ASSESSMENT OF DURABILITY CRITERIA OF THE ARMOURSTONES USED IN MERSİN AND KUMKUYU HARBOURS BASED ON THEIR SITE AND LABORATORY PERFORMANCES

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ABSTRACT

ASSESSMENT OF DURABILITY CRITERIA OF THE ARMOURSTONES USED IN MERSİN AND KUMKUYU HARBOURS BASED ON THEIR SITE AND LABORATORY PERFORMANCES

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Breakwaters are constructed in coastal areas to protect coastal engineering structures from wave actions. Due to economic reasons, natural stones (armourstone) are very frequently used for the constructions of the breakwaters. Considering the functions of the stones at different zones of the breakwaters, various sizes with variable properties of the armourstones are used in breakwaters. Deterioration of armourstones with time in the form of abrasion and disintegration may end up with the damage of the engineering structures. Therefore, it is necessary to investigate the long-term performance and quality of the armourstones, which should be sound and durable.

In this thesis, the properties of four limestones taken from two quarries with a known site performances as armourstones in Mersin and Kumkuyu harbors are studied .The site performances and durability of the limestones are compared with the field measurements and laboratory works.

For this purpose, the material and mass properties of the limestones are studied. Thus, the information obtained is used to assess long-term durability of the armourstones. The long–term performaces of the Değirmençayı and Tirtar upper level limestones are observed to be good whereas it is rather poor for the Tirtar middle and lower level limestones. Comparison between the predicted and observed durabilities of the armourstones indicated that CIRIA/CUR, RDI_d, RERS, and wet to dry strength ratio give better results based on their field performances. However, the prediction of the durability of the limestones is poor in case RDIs, average pore diameter, and saturation coefficient are used.

Keywords: Armourstone, breakwater, durability, Kumkuyu, Mersin

ÖZ

MERSİN VE KUMKUYU LİMANLARINDA KULLANILAN ANROŞMANLARIN SAHA VE LABORATUVAR PERFORMANSLARI DİKKATE ALINARAK DAYANIKLILIK KRİTERLERİNİN BELİRLENMESİ

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Denizde inşa edilen mühendislik yapılarını dalga etkisinden korumak için dalgakıranlar yapılmaktadır. Ekonomik olması nedeniyle, dalgakıran inşaatlarında doğal kayaçlar (anroşman) sıkça kullanılmaktadır. Anroşmanların dalgakıran tasarımındaki işlevleri dikkate alınarak, çeşitli boy ve özelliklerde olması gerekmektedir. Anroşmanlar da zaman içinde oluşabilecek önemli miktarda aşınma ve parçalanma, mühendislik yapısının zarar görmesine neden olabilmektedir. Bu nedenle, sağlam ve dayanıklı olması istenen anroşmanların kalitesinin belirlenerek kullanılabilirliğinin ve uzun vadeli performansının araştırılması gerekmektedir.

Bu tezde kapsamında, yapımı tamamlanmış olan Mersin ve Kumkuyu limanlarında anroşman olarak kullanılan ve performansı bilinen, ve iki ayrı taş ocağından alınan dört farklı kireçtaşı incelenmiştir. Kireçtaşlarının saha performansı ve dayanıklılığı, arazi ölçümleri ve laboratuvar calışmaları ile karşılaştırılmıştır.

Bu amaçla, kireçtaşlarının malzeme ve kütle özellikleri çalışılmıştır. Elde edilen veriler, anroşmanların uzun vadeli dayanıklılık değerlendirmesi amacıyla kullanılmıştır. Uzun dönem performansları dikkate alındığında, Değirmençayı ve Tirtar üst seviye kireçtaşlarının iyi; Tirtar orta ve alt seviye kireçtaşlarının ise zayıf olduğu gözlenmiştir. Anroşmanların bilinen ile tahmin edilen performansları karşılaştırıldığında, CIRIA/CUR, RDI_d, RERS, ve ıslak-kuru dayanım oranı yöntemleri daha iyi sonuç vermektedir. Buna karşın, arazi performansı dikkate alındığında RDIs, ortalama gözenek çapı ve donma katsayısının tahmini oldukça zayıftır.

Anahtar Sözcükler: Anroşman, dalgakıran, dayanıklılık, Kumkuyu, Mersin

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At the end, thanks God to finish this challenging study. I would like to dedicate this thesis to my mother ,father and my sister and my aunt Nilüfer YEĞİNALTAY for their trust, patience and support on me during my life, but especially to my mother that I will carry her spirit in me, throughout the eternity.

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To my lovely grandmother ;

Kadriye Gülşen **YEĞİNALTAY**

CHAPTER 1

INTRODUCTION

1.1 Purpose and Scope

Rock (stone) has been used as a protector to prevent the erosion, especially caused by hydraulic forces since the coastline structures are developed. Coastal and shoreline structures such as harbors, shipyards, shelters and other beach conservations are subjected to destructive wave movements and severe different environmental conditions during their engineering time. The requirements of coastal and shoreline protection schemes vary widely; they include harbor protection, coastal erosion protection, leisure facilities and beach conservation. All these structures must satisfy the objective at the study area and they must satisfy the local economic constrains. (CIRIA/CUR, 1991).

Breakwaters are structures that are built of quarried rock or stone materials to protect the costal structures from wave attack. Rubble mound breakwaters are one of those civil structures constructed to prevent the coastal features (mainly ports and marine facilities) against the erosive and destructive effects of the offshore-originated wave movements (Ergin et al., 1971). Breakwaters are used to reduce wave energy reaching the beach, and thus reduce sediment transport and the potential for coastal erosion in the back of the breakwaters. Rubble mound breakwaters are made up of mainly four layers of different armourstone cover blocks. Turbulence is generated in voids between adjacent blocks.

By turbulence, the wave energies are dissipated to a considerable level. One desirable feature of breakwaters is that they do not interrupt the clear view of the sea from the beach. This aesthetic feature is important for maintaining the tourist value of many beaches, and it is one of the considerations in using such structures for shoreline protection.

Armourstone consists of stones of different sizes and shapes, which are used in hydraulic protection and regulation structures in breakwaters (CEN, 1996). Due to economic reasons, armourstone (rock armour) is generally used for the construction of the breakwaters. Also, for better interlocking and better stability, armourstone is preferred.

Although, there are other artificial materials such as concrete and asphalt but armourstone is used as a major component in the construction of breakwaters (Smith, 1999). Millions of tons of quarried stone are used each year as a protector all over the world. Rock materials selected for use in a coastal structure are subjected to severe environmental conditions. Especially in stormy days, they can be subjected to very huge and strong waves. For this reason, such materials are required to conform to specific size, shape, and grading criteria by the designers of coastal defense structures and rock properties such as density, strength, resistance to abrasion, porosity and durability for the design.

The durability of armourstone is a very important consideration in the design of rubble mound structures. There may be deterioration in the weight, angularity and integrity of the armourstone. The deterioration of the armourstones with time, in the form of abrasion and disintegration may cause damage to the coastal engineering structures. The base properties of the rock depend on many characteristics such as the strength of the matrix of the rock, the chemical composition of the rock (relative to the environment in which it exists), the existence of weakness planes within the rock and the existence of micro cracks.

In fact, many breakwaters exhibit low durability that would meet the developed criteria. For the selection of the suitable armourstone, the only criterion used in Turkey is a density with 2.2 g/cm^3 value (Topal, 2005). The principal limitation of the standard tests is that they only address the properties of a small sample. They do not address the fact that a final armourstone may contain weakness planes or micro fractures resulting from blasting or handling.

Rubble mound breakwaters were constructed for Mersin and Kumkuyu harbors in the past (Figures 1.1 and 1.2). For the construction of the Mersin harbor, armourstones were obtained from Değirmençayı quarry. However, the stones collected from Tirtar quarry (with 3 different levels) were used for Kumkuyu harbor (Figure 1.3). Some of the stones used in these breakwaters show poor site performances.

The purpose of this study is to determine the properties of the stones taken from the two quarries, and assess the quality and durability of the stones through laboratory tests and field study. The results obtained are compared with their visual site performances in Mersin and Kumkuyu harbors where the same stones were used. The comparison between predicted and observed durability of the armourstones is expected to provide valuable information on the essential parameters (criteria) to be used for the assessment of armourstone durability.

Figure 1.1 A view of armourstones used in Mersin harbor.

Figure 1.2 A view of armourstones used in Kumkuyu harbor.

In order to accomplish this task, extensive laboratory tests and some field studies were performed. The laboratory tests were conducted to assess the behaviour of the potential armourstones under different environmental conditions. They included the tests regarding physico-mechanical properties and durability of the stones. Field studies included detailed discontinuity survey in the quarries.

1.2 Location and Physiography

The whole study area is located in the Mediterranean region. Mersin-Adana transit highway is the major connection line in the study area. The armourstone in the Mersin harbour was taken from a quarry in Değirmençayı with an elevation of 486 m above mean sea level. It is located 15 km north of Mersin city center. However, for the construction of the Kumkuyu harbour, the armourstone was taken from the Tirtar quarry having an elevation of 54 above mean sea level, near Tirtar village. It is located 55 km southwest of Mersin and 20 km northeast of Silifke (Figure 1.3).

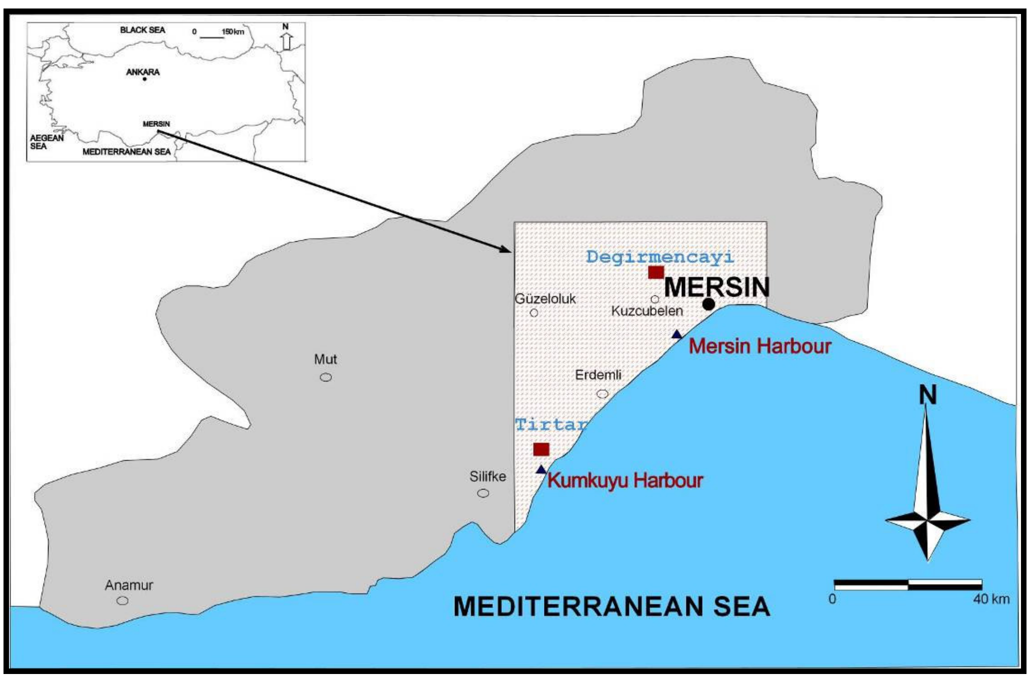


Figure 1.3 Location map of the study area.

Değirmençayı is located within 1/250.000 scale Mersin O 32- b4 topographic map sheet. In the western part of the quarry, Güzeloluk town is located. The study area is accessible from the Mersin-Adana highway with the connection of Aslanköy subsidiary road.

In the study area, there are ore minerals such as chromite, copper and gold as well as construction and road materials such as sandstones, sand, conglomerate and gravel . The undulating and very steep topography in the north parts of the study area decreases tword the coastal line.

Tirtar is located within 1/250.000 scale Mersin P 32- a1 topographic map sheet. In the eastern part of the quarry, it is located between Silifke and Erdemli towns. The quarry is very close to Kumkuyu harbour. This is also the reason why this quarry is selected.

The rivers are flowing throughout the year. Lemon and olive trees are dominant in the study area. They are the most important economical values of the Tirtar village.

1.3 Climate and Vegetation

A typical Mediterranean climate is dominant in the southern Turkey where both quarries are located. Summers are hot and dry, whereas winters are mild and rainy with very high relative humidity. The meteorological data of Mersin for the last five years is given in Table 1.1.

Months	Average Daily Temperature (°C)	Sea Water Temperature (°C)	Average Relative Humidity (%)	Precipitation (mm)	Number of Wet Days
January	11,7	16,4	69	105,3	9
February	12,1	15,1	68	70,6	7
March	13,8	15,8	68	59	10
April	17,3	17,1	71	43,3	9
May	22,7	20,6	74	13,4	4
June	25,3	25,3	77	11,1	2
July	27,4	28,4	77	21	1
August	28,8	29,3	76	3,3	1
September	26,7	27,8	68	11,5	2
October	21,8	24,8	67	66,4	6
November	17,1	21,1	65	92,2	7
December	13,4	17,9	70	149,2	12
Average	**19,8**	**21,6**	**71**	**53,9**	**70**

Table 1.1 Meteorological data of Mersin for the last 5 years (DMİ, 2006)

1.4 Methods of the Study

The study is carried out in five main stages. The first stage begins with the literature survey, including the collection of 1/25.000 scale topographical and geological maps of the study area and its vicinity with published and unpublished reports and papers. Supplementary documents, which cover the corresponding economical, statistical and engineering data, were also gathered.

In the second stage, a reconnaissance field trip performed in the study area. During this stage, the existing documents and data were correlated with the site conditions. In this stage, two potential armourstone sources (quarries) near Kumkuyu and Mersin have been visited.

In the third stage, field studies for detailed discontinuity survey were performed in order to assess the volume and size of the stone blocks in both armourstone sites. Meanwhile, a number of rock samples were taken from both quarries for laboratory studies.

Fourth stage covers both short and long-term laboratory experiments. In this stage, rock samples taken from the field were first prepared for the tests. Then, the samples were undergone into a set of chemical, physical and mechanical tests. For strength related tests, they were performed both in dry and saturated conditions. The properties of the stones determined include effective porosity, unit weight, water absorption, uniaxial compressive strength, point load strength index, Schmidt rebound hardness, sonic velocity, slake durability, methylene blue adsorption, wet-dry, freeze-thaw, Los Angeles abrasion, magnesium and sodium soundness, pore size distribution, impact resistance, modified impact value, 10 percent fines and crushing value of the stones. Mineralogical and petrographical studies were done on thin sections. The results of these studies were classified according to the coastal engineering parameters. At the end of this stage, index laboratory properties of rock amours were identified.

The fifth stage covers the final evaluation of the overall gathered data and durability of the armourstone to assess the quality and suitability of the potential armourstone sources.

1.5 Previous Works

This section gives the previous information about the studies performed in the area. Most of the studies, except a few, are related to the regional geology.

Schmidt (1961) carried out a geological study for the Adana region for the purpose of petroleum exploration. He performed a detailed study about the stratigraphy and structure of the Adana region and defined 47 rock formations.

İlker (1975) had investigated all the formations in the Adana basin from Paleozoic to Quaternary. The main aim of the study was to search the petrolum sources. He pointed out that the Permian rocks with fossils in Paleozoic, Yavça formation in Mesozoic and the thick carbonate column stated through the Mesozoic units were identified.

Özgül et al. (1976) stated that the ages of the rocks in Taurids are between Cambrian and Tertiary. They separated the Taurids into various unions. They indicated that these unions were so long and uncomformable with each other. As a result of their study in the region, they named these units such as Bolkardağı Union, Aladağ Union, Geyikdağı Union, Alanya Union, Bozkır Union and Antalya Union.

Yalçın and Görür (1984) performed a detailed geological study to point out the evaluation of Adana basin. They stated that Quaternary and Tertiary columns were developed during Burdigalian to present time interval. In addition, they pointed out that the evaporate sediments whose ages are between Late Tortonian and Early Messinian were developed in the basin.

Yetiş and Demirkol (1986) prepared 1:25 000 scale geological map of Adana basin, including the study area. They divided the rocks into 17 lithological units, especially six of them were found by them at first. They indicated that the Tertiary units were uncomformable with the Paleozoic and Mesozoic units.

Şenol et al. (1998) prepared geological maps of the study area, at a scale of 1:100.000. They observed that Tertiary and Quaternary units are exposed in the study area.

Gökten (1976) studied the south part of Mersin. He named the rocks with the age of Devonian-Lutetian. He identified the Silifke formation and divided it into Bozoğlan, Medetsiz, and Çamdüzü and İmamlı members. He stated that the youngest rock in the region is Sarıaydın limestone with the age of Tortonian.

Kocyigit (1976) carried out a detailed geological study and described the stratigraphy and structure of the Mersin region. He identified the Mesozoic Ophiolitic Series in the study area.

Gedik et al. (1979) studied the Mut-Silifke-Ermenek basins. They prepared geological maps at a scale of 1:25.000. They investigated the petroleum sources in the Paleozoic and Mesozoic units. They identified Adras formation (Miocene) which is also exposed in the study area and Mut formation (Langhian-Serravallian).

Bilgin et al. (1994) investigated the region between Mut and Silifke, including the study area. They identified Adras formation which is also exposed in the study area, although it is named Göktepe formation by Koçyiğit (1976), Silifke formation by Gökten (1976), and Mut formation by Gedik et al. (1979).

Özbek et al. (2003) studied Miocene limestone, which is used as building stones in and around the province of Mersin was investigated in petrography, block size and variations of the physical and mechanical properties resulting from interactions with seawater in time. The samples tested were mainly taken from Degirmencayı quarry which is also investigated in this thesis. They stated that Miocene limestone is not suitable to be used as rock fill material or building stone because its properties are reduced by interaction with seawater in time.

Özbek et al. (2006) studied the reefal limestone used as a construction material for different projects/buildings around Mersin province. Some of the samples were also taken from Değirmençayı quarry. They stated that the the reefal limestone is attractive as a construction material, although some of the material properties are not so good.

CHAPTER 2

GEOLOGICAL DESCRIPTION OF THE QUARRIES

2.1 Geology of the Değirmençayı Quarry

In Değirmençayı quarry, the rock is beige, thick bedded to massive, moderately weathered near the surface but slightly weathered with below the surface, micritic fossiliferous limestone (Figure 2.1). Under the microscope, locally clayey lenses or veins exist within the rock. Fossil fragments and intraclasts are embedded within calcareous matrix (Figure 2.2).

The limestone also contains solution cavities near the surface. Based on the fossil content, the age of the limestone is indicated to be Early–Middle Miocene (Şenol, et al., 1998). The rock corresponds to the Karaisali formation (Schmidt, 1961; Ilker, 1975; Yalçın and Görür, 1984; Yetiş and Demirkol, 1986).

2.2 Geology of the Tirtar Quarry

In Tirtar quarry, there are three limestone levels (Figure 2.3). They are named such as Tirtar upper level limestone, Tirtar middle level limestone and Tirtar lower level limestone.

Bilgin et al. (1994) indicated that the age of the limestone exposed in the quarry is Middle Miocene based on the fossil content. It corresponds to the Adras formation based on the mineralogical and petrographical characteristics (Gedik et al., 1979).

Figure 2.1 A view from the armourstone quarry in the Değirmençayı area.

