49680    1550    4102
  3      36.2742     2.47453    17      0.47850     259     669
  4      39.7172     2.26759    25      0.50160     384    1023
  5      43.4566     2.08074    20      0.47470     316     773
  6      47.7469     1.90330    28      0.59910     438    1397
  7      48.8055     1.86446    31      0.47650     488    1181
  8      56.8434     1.61842     6      0.50120     90      231
  9      57.6885     1.59671    16      0.48560     245     685
 10      61.0240     1.51718     9      0.56240     141     464
 11      61.8237     1.49946     4      0.26340     55      220
 12      63.3247     1.46748     3      0.49410     52      146
 13      64.9404     1.43482     9      0.50200    140     371
 14      65.9093     1.41606     5      0.53030     82      239
 15      73.1704     1.29241     5      0.48100     81      256
 16      77.4409     1.23145     3      0.50660     47      222
 17      81.8212     1.17624     6      0.53040     87      295
 18      84.0515     1.15062     7      0.54950    116     326
 19      85.0859     1.13926     3      0.50880     53      148
    
```

#### Rock Sample A

```

*** Basic Data Process ***

# Data Information
Group      : 2020
Data       : 590
Sample Nmae :
Comment    :
Date & Time : 10-23-09 01:51:55

# Measurement Condition
X-ray tube
target     : Cu
voltage    : 40.0 (kV)
current    : 30.0 (mA)

Slits
Auto Slit  : not Used
divergence slit : 1.00000 (deg)
scatter slit : 1.00000 (deg)
receiving slit : 0.30000 (mm)

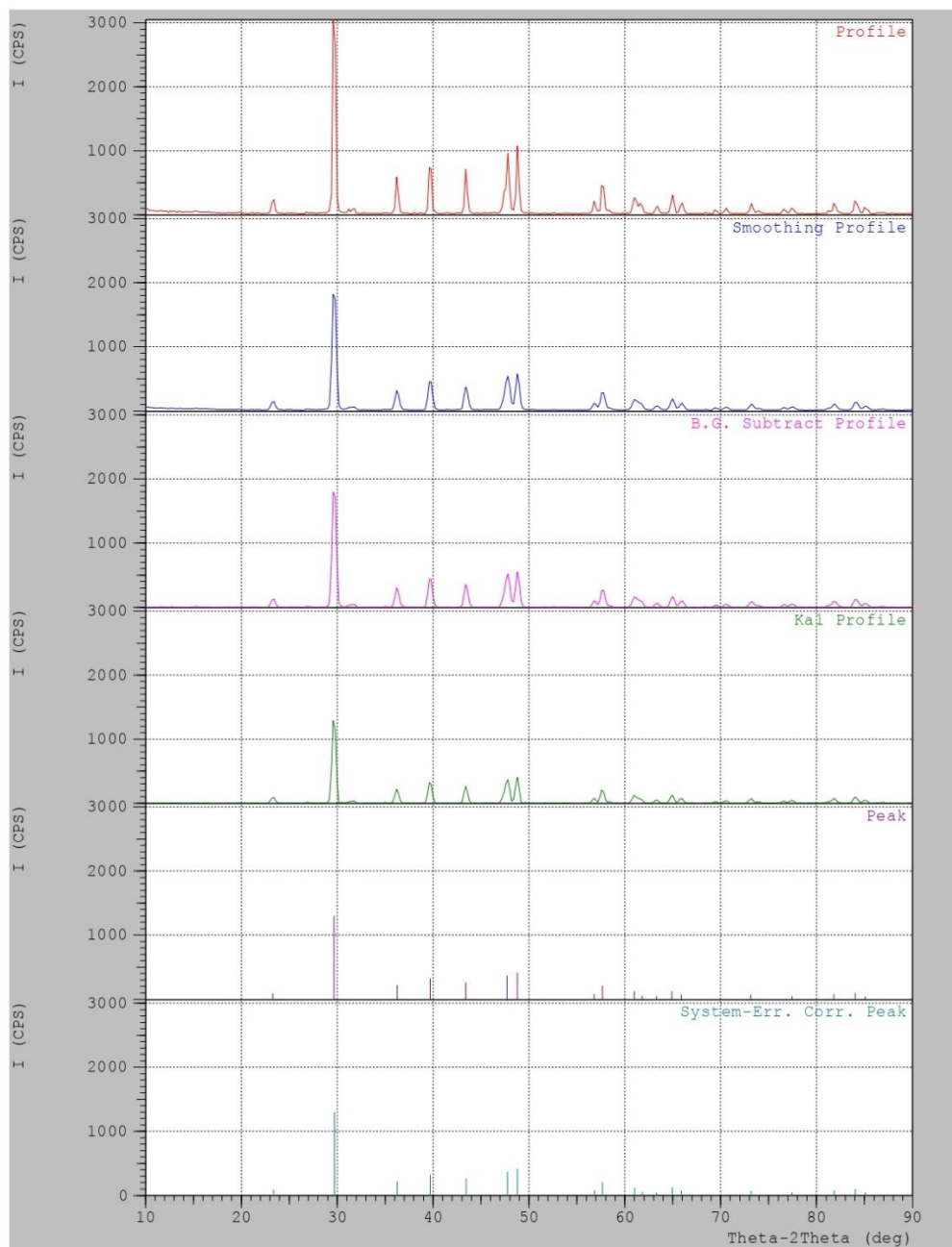
Scanning
drive axis : Theta-2Theta
scan range : 10.0000 - 90.0000 (deg)
scan mode  : Continuous Scan
scan speed : 10.0000 (deg/min)
sampling pitch : 0.2000 (deg)
preset time : 1.20 (sec)

# Data Process Condition
Smoothing      [ AUTO ]
smoothing points : 3
B.G.Subtraction [ AUTO ]
sampling points : 3
repeat times   : 30
Kal-a2 Separate [ MANUAL ]
Kal a2 ratio   : 50 (%)
Peak Search    [ AUTO ]
differential points : 3
FWHM threshold : 0.050 (deg)
intensity threshold : 30 (par mil)
FWHM ratio (n-1)/n : 2
System error Correction [ YES ]
Precise peak Correction [ NO ]
    
```

APPENDIX B (Continue)

Rock Sample A

< Group: 2020 Data: 590 >



## APPENDIX B (Continue)

### Rock Sample B

```

*** Basic Data Process ***
Group      : 2020
Data       : 591

# Strongest 3 peaks
no. peak  2Theta      d      I/I1  FWHM      Intensity  Integrated Int
   no.    (deg)        (A)    (deg)  (deg)    (Counts)  (Counts)
  1  3    31.3546    2.85065  100  0.67110    765    2829
  2  12   47.9901    1.89422   97  0.45000    741    1730
  3   9    41.5119    2.17361   33  0.60870    256     839

# Peak Data List
peak      2Theta      d      I/I1  FWHM      Intensity  Integrated Int
no.      (deg)        (A)    (deg)  (deg)    (Counts)  (Counts)
  1    24.4936    3.63138   4  0.61670     30     182
  2    29.8731    2.98856  32  0.67710    246     833
  3    31.3546    2.85065 100  0.67110    765    2829
  4    33.9522    2.63826   4  0.57330     32     100
  5    35.6373    2.51728   5  0.52500     35     93
  6    36.3749    2.46791  10  0.56980     74    220
  7    37.8080    2.37759  11  0.66030     81    276
  8    39.8684    2.25934  14  0.51150    105    275
  9    41.5119    2.17361  33  0.60870    256    839
 10    43.9571    2.05820  12  0.65160     93    344
 11    45.3590    1.99779  17  0.65710    130    442
 12    47.9901    1.89422  97  0.45000    741    1730
 13    49.1189    1.85330  13  0.95620     99    820
 14    51.1837    1.78328  26  1.17540    199   1234
 15    57.5918    1.59916   4  0.86670     31    150
 16    59.2579    1.55811   5  0.57330     39    117
 17    60.1832    1.53635  11  0.61550     83    254
 18    61.4559    1.50755   5  0.96430     40    212
 19    63.7949    1.45780   8  0.67460     60    205
 20    65.4254    1.42535   8  1.09440     60    376
 21    67.7652    1.38172   9  0.59330     69    237
 22    70.5036    1.33461   8  0.59270     63    228
 23    73.2275    1.29154   3  0.61430     25    134
 24    77.4143    1.23181   6  0.70450     44    211
 25    82.8469    1.16427   3  0.59170     23    133
 26    88.2090    1.10680   7  0.62220     53    224
    
```

### Rock Sample B

```

*** Basic Data Process ***

# Data Information
Group      : 2020
Data       : 591
Sample Name :
Comment    :
Date & Time : 10-23-09 02:03:31

# Measurement Condition
X-ray tube
target     : Cu
voltage    : 40.0 (kV)
current    : 30.0 (mA)

Slits
Auto Slit      : not Used
divergence slit : 1.00000 (deg)
scatter slit   : 1.00000 (deg)
receiving slit : 0.30000 (mm)

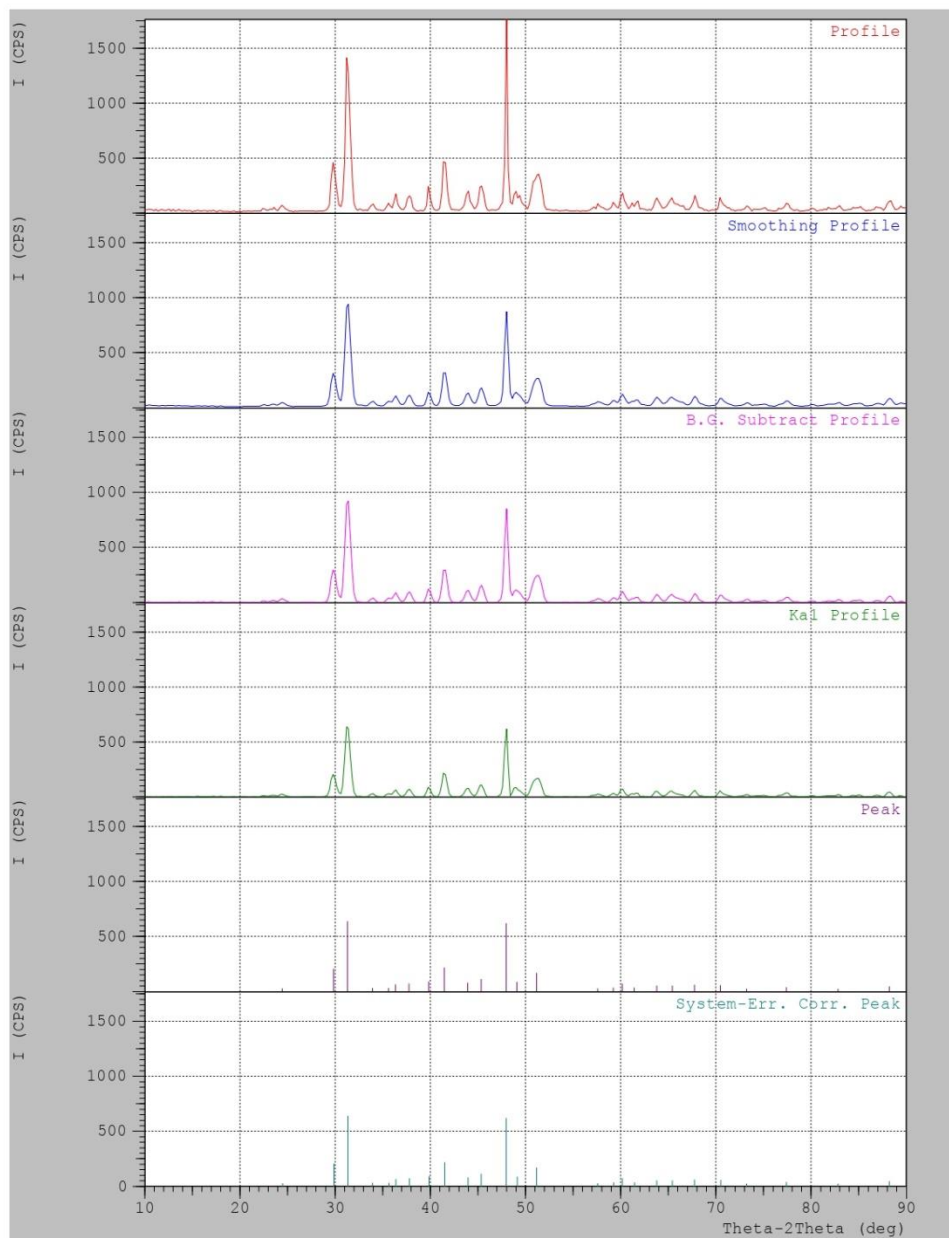
Scanning
drive axis    : Theta-2Theta
scan range    : 10.0000 - 90.0000 (deg)
scan mode     : Continuous Scan
scan speed    : 10.0000 (deg/min)
sampling pitch : 0.2000 (deg)
preset time   : 1.20 (sec)