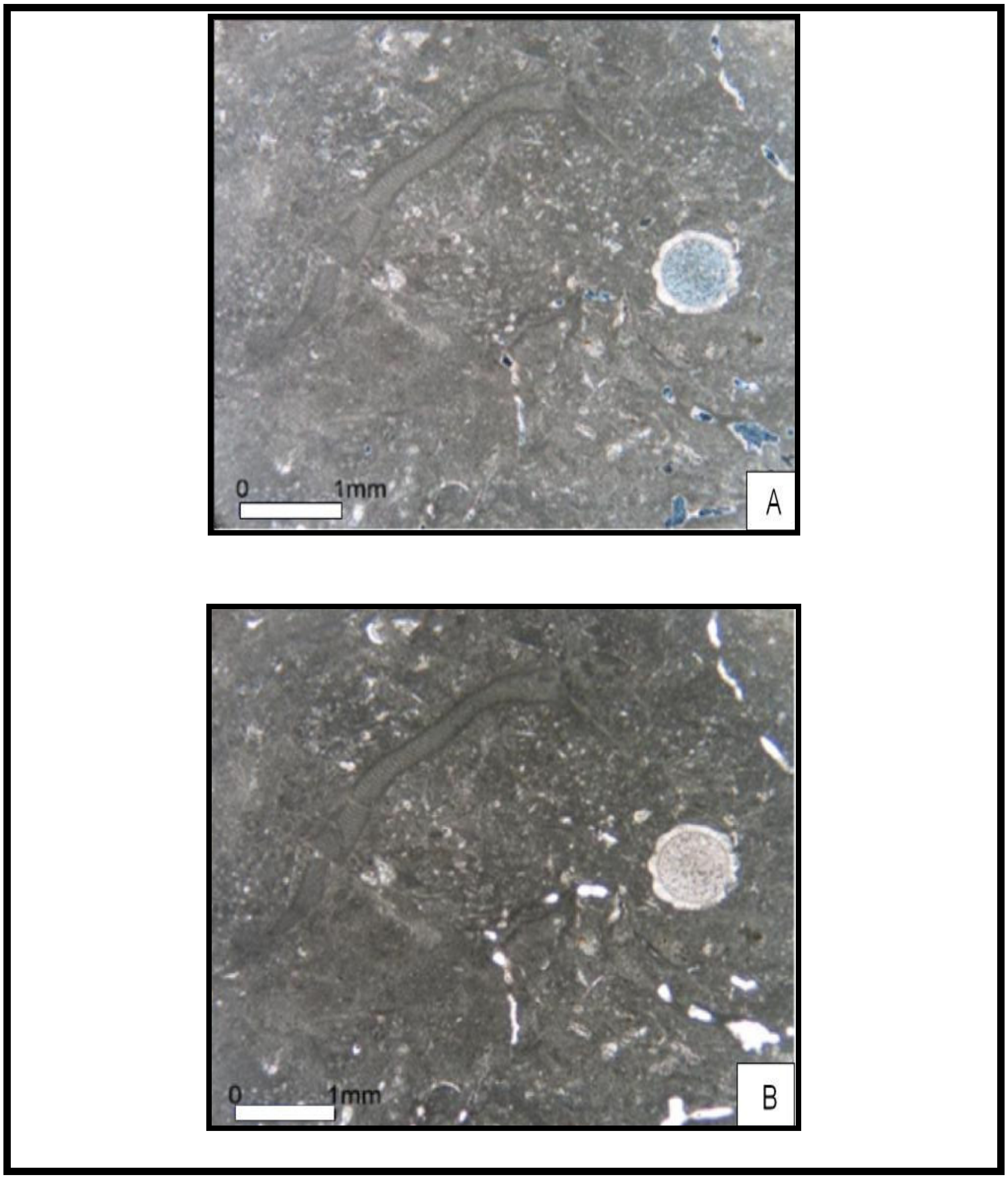


Figure 2.2 Photomicrographs of the Değirmençayı limestone (A) Plaine polarized light (PPL)x5, (B) Cross polarized light (CPL)x5

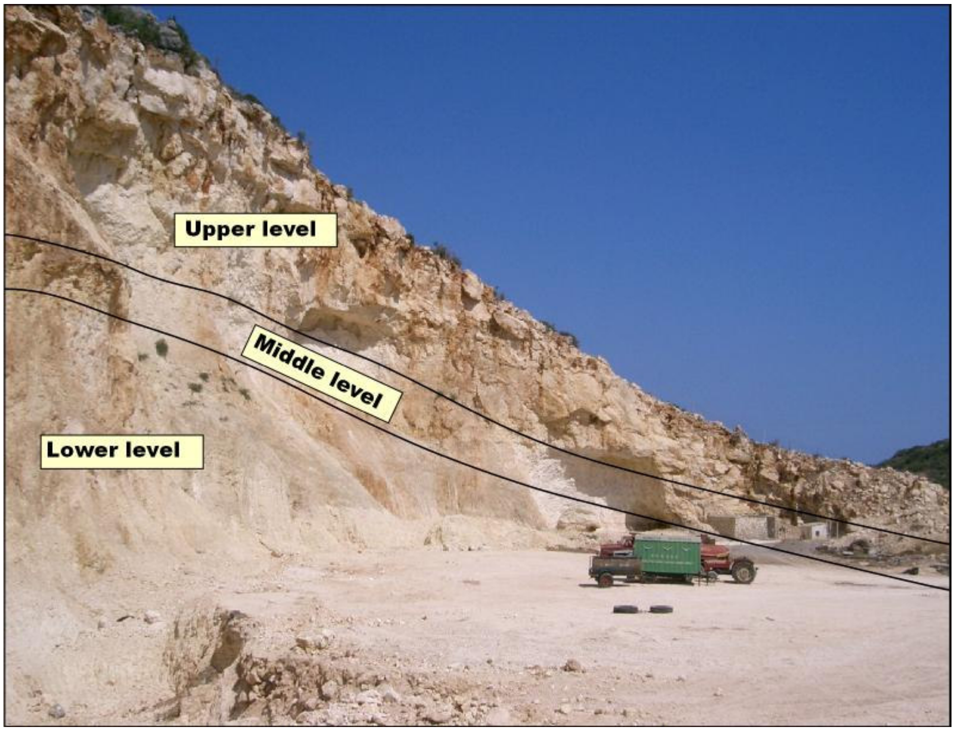


Figure 2.3 Photograph of the armourstone quarry in Tirtar area.

Upper level of the quarry includes light brown, fine grained, thick bedded, slightly weathered, microsparitic-sparitic fossiliferous limestone containing oolite, pisolite and other fossil fragments (Figure 2.4).

These fragments are embedded in sparitic calcareous matrix. The limestone contains local solution cavities for the upper 1-2m of the quarry. No dissolution effect can be observed below this level. The total thickness of the upper limestone level ranges between 4-6 m.

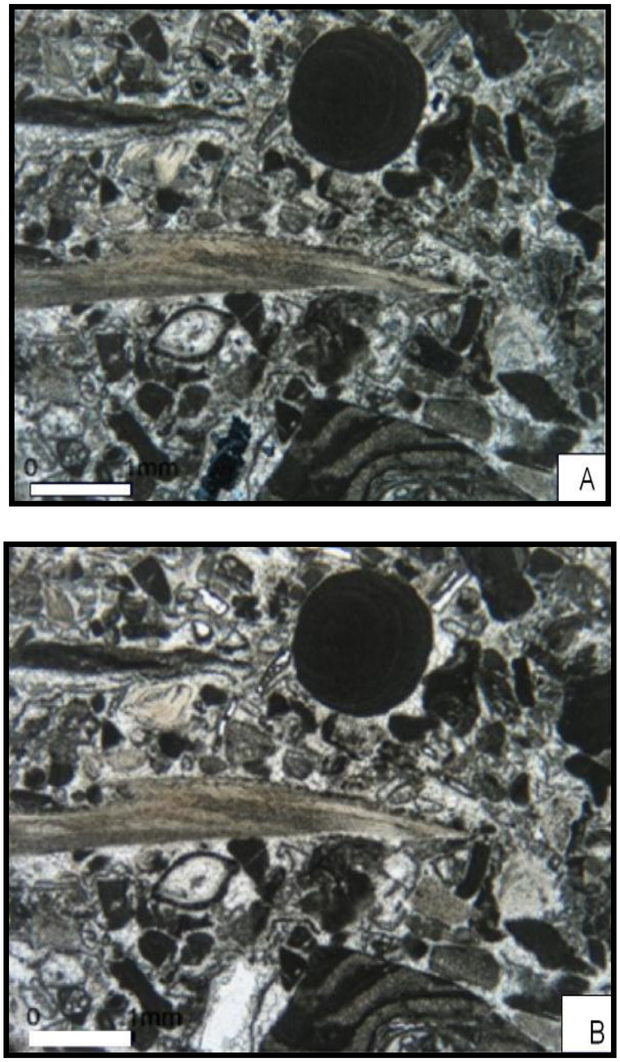


Figure 2.4 Photomicrographs of the Tirtar upper level limestone (A) Plaine polarized light (PPL)x5, (B) Cross polarized light (CPL)x5

The middle level limestone is weaker than the upper level limestone but stronger than the lower level limestone. The middle level limestone is beige to light brown. This limestone is classified as biomicritic limestone. Microsparitic-sparitic limestone contains nummulites within the calcareous matrix. In limestone, there are solutions holes in microscale filling with recrystalline sparitic matrix (Figure 2.5). It also includes fewer amounts of oolite. The cement in the limestone is formed by sparitic calcite.

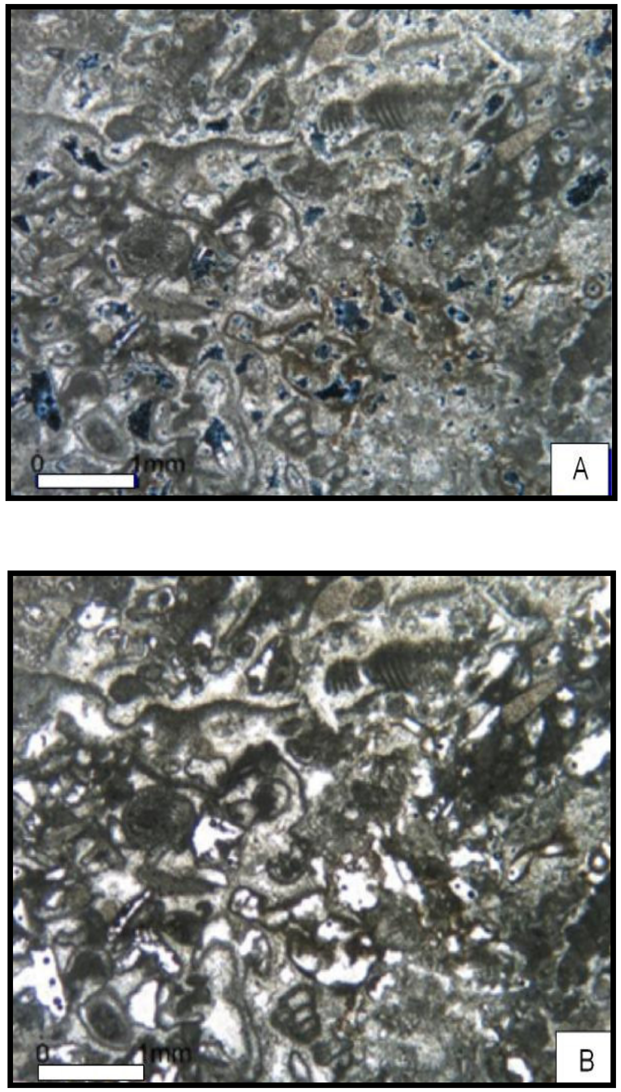


Figure 2.5 Photomicrographs of the Tirtar middle level limestone (A) Plaine polarized light (PPL)x5, (B) Cross polarized light (CPL)x5

Although the lower level of the quarry also consists of limestone, it is the weakest level. It is light brown to beige, fine grained, slightly weathered, biomicritic limestone with some fossil fragments. Oolite and pisolite contents at the lower level decrease in the quarry. This unit locally contain clayey matrix (Figure 2.6).

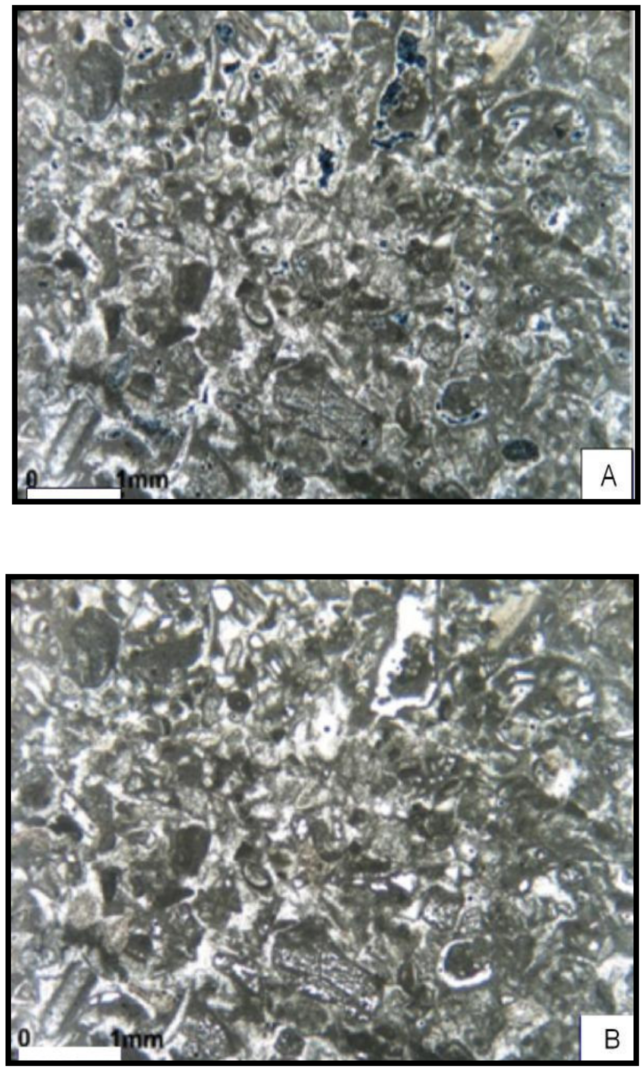


Figure 2.6 Photomicrographs of the Tirtar lower level limestone (A) Plaine polarized light (PPL)x5, (B) Cross polarized light (CPL)x5

CHAPTER 3

ARMOURSTONE

3.1 Armourstone Terminology

Armourstone, according to the definition in the draft European Standard (CEN, 1996), consists of stones of different sizes and shapes which are used in hydraulic protection and regulation structures. They are typically large equant blocks of rocks usually considered to have masses greater than 0.25 tones. The armour layers used on hydraulic structures are composed of these blocks, which are normally laid to maximize interlock among the blocks, and minimize the voids.

Armoring in the context of coastal engineering implies permanent protection to a structure in water. Such armour may consist of blocks of rock or concrete units of the appropriate size if rock is not available. Depending on the design criteria limitations, the rock armour has to be massive enough either to remain static under storm conditions or to assume an eventual stable configuration after an initial period of movement and sorting (i.e. re-profiling) by wave action during the first few periods of major storm activity (Smith, 1999).

Armourstone is mostly selected in breakwaters. Because, using armourstone in breakwater design is an economical and practical solution. They also have adaptable impact on the environment. In breakwater design, constructors select different sizes and grades of armourstones blocks carefully.

Rubble mound breakwaters are made up of mainly four layers of different armourstone covers (Figure 3.1). In this thesis, however, the term "armourstone" is used for all the breakwater layers consisting of natural stones, although this term is also used to define armour layer of the breakwater in some publications (Dibb et al., 1983). Each armourstone layer has a specific uniform weight and dimension (Table 3.1). These layers consist of homogenous equant blocks to form a stable structure (Bradbury et al., 1990). Terminology used for those layers and the corresponding properties are summarized as follows;

1. Primary armourstone: It will be specified by its mass (M) depending on the design requirement, 8-12 tones. It forms the outer protective layer on the structure. Equate block shapes are preferred and usually placed in random arrangement in one or two layers. Blocks must be strong and durable because they will be subjected to very aggressive conditions such as wave attack, wetting and drying. In addition, they should not break into two or more pieces during transportation and placement. Moreover, one disadvantage is that planes of weakness are often difficult to detect in large blocks so intensive care has to be paid.

2. Secondary armourstone: It is used for a support layer for the primary armour. As with the primary armour, turbulence within the voids between blocks in the secondary armour layer helps to absorb the incident wave energies rather than reflecting the waves back. Thus the requirement for mechanical strength, durability and shape will be similar to the primary armourstone. These layers are partly protected by the primary armourstone.The size of the secondary armour blocks can be smaller and it is typically about one tenth of the primary blocks.

3.Filter layers: It lies between the armour layers and the core materials of the breakwater. They are composed of relatively small rock particles and aggregate materials. The filter may be required to contribute to the dissipation of wave energies and will need to be designed to act as a filter preventing the washing out of the core material through the layer.

4. The core: This is the largest part of the structure. It is the inner most layer of the breakwater structure having a material with minimum size and weight. The cores of the great majority of rubble mound breakwaters are composed of rock fill or quarry run material because of their relative cheapness.

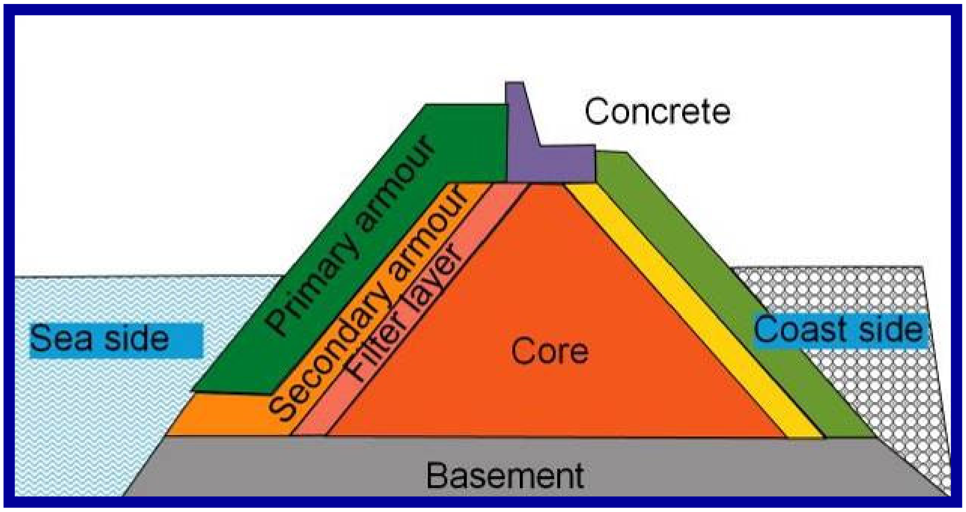


Figure 3.1 Simplified cross section of a rubble mound breakwater.

Typically conventional designs require the primary armourstone, the secondary armourstone and the under layers to be single size, or within narrow size grading. Both the constraints on block size and their geometric shape are carefully specified at the design stage.

Table 3.1 Weight-size relation of rock layers in rubble mound breakwaters (CIRIA/CUR, 1991).

Orientation	Block Weight (tones)	Block Shape (representative cubic form)
Primary armour	**8-10**	**1.5:1.5:1**
Secondary armour	**4-6 , 6-8**	**2:1:1 - 4:1:1**
Filter layer	**2-4**	**2:1:1**
Core material	**0-2**	**-**

However, estimation of the weight of armour blocks can be made from rock density and volume, and is critical to the particular design in that the block mass selected for primary armour will control many other aspects of the design. A number of equations have been proposed for estimating armour weight in a given situation. In concept, these equations relate damage levels to significant wave height, wave period, storm duration, and the relative density and weight of the armourstone for a particular structure. Armourstone block sizes are controlled by the spacing of discontinuities (joints and bedding) in the quarry. The equations clearly indicate the importance of relative density and the block size or weight of the armourstones in resisting damage under wave attack.

3.2 Rock Types

The selection of appropriate rock materials for use in a marine structure, whether from extension of an existing quarry or from the development of a new quarry source, must eventually be made on the detailed assessment of the rock's physical properties and the geological considerations at the quarry. However, a number of generalizations concerning the relevant properties of groups of rocks may be made which are helpful in the initial selection of potential sources. Once particular sources have been identified, it is, of course, essential for them to be investigated in detail, since the state of the rock weathering can give rise to considerable variations in the properties determined by testing. The validity of these generalizations arise as a result of common mineralogy, textures and modes of formation of various groups of rocks, and can rapidly establish a framework of expected properties for different sources of rock materials. We can select rocks from the three broad categories, which are igneous, sedimentary and metamorphic rocks (Table 3.2).

Table 3.2 Generalized evaluation of the use of fresh rock in marine structures (CIRIA/CUR, 1991).

Rock group	Armour Facings	Under layers Filters	Core Fill	Comments
Igneous				
Granite	*	*	*	Good equant shapes. Beware of weathered rock
Gabbro	*	*	*	Good equant shapes. Beware of weathered rock
Fresh rhyolite		*	*	Blocks typically angular, equant but small
Andesite	*	*	*	Block sizes sometimes small Beware of weathered rock
Basalt	*	*	*	Equant blocks sometimes small, Beware of weathered or vesicular rock
Serpentine	*	*	*	Often the blocks are angular and small
Sedimentary				
Pure quarzite	*	*	*	Sometimes poor tabular shapes Abrasion resistance sometimes poor
Sandstone	*	*	*	Sometimes tabular shapes Abrasion resistance sometimes poor
Siltstone			*	Usually tabular and of small size
Shale			*	Small tabular fragments, soft +
Pure limestone	*	*	*	Sometimes tabular ,sometimes soft +
Chalks			*	Soft ,easily eroded
Metamorphic				
Slate			*	Tabular shape, hard has been used as an Armour
Phyllite			*	Elongate shapes, often soft
Schist	*	*	*	Elongate and tabular shapes common
Gneiss	*	*	*	Good equant shapes, hard, beware of weathered rock and micaceous shapes
Marble	*	*	*	Usually good equant shapes

"*" potentially use, "+" when it is necessary to use these materials, consideration should be given to design options using geotextiles

Those supplying rock for coastal and shoreline structures should be capable of producing large block stone by the appropriate choice of cutting, drilling or blasting technique. Typically, quarry outputs produce excess smaller grading compared to the proportion of armour-sized blocks. The expected properties of the various sources have been evaluated in the general way, the essential walkover survey, detailed site investigation and laboratory-testing programs will establish the actual materials properties of the potential sources. (CIRIA/CUR,1991).

3.3 Functions and Required Properties of Armourstone

It is important to establish the availability and quality of rock materials for a particular site at an early stage when considering design options. The requirement for rock used in marine structures and particularly as armouring to be both strong and durable is quite clear.

In a world survey (Stickland, 1984), 75% of breakwaters were found to be constructed in depths of water which were less than 15 m. Thus, the wave climate and wave directions are important in shoreline engineering design.

However, wave actions are mostly civil engineering subject; we will only check the effects of the water on the rock such as freeze-thaw conditions, wet and dry durability. Other factors of importance will include the density, ground conditions and general climatic conditions of the submarine site, the rock type, rock properties, soil, air, strengths, durability, water, weathering grade, etc.