# Data Process Condition
Smoothing      [ AUTO ]
smoothing points : 3
B.G.Subtraction [ AUTO ]
sampling points : 5
repeat times   : 30
Kal-a2 Separate [ MANUAL ]
Kal a2 ratio   : 50 (%)
Peak Search    [ AUTO ]
differential points : 5
FWHM threshold : 0.050 (deg)
intensity threshold : 30 (par mil)
FWHM ratio (n-1)/n : 2
System error Correction [ YES ]
Precise peak Correction [ NO ]
    
```

# APPENDIX B (Continue)

## Rock Sample B

< Group: 2020 Data: 591 >



## APPENDIX B (Continue)

### Rock Sample C

```

*** Basic Data Process ***

Group      : 2020
Data       : 592

# Strongest 3 peaks
no. peak  2Theta      d      I/I1  FWHM      Intensity  Integrated Int
   no.      (deg)      (A)      (deg)  (Counts)  (Counts)
  1  2      29.8459    2.99123  100  0.46780    1511    3626
  2  7      48.9329    1.85991   28  0.48870     423    1252
  3  5      43.5969    2.07436   24  0.45210     362     845

# Peak Data List
peak      2Theta      d      I/I1  FWHM      Intensity  Integrated Int
  no.      (deg)      (A)      (deg)  (Counts)  (Counts)
  1      23.4989    3.78280    8  0.48990     116     324
  2      29.8459    2.99123   100  0.46780    1511    3626
  3      36.4104    2.46558   17  0.45230     251     593
  4      39.8675    2.25939   24  0.46960     359     883
  5      43.5969    2.07436   24  0.45210     362     845
  6      47.6294    1.90772   15  0.48480     226    1277
  7      48.9329    1.85991   28  0.48870     423    1252
  8      56.9918    1.61456    5  0.44850     82     146
  9      57.8295    1.59315   15  0.46980     226     636
 10      61.2412    1.51232    8  0.76530     124     397
 11      61.8237    1.49946    4  0.45520     62     167
 12      63.4709    1.46445    3  0.46460     49     120
 13      65.0910    1.43187    9  0.47880     130     296
 14      66.0252    1.41385    5  0.47630     79     228
 15      70.6404    1.33236    3  0.50530     45     190
 16      73.3153    1.29021    4  0.52520     63     209
 17      77.5932    1.22942    4  0.50190     57     246
 18      81.9230    1.17504    4  0.61000     58     236
 19      84.2348    1.14858    7  0.47320    111     268
 20      85.2045    1.13797    3  0.46340     45     141
    
```

### Rock Sample C

```

*** Basic Data Process ***

# Data Information
Group      : 2020
Data       : 592
Sample Name :
Comment    :
Date & Time : 10-23-09 02:18:00

# Measurement Condition
X-ray tube
target     : Cu
voltage    : 40.0 (kV)
current    : 30.0 (mA)

Slits
Auto Slit  : not Used
divergence slit : 1.00000 (deg)
scatter slit : 1.00000 (deg)
receiving slit : 0.30000 (mm)

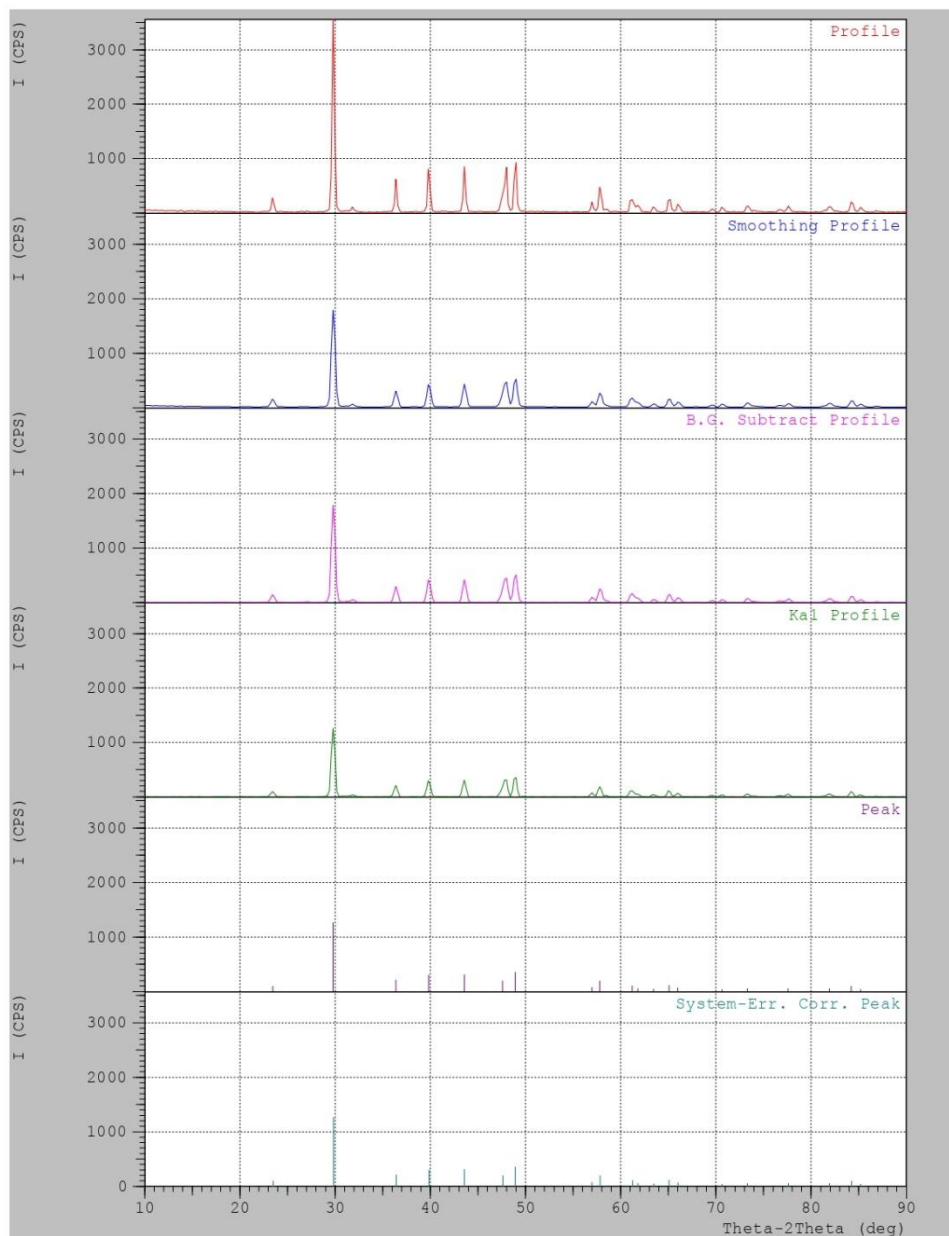
Scanning
drive axis : Theta-2Theta
scan range : 10.0000 - 90.0000 (deg)
scan mode  : Continuous Scan
scan speed : 10.0000 (deg/min)
sampling pitch : 0.2000 (deg)
preset time : 1.20 (sec)

# Data Process Condition
Smoothing [ AUTO ]
smoothing points : 3
B.G.Subtraction [ AUTO ]
sampling points : 5
repeat times : 30
Kal-a2 Separate [ MANUAL ]
Kal a2 ratio : 50 (%)
Peak Search [ AUTO ]
differential points : 5
FWHM threshold : 0.050 (deg)
intensity threshold : 30 (par mil)
FWHM ratio (n-1)/n : 2
System error Correction [ YES ]
Precise peak Correction [ NO ]
    