It can easily be concluded that physical and environmental factors are effective on the breakwaters design. These factors will vary from location to location and from structure to structure. The physical factors may show different variation for different parts of a single structure.

Thus, the evaluations of all the physical and environmental factors are very important during project planning and design. Consequently, a well-designed breakwater has to fit for the purpose; it has to be durable during its design life; it has to have an acceptable impact on the local environment. Rock is very commonly used as the major, and in some cases, it is the only, construction material for such structures.

Thus, the rock properties are very important in the design stage. The extraction, handling and placing of rock are also important implications of the design objectives. The rock must be able to withstand rapidly fluctuating and severe hydraulic pressure changes, impact due to movement, abrasion and attrition, wetting and drying, thermal cycling, and possibly freezing/thawing, salt and solution damage. Therefore, the most important requirement of rock blocks used as armour is stability against wave action. Thus, while selecting the armourstone; we have to select durable and strong rocks.

CHAPTER 4

ENGINEERING GEOLOGICAL PROPERTIES OF THE ARMOURSTONES USED IN TWO HARBOURS

It is important to establish the availability and quality of rock materials for a particular site at an early stage. Therefore, to find out its suitability and durability in our design, engineering geological properties have to be known. Evaluation of the engineering geological properties of the limestones is based on the field observations and laboratory tests. For the laboratory tests, 50 block samples from Tirtar quarry, 30 block samples from Değirmençayı quarry were taken and cubic samples with 5cm x 5cm dimensions were prepared from those block samples.

The four limestones observed in the two quarries were used for the construction of the breakwaters. The index properties of the rocks were determined through laboratory tests. They included the determination of dry and saturated unit weights, effective porosity, water absorption, saturation coefficient, methylene blue adsorption, wet-dry resistance, freeze-thaw resistance, magnesium sulphate soundness, micro-deval abrasion, Los Angeles abrasion loss, slake durability index, point load strength index, fracture toughness, sonic velocity and dry and saturated uniaxial compressive strengths, aggregate impact, aggregate crushing and 10 % fines value.

The laboratory tests were carried out at the Engineering Geology Laboratory of the Department of Geological Engineering (METU). They were performed according to ISRM (1981), RILEM (1980), TS699 (1987) and TS EN1097-1 (2002). The field observations involved the assessment of the rock mass properties such as discontinuity characteristics and the weathering grade. The description of rock material and mass characteristics is based on Anon (1977), BSI (1981) and ISRM (1981).

The tests were applied to four limestones, namely Değirmençayı limestone, Tirtar upper-middle and lower limestones (three levels). The average test results values are presented within the text.

4.1 Material Properties of the Armourstone

In Değirmençayı quarry, the rock is beige, thick bedded to massive, slightly weathered (Figure 4.1). Under the microscope, locally clayey lenses or veins are observed within the rock. The limestone also contains solution cavities near the surface. Petrographic examination of the limestone in and around the province of Mersin revealed that intraparticle voids have been filled by clay matrix. The samples are described as intraclast biomicrit and wackestone-packstone (Özbek et.al, 2003).

In Tirtar quarry, there are three limestone levels. The upper level of the quarry is light brown; fine grained, thick bedded, slightly weathered (Figure 4.2). The limestone contains local solution cavities for the upper 1-2 m of the quarry. No dissolution effect can be observed below this level. The total thickness of the upper limestone level ranges between 4 m and 6 m.

The middle level limestone is beige to light brown. It is also fine grained. It is microsparitic-sparitic limestone containing nummilites in the carbonate calcareous matrix.

Although the lower level of the quarry also consists of limestone, it is weaker than the upper level. It is light brown to beige, fine grained, slightly weathered, biomicritic limestone with some fossil fragments. Mainly it contains oolite and pisolite in sparitic calcite matrix with light yellowish beige fresh surface color.

Figure 4.1 General view (A) of the Değirmençayı quarry and (B) close-up view of the Değirmençayı limestone.

Figure 4.2 General view (A) of Tirtar quarry, (B) close-up view of the Tirtar upper level, (C) close-up view of the Tirtar middle level and (D) close-up view of the Tirtar lower level limestone.

4.1.1 Effective Porosity and Unit Weight

Effective porosity and unit weight are the two basic and important index properties of the intact rock. Presence of the pores in the fabric of a rock material decreases its strength, and increases its deformability. The pore also affects the unit weight. They can be determined by the same tests. Effective porosity, dry and saturated unit weight of the Değirmençayı and Tirtar limestones were determined by using saturation and buoyancy techniques according to ISRM (1981). For these test; 180 Değirmençayı limestone samples, 155 Tirtar limestone samples from the upper level, 40 Tirtar limestone samples from the middle level, and 110 Tirtar limestone samples from the lower level were used.

Based on the measurements, the average effective porosity, dry and saturated unit weights of the measurements are also shown in Table 4.1.

Table 4.1 Average effective porosity and unit weight values of the limestones.

Sample Name	The average effective porosity (%)	Engineering Classification for unit weight ANON (1979)	Dry unit Weight (kN/m^3)	Engineering Classification for dry unit weight ANON (1979)	Saturated unit Weight (kN/ m^3)	Engineering Classification for saturated unit weight ANON (1979)
Değirmençayı limestone	9.62	Medium	23.71	Moderate	24.65	Moderate
Tirtar upper level limestone	4.87	Low	25.90	High	26.38	High
Tirtar middle level limestone	13.16	Medium	21.74	Moderate	23.03	Moderate
Tirtar lower level limestone	14.54	Medium	22.64	Moderate	24.07	Moderate

According to Anon (1979), the Değirmençayı limestone is considered as having medium porosity and moderate unit weight in dry and saturated state. However, the Tirtar upper level limestone has low porosity and high unit weight;

the middle level has medium porosity and moderate unit weight; and the lower level has medium porosity and moderate unit weight in dry and saturated state.

4.1.2 Water Absorption under Atmospheric Pressure

This test is intended to measure the amount of water absorbed by a rock under atmospheric pressure and expressed in percentage. The tests were performed according to TS699 (1987) and BSI (1975). The averages are given in Table 4.2.

Table 4.2 Average water absorption values of the limestones under atmospherc pressure.

Sample Name	Water absorption by weight (%)	Water absorption by volume (%)
Değirmençayı limestone	3.31	7.59
Tirtar upper level limestone	1.38	3.54
Tirtar middle level limestone	4.77	10.44
Tirtar lower level limestone	5.58	12.38

4.1.3 Water Absorption under Pressure

This test is also intended to measure the amount of water absorbed within the rock and expressed in percentage. The water is absorbed by rock under certain vacuum pressure.

Water absorption under pressure test was performed according to ISRM (1981) on the same samples used for the water absorption under atmospheric pressure test. During the tests, the water absorption percentages by weight and volume were determined. The average water absorptions results are given in Table 4.3.

Based on the test results, it can be stated that the Değirmençayı and Tirtar upper level limestone have considerably low water absorption under pressure compared to that of the Tirtar middle level and Tirtar lower level limestone. In addition, by using the water absorption under atmospheric pressure and pressure data, saturation coefficient is calculated (see Table 4.3).

Table 4.3 Average water absorption values of the limestones under pressure.

Sample Name	Water absorption by weight (%)	Water absorption by volume (%)	Saturation coefficient-weight	Saturation coefficient-volume
Değirmençayı limestone	4.13	9.62	0.82	0.81
Tirtar upper level limestone	1.88	4.87	0.74	0.73
Tirtar middle level limestone	6.02	13.16	0.79	0.78
Tirtar lower level limestone	6.43	14.56	0.97	0.95

4.1.4 Uniaxial Compressive Strength

The Uniaxial compressive strength (UCS) test is mainly used for the strength classification and characterization of an intact rock (ISRM, 1981). Cubic samples (5cm x 5cm in size) are used for the test. Length to diameter ratio D/L) of the samples was 1. During the tests, a motorized hydraulic compression machine with a loading capacity of 1500 kN was used. The pace rate of hydraulic compression machine was so adjusted that failure takes place in about 5 minutes.

The tests were carried out on 10 dry and 10 saturated samples (20 in total) of each potential armourstone. The average dry and saturated UCS values of the are given in Tables 4.4 and 4.5 .

According to ISRM (1981), the Değirmençayı and the Tirtar upper level limestones are moderately strong in both dry and saturated state. The Tirtar middle level limestone is moderately strong in dry sate, but in saturated state its strength is relatively lower than the dry state and it belongs to low strength class. The Tirtar lower level limestone has very low strength in both dry and saturated states**.** The uniaxial compressive strength is always higher in dry state than in saturated state. Moreover, it can be also said that the Değirmençayı and Tirtar upper level limestones have relatively higher strength than the Tirtar lower level limestone. The Tirtar middle level limestone has a strength, which lies between the Tirtar upper level and the Tirtar lower level limestones.

According to ANON (1979), the Değirmençayı limestone, Tirtar upper level limestone and the Tirtar middle level limestone is moderately strong in dry state. However , it is weak strength in saturated state. The Tirtar lower level limestone is weak strength in both dry state and saturated states. (Tables 4.4 and 4.5)

Table 4.4 Average UCS values of the Değirmençayı and Tirtar limestones in dry state.

Sample Name	**# of Samples**	**Dry UCS* (MPa)**	**Engineering Classification**	
			Anon (1979)	**ISRM (1981)**
Değirmençayı limestone	10	35.70	Moderately strong	Moderate
Tirtar upper level limestone	10	32.80	Moderately strong	Moderate
Tirtar middle level limestone	10	21.70	Moderately strong	Moderate
Tirtar lower level limestone	10	14.70	Weak	Low

* UCS- Uniaxial compressive strength

Table 4.5 Average UCS values of the Değirmençayı and Tirtar limestones in saturated state.

Sample Name	**# of Samples**	**Saturated UCS* (MPa)**	Engineering Classification	
			Anon (1979)	ISRM (1981)
Değirmençayı limestone	10	26.90	Moderately strong	Moderate
Tirtar upper level limestone	10	25.25	Moderately strong	Moderate
Tirtar middle level limestone	10	14.60	Weak	Low
Tirtar lower level limestone	10	9.20	Weak	Low

* UCS- Uniaxial compressive strength

4.1.5 Point Load Strength Index

Point load strength test is intended as another index test for the strength classification of rock materials (ISRM, 1985). It may also be used to predict other strength parameters with which it is correlated. In this thesis, 10 block tests in both dry and saturated conditions for each potential armourstone samples were performed in accordance with ISRM (1985). The uncorrected point load strength index (Is) is calculated using the formula,

$Is : P/De^2$ (4.1)

Where,
P is the applied load,
De is the equivalent core diameter, given by:

De^2 : D^2 for diametric test
De^2 : 4A/л for axial, block and lump tests

(A=:W*D) (4.2)

The size corrected point load strength, $Is_{(50)}$, is calculated from Is, using equivalent core diameter method (Brook, 1985). According to this,

$Is_{(50)}$: F*Is. (4.3)
The size correction factor, F, is obtained from the following formula,

$F : (De/50)^{0.45}$ (4.4)

The point load strength test results of the limestones for block tests are given in Table 4.6. Based on the test results, the highest and the lowest values are omitted. The average $Is_{(50)}$ values of thelimestones are given in Table 4.6. According to Broch and Franklin (1972), the values correspond to high-medium strength rock.

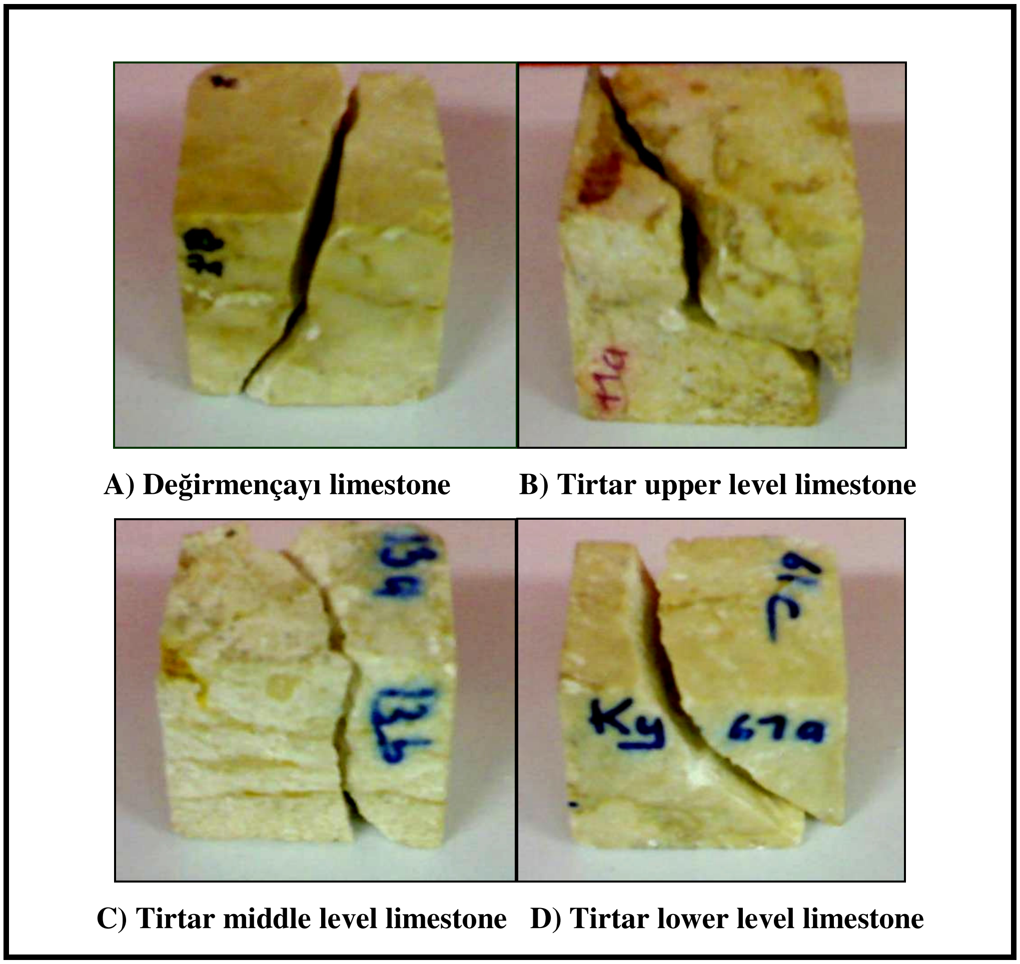
The limestone samples after the point load test is shown in Figure 4.3. The failure occurred along one side of the block.

Table 4.6 Average point load strength indexes of the Değirmençayı and Tirtar limestones.

Sample Name	**# of Samples**	**Dry $Is_{(50)}$* (MPa)**	**Saturated $Is_{(50)}$* (MPa)**	**Engineering Classification Franklin and Broch (1972)**
Değirmençayı Limestone	8	1.86	1.43	High strength
Tirtar upper level limestone	8	1.78	1.40	High strength
Tirtar middle level limestone	8	1.34	0.95	High to medium strength
Tirtar lower level limestone	8	0.94	0.65	Medium strength

* **$Is_{(50)}$** -point load strength index

It is customary to convert $Is_{(50)}$ to an equivalent unconfined compressive strength by multiplying by a correlation factor, k. A wide scatter of k ranging between 8 and 54 is observed in the literature (Broch and Franklin, 1972; Anon, 1972; Bieniawski, 1975; Anon, 1977; Beavis et al., 1982; Foster, 1983; I.S.R.M., 1985; Topal, 2000), although there is a preponderance of values between 16 and 24 (Norbury, 1986). In general, weak rocks like shale and siltstone give low k values whereas strong rocks give high k values. In this study, however, correlation factors ranging from 19.2 to 14.2 are obtained if average $Is_{(50)}$ values are considered for the dry and saturated limestones. These low figures are in good agreement with the correlation factor of the weaker rocks given in the literature (Topal, 2000).



A) Değirmençayı limestone **B) Tirtar upper level limestone**

C) Tirtar middle level limestone **D) Tirtar lower level limestone**

Figure 4.3 The limestones after the point load tests.

4.1.6 Fracture Toughness Test

Fracture toughness test is used for the detailed appraisal of intact rock strength (Dibb et al., 1983; ISRM, 1988). The resistance of the mineral fabric to breakage caused by impact is a strength property that is not sensitive to the possibility of the weakness zones. It relates to the fracture toughness strength to resist new breakages through the mineral or grain fabric, which typically occurs at the corners and edges of blocks when knocked during handling and in service

(Latham, 1998). This test has a great importance for assessing the armourstone quality.

However, the test equipment is not available neither in universities nor in governmental laboratories in Turkey. Therefore, the fracture toughness of the limestones was calculated from the point load strength index data with a suggested correlation factor of 0.209 (Bearman, 1999). The following formula shows the relationship between $Is_{(50)}$ and K_{IC},

K_{IC} : 0.209* $Is_{(50)}$ (4.5)

Where;

K_{IC} : fracture toughness strength

$Is_{(50)}$: point load strength index

Based on the calculations, the assessed dry fracture toughness values of the limestones are given in Table 4.7. According to Table 4.7 , the saturated values are lower than that of the dry ones.

Table 4.7 Average fracture toughness values of the Değirmençayı and Tirtar limestones.

Sample Name	# of Samples	Dry $Is_{(50)}$* (MPa)	Saturated $Is_{(50)}$* (MPa)	Dry $K_{(IC)}$** (MPa)	Saturated $K_{(IC)}$** (MPa)
Değirmençayı limestone	8	1.86	1.43	0.39	0.30
Tirtar upper level limestone	8	1.78	1.40	0.37	0.29
Tirtar middle level limestone	8	1.34	0.95	0.28	0.20
Tirtar lower level limestone	8	0.94	0.65	0.20	0.14

* **$Is_{(50)}$** -point load strength index

** **$K_{(IC)}$** -fracture toughness strength

Based on the test results, the assessed fracture toughness of the limestones decreases relatively from the Değirmençayı limestone to the Tirtar lower level limestone.

4.1.7 Schmidt rebound hardness test

This test is suggested for the rebound hardness determination of rocks by use of Schmidt hammer (ISRM, 1981). The test with L-Type hammer is repeated 20 times on both dry and saturated samples in the laboratory. The Schmidt rebound hardness value is obtained from the average 10 highest measurements. The average Schmidt rebound hardness value of the limestones are given in Table 4.8. The test results reveal that both Değirmençayı and Tirtar limestone are slightly affected from saturation (Table 4.8).

Table 4.8 Schmidt rebound hardness value of the Değirmençayı and Tirtar limestone.

Sample Name	# of Samples	Schmidt rebound hardness dry value	Schmidt rebound hardness saturated value
Değirmençayı limestone	10	61	58
Tirtar upper level limestone	10	52	48
Tirtar middle level limestone	10	49	47
Tirtar lower level limestone	10	43	41

4.1.8 Sonic velocity test

There is a considerable interest in using sonic or ultrasonic sound wave propagation through large rock samples to evaluate the intact strength of the rock and detect incipient flaws. The method is very sensitive to the degree of saturation, and the test specimens require careful preparation.

The sonic velocity test is intended as a method to determine the velocity of propagation of elastic waves in rocks (ISRM, 1981). The test also provides useful information about the degree of fissuring and porosity of a rock material. Potential armourstone cube samples were tested in both dry and saturated states. For the testing, longitudinal (P) velocities were measured by using ultrasonic pulse method. In the pulse method, an impulse is imparted to a specimen and the time for the transient pulse to traverse the length of the specimen is used to calculate the velocity of the waves by the formula ;

$$V = L/t \qquad (4.6)$$

Where,

V : Velocity

L : Distance traversed by the wave

t : Travel time

PUNDIT-PLUS model equipment was used for the sonic velocity measurements. Before the measurements, the end surfaces of the cubic samples were made smooth and flat. A thin film of vaseline was applied to the surface of the transducers (transmitter and receiver). Pulse transmission technique was applied during the test so that the transmitter and receiver were positioned on the opposite end surfaces of the cubic test specimen.

The test results are given in Tale 4.9. Based on the dry sonic velocity test results, Değirmençayı limestone has high sonic velocity, Tirtar upper level has very high sonic velocity. However, Tirtar middle and lower level limestones have Moderate sonic velocities. On the other hand, the saturated sonic velocity values are higher than the dry ones.

Table 4.9 Dry and Saturated sonic velocity values of the Değirmençayı and Tirtar limestone.

Sample Name	# of Samples	Dry sonic velocity (m/sec)	Engineering Classification Anon (1979)	Saturated sonic velocity (m/sec)	Engineering Classification Anon (1979)
Değirmençayı limestone	180	4806.48	High	5219.69	Very high
Tirtar upper level limestone	155	5113.1	Very high	5503.4	Very high
Tirtar middle level limestone	40	4022.2	Moderate	4276.9	High
Tirtar lower level limestone	110	3868.9	Moderate	4287.4	High

4.1.9 Slake durability index test

This test is intended to assess the resistance offered by a rock sample to weakening and disintegration when subjected to two standard cycles of drying and wetting (ISRM, 1981). The samples, each weighting is about 40-60 g, were selected and put into the rotating drums of the apparatus. Two drums, each containing about ten lump samples were used for the test. The drums were rotated for 200 revolutions during a period of 10 minutes for one cycle. The weight loss was determined at the end of each cycle. Average slake durability indexes of the limestones are given in Table 4.10.

According to the Gamble's slake durability classification for one 10-min slake durability cycles given in Goodman (1989), Değirmençayı limestone has high durability, Tirtar upper level limestone and Tirtar middle level limestone have medium high durability, on the other hand Tirtar lower level limestone has high durability. According to the Gamble's slake durability classification for two 10-min slake durability cycles given in Goodman (1989), Değirmençayı limestone, Tirtar upper level limestone have high durability, Tirtar middle level limeston and Tirtar lower level limestone have medium high durability.

Table 4.10 Slake durability indexes of the Değirmençayı and Tirtar limestone.

Sample Name	# of Samples	Weight Loss, (%) 1st cycle	Gamble's Engineering Classification 1st cycle	Weight loss (%) 2nd cycle	Gamble's Engineering Classification 2nd cycle	Weight loss (%) 20 th cycle
Değirmençayı limestone	2	98	High durability	97.1	High durability	82.2
Tirtar upper level limestone	2	97.7	Medium-High durability	97	High durability	88.6
Tirtar middle level limestone	2	96	Medium-High durability	92.9	Medium-High durability	81.6
Tirtar lower level limestone	2	98	High durability	95.6	Medium-High durability	78.4

It is clear that the differences in weight loss cannot be distinguished at the end of the 2 nd cycle. So, the test is repeated for 20 times to evaluate the changes in long-term durability. Based on the test results, the reduction in slake durability index of the Değirmençayı and Tirtar upper level limestone is more at the end of the 6 th slake durability cycle. However, the reduction in slake durability index of the Tirtar middle level limestone and the Tirtar lower level limestone becomes more at the end of the 5 th slake durability cycle. The decrease in weight is rather uniform after 5th cycle (Figure 4.4). It is clear that two-cycle conventional slake durability testing did not appear to offer an acceptable indication of the durability of rocks especially weak rocks when compared with multiple-cyclic wetting and drying as stated by Gökçeoğlu et al., 2000.

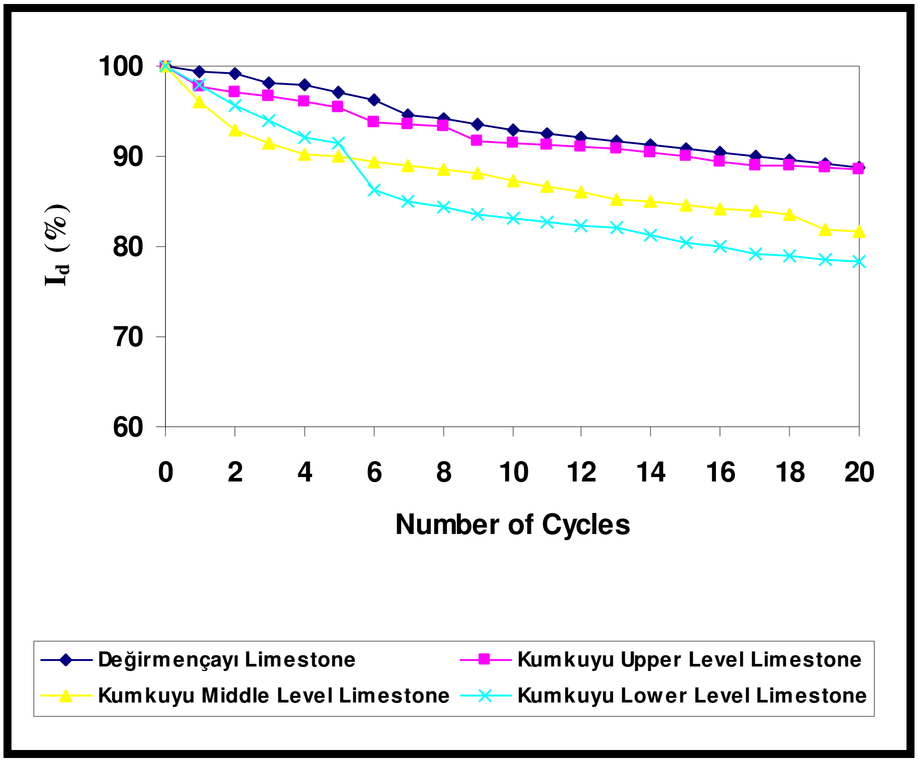


Figure 4.4 The variation of slake durability indexes of the limestones for various test cycles.

4.1.10 Methylene blue test

This test is used to quantify the existence of clay minerals (especially smectite group) which may be present in quarried rock and hence to indicate the soundness of the quarried rock (Stapel and Verhoef, 1989; CIRIA/CUR, 1991; Çokça, 1991; Verhoef, 1992; Topal, 1996).

The methylene blue adsorption test was performed on the limestones to obtain information on the presence of clay minerals in accordance with AFNOR (1980). The test is based on the absorption capacity of methylene blue by the rock material (Stewart and McCullough, 1985).

A certain concentration of methylene blue solution is added in definite volumes to a suspension of each fine-grained rock samples, which are powdered in the laboratory. The methylene blue value (M.B.A.) is calculated through the total amount of methylene blue solution that is adsorbed.

Calculated M.B.A values of the Değirmençayı limestone, Tirtar upper level limestone, Tirtar middle level limestone and Tirtar lower level limestone are 0.30, 0.30, 0.43 and 0.71, respectively. However, there are more clay minerals in the Tirtar lower level limestone rather than the others. The results are given in Table 4.11.

Table 4.11 MBA and CEC values of the Değirmençayı and Tirtar limestones.

Sample Name	**MBA (gr/100 gr)**	**CEC (meq./100g)**
Değirmençayı limestone	0.30	0.68
Tirtar upper level limestone	0.30	0.68
Tirtar middle level limestone	0.43	0.99
Tirtar lower level limestone	0.71	1.61

4.1.11 X-Ray diffraction analyses

The X-ray diffraction (XRD) analyses were carried out on the Degirmencayi limestone and all levels of the Tirtar limestone. This test was performed on one sample from each limestone to assess the abundance of all minerals and the types of clay minerals within the limestones. The samples were powdered to pass through 200-mesh sieve. A RIGAKU diffractometer with CuKα radiation was used for the unoriented samples. The measurements were performed at the General Directorate of Mineral Research and Exploration (M.T.A).

All the XRD results of limestone samples yield similar diffraction patterns. The XRD analyses of the unoriented samples of all samples reveal that there are no remarkable peaks of clay minerals which exist within the limestones. The unoriented XRD analyses indicated mainly calcite mineral (Figure 4.5). Due to the very low clay content, no oriented XRD analyses were performed. In order to calculate the clay content, sedimentation method was used.

The amount of clay minerals (alteration products) of each sample was determined by using a sedimentation method. The sedimentation method is a simple and an effective way of determining the amount of clay mineral percentages of the rocks. In this method, the samples were disintegrated in water and clay fractions were separated by sedimentation (Craig, 1992). The test results are given in Table 4.12. The clay percentages of the Degirmencayi limestone, Tirtar upper level limestone, Tirtar middle level limestone and Tirtar lower level limestone are 0.40 %, 0.49 %, 0.80 % and 0.91 %.

Table 4.12 The average clay content of the samples determined by the sedimentation method.

Sample Name	**Clay fraction (%)**
Değirmençayı limestone	0.40
Tirtar upper level limestone	0.49
Tirtar middle level limestone	0.80
Tirtar lower level limestone	0.91

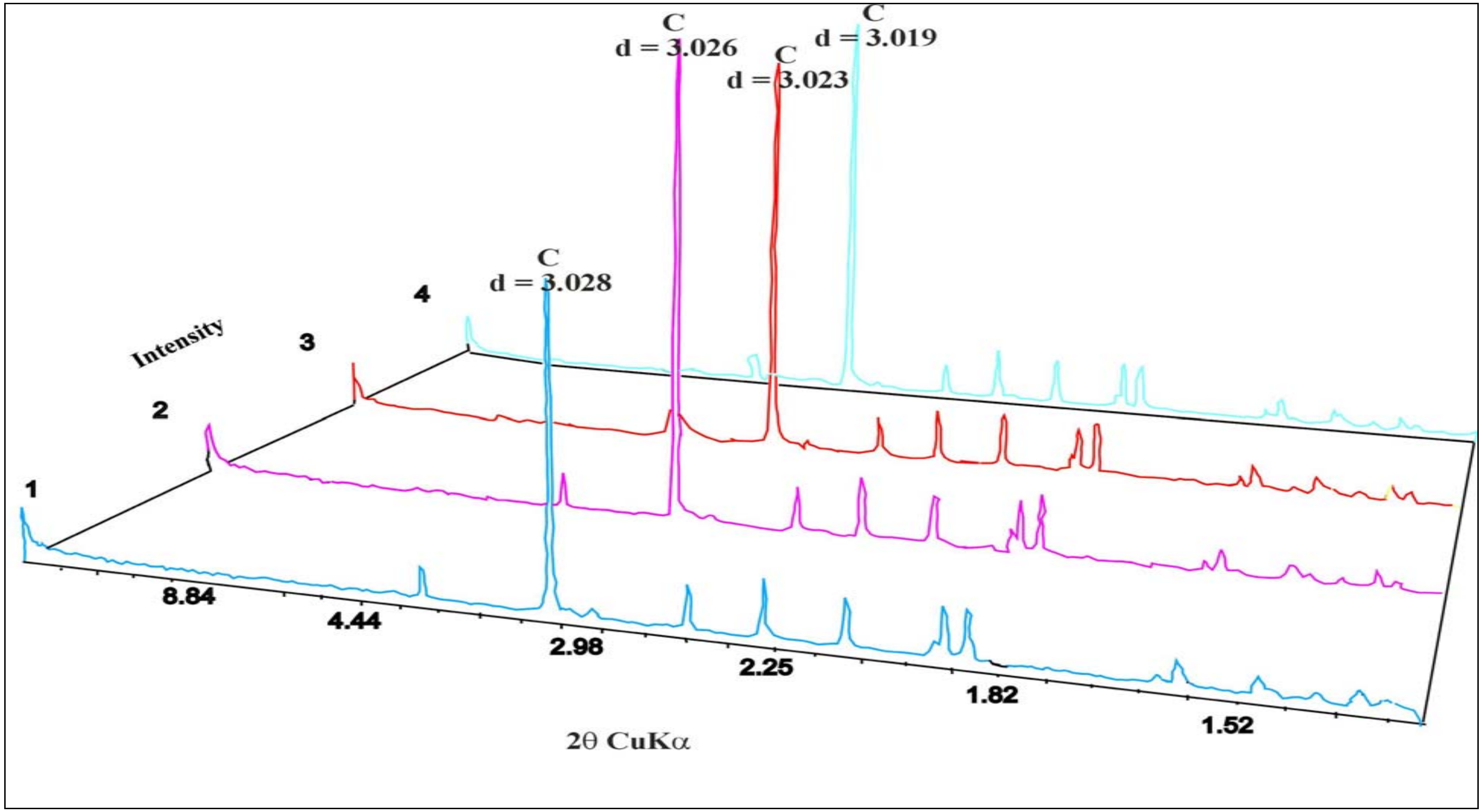


Figure 4.5 The XRD diffractograms of the unoriented samples (C= $CaCO_3$, blue line shows Değirmençayı limestone, pink line shows Tirtar upper level limestone, red line shows Tirtar middle level limestone, turquoise line shows Tirtar lower level limestone.

4.1.11 Wetting – Drying test

Physical weathering essentially breaks down the rock material by application of a series of cyclic stresses. Wetting drying, which is one of these cyclic stresses, leads to the eventual rupture of the rock material (Lienhart and Stansky, 1981; ASTM D5313, 1992). Wetting-drying test is important to understand the performance of armourstone used in marine structures. In this study, the wetting-drying test was performed on cubic samples. These samples were subjected to continuous cycles of submerging into water (6 hours) and heating in oven for 24 hours. At the end of 80 wetting-drying cycles, the total weight loss in terms of the initial sizes was calculated. Based on the test results, the wetting-drying test values of the Değirmençayı limestone, Tirtar upper level limestone, Tirtar middle level limestone and Tirtar lower level limestone, 0.57, 1.48, 2.03 and 5.14, respectively (Table 4.13).

Table 4.13 Wetting- drying loss values of the Degirmencayi and Tirtar limestones.

Sample Name	# of Samples	Weight loss value (%)
Değirmençayı limestone	8	0.57
Tirtar upper level limestone	8	1.48
Tirtar middle level limestone	8	2.03
Tirtar lower level limestone	8	5.14

The dry unit weight, saturated unit weight, effective porosity, weight, water absorption under atmospheric pressure, water absorption under pressure, sonic velocity and uniaxial compressive strength (UCS) of the samples were also recorded at 20, 40, 60, 70, 80 wetting-drying test cycles and compared with those of the fresh samples. Tables 4.14, 4.15, 4.16 and 4.17 show normalized average values of the limestones after wetting-drying test cycles.

Table 4.14 Normalized average physical and mechanical properties of the Değirmençayı limestone after the wetting-drying tests.

Number of Cycle	Weight (%)	Porosity (%)	Dry Unit Weight (%)	Saturated Unit Weight (%)	Water abs. (atm. pressure) (%)	Water abs. (pressure) (%)	Sonic Velocity (%)	UCS (%)
0	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
20	99.93	101.34	99.85	99.88	101.59	100.40	95.83	94.63
40	99.84	103.42	99.84	99.91	103.48	101.48	94.67	92.49
60	99.74	103.53	99.66	99.73	103.84	102.69	93.75	88.51
70	99.68	103.95	99.62	99.71	104.29	103.46	92.87	86.46
80	99.43	104.98	99.16	99.35	104.98	105.74	91.31	83.08

Table 4.15 Normalized average physical and mechanical properties of the Tirtar upper level limestone after the wetting-drying tests.

Number of Cycle	Weight (%)	Porosity (%)	Dry Unit Weight (%)	Saturated Unit Weight (%)	Water abs. (atm. pressure) (%)	Water abs. (pressure) (%)	Sonic Velocity (%)	UCS (%)
0	100.00	100.00	100,00	100.00	100.00	100.00	100,00	100.00
20	99.88	100.35	99.31	99.33	100.53	100.93	96,49	89.07
40	99.40	104.61	98.71	98.80	104.55	105.76	94,14	88.79
60	99.05	105.84	98.85	98.96	104.97	106.70	92,36	86.85
70	98.74	106.27	98.42	98.53	105.15	106.97	91,50	84.18
80	98.52	106.82	97.92	98.05	107.91	108.83	90,98	75.84

Table 4.16 Normalized average physical and mechanical properties of the Tirtar middle level limestone after the wetting-drying tests.

Number of Cycle	Weight (%)	Porosity (%)	Dry Unit Weight (%)	Saturated Unit Weight (%)	Water abs. (atm. pressure) (%)	Water abs. (pressure) (%)	Sonic Velocity (%)	UCS (%)
0	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
20	99.81	100.37	99.46	99.52	101.05	100.98	99.79	93.70
40	99.37	103.03	99.01	99.27	101.12	104.24	99.39	89.44
60	98.88	105.00	98.82	99.23	104.00	106.26	94.13	84.57
70	98.35	106.37	98.12	98.66	106.43	108.51	92.22	83.20
80	97.97	107.07	97.36	98.00	108.91	110.15	89.63	72.49

Table 4.17 Normalized average physical and mechanical properties of the Tirtar lower level limestone after the wetting-drying tests.

Number of Cycle	Weight (%)	Porosity (%)	Dry Unit Weight (%)	Saturated Unit Weight (%)	Water abs. (atm. pressure) (%)	Water abs. (pressure) (%)	Sonic Velocity (%)	UCS (%)
0	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
20	99.32	101.63	99.56	99.76	101.70	101.83	94.88	87.81
40	98.73	102.89	98.23	98.66	102.98	104.42	91.97	80.67
60	98.04	105.01	97.48	98.18	103.76	107.27	89.67	74.10
70	97.23	107.53	96.63	97.64	106.66	111.34	88.05	70.36
80	94.86	110.95	96.08	97.46	112.00	115.91	86.96	70.18

The variation of the above physical and mechanical properties of the limestones is shown in Figure 4.6. The fresh sample is represented by 100 % for all variables.

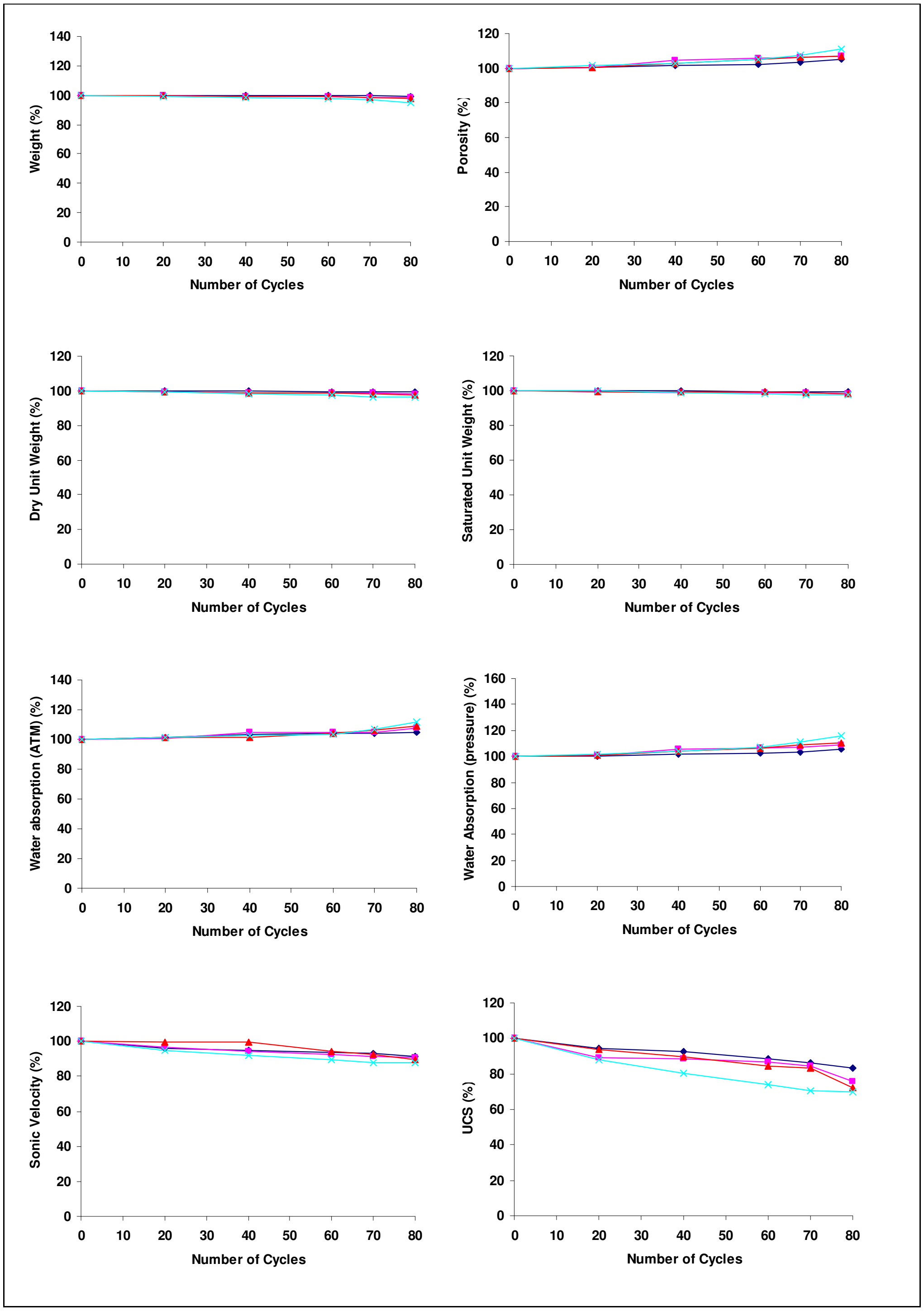


Figure 4.6 Variation of the physico-mechanical properties of the limestone after wetting-drying tests (blue line shows Değirmençayı limestone, pink line shows Tirtar upper level limestone, red line shows Tirtar middle level limestone, turquoise line shows Tirtar lower level limestone)

Weight is decreased by 0.57 % in the Değirmençayı limestone, 1.48 % in the Tirtar upper level limestone, and 2.03 % in the Tirtar middle level limestone and 5.14 % in the Tirtar lower level limestone. After all wetting-drying cycles, no noticeable change in weight is observed. The effective porosity of the Değirmençayı limestone, Tirtar upper level limestone, Tirtar middle level limestone, Tirtar lower level limestone is increased by 4.98 %, 6.82 %, 7.07% and 10.95 %. The porosity is generally increased at 80th test cycles in all samples. The maximum change of weight occurred in the Tirtar lower level limestone (Figure 4.6).

Dry unit weight is decreased by 0.84 % in the Değirmençayı limestone. However, it is decreased by 2.08 % in the Tirtar upper level limestone, 2.64 % in the Tirtar middle level limestone and 3.92 % in the Tirtar lower level limestone. The change in saturated unit weight is similar to the change in the dry unit weight. Saturated unit weight is decreased by 0.65 % in the Değirmençayı limestone. However, the saturated unit weight is decreased by 1.95 % in the Tirtar upper level limestone, 2.00 % in the Tirtar middle level limestone and 2.54 % in the Tirtar lower level limestone (Figure 4.6).