```

# APPENDIX B (Continue)

## Rock Sample C

< Group: 2020 Data: 592 >



## APPENDIX C

The uniaxial compression test result, graphs obtained from test device (Microcomputer Controlled Electronic Universal testing machine) Model: WDW-200

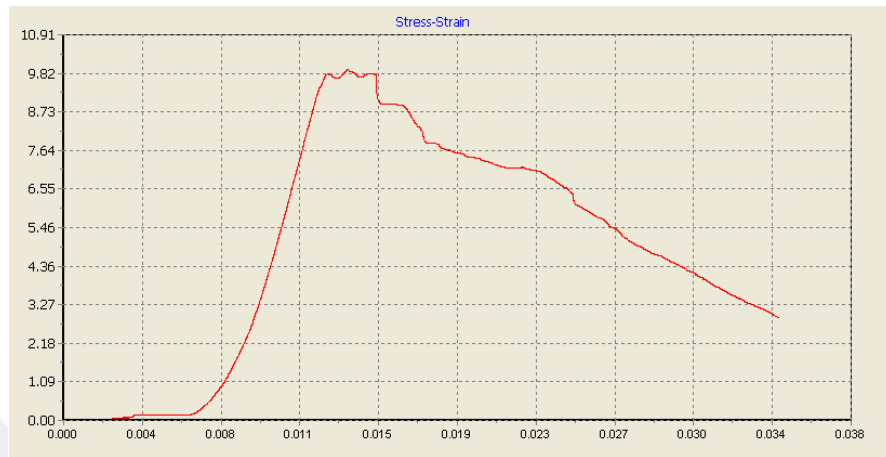


Figure showing the stress-strain relationship of sample A1 in the dry state

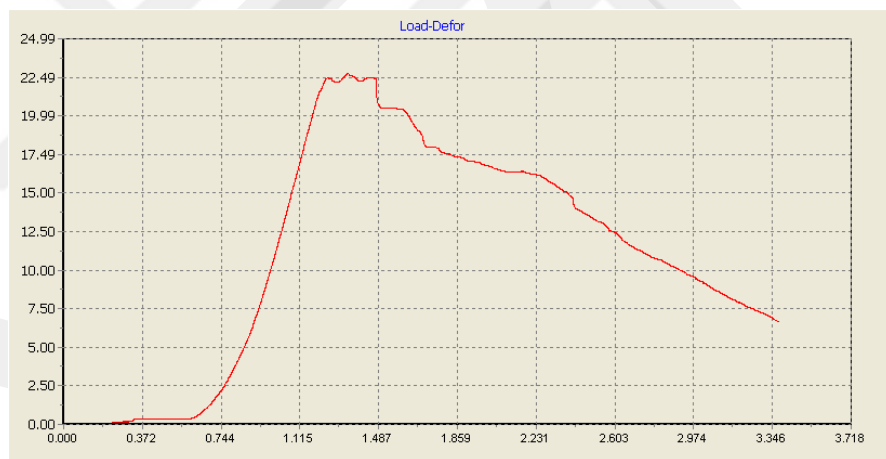


Figure showing the load-deformation relationship of sample A1 in the dry state

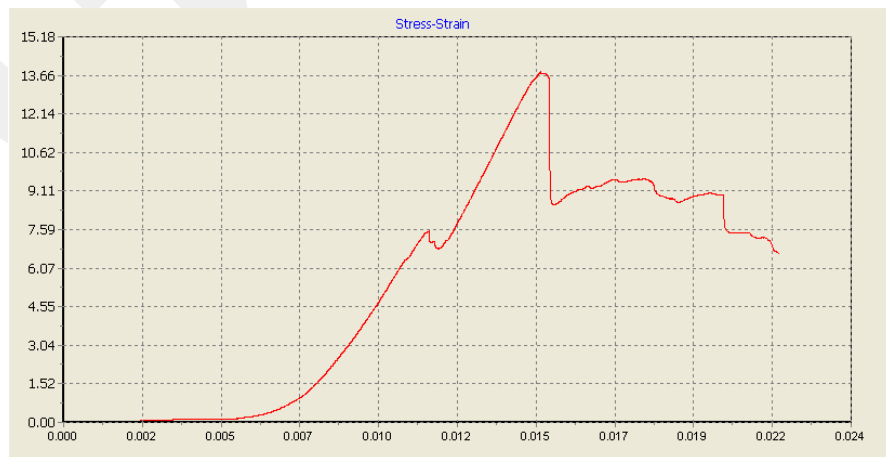


Figure showing the stress-strain relationship of sample A2 in the dry state

APPENDIX C (Continue)

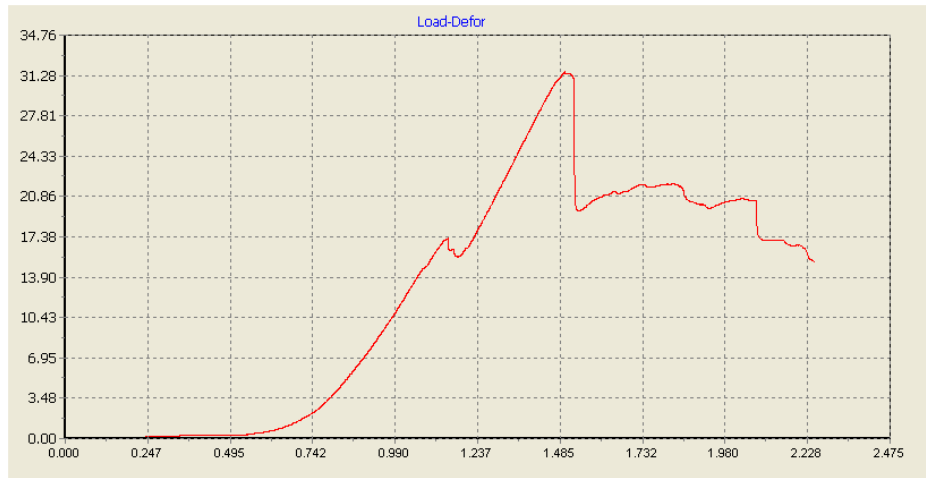


Figure showing the load-deformation relationship of sample A2 in the dry state

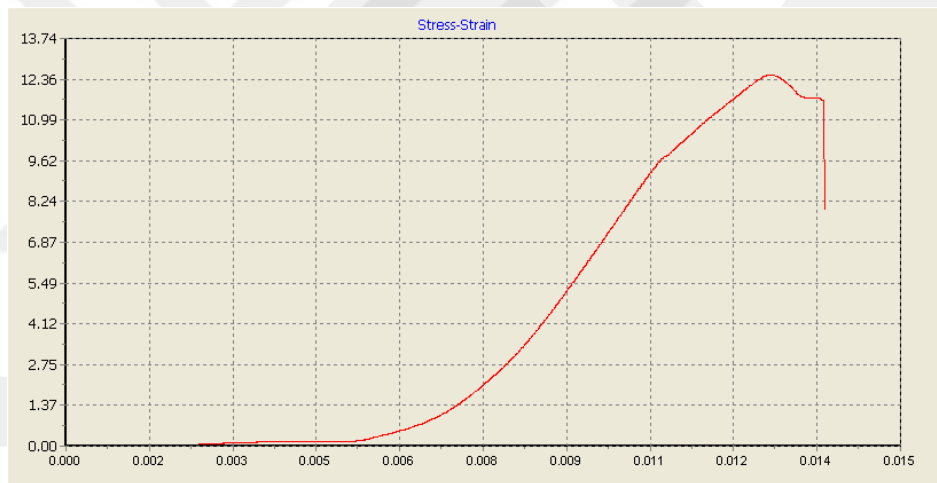


Figure showing the stress-strain relationship of sample A3 in the dry state

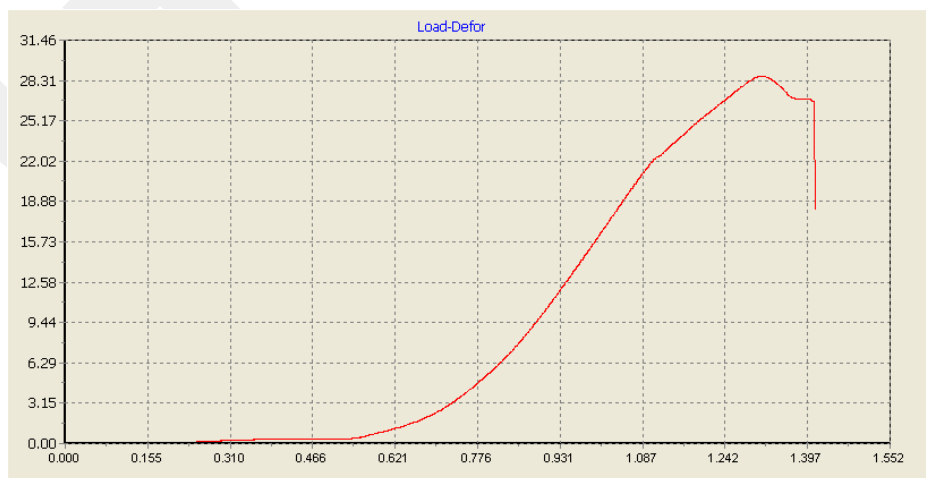


Figure showing the load-deformation relationship of sample A3 in the dry state

APPENDIX C (Continue)



Figure showing the stress-strain relationship of sample A4 in the dry state



Figure showing the load-deformation relationship of sample A4 in the dry state



Figure showing the stress-strain relationship of sample A5 in the dry state

APPENDIX C (Continue)

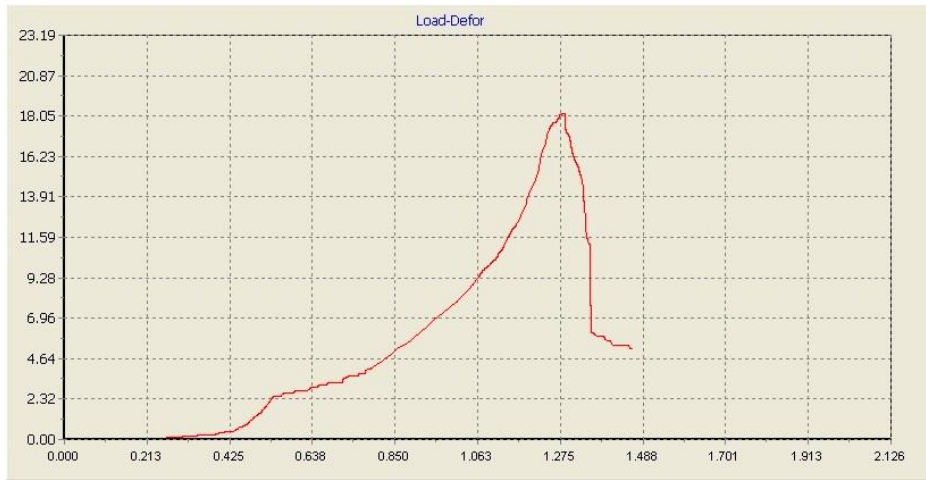


Figure showing the load-deformation relationship of sample A5 in the dry state

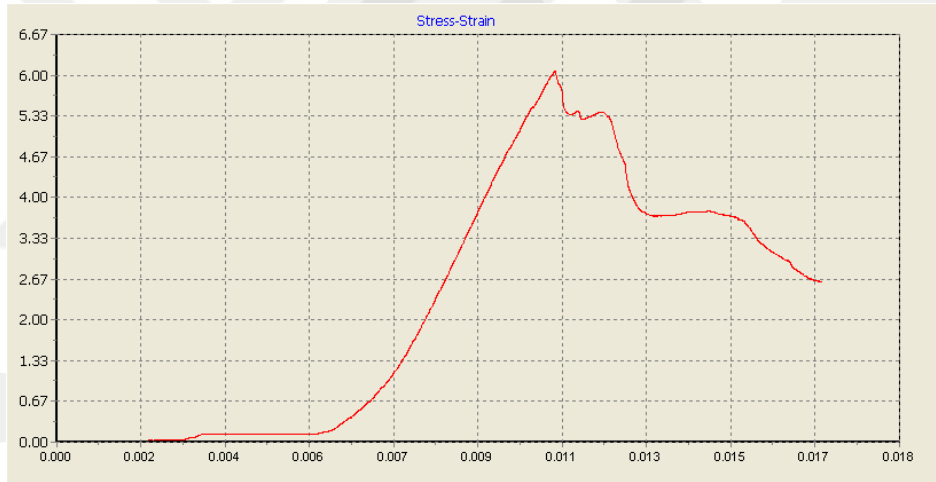


Figure showing the stress-strain relationship of sample B1 in the dry state

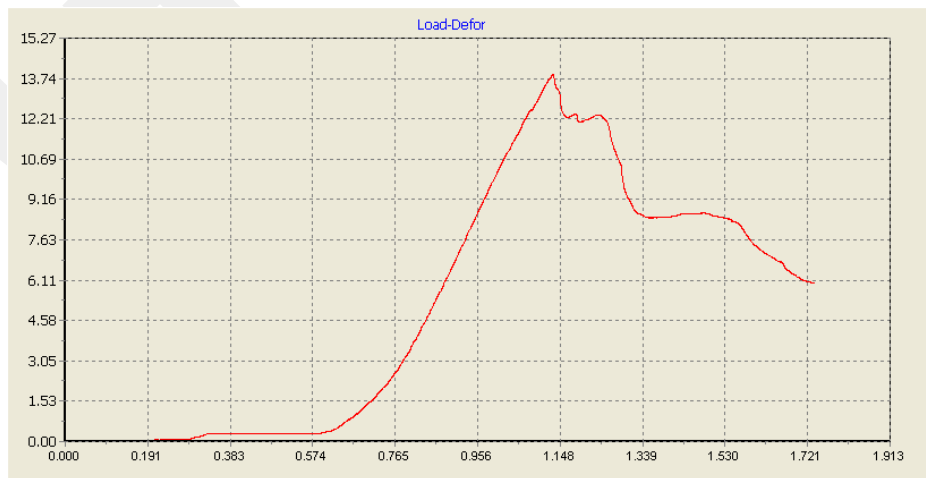


Figure showing the load-deformation relationship of sample B1 in the dry state

APPENDIX C (Continue)

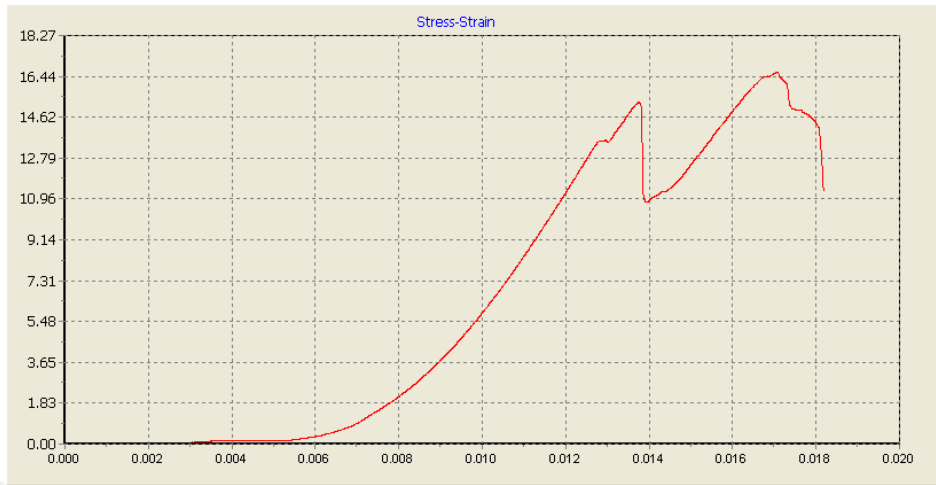


Figure showing the stress-strain relationship of sample B2 in the dry state

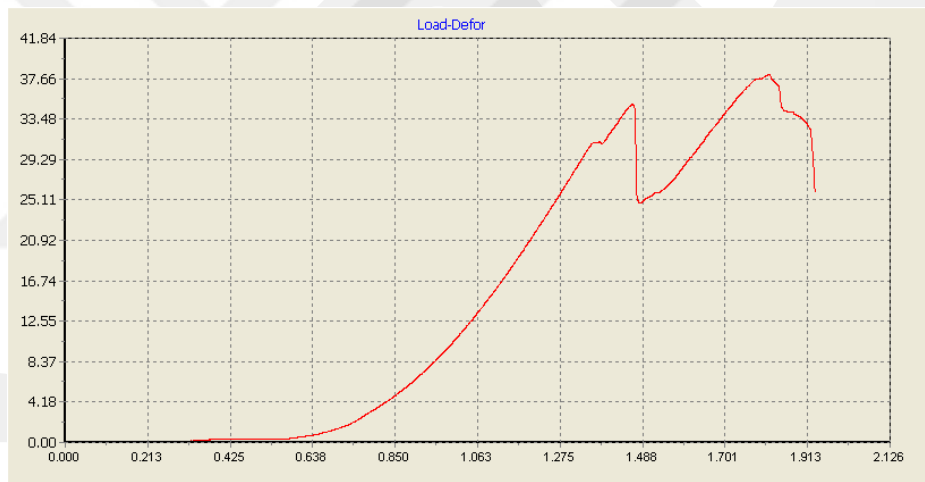


Figure showing the load-deformation relationship of sample B2 in the dry state

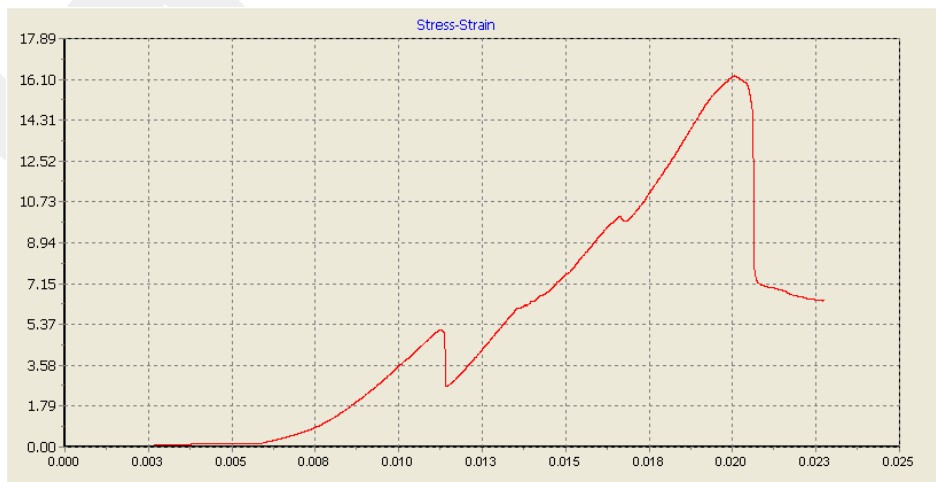


Figure showing the stress-strain relationship of sample B3 in the dry state

APPENDIX C (Continue)

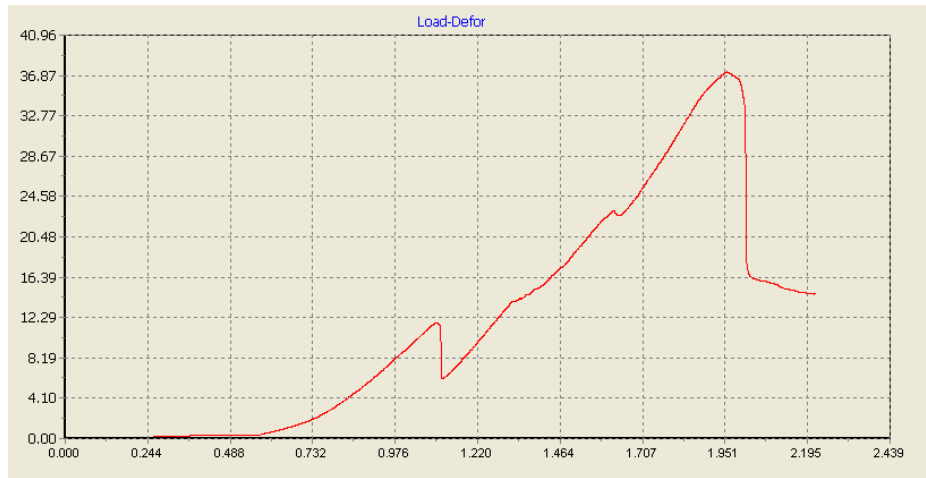


Figure showing the load-deformation relationship of sample B3 in the dry state

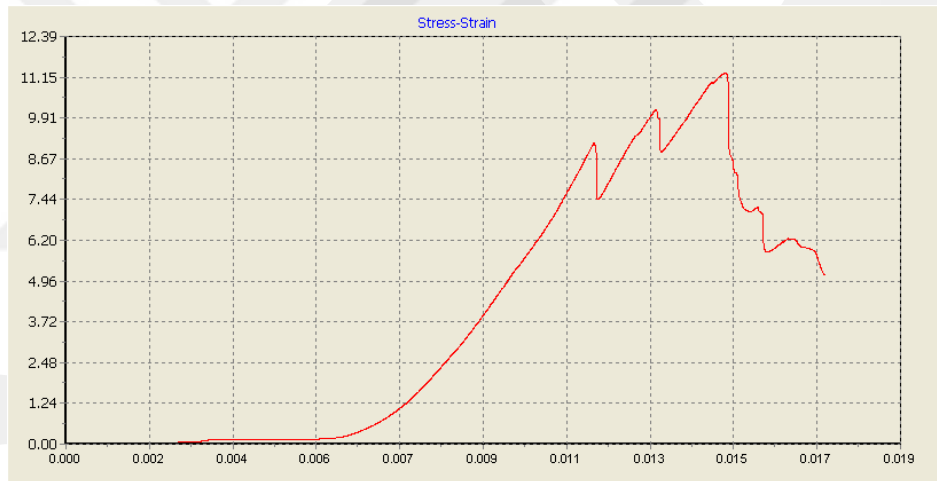


Figure showing the stress-strain relationship of sample B4 in the dry state

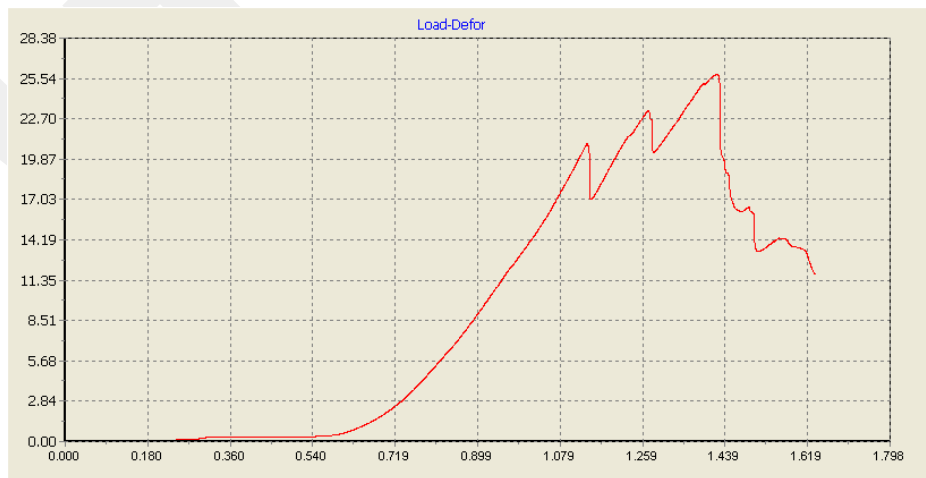


Figure showing the load-deformation relationship of sample B4 in the dry state

APPENDIX C (Continue)

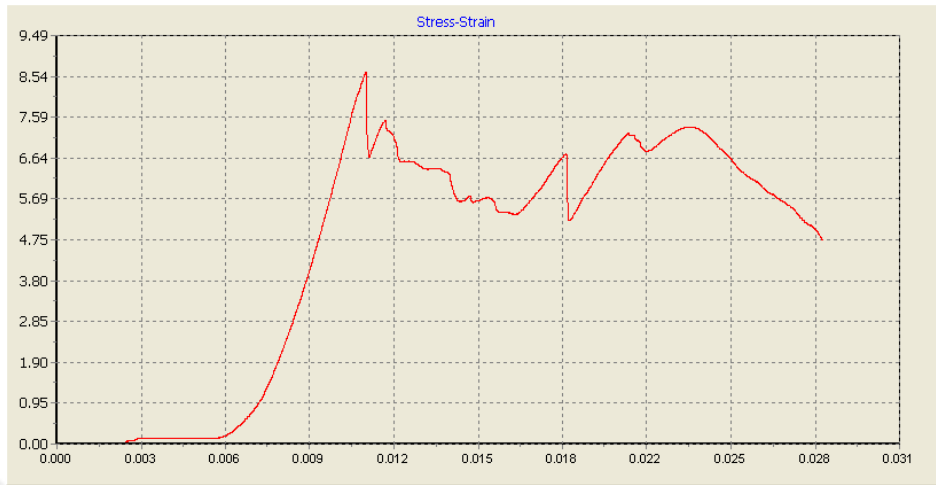


Figure showing the stress-strain relationship of sample B5 in the dry state