Water absorption under atmospheric pressure and water absorption under pressure of the limestones tested are generally increased. The rate of increase is pronounced after 70 test cycles (Figure 4.6).

Sonic velocity of the limestone is decreased by the increase of test cycles. At the end of 20-test cycle, there is no remarkable change in sonic velocities. Reduction in sonic velocity is 8.69 % in the Değirmençayı limestone, 9.02 % in Tirtar upper level limestone, 10.37 % in Tirtar middle level limestone and 13.04 % in Tirtar lower level limestone (Figure 4.6).

UCS is another important physico-mechanical parameter of the armourstone. UCS is the most affected parameter among all parameters. It is much more reduced in the limestones as compared to the other parameters. This reduction also increases as the number of test cycles increase. At the end of the 80-test cycle, the UCS of the Değirmençayı limestone is reduced by 16.92 %, the UCS of the Tirtar upper level limestone is reduced by 24.66 %, the UCS of the Tirtar middle level limestone is reduced by 27.51 %, the UCS of the Tirtar lower level limestone is reduced by 29.82 % (Figure 4.6).

In general, the reduction in dry and saturated density of the Değirmençayı limestone, Tirtar upper and middle level limestone is minor. The change in weight is not remarkable in all samples. The change in porosity becomes more significant in the Tirtar lower level limestone at the 80th cycle. In addition, the reduction in sonic velocity and UCS of the Tirtar lower level limestone is more than the other samples. All the samples are affected from the wetting- drying test cycles. The changes are mostly occurred at 70th and 80th cycles. However, the Değirmençayı and Tirtar upper level limestones are more resistant to wetting-drying activity than the Tirtar lower level limestone. Tirtar middle level limestone shows average changes between the Tirtar upper level limestone and Tirtar lower level limestone. The changes in shapes of the samples before and after the tests are shown in Figures 4.7, 4.8, 4.9 and 4.10.

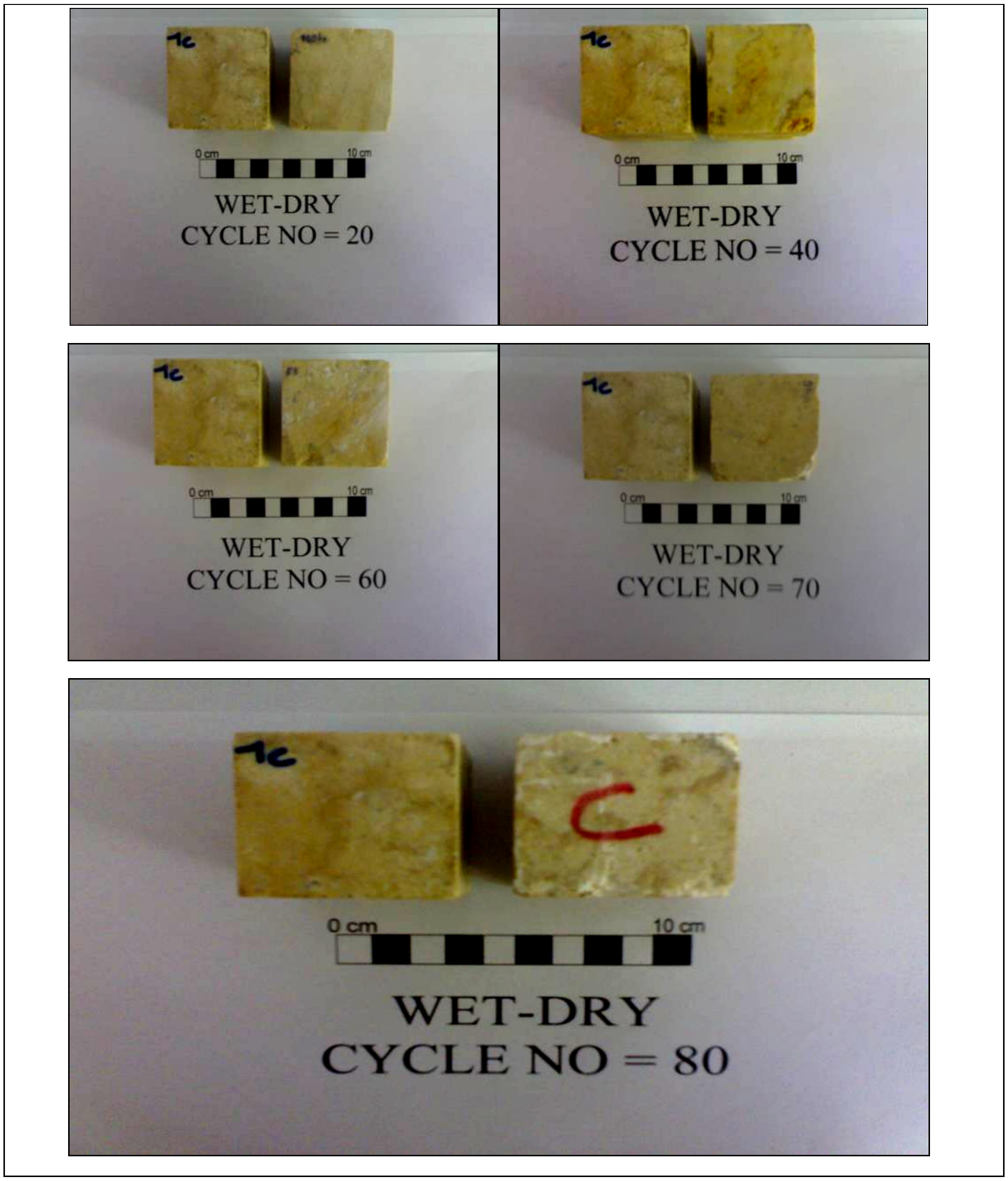


Figure 4.7 Physical appearance of the Değirmençayı limestone subjected to 80 wetting-drying test cycles. The sample at the left side of the photograph is a fresh reference sample.

Figure 4.8 Physical appearance of the Tirtar upper level limestone subjected to 80 wetting-drying test cycles. The sample at the left side of the photograph is a fresh reference sample.

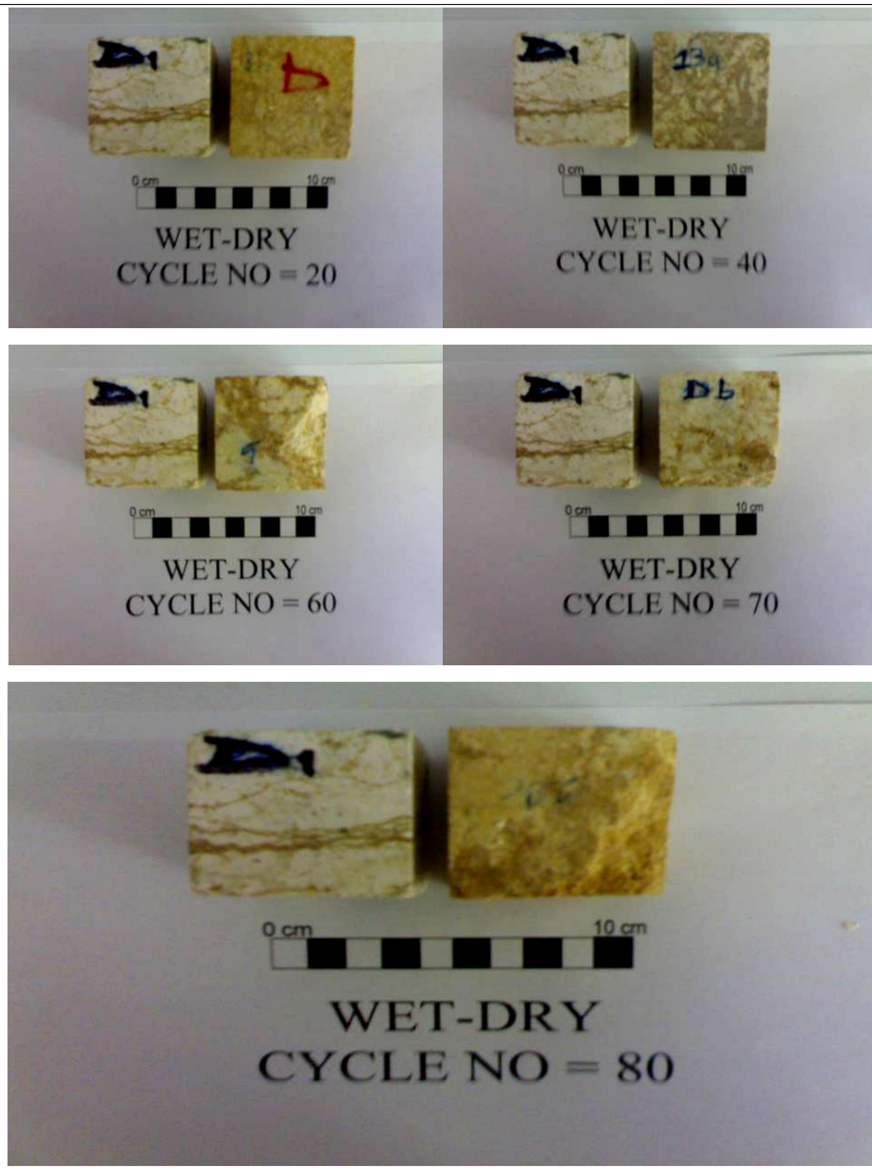


Figure 4.9 Physical appearance of the Tirtar middle level limestone subjected to 80 wetting-drying test cycles. The sample at the left side of the photograph is a fresh reference sample.

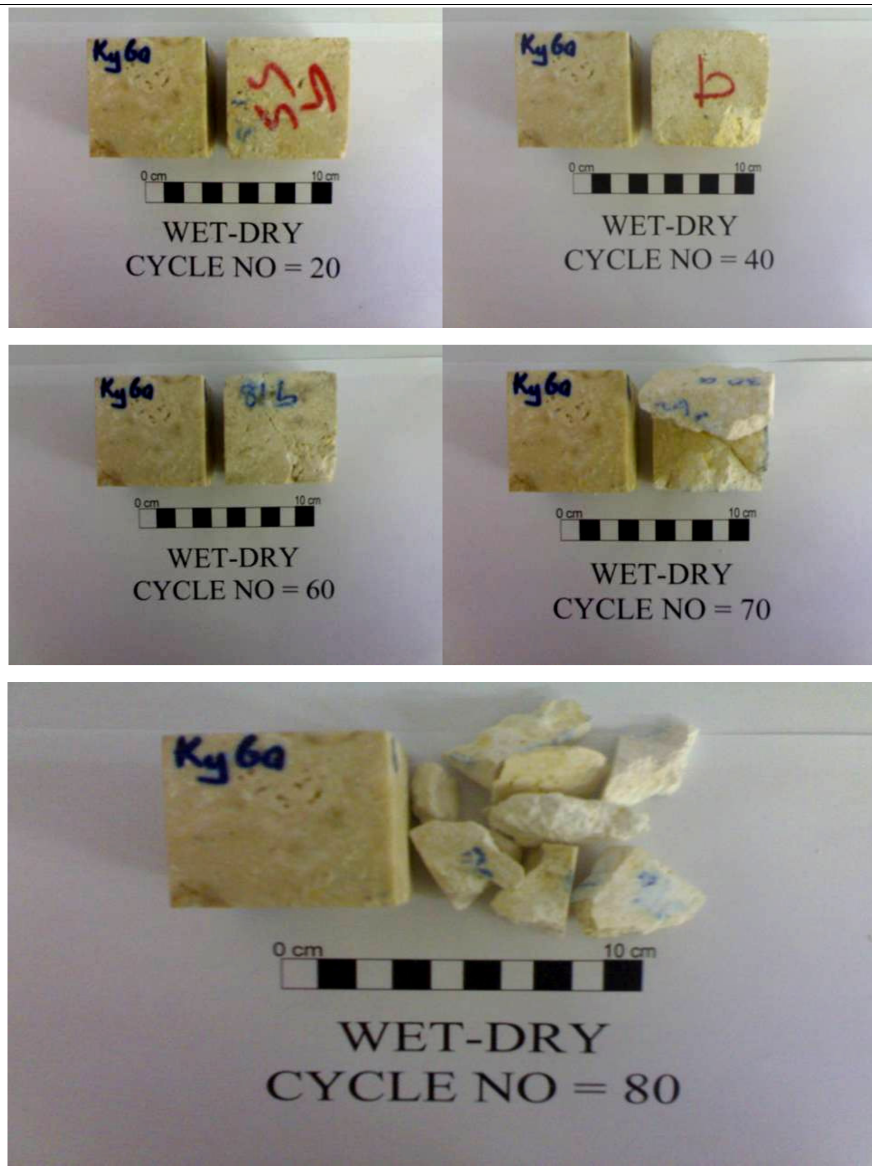


Figure 4.10 Physical appearance of the Tirtar lower level limestone subjected to 80 wetting-drying test cycles. The sample at the left side of the photograph is a fresh reference sample.

4.1.13 Freezing-Thawing test

Freezing-thawing test attempts to reproduce stresses, which may arise inside the stone when ice crystals are formed. Those effects are generally obtained by varying temperature under and above 0 ^{o}C on samples containing a known amount of water. Freezing-thawing test is usually performed for rocks having water absorption under atmospheric pressure value greater than 1 % according to Clark (1988), and greater than 0.5 % according to CIRIA/CUR (1991).

In this study, freeze-thaw machine is used to determine the degree of degradation under the heat and cold states. For the freezing-thawing tests, the cubic samples were immersed for 24 hours in distilled water at 15 to 20 ^{o}C. The machine is automatically changed the heat from -15 to +2 ^{o} C for 12 hours period of freezing. The average values are recorded at 0, 5, 10, 15, 20 and 25 test cycles as in the case of the wetting-drying tests. At the end of 25 freezing-thawing cycles, the total weight loss in terms of the initial sizes is calculated. The average values are given in Table 4.18.

Table 4.18 Freeze-Thaw values of the Değirmençayı and Tirtar limestones.

Sample Name	# of Samples	Weight loss value (%)
Değirmençayı limestone	8	1.25
Tirtar upper level limestone	8	1.95
Tirtar middle level limestone	8	2.06
Tirtar lower level limestone	8	11.60

Normalized average values associated with the percent change in physico-mechanical properties of limestone after the freezing-thawing tests are presented in Tables 4.19, 4.20, 4.21 and 4.22. The fresh sample is also represented by 100% for all variables and the others are normalized with respect to the fresh sample.

Table 4.19 Normalized average physical and mechanical properties of the Değirmençayı limestone after freezing-thawing tests.

Number of Cycle	Weight (%)	Porosity (%)	Dry Unit Weight (%)	Saturated Unit Weight (%)	Water abs. (atm. pressure) (%)	Water abs. (pressure) (%)	Sonic Velocity (%)	U.C.S. (%)
0	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
5	99.89	100.58	99.96	99.98	101.02	100.47	91.12	95.25
10	99.71	102.52	99.85	99.74	105.18	103.75	89.98	88.00
15	99.36	104.38	99.05	99.04	106.92	105.31	88.20	85.24
20	99.15	105.04	98.75	98.89	107.43	107.84	87.63	82.22
25	98.75	108.11	98.15	98.37	109.83	111.27	85.37	76.80

Table 4.20 Normalized average physical and mechanical properties of the Tirtar upper level limestone after freezing-thawing tests.

Number of Cycle	Weight (%)	Porosity (%)	Dry Unit Weight (%)	Saturated Unit Weight (%)	Water abs. (atm. pressure) (%)	Water abs. (pressure) (%)	Sonic Velocity (%)	U.C.S. (%)
0	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
5	99.88	102.16	98.89	98.95	101.95	102.96	89.94	93.25
10	99.70	105.14	98.79	98.90	105.96	106.23	86.03	87.83
15	99.39	105.87	98.45	98.58	107.88	107.18	84.66	85.67
20	98.84	106.78	98.08	98.02	108.81	107.65	83.90	84.17
25	98.05	110.72	97.71	97.94	111.01	112.58	83.39	73.14

Table 4.21 Normalized average physical and mechanical properties of the Tirtar middle level limestone after freezing-thawing tests.

Number of Cycle	Weight (%)	Porosity (%)	Dry Unit Weight (%)	Saturated Unit Weight (%)	Water abs. (atm. pressure) (%)	Water abs. (pressure) (%)	Sonic Velocity (%)	U.C.S. (%)
0	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100
5	99.93	100.01	99.79	99.81	100.76	100.19	94.56	99.05
10	99.59	102.20	99.38	99.56	103.06	102.85	92.40	96.07
15	99.26	104.06	98.85	99.19	104.90	105.24	91.26	82.64
20	98.91	105.50	98.59	99.04	107.40	106.95	88.77	78.77
25	97.94	112.18	96.40	97.42	113.04	116.31	82.95	69.79

Table 4.22 Normalized average physical and mechanical properties of the Tirtar lower level limestone after freezing-thawing tests.

Number of Cycle	Weight (%)	Porosity (%)	Dry Unit Weight (%)	Saturated Unit Weight (%)	Water abs. (atm. pressure) (%)	Water abs. (pressure) (%)	Sonic Velocity (%)	U.C.S. (%)
0	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
5	98.84	100.76	99.81	99.88	102.42	101.09	99.23	88.72
10	97.81	103.38	99.60	99.86	106.18	103.03	98.47	78.35
15	96.13	105.95	97.84	98.40	110.58	108.18	82.19	72.89
20	92.94	115.01	97.04	98.28	114.06	118.41	81.67	71.65
25	88.40	115.81	92.62	94.22	121.04	125.76	81.42	60.24

The variation of the above physical and mechanical properties of the limestones is shown in Figure 4.11. The fresh sample is represented by 100 % for all variables.

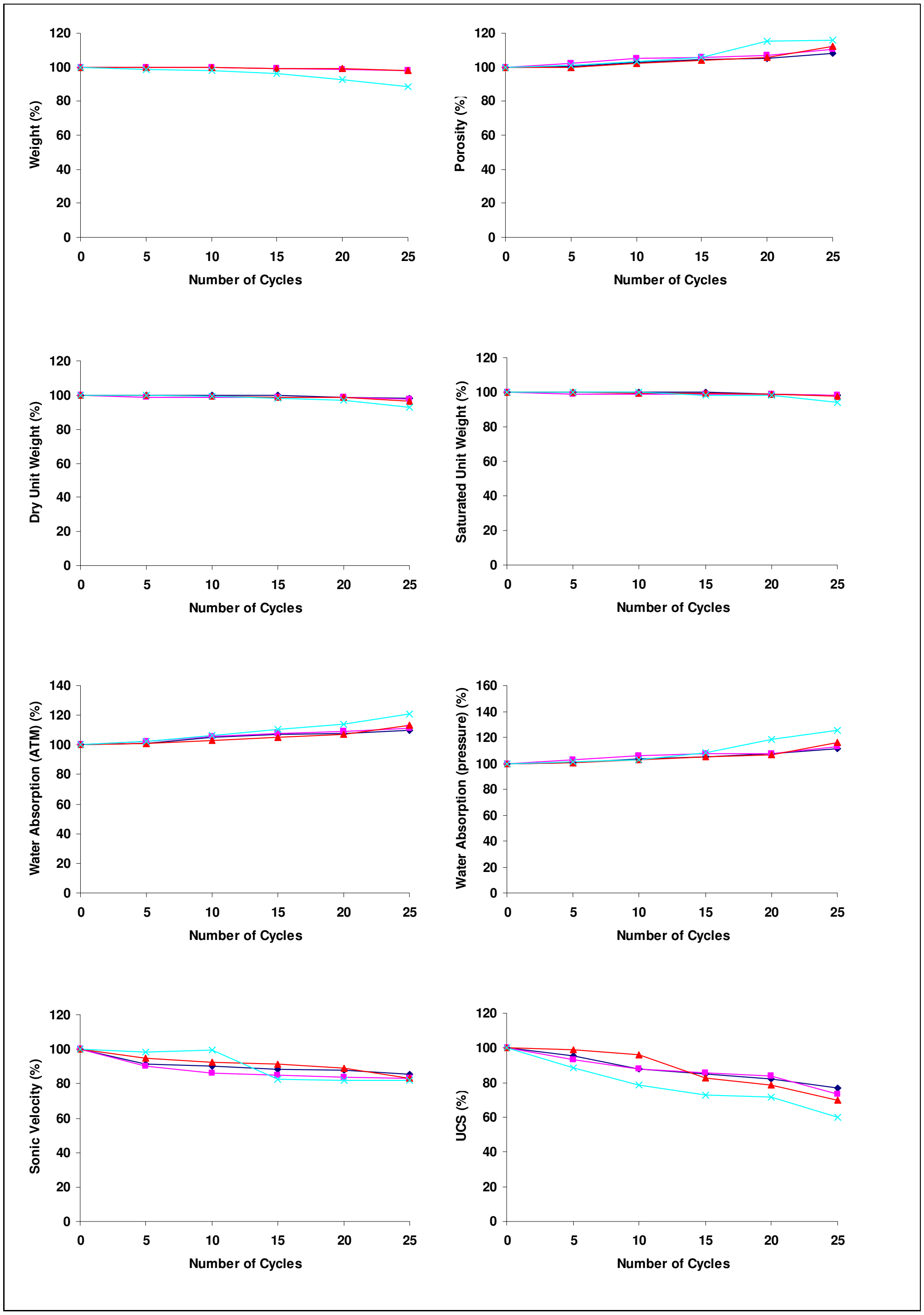


Figure 4.11 Variation of physico-mechanical properties of the limestones after the freezing-thawing tests blue line shows (blue line shows Değirmençayı limestone, pink line shows Tirtar upper level limestone, red line shows Tirtar middle level limestone, turquoise line shows Tirtar lower level limestone).