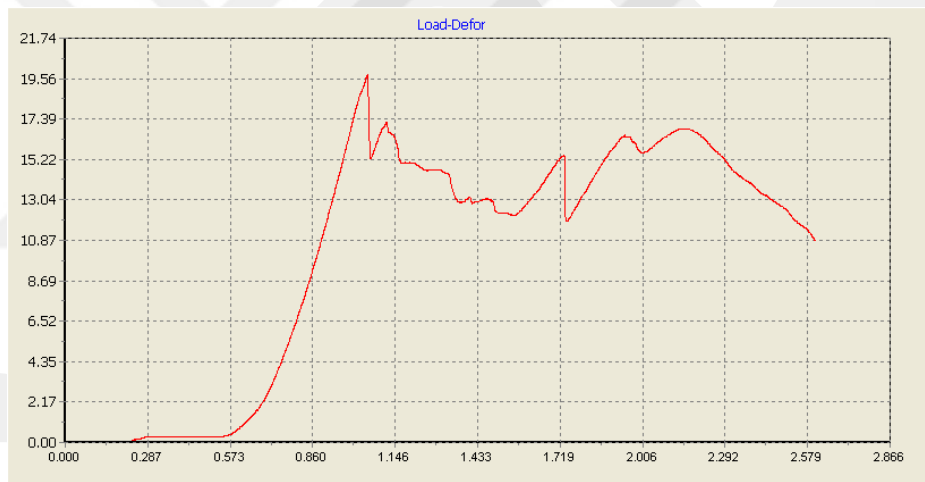


Figure showing the load-deformation relationship of sample B5 in the dry state

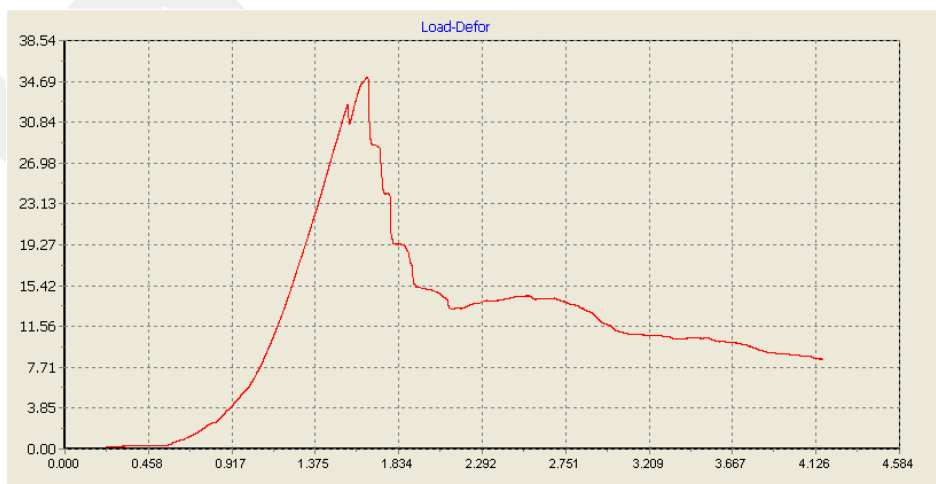


Figure showing the load-deformation relationship of sample C1 in the dry state

APPENDIX C (Continue)

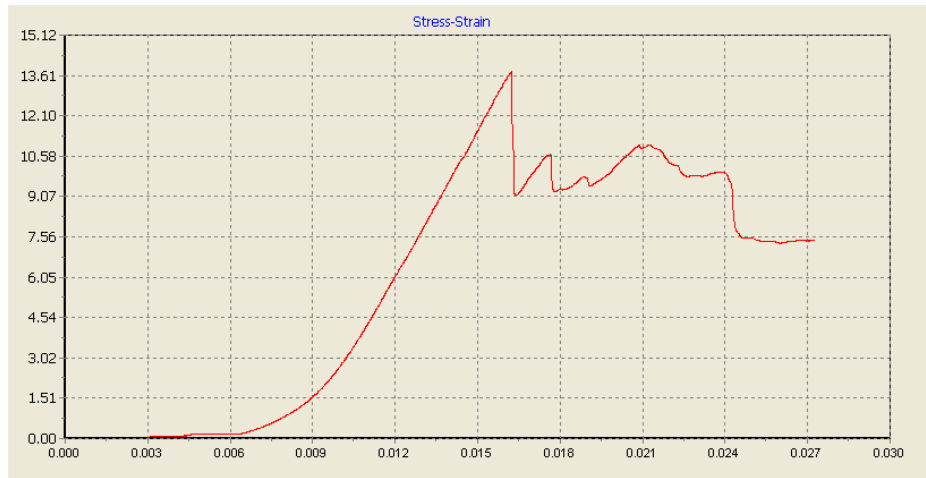


Figure showing the stress-strain relationship of sample C2 in the dry state

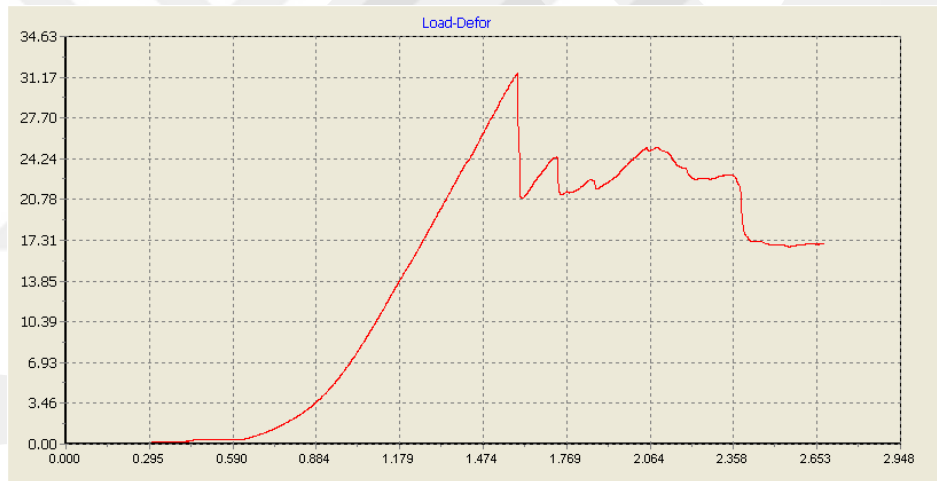


Figure showing the load-deformation relationship of sample C2 in the dry state



Figure showing the stress-strain relationship of sample C3 in the dry state

APPENDIX C (Continue)

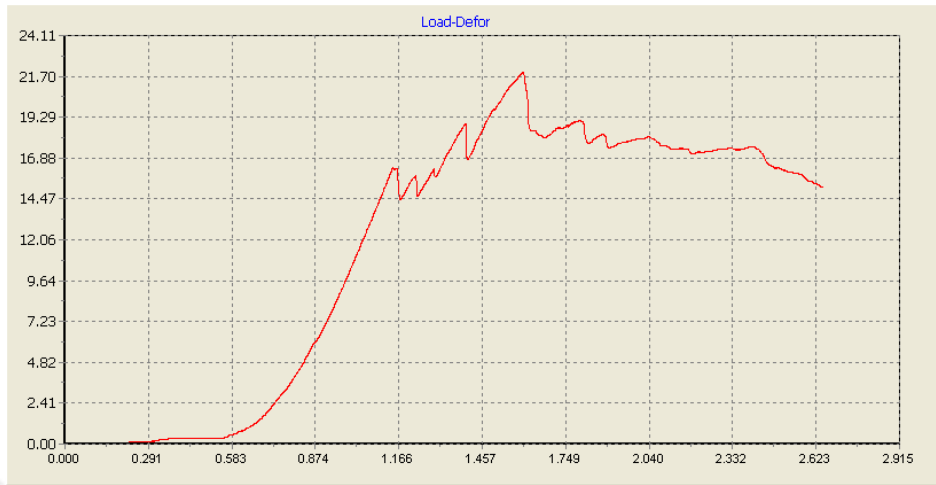


Figure showing the load-deformation relationship of sample C3 in the dry state



Figure showing the stress-strain relationship of sample C4 in the dry state

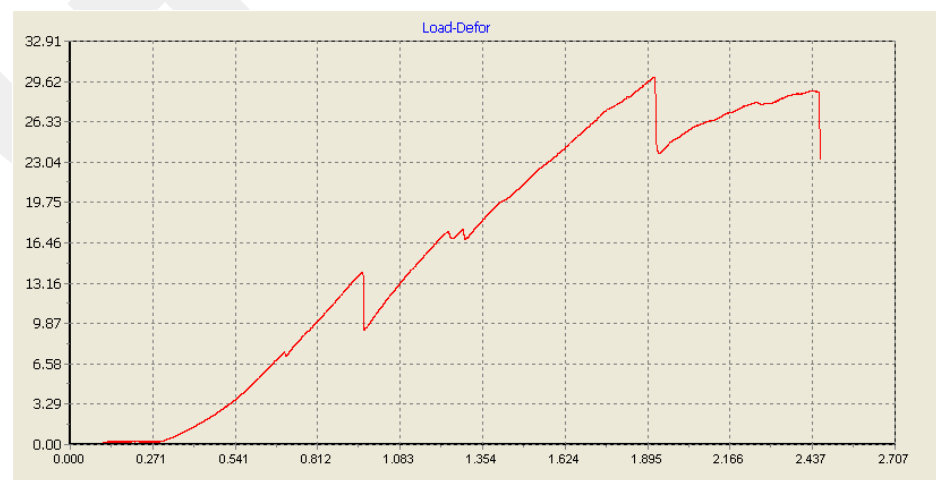


Figure showing the load-deformation relationship of sample C4 in the dry state

APPENDIX C (Continue)

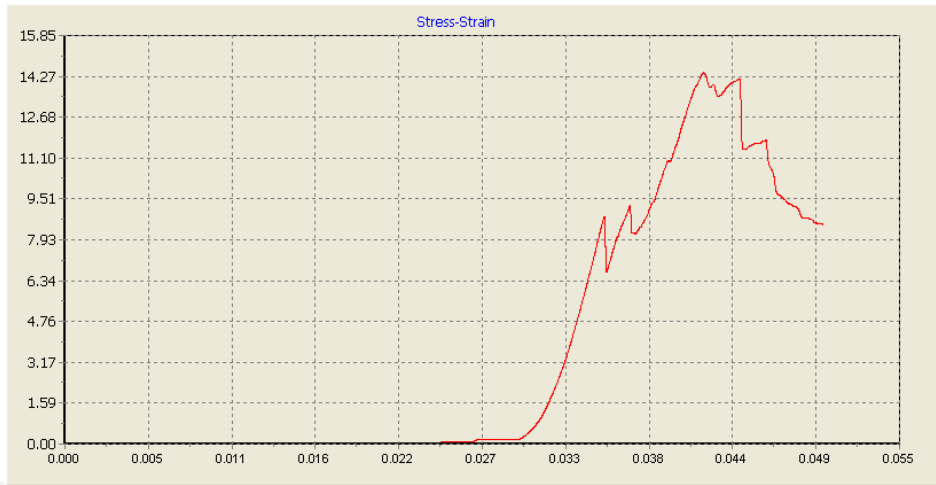


Figure showing the stress-strain relationship of sample C5 in the dry state

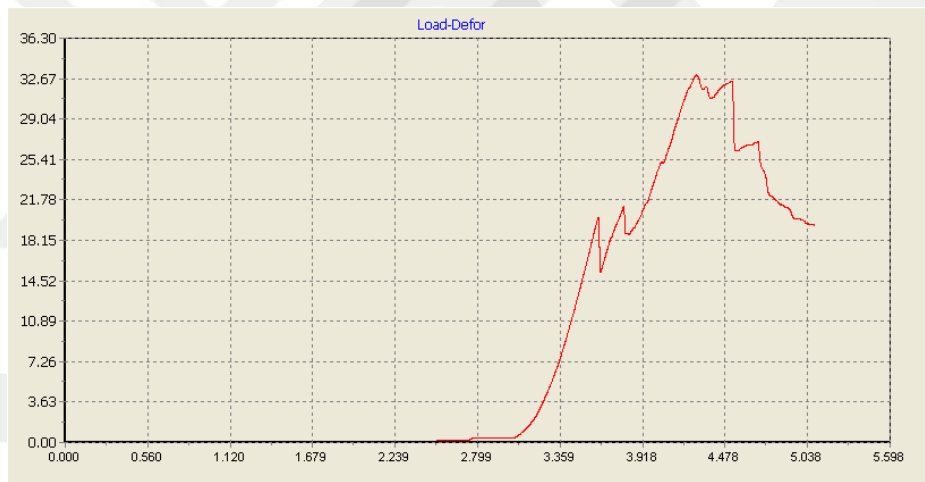


Figure showing the load-deformation relationship of sample C5 in the dry state

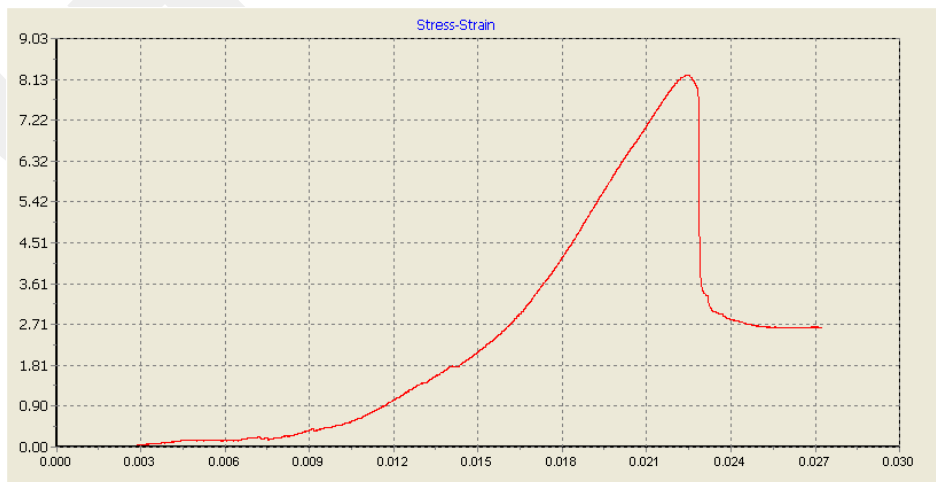