Minor variations are observed in weight of all samples. Weight is decreased by 1.25 % in the Değirmençayı limestone, 1.95 % in the Tirtar upper level limestone, and 2.06 % in the Tirtar middle level limestone and 11.60 % in the Tirtar lower level limestone. The effective porosity of the Değirmençayı, Tirtar upper level-middle-lower level limestone is increased by 8.11 %, 10.72 %, 12.18 % and 15.81 %, respectively. The maximum change occurred in the Tirtar lower level limestone (Figure 4.11).

Dry and saturated unit weights are also not changed at the end of the five test cycles. The remarkable change occurred only at the end of the 25-test cycles. Dry unit weight is decreased by 1.85 % in the Değirmençayı limestone, 2.29 % in the Tirtar upper level limestone, 3.60 % in the Tirtar middle level limestone and 7.38 % in the Tirtar lower level limestone. The change in saturated unit weight is similar to the change in the dry unit weight. Saturated unit weight is decreased by 1.63 % in the Değirmençayı limestone and 2.06 % in the Tirtar upper level limestone, 2.58 % in the Tirtar middle level limestone and 5.78 % in the Tirtar lower level limestone (Figure 4.11).

Water absorption under atmospheric pressure of the Degirmencayi, Tirtar upper level, Tirtar middle level, and Tirtar lower level limestones is 9.83 %, 11.01 %, 13.04 %, and 21.04 %, respectively. However, the water absorption under pressure values of the Değirmençayı, Tirtar upper level, Tirtar middle level, and Tirtar lower level limestones is 11.27 %, 12.58 %, 16.31 %, and 25.76 %, respectively. The change in water absorption under pressure is more than the change in water absorption under atmospheric pressure because of the porosity (Figure 4.11).

Effect of freezing-thawing tests on sonic velocity and UCS of the limestones is very significant. This reduction also increases as the number of test cycles increase. At the end of the 5-test cycle, there is no remarkable change in sonic velocities. However, Reduction in sonic velocity may reach up to 14.63 % in the Değirmençayı limestone, 16.61 % in Tirtar upper level limestone, 17.05 % in

Tirtar middle level limestone and 18.58 % in Tirtar lower level limestone, at the end of the 25-test cycles. The UCS is the most affected parameter at the end of the freezing-thawing tests and among other parameters. The UCS of the limestones is decreased by the increase in the test cycles. At the end of the 80-test cycle, the UCS of the Değirmençayı limestone is reduced by 23.20 %, the Tirtar upper level limestone 26.86 %, the Tirtar middle level limestone 30.21%, and the Tirtar lower level limestone 39.76 % (Figure 4.11).

In general, the samples were partly disintegrated at the end of the freezing-thawing tests from the sides and corners. Except the Tirtar lower level, the reduction in dry and saturated unit weights of the Değirmençayı, Tirtar upper and middle level limestones is minor. The change in weight is also not remarkable in all samples. The change in porosity becomes more significant in the Tirtar lower level limestone at the end of 25 test cycles. In addition, the reduction in sonic velocity and UCS of the Tirtar lower level limestone is more than the other samples. The changes were mostly occurred at the end of 25 test cycles. The upper and lower end surfaces of the samples were mostly deformed at this cycle. (Figure 4.11). However, the Değirmençayı limestone and Tirtar upper level and middle level limestones are more resistant to freezing-thawing activity than the Tirtar lower level limestone. Reduction in UCS reached to about 40 % in Tirtar lower level the limestone at the end of 25 test cycles .This means that the freezing-thawing tests are effective on the Tirtar lower level limestone. The changes in shapes of the samples before and after the tests are shown in Figures 4.12, 4.13, 4.14 and 4.15.

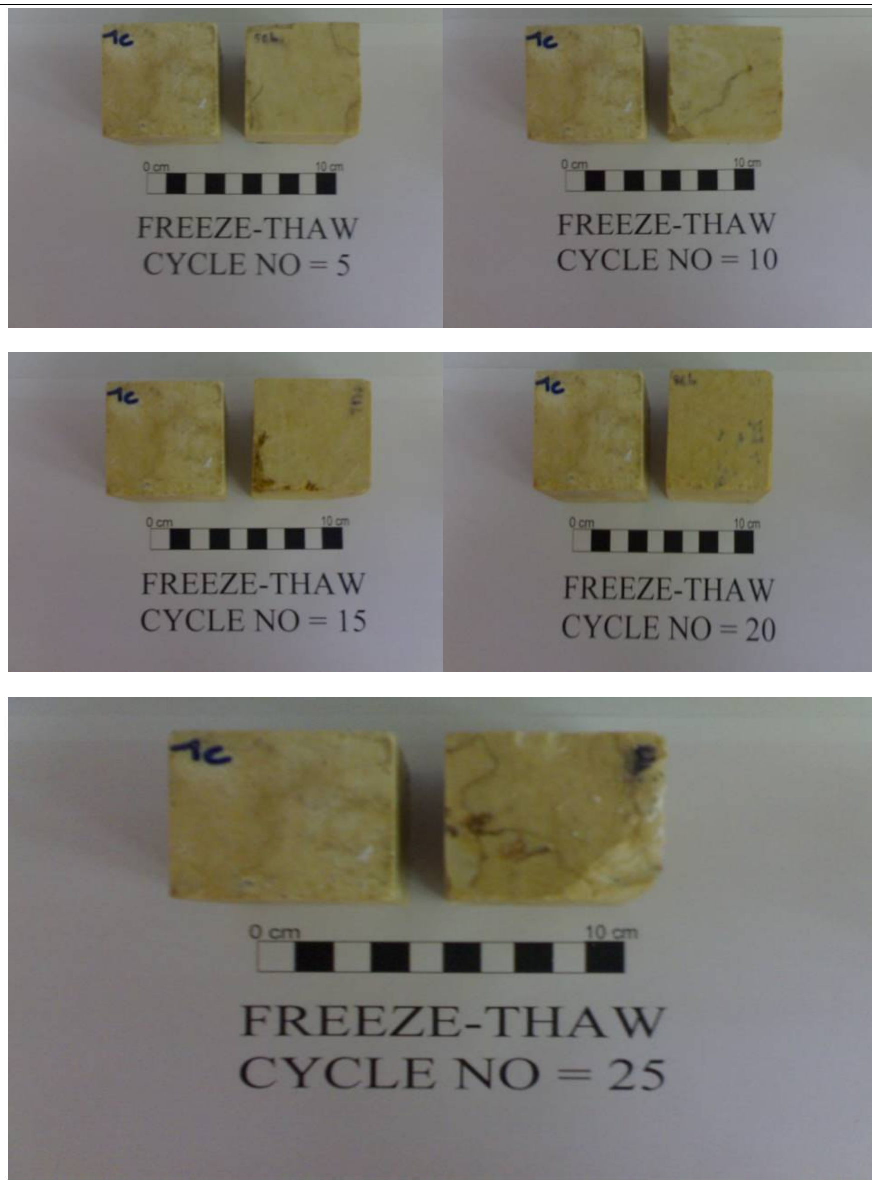


Figure 4.12 Physical appearance of the Değirmençayı limestone subjected to 25 freezing-thawing test cycles. The sample at the left side of the photograph is a fresh reference sample

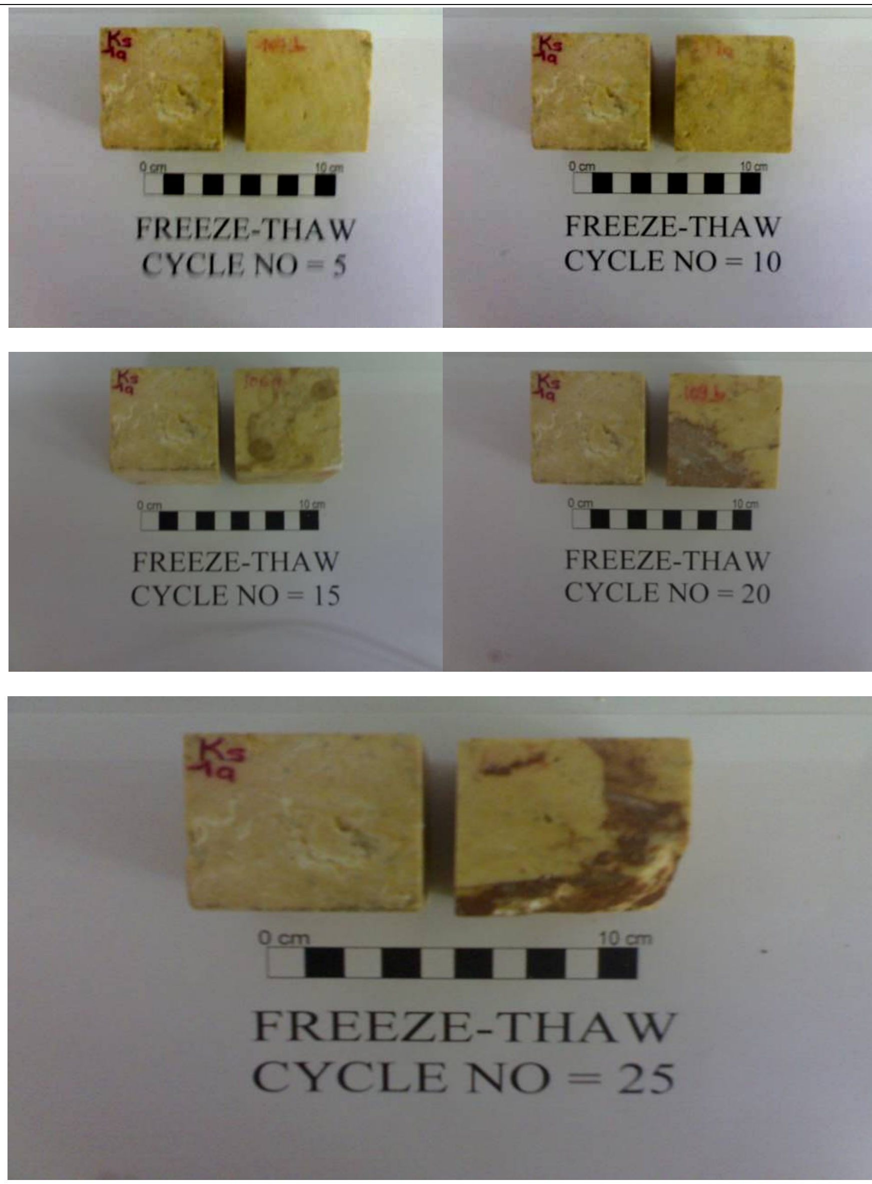


Figure 4.13 Physical appearance of the Tirtar upper level limestone subjected to 25 freezing-thawing test cycles. The sample at the left side of the photograph is a fresh reference sample.

Figure 4.14 Physical appearance of the Tirtar middle level limestone subjected to 25 freezing-thawing test cycles. The sample at the left side of the photograph is a fresh reference sample.

Figure 4.15 Physical appearance of the Tirtar lower level limestone subjected to 25 freezing-thawing test cycles. The sample at the left side of the photograph is a fresh reference sample.

4.1.14 Salt Crystallization tests

4.1.14.1 $MgSO_4$ sulphate soundness test

The $MgSO_4$ soundness test is used to measure the physical breakdown of the rock samples due to the formation of salt crystals inside the pores of the rock samples. The test results are accepted as the qualitative indicator of the soundness of a rock subjected to weathering action, especially by salt crystallization. The samples are put into a solution having 350 gr $MgSO_4$ per/l for the test. The same physico-mechanical tests of the limestones as done after the freezing-thawing tests were performed. The test is applied according to ASTM C88, (1990). The test consists of a number of immersion cycles for a sample in a sulphate solution; this creates a pressure through salt-crystal growth similar to that produced by freezing water. The sample is then oven dried and the percentage loss in mass is calculated.

Based on the test results, the weight loss of Değirmençayı, Tirtar upper level, Tirtar middle level and Tirtar lower level limestone after $MgSO_4$ test is 4.56 %, 8.59 %, 9.49 % and 23.14 %, respectively (Table 4.23).

Table 4.23 $MgSO_4$ Sulphate soundness values of the Değirmençayı and Tirtar limestones.

Sample Name	**# of Samples**	**Weight loss value (%)**
Değirmençayı limestone	8	4.56
Tirtar upper level limestone	8	8.59
Tirtar middle level limestone	8	9.49
Tirtar lower level limestone	8	23.14

Normalized average values associated with the percent change in physico-mechanical properties of limestone are presented in Tables 4.24, 4.25, 4.26 and 4.27. The fresh sample is also represented by 100 % for all variables and the others are normalized with respect to the fresh sample.

Table 4.24 Normalized average physical and mechanical properties of the Değirmençayı limestone after $MgSO_4$ sulphate soundness tests.

Number of Cycle	Weight (%)	Porosity (%)	Dry Unit Weight (%)	Saturated Unit Weight (%)	Water abs. (atm. pressure) (%)	Water abs. (pressure) (%)	Sonic Velocity (%)	U.C.S. (%)
0	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
5	99.28	101.44	99.92	99.99	103.40	101.02	96.57	94.47
10	98.48	103.48	98.47	98.71	104.71	103.73	95.83	88.46
15	97.13	112.18	94.28	95.12	105.01	118.31	93.94	82.42
20	96.18	115.48	93.91	94.93	112.92	122.39	92.16	76.98
25	95.44	119.42	92.20	93.49	115.43	128.35	81.94	71.82

Table 4.25 Normalized average physical and mechanical properties of the Tirtar upper level limestone after $MgSO_4$ sulphate soundness tests.

Number of Cycle	Weight (%)	Porosity (%)	Dry Unit Weight (%)	Saturated Unit Weight (%)	Water abs. (atm. pressure) (%)	Water abs. (pressure) (%)	Sonic Velocity (%)	U.C.S. (%)
0	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
5	101.03	100.19	99.70	99.99	101.25	101.10	91.99	88.76
10	98.33	102.70	99.41	99.78	101.63	103.69	88.04	85.80
15	97.78	107.70	97.82	98.30	105.01	109.86	85.72	84.67
20	97.09	117.02	96.40	97.10	113.13	121.08	82.60	76.54
25	91.41	121.94	91.43	92.35	116.72	130.94	81.56	68.59

Table 4.26 Normalized average physical and mechanical properties of the Tirtar middle level limestone after $MgSO_4$ sulphate soundness tests.

Number of Cycle	Weight (%)	Porosity (%)	Dry Unit Weight (%)	Saturated Unit Weight (%)	Water abs. (atm. pressure) (%)	Water abs. (pressure) (%)	Sonic Velocity (%)	U.C.S. (%)
0	100	100.00	100.00	100.00	100.00	100.00	100.00	100.00
5	98.68	100.57	97.82	97.89	101.84	102.84	93.29	94.82
10	97.96	104.58	96.71	96.93	105.28	108.20	86.04	91.30
15	96.92	112.87	95.69	96.17	111.01	118.01	87.01	81.45
20	96.09	114.96	93.40	94.01	117.45	123.31	85.24	69.94
25	90.51	133.85	88.67	89.94	124.93	132.30	80.95	60.34

Table 4.27 Normalized average physical and mechanical properties of the Tirtar lower level limestone after $MgSO_4$ sulphate soundness tests.

Number of Cycle	Weight (%)	Porosity (%)	Dry Unit Weight (%)	Saturated Unit Weight (%)	Water abs. (atm. pressure) (%)	Water abs. (pressure) (%)	Sonic Velocity (%)	U.C.S. (%)
0	100	100.00	100.00	100.00	100.00	100.00	100.00	100.00
5	98.55	104.74	98.85	99.21	104.51	106.55	99.11	90.34
10	96.33	105.84	98.16	98.62	105.92	107.17	91.19	74.30
15	93.72	108.25	97.35	98.01	115.67	112.09	85.04	70.79
20	85.65	117.02	93.90	95.28	118.33	124.03	83.83	57.87
25	76.86	134.58	86.33	89.23	130.61	154.94	79.05	47.66

The variation of the above physical and mechanical properties of the limestones is shown in Figure 4.16. The fresh sample is represented by 100 % for all variables.

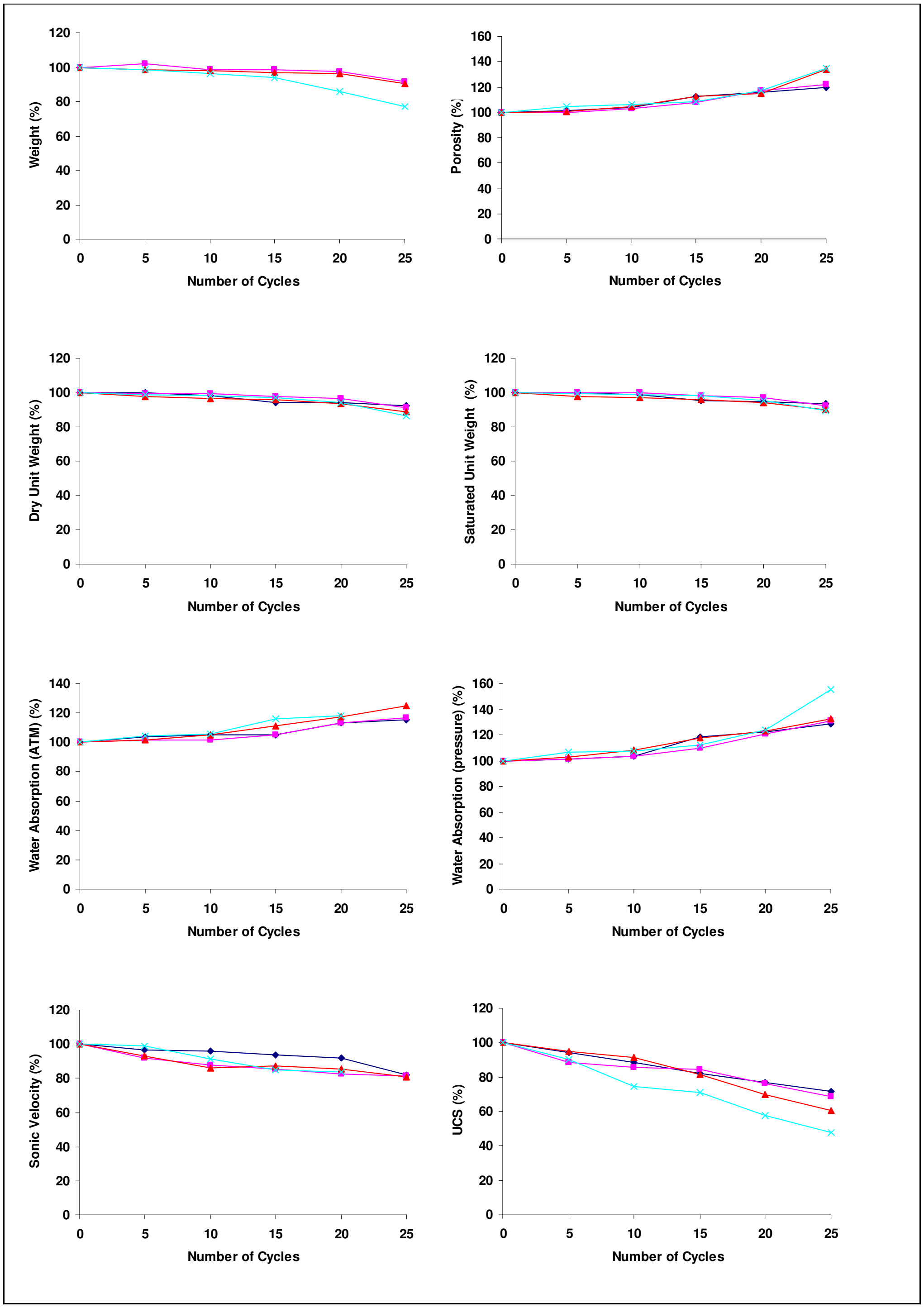


Figure 4.16 Variation of physico-mechanical properties of the limestones after $MgSO_4$ salt crystallization tests (blue line shows Değirmençayı limestone, pink line shows Tirtar upper level limestone, red line shows Tirtar middle level limestone, turquoise line shows Tirtar lower level limestone).

Minor variations are observed in weight of all samples. Weight is decreased by 4.56 % in the Değirmençayı limestone, 8.59 % in the Tirtar upper level limestone, and 9.49 % in the Tirtar middle level limestone and 23.14 % in the Tirtar lower level limestone. The effective porosity of the Değirmençayı, Tirtar upper level-middle-lower level limestone is increased by 19.42 %, 21.94 %, 33.85 % and 34.58 %, respectively. The maximum change occurred in the Tirtar lower level limestone (Figure 4.16).

Dry and saturated unit weights are also not changed at the end of 5 test cycles. The remarkable change occurred only at the end of the 25 test cycles. Dry unit weight is decreased by 7.80 % in the Değirmençayı limestone, 8.57 % in the Tirtar upper level limestone, 11.33 % in the Tirtar middle level limestone and 13.67 % in the Tirtar lower level limestone. Saturated unit weight is decreased by 6.51 % in the Degirmencayi limestone, 7.65 % in the Tirtar upper level limestone, 10.06 % in the Tirtar middle level limestone and 10.77 % in the Tirtar lower level limestone (Figure 4.16).