Figure showing the stress-strain relationship of sample A1 in the saturated state

APPENDIX C (Continue)

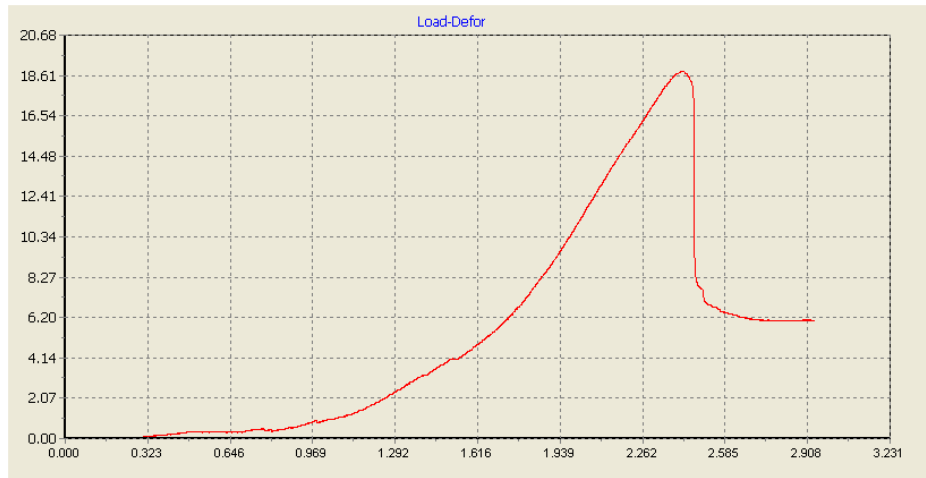


Figure showing the load-deformation relationship of sample A1 in the saturated state

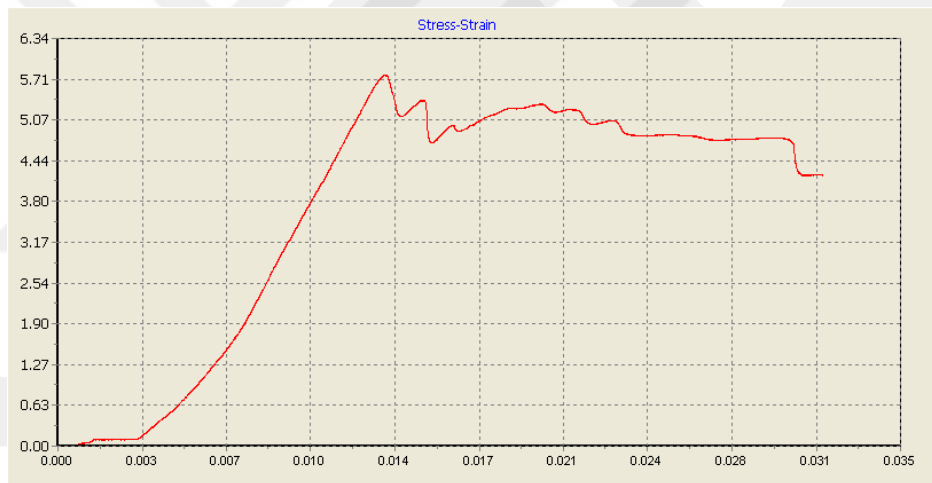


Figure showing the stress-strain relationship of sample A2 in the saturated state

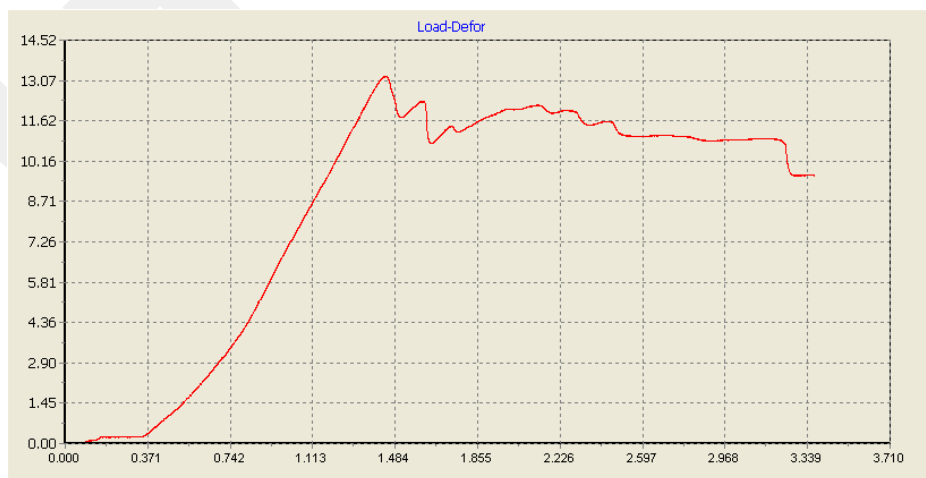


Figure showing the load-deformation relationship of sample A2 in the saturated state

APPENDIX C (Continue)

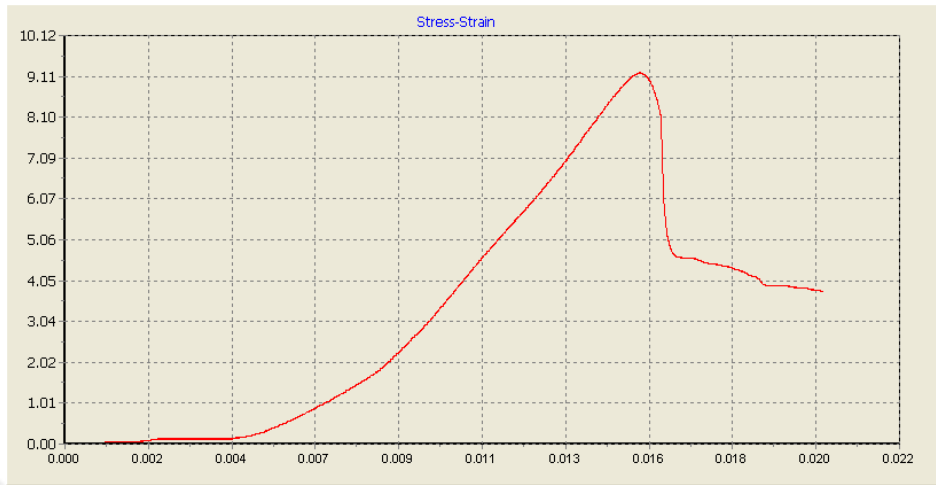


Figure showing the stress-strain relationship of sample A3 in the saturated state

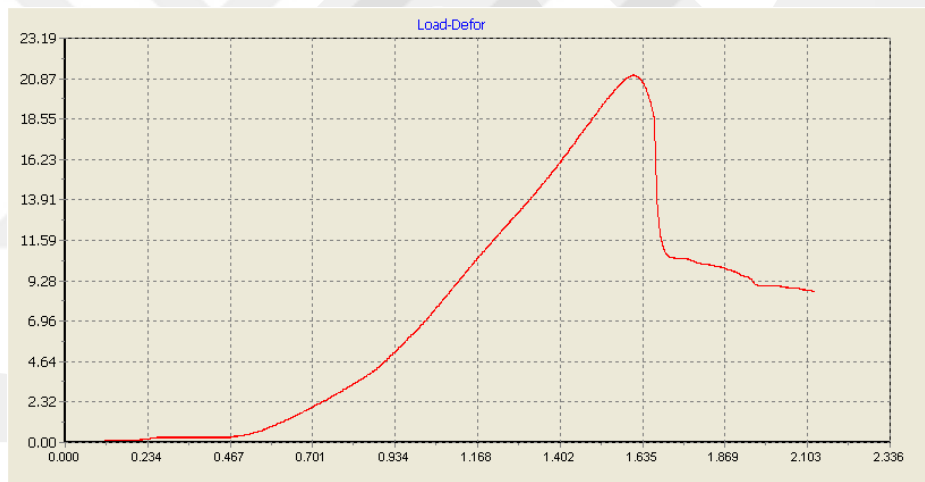


Figure showing the load-deformation relationship of sample A3 in the saturated state

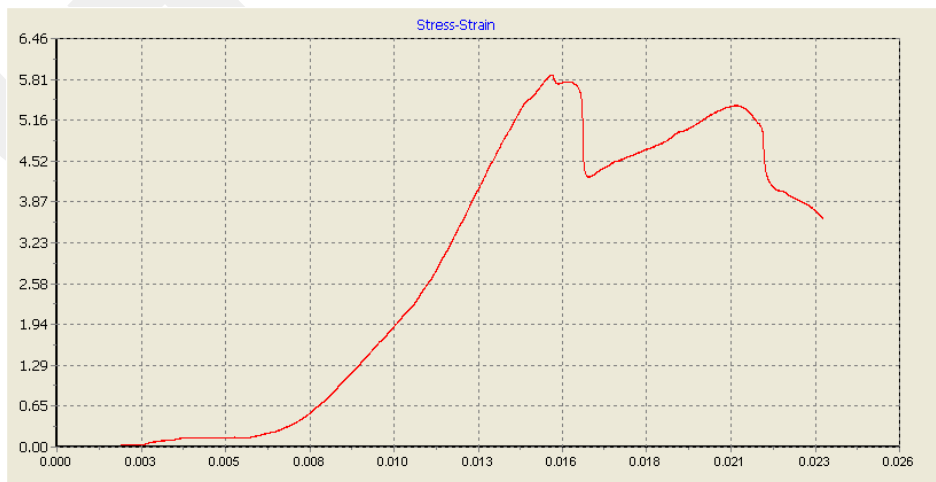


Figure showing the stress-strain relationship of sample A4 in the saturated state

APPENDIX C (Continue)

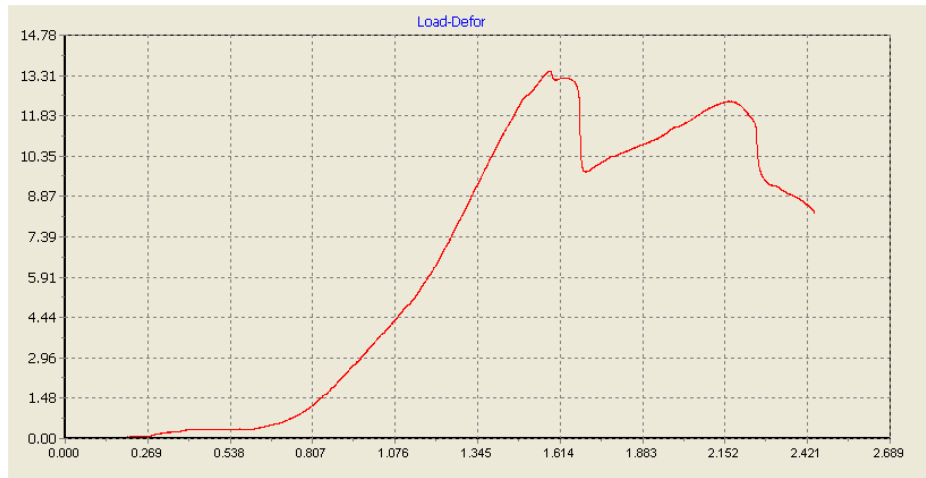


Figure showing the load-deformation relationship of sample A4 in the saturated state

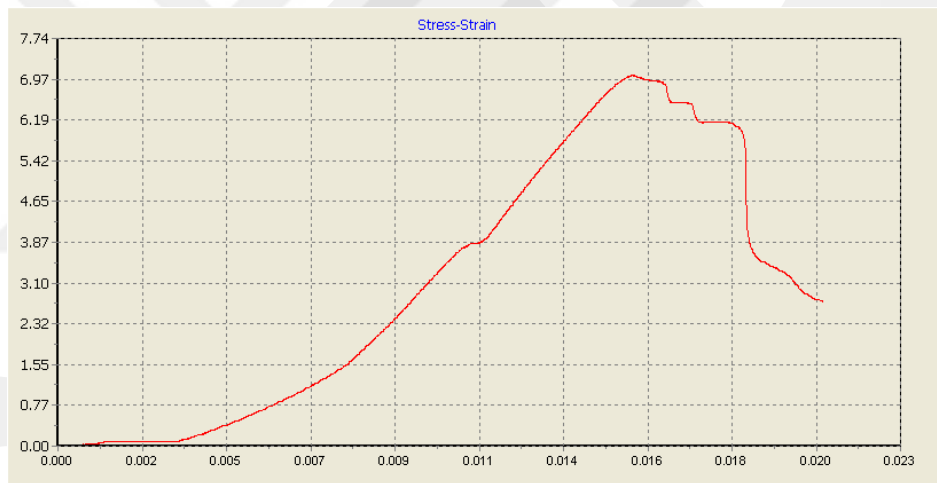


Figure showing the stress-strain relationship of sample A5 in the saturated state

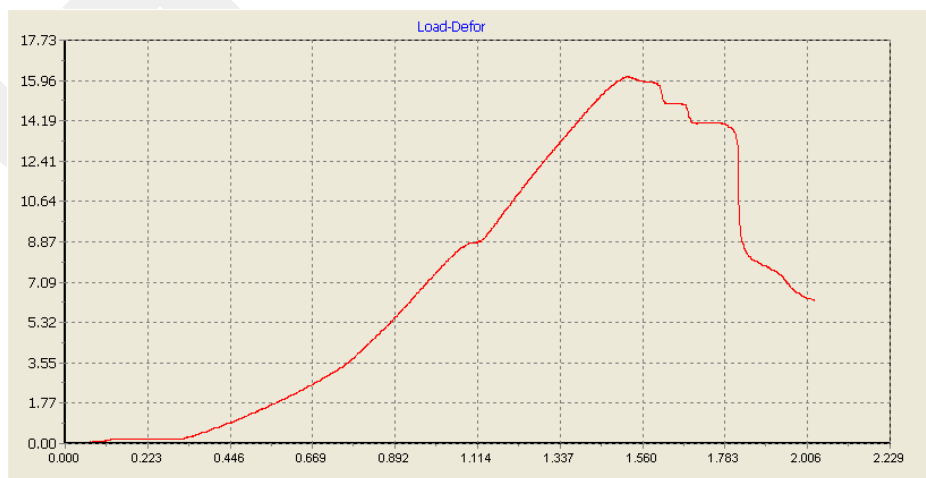


Figure showing the load-deformation relationship of sample A5 in the saturated state

APPENDIX C (Continue)



Figure showing the stress-strain relationship of sample B1 in the saturated state

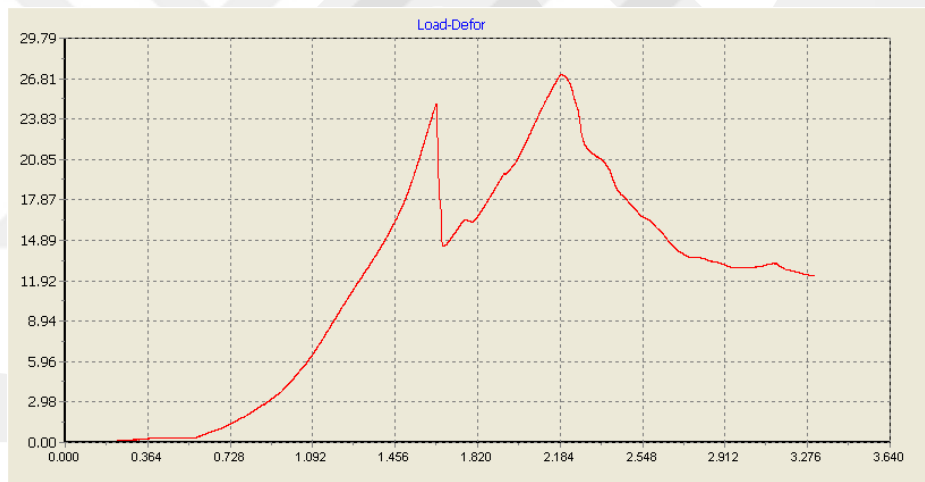


Figure showing the load-deformation relationship of sample B1 in the saturated state



Figure showing the stress-strain relationship of sample B2 in the saturated state

APPENDIX C (Continue)

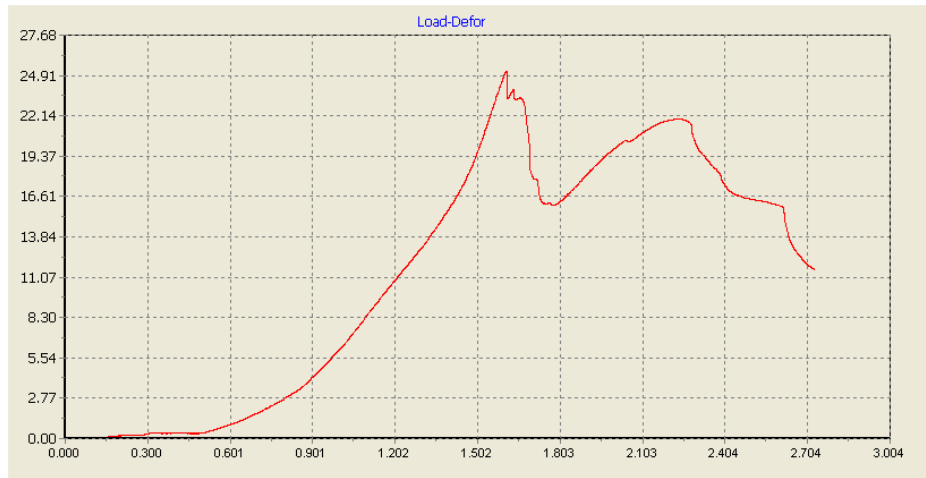


Figure showing the load-deformation relationship of sample B2 in the saturated state



Figure showing the stress-strain relationship of sample B3 in the saturated state

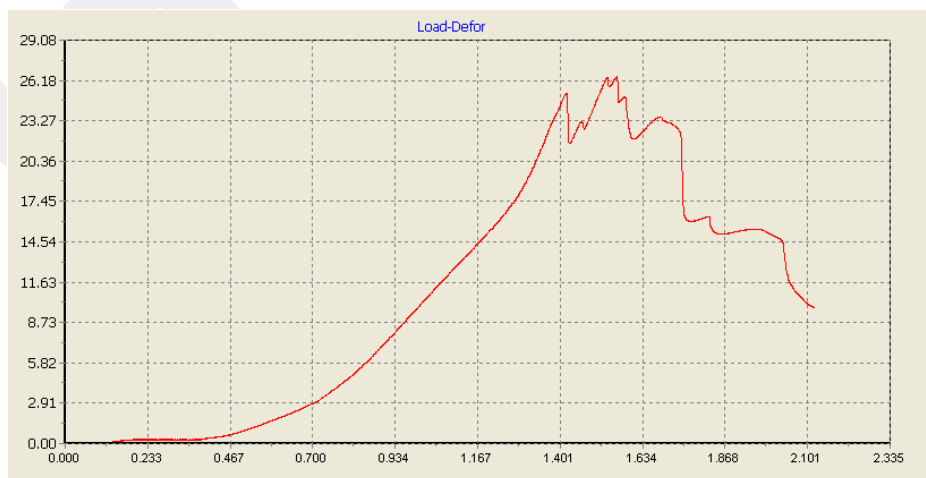


Figure showing the load-deformation relationship of sample B3 in the saturated state

APPENDIX C (Continue)

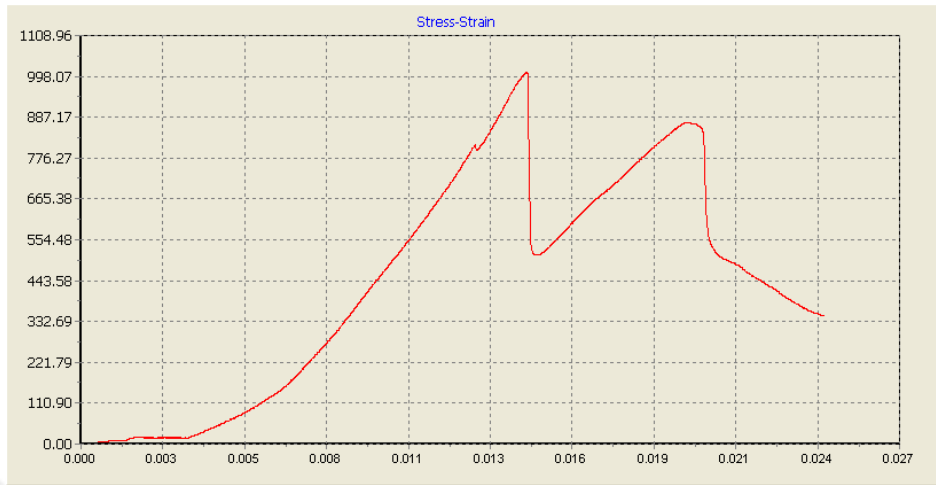


Figure showing the stress-strain relationship of sample B4 in the saturated state

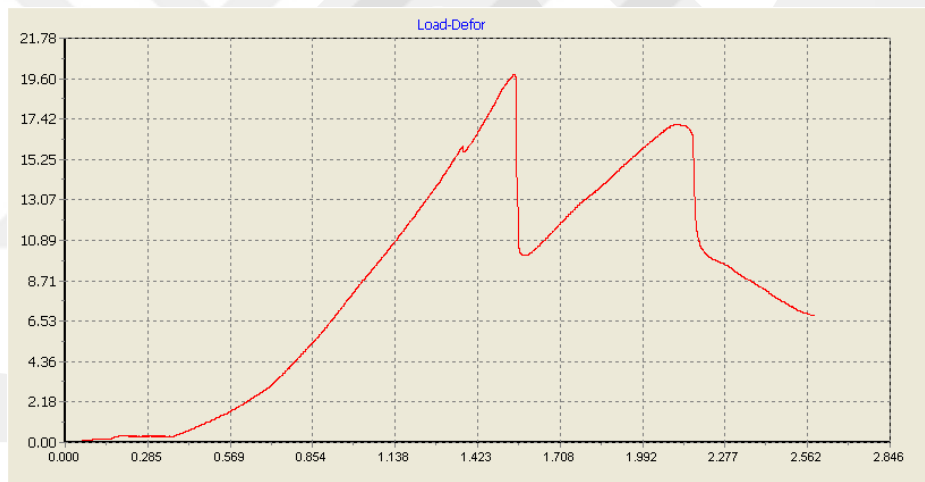


Figure showing the load-deformation relationship of sample B4 in the saturated state

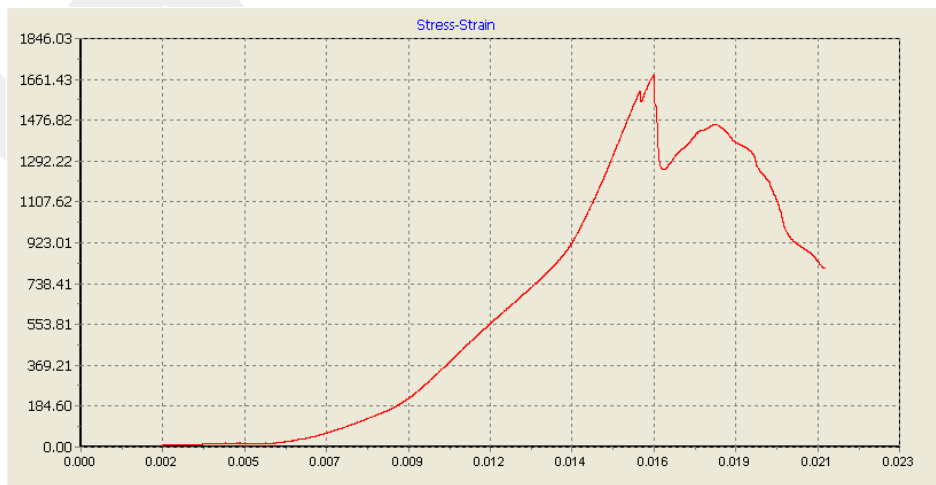


Figure showing the stress-strain relationship of sample B5 in the saturated state

APPENDIX C (Continue)

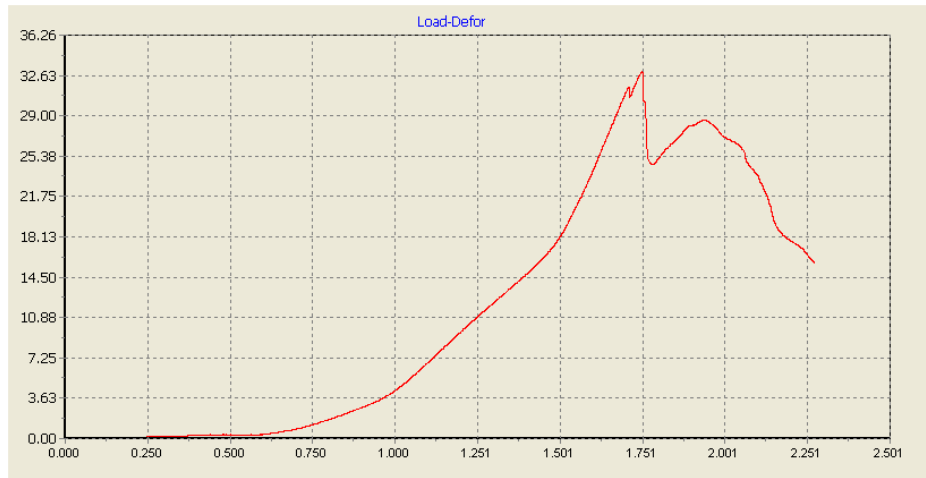


Figure showing the load-deformation relationship of sample B5 in the saturated state