Water absorption under atmospheric pressure and water absorption under pressure of the Değirmençayı limestone are increased by 15.43 % and 28.35 %, respectively. They are 16.72 % and 30.94 %. For the Tirtar upper level limestone, 24.93 % and 32.30 % for the Tirtar middle level limestone, and 30.61 % and 59.94 % for the Tirtar lower level limestone. The change in water absorption under pressure is more than the change in water absorption under atmospheric pressure because of the porosity (Figure 4.16).

Effect of $MgSO_4$ salt crystallization tests in sonic velocity and UCS of the limestones is very significant. This reduction also increases as the number of test cycles increase. At the end of 20-test cycle, there is no remarkable change in sonic velocities. The reduction in sonic velocity is 18.06 % in the Değirmençayı limestone, 18.44 % in the Tirtar upper level limestone, 19.05 % in Tirtar middle level limestone, 20.95 % in Tirtar lower level limestone. UCS is the most affected parameter at the end of the freezing-thawing tests. In addition, it is the most affected parameter among other parameters. The UCS of the limestone is decreased by the increase in test cycles. At the end of the 80-test cycle, the UCS of the Değirmençayı limestone is reduced by 28.18 %, the Tirtar upper level limestone 31.41 %, the Tirtar middle level limestone 39.66 %, and the Tirtar lower level limestone 52.34 % (Figure 4.16).

In general, the samples were disintegrated at the end of the $MgSO_4$ salt crystallization tests from the sides and corners. The reduction in dry and saturated unit weights of the Değirmençayı limestone, Tirtar upper and middle level limestone is minor. The change in weight is not remarkable in all samples. The change in porosity becomes more significant in the Tirtar lower level limestone at the end of 25 test cycles. In addition, the reduction in sonic velocity and UCS of the Tirtar lower level limestone is more than the other samples. The changes mostly occurred at the end of 25 test cycles. The upper and lower end surfaces are mostly deformed at this cycle. However, the Değirmençayı limestone, Tirtar upper and middle level limestones are more resistant to freezing-thawing activity than the Tirtar lower level limestone. Reduction in UCS reached to about 50 % in the Tirtar lower level the limestone at the end of 25 test cycles .This means that the $MgSO_4$ salt crystallization process is most effective on the Tirtar lower level limestone. The changes in shapes of the samples before and after the tests are shown in Figures 4.17, 4.18, 4.19 and 4.20.

Figure 4.17 Physical appearance of the Değirmençayı limestone subjected to 25 salt crystallization ($MgSO_4$) test cycles. The sample at the left side of the photograph is a fresh reference sample.

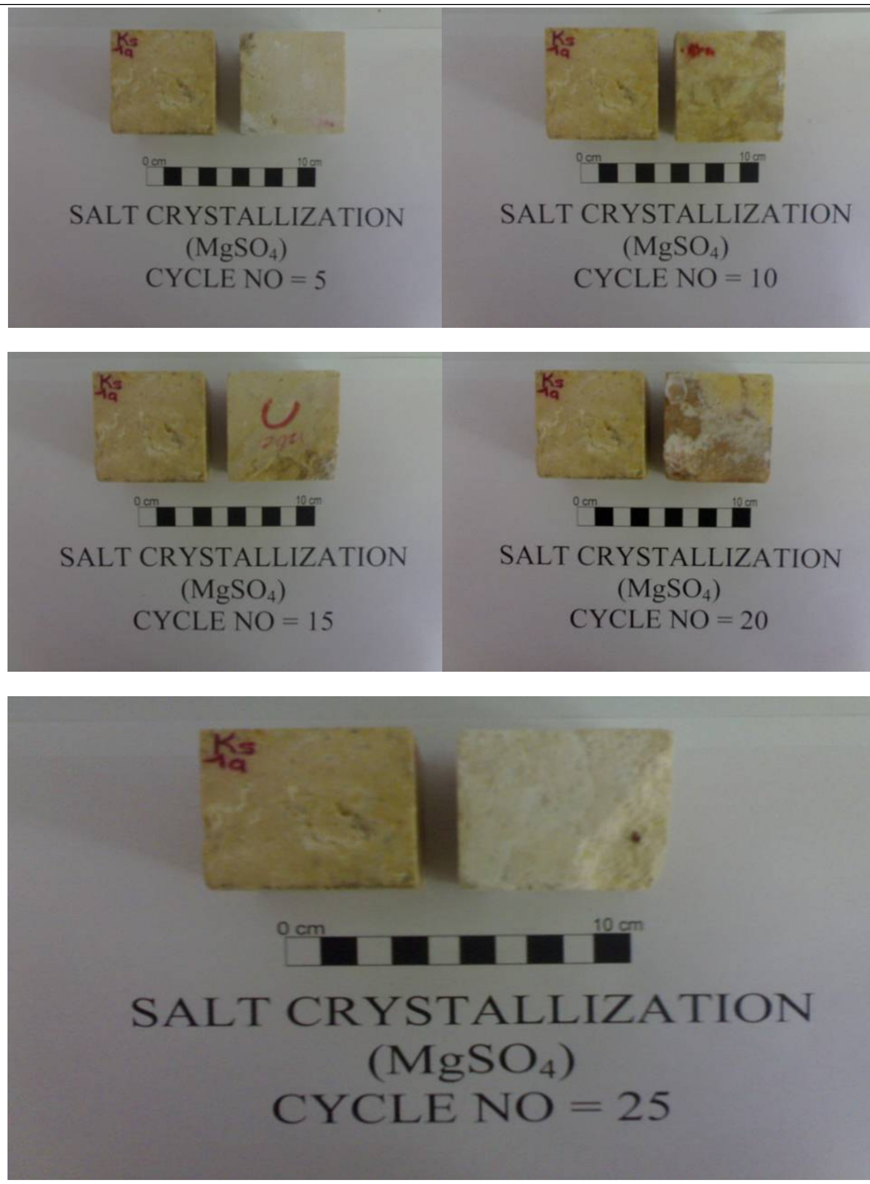


Figure 4.18 Physical appearance of the Tirtar upper level limestone subjected to 25 salt crystallization ($MgSO_4$) test cycles. The sample at the left side of the photograph is a fresh reference sample.

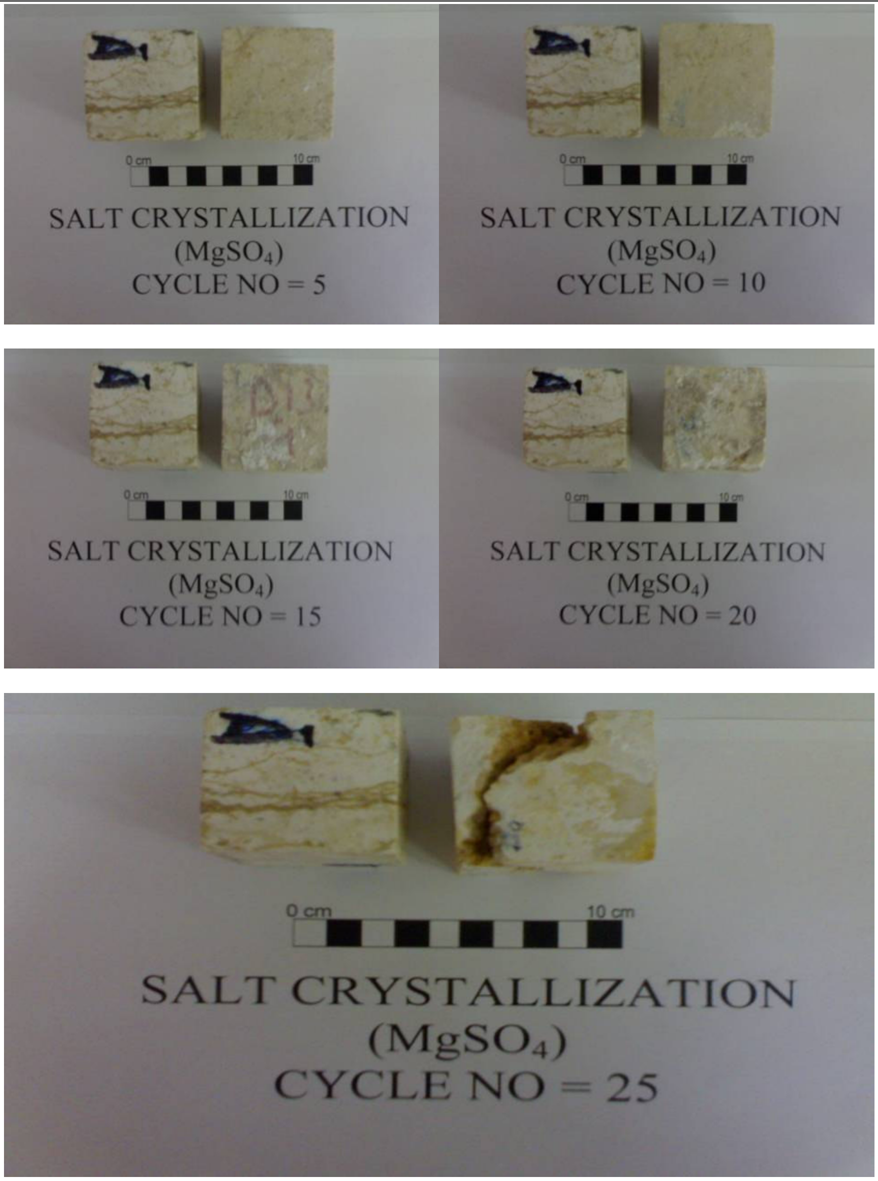


Figure 4.19 Physical appearance of the Tirtar middle level limestone subjected to 25 salt crystallization ($MgSO_4$) test cycles. The sample at the left side of the photograph is a fresh reference sample.

Figure 4.20 Physical appearance of the Tirtar lower level limestone subjected to 25 salt crystallization ($MgSO_4$) test cycles. The sample at the left side of the photograph is a fresh reference sample.

4.1.14.2 Na_2SO_4 sulphate soundness test

The sulphate soundness test consider two types of important salts, one of them is magnesium sulphate ($MgSO_4$) and the other one is sodium sulphate (Na_2SO_4). The sodium sulphate test is also used to measure the resistance of the rock samples through the salt crystals which are injected inside the pores of the rock during the destructive cycles. We applied a solution with 215 gr Na_2SO_4 per/lt. During the test, the samples are subjected 25 immersion cycles in sodium sulphate, followed by oven drying. Based on the test results, the weight losses of the Değirmençayı , Tirtar upper-middle-lower level limestone after Na_2SO_4 are 2.25 %, 5.03 %, 5.29 %, 15.23 % (Table 4.28).

Table 4.28 Na_2SO_4 sulphate soundness value of Değirmençayı and Tirtar limestone.

Sample Name	**# of Samples**	**Weight loss value (%)**
Değirmençayı limestone	8	2.25
Tirtar upper level limestone	8	5.03
Tirtar middle level limestone	8	5.29
Tirtar lower level limestone	8	15.23

The dry unit weight, saturated unit weight, effective porosity, weight, water absorption under atmospheric pressure, water absorption under pressure, sonic velocity and uniaxial compressive strength (UCS) of the samples were recorded at 5, 10, 15, 20 and 25 test cycles and compared with those of the fresh samples. These values are shown in Tables 4.29, 4.30, 4.31, 4.32. The fresh sample is also represented by 100% for all variables and the others are normalized with respect to the fresh sample.

Table 4.29 Average physical and mechanical properties of the Değirmençayı limestone after Na_2SO_4 sulphate soundness tests.

Number of Cycle	Weight (%)	Porosity (%)	Dry Unit Weight (%)	Saturated Unit Weight (%)	Water abs. (atm. pressure) (%)	Water abs. (pressure) (%)	Sonic Velocity (%)	U.C.S. (%)
0	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
5	99.76	102.64	99.92	100.01	101.07	102.56	96.26	94.90
10	99.25	102.77	98.62	98.76	102.48	104.04	95.49	90.82
15	98.97	102.79	98.64	98.77	103.60	104.19	91.96	83.31
20	98.45	107.04	97.64	97.94	107.36	109.65	91.21	79.90
25	97.75	114.49	97.05	97.61	112.45	118.34	83.63	75.00

Table 4.30 Average physical and mechanical properties of the Tirtar upper level limestone after Na_2SO_4 sulphate soundness tests.

Number of Cycle	Weight (%)	Porosity (%)	Dry Unit Weight (%)	Saturated Unit Weight (%)	Water abs. (atm. pressure) (%)	Water abs. (pressure) (%)	Sonic Velocity (%)	U.C.S. (%)
0	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
5	99.27	100.48	97.99	98.03	101.02	102.42	93.46	90.06
10	98.63	109.13	96.98	97.18	102.53	112.02	89.55	86.89
15	97.51	110.63	96.85	97.08	102.98	114.07	88.49	82.49
20	95.97	113.81	96.34	96.64	105.92	117.08	86.24	79.51
25	94.97	115.06	95.14	95.48	113.21	119.72	82.76	72.26

Table 4.31 Average physical and mechanical properties of the Tirtar middle level limestone after Na_2SO_4 sulphate soundness tests.

Number of Cycle	Weight (%)	Porosity (%)	Dry Unit Weight (%)	Saturated Unit Weight (%)	Water abs. (atm. pressure) (%)	Water abs. (pressure) (%)	Sonic Velocity (%)	U.C.S. (%)
0	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
5	99.35	101.31	99.79	99.89	102.11	101.52	95.17	94.00
10	98.90	101.76	99.38	99.54	103.60	104.47	93.56	90.01
15	98.25	102.37	98.23	98.51	104.74	106.33	92.48	75.68
20	96.73	108.40	96.71	97.48	107.89	114.37	88.30	72.65
25	94.71	117.82	93.24	94.87	118.26	128.74	81.17	65.45

Table 4.32 Average physical and mechanical properties of the Tirtar lower level limestone after Na_2SO_4 sulphate soundness tests.

Number of Cycle	Weight (%)	Porosity (%)	Dry Unit Weight (%)	Saturated Unit Weight (%)	Water abs. (atm. pressure) (%)	Water abs. (pressure) (%)	Sonic Velocity (%)	U.C.S. (%)
0	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
5	98.19	101.05	99.46	100.27	104.78	112.34	92.84	89.97
10	97.20	101.68	97.92	98.86	119.00	114.58	88.80	80.01
15	95.81	104.36	97.11	98.29	114.34	118.44	85.81	71.20
20	91.31	112.60	92.70	94.72	117.35	134.09	81.39	69.50
25	84.77	125.63	87.58	90.81	129.76	140.96	80.63	57.06

The variation of the above physical and mechanical properties of the limestones is shown in Figure 4.21. The fresh sample is represented by 100 % for all variables.

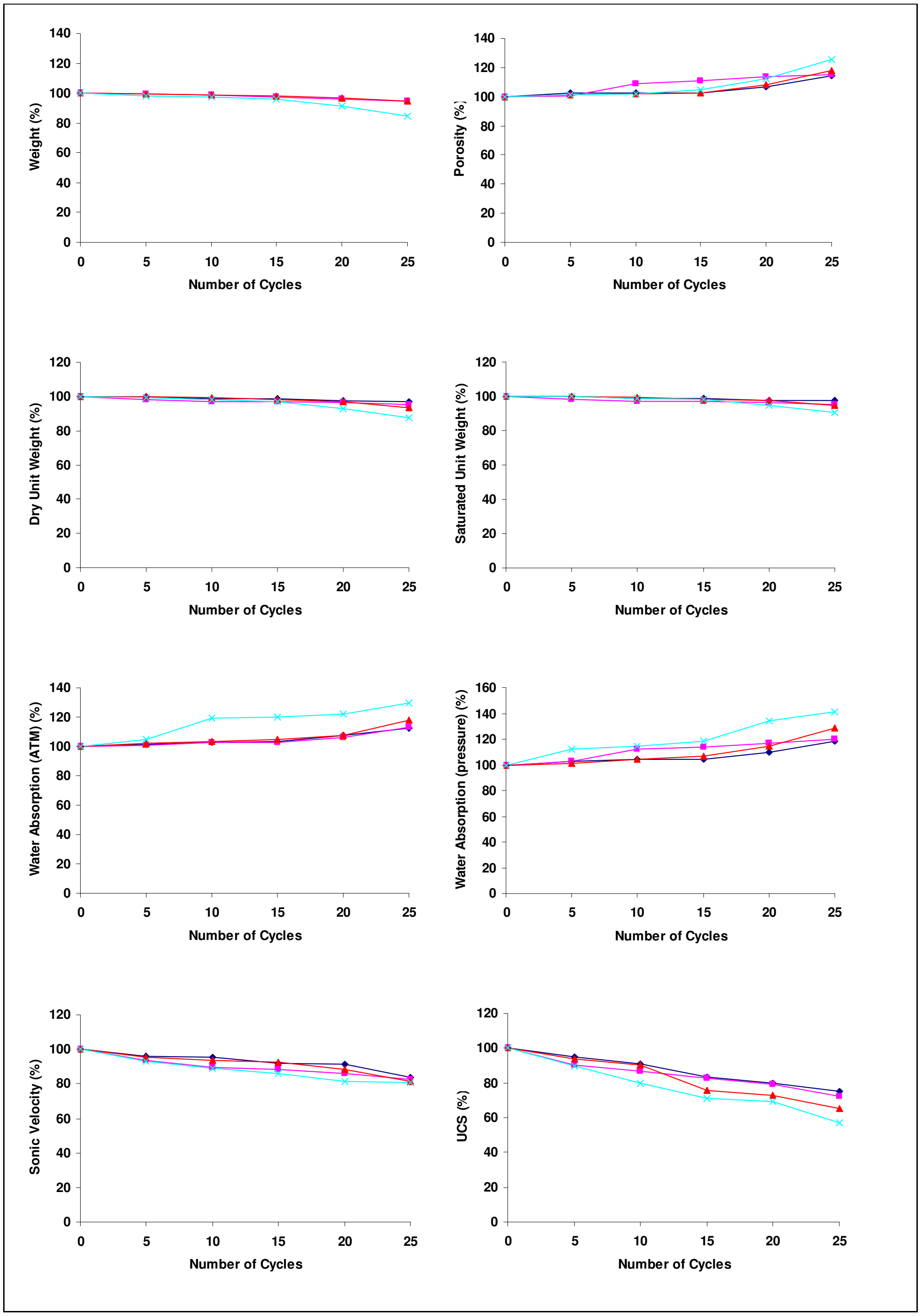


Figure 4.21 Variation of physico-mechanical properties of the limestones after Na_2SO_4 salt crystallization tests (blu line shows Değirmençayı limestone, pink line shows Tirtar upper level limestone, red line shows Tirtar middle level limestone, turquoise line shows Tirtar lower level limestone).

Minor variations are observed in weight of all samples. Weight is decreased by 2.25 % in the Değirmençayı limestone, 5.03 % in the Tirtar upper level limestone, and 5.29 % in the Tirtar middle level limestone and 15.23 % in the Tirtar lower level limestone. The effective porosity of the Değirmençayı, Tirtar upper level-middle-lower level limestone is increased by 14.49 %, 15.06 %, 17.82 % and 25.63 %. The maximum change is occurred in the Tirtar lower level limestone (Figure 4.21).

Dry unit weight and saturated unit weight are also not changed at the end of 5 test cycles. The remarkable change is occurred only at the end of the 25 test cycles. Dry unit weight is decreased by 2.95 % in the Değirmençayı limestone, 4.86 % in the Tirtar upper level limestone, 6.76 % in the Tirtar middle level limestone and 12.42 % in the Tirtar lower level limestone. Saturated unit weight is decreased by 2.39 % in the Değirmençayı limestone, 4.52 % in the Tirtar upper level limestone, 5.13 % in the Tirtar middle level limestone and 9.19 % in the Tirtar lower level limestone (Figure 4.21).

Water absorption under atmospheric pressure and water absorption under pressure of the Değirmençayı limestone are increased by 12.45 % and 18.34 %. Water absorption under atmospheric pressure and water absorption under pressure of the Tirtar upper level limestone are increased by 13.21 % and 19.72 %. Water absorption under atmospheric pressure and water absorption under pressure of the Tirtar middle level limestone are increased by 18.26 % and 28.74 %. Water absorption under atmospheric pressure and water absorption under pressure of the Tirtar lower level limestone are increased by 29.76 % and 40.96 % (Figure 4.21).

Effect of Na_2SO_4 sodium sulphate tests in sonic velocity and UCS of the limestones is very significant. This reduction also increases as the number of test cycles increase. At the end of 20-test cycle, there are no remarkable changes in sonic velocities. Reduction in sonic velocity is 16.37 % in the Değirmençayı limestone, 17.24 % in Tirtar upper level limestone, 18.83 % in Tirtar middle level limestone, 19.37 % in Tirtar lower level limestone (Figure 4.21).

UCS is the most affected parameter at the end of the salt crystallization tests. In addition, it is the most affected parameter in all over the parameters. UCS of the limestone is decreased by the increase in test cycles. At the end of the 80-test cycle, the UCS of the Değirmençayı limestone is reduced by 25 %, the UCS of the Tirtar upper level limestone is reduced by 27.74 %, the UCS of the Tirtar middle level limestone is reduced by 34.55 %, the UCS of the Tirtar lower level limestone is reduced by 42.94 % (Figure 4.21).

In general, the samples are disintegrated at the end of the salt crystallization tests from the sides and corners. The reduction in dry and saturated density of Değirmençayı limestone, Tirtar upper and middle level limestone is minor. The change in weight is not remarkable in all samples. The change in porosity becomes more significant in the Tirtar lower level limestone at the end of 25 test cycles. In addition, the reduction in sonic velocity and UCS of the Tirtar lower level limestone is more than the other samples. The changes are mostly occurred at the end of 25 test cycles. The upper and lower end surfaces are mostly deformed at this cycle. However, Değirmençayı limestone and Tirtar upper level and middle level limestones are more resistant to freezing-thawing activity than the Tirtar lower level limestone. Reduction in UCS is reached to about 40 % in Tirtar lower level the limestone at the end of 25 test cycles .This means Na_2SO_4 sodium sulphate tests are effective on the Tirtar lower level limestone. The changes in shapes of the samples before and after the tests are shown in Figures 4.22, 4.23, 4.24 and 4.25.

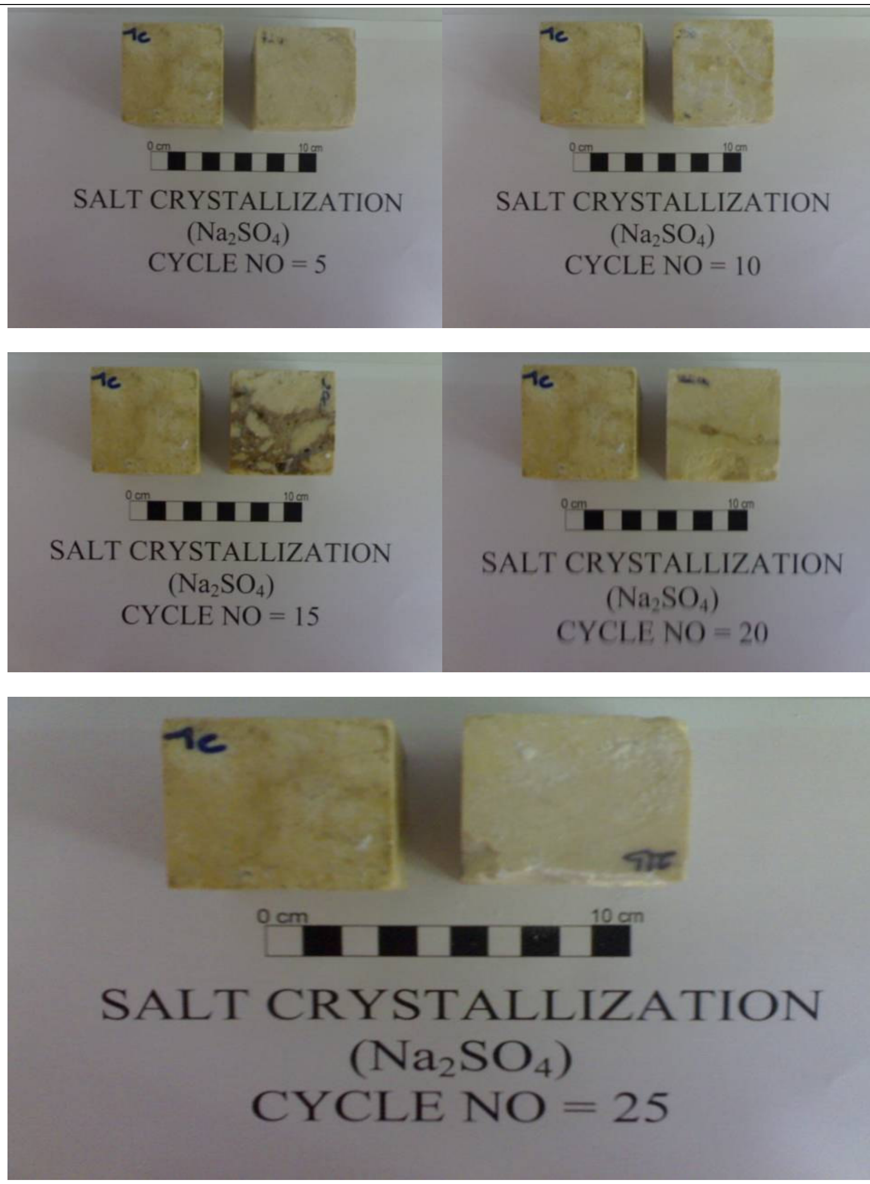


Figure 4.22 Physical appearance of the Değirmençayı limestone subjected to 25 salt crystallization (Na_2SO_4) test cycles. The sample at the left side of the photograph is a fresh reference sample.

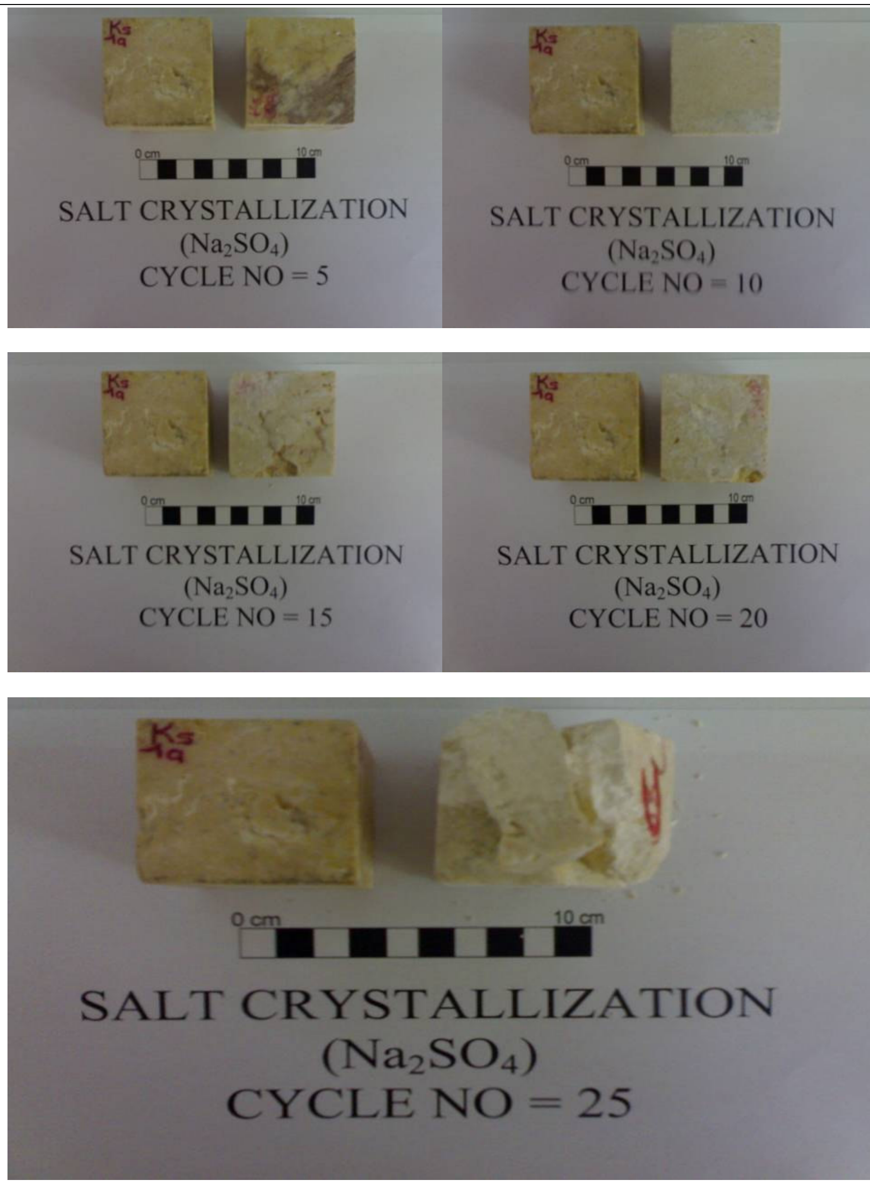


Figure 4.23 Physical appearance of the Tirtar upper level limestone subjected to 25 salt crystallization (Na_2SO_4) test cycles. The sample at the left side of the photograph is a fresh reference sample.

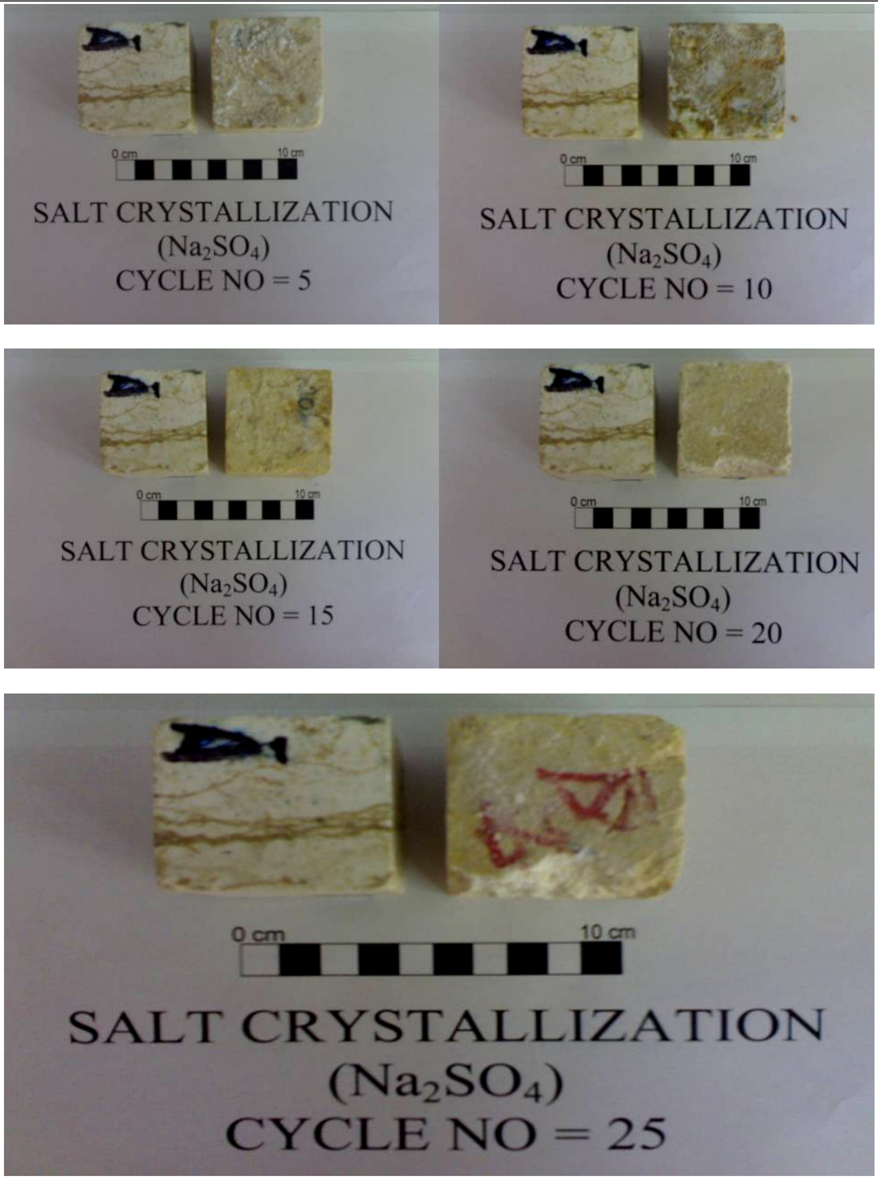


Figure 4.24 Physical appearance of the Tirtar middle level limestone subjected to 25 salt crystallization (Na_2SO_4) test cycles. The sample at the left side of the photograph is a fresh reference sample.

Figure 4.25 Physical appearance of the Tirtar lower level limestone subjected to 25 salt crystallization (Na_2SO_4) test cycles. The sample at the left side of the photograph is a fresh reference sample.

4.1.15 Los Angeles test

Los Angeles Test is used to determine the resistance to abrasion of aggregate by use of the Los Angeles Machine. The Los Angeles test (LAV) uses a steel drum containing a specified number of steel balls. When rotating with the specified sample this applies a combination of attrition due to wear between rock particles and impacts from the charge of steel balls, which may be sufficient to cause whole-lump fracture. (ASTM C 535, 1989).

It was designed for testing highway materials, and the simulation of loading combines fracture with abrasion in a manner, which bears little relation to processes in costal structures. Varying degrees of cracking caused during sample preparation can influence results. However, it remains popular as the only standardized indicator of wear or impact resistance used in US and Canadian specifications. The machines are widely available in the USA, Canada and parts of Europe.

For this test, 10 kg samples of passing 31.5 mm sieve are prepared from each limestone. The amount of fines (<1.70 mm) produced after 1000 revolutions for both dry and saturated rock samples are recorded. Los Angeles Value (LAV) expresses the difference between the original weight and the final weight and the final weight of the sample as a percentage of the original weight of the test sample.

After 200 revolutions, no remarkable change in weight is observed in all limestones. However, after 1000 revolutions the samples are affected significantly. In addition, the weight loss is increased from Değirmençayı limestone to the Tirtar lower level limestone as shown in the Table 4.33.

Table 4.33 Los Angeles values of the Değirmençayı and Tirtar limestones.

Sample Name	**# of Samples**	**LAV % Dry**	**LAV % Saturated**
Değirmençayı limestone	2	13.51	14.82
Tirtar upper level limestone	2	16.20	16.70
Tirtar middle level limestone	2	17.92	18.13
Tirtar lower level limestone	2	27.77	32.80

A) Değirmençayı limestone

B) Tirtar upper level limestone

B) Tirtar middle level limestone

D) Tirtar lower level limestone

Figure 4.26 The physical changes of limestones after 1000 revolutions Los Angeles test cycles. Figures show materials passing 1.7 mm sieve (left side) and retained (right side).

4.1.16 Micro-Deval test

Micro-Deval test is another test used to determine the mechanical and physical properties of aggregates. This test is gives a relative measure of the resistance ware. The French standard (LCPC, 1989) recommends the use of the wet Deval test for assessing wear resistance of armourstone. The wet attrition test and the Wet Deval test are practically identical and give good simulations of rock-to-rock surface grinding but their procedures, though simple, are often criticized as having poor reproducibility and discrimination, problems which have now been overcome with the QMW mill-abrasion test. This test is applied according to TSE 1097-1.The standard micro-deval test shall be made on 2 kg aggregates passing a 14 mm test sieve and retained on a 10 mm square hole test sieve. For this test, Micro-Deval machine was used. There are four rotating drums and equal size steel balls. When rotating with the specified sample this applies a combination of attrition due to wear between rock particles and impacts from the charge of steel balls, which may be sufficient to cause whole-lump fracture (TSE 1097, 2002). Then, we put 500 gr samples in each drums with 2.5 lt water. And, put the adequate steel balls. Drums are rotated with 100+5 rev/min speed until completed 12000+10 revolutions. After 12000 revolutions, the amount of fines passing 1.6 mm sieve is used for calculating the Micro Deval coefficient The lower value of MDE means the more resistant to ware. It is calculated with the following formula,

$$\mathbf{M_{DE} : \ (500 - m)/ 5} \qquad \mathbf{(4.6)}$$

Where;

$\mathbf{M_{DE}}$: the coefficient of Micro-Deval

m : the weight of the fines which is passed from 1.6 mm sieve

M_{DE} value of the Değirmençayı limestone is recorded as 19.60 %, Tirtar upper level limestone 22.19 %, Tirtar middle level limestone 32.76 %, Tirtar lower level limestone 52.53 %, respectively (Table 4.34). The changes in shape is shown in Figure 4.27.

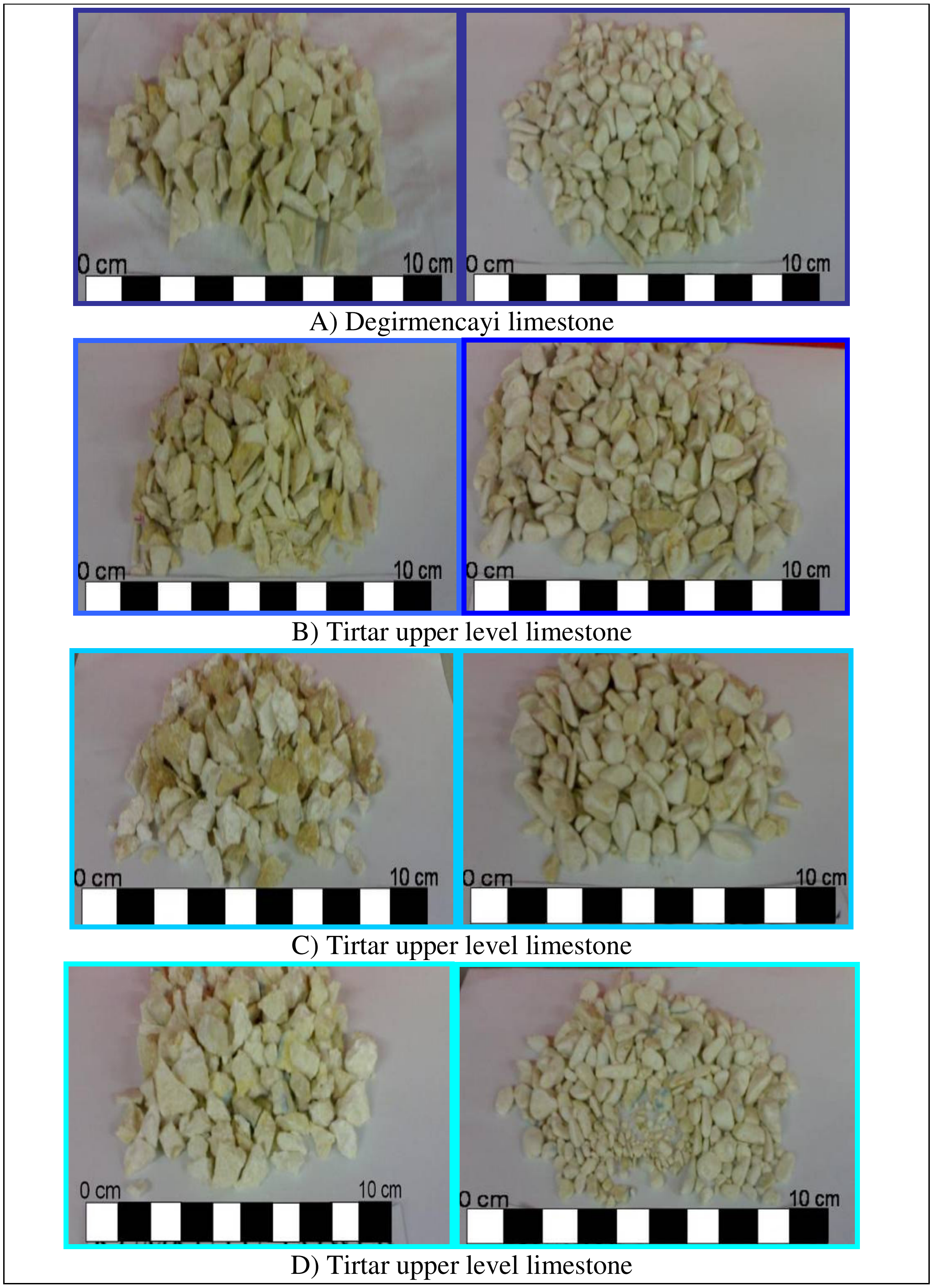


Figure 4.27 The physical appearance of limestones after Micro-Deval test. Fresh reference sample is placed at the left side of the photograph.

Table 4.34 Average micro-deval values of the Değirmençayı and Tirtar limestones.

Sample Name	# of Samples	M_{DE}	mill abrasion value (k_s)*	Engineering CIRIA/CUR (1991)	Classification CIRIA/CUR (1991)
Değirmençayı limestone	2	19.60	0.0039	Good	Good
Tirtar upper level limestone	2	22.19	0.0047	Upper Marginal	Upper Marginal
Tirtar middle level limestone	2	32.76	0.0079	Upper Marginal	Upper Marginal
Tirtar lower level limestone	2	52.53	0.0152	Poor	Poor

* assessed from micro-deval

4.1.17 Aggregate impact value test

Aggregate impact value (AIV) gives relative measure of the resistance of an aggregate to sudden shock or impact. The aggregate impact value, BS812 and variants of it are the most commonly specified tests. The AIV is determined by dropping a 14 kg weight through 381 mm onto an aggregate sample contained in a steel cup. The aggregates/crushed rocks passing 14 mm square hole test sieve and retained on a 10 mm square hole test sieve are used for the test. In this test, a test specimen (filling the standard cylindrical steel cup-approximately 300 gr) is compacted, in a standardized manner, into an open steel cup. The amount of crushed material passing a 2.36 mm sieve after 15 blows is determined. The action breaks the aggregate/crushed rock to a degree, which is dependent on the impact resistance of the material. This provides an indication of the sample aggregate's resistance to impact damage.

For this test, a standard apparatus suggested by BS 812 (BSI, 1990a) is used. The test is performed on both dry and saturated samples in the laboratory. The test results are given in the Table 4.35.

Table 4.35 Average aggregate impact values of the Değirmençayı and Tirtar limestones.

Sample Name	# of Samples	Dry Aggregate Impact Value (%)	Saturated Aggregate Impact Value (%)
Değirmençayı limestone	2	16.79	18.25
Tirtar upper level limestone