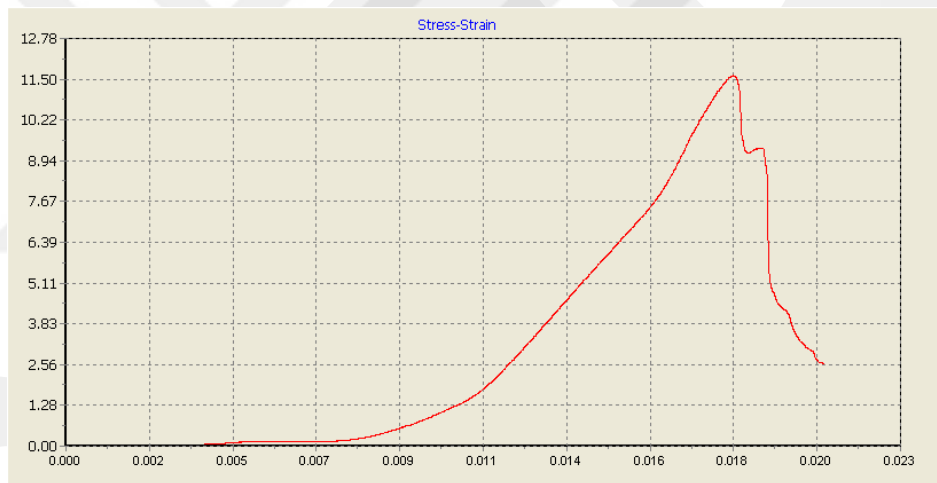


Figure showing the stress-strain relationship of sample C1 in the saturated state

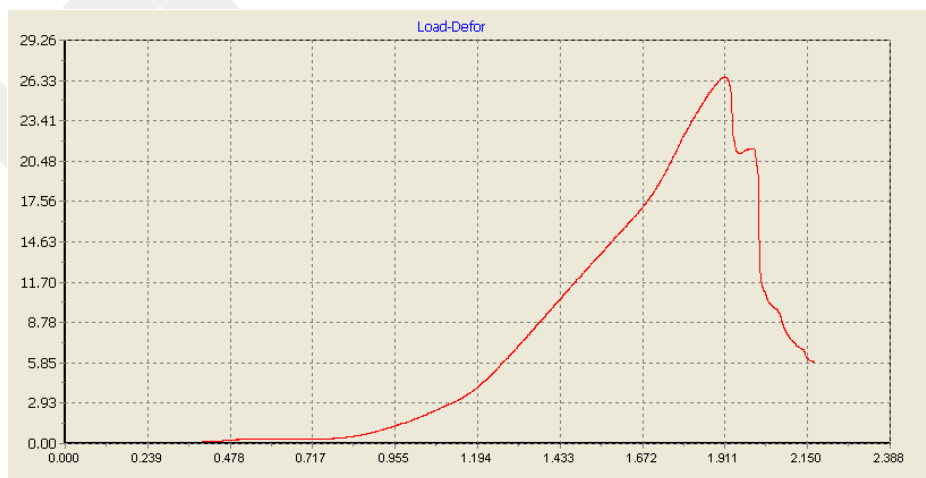


Figure showing the load-deformation relationship of sample C1 in the saturated state

APPENDIX C (Continue)



Figure showing the stress-strain relationship of sample C2 in the saturated state

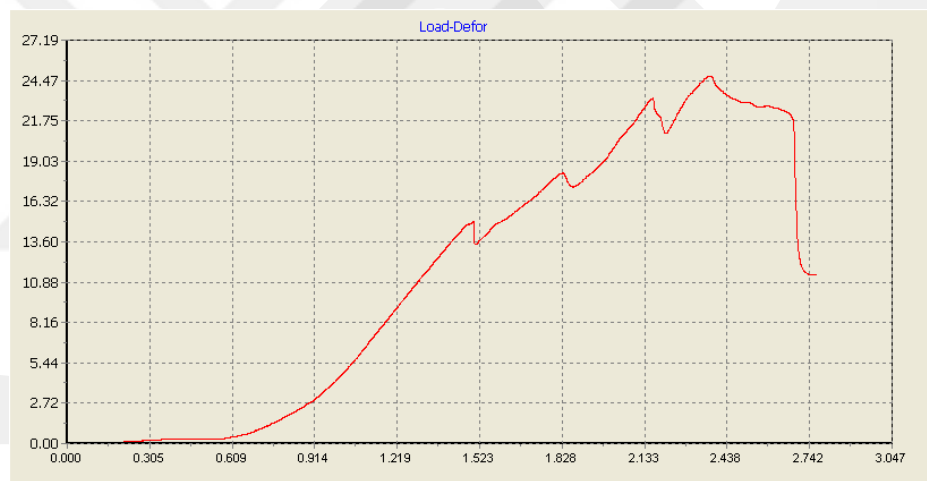


Figure showing the load-deformation relationship of sample C2 in the saturated state

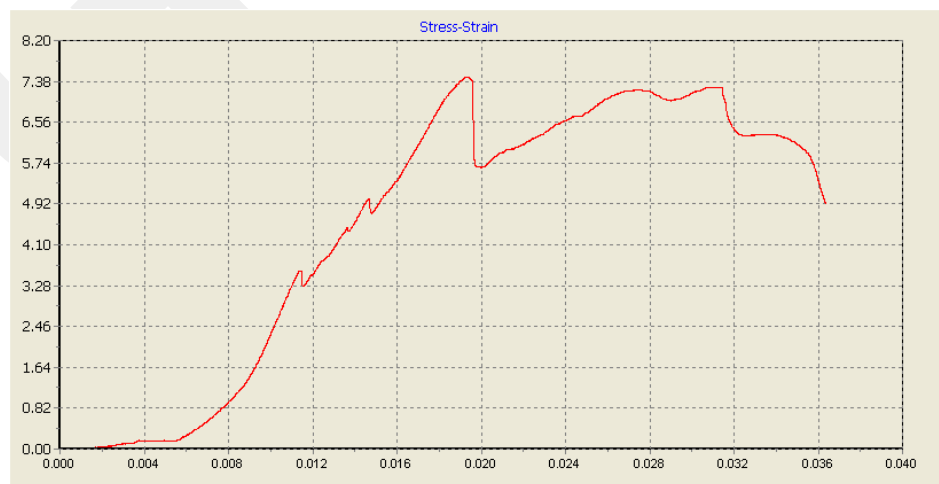


Figure showing the stress-strain relationship of sample C3 in the saturated state

APPENDIX C (Continue)

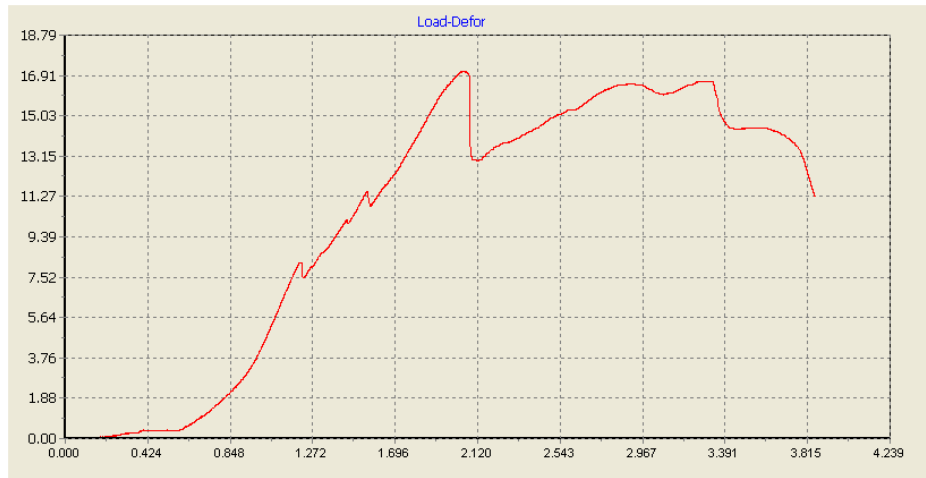


Figure showing the load-deformation relationship of sample C3 in the saturated state



Figure showing the stress-strain relationship of sample C4 in the saturated state

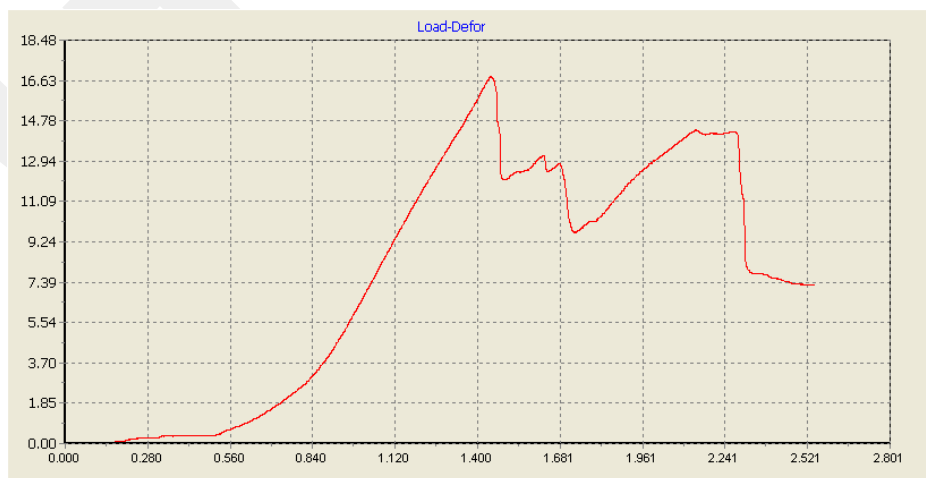


Figure showing the load-deformation relationship of sample C4 in the saturated state

APPENDIX C (Continue)

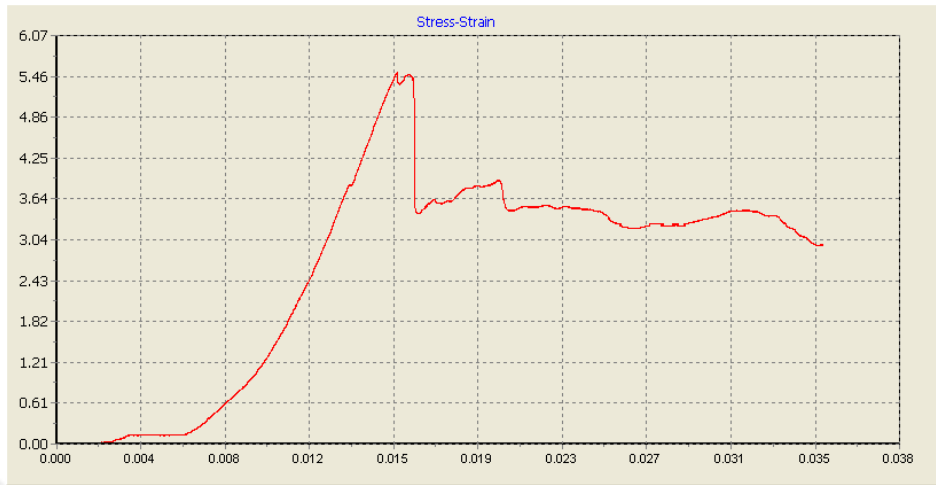


Figure showing the stress-strain relationship of sample C5 in the saturated state

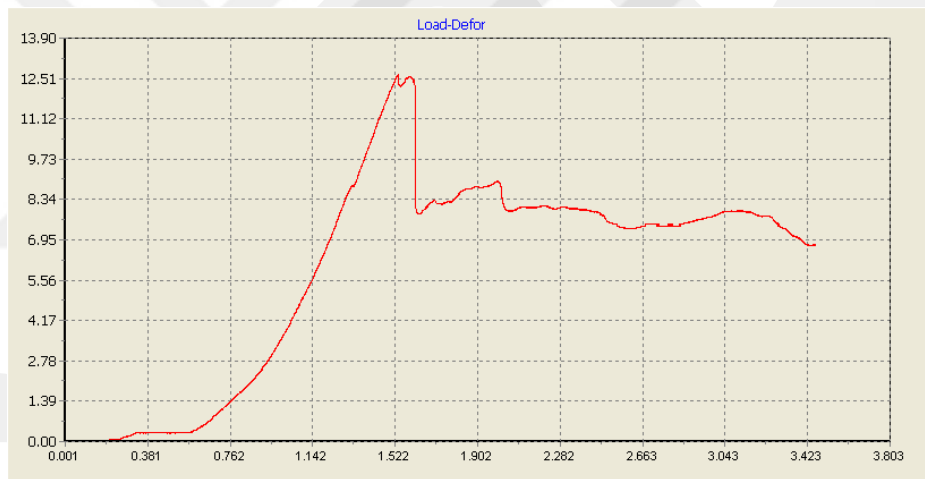


Figure showing the load-deformation relationship of sample C5 in the saturated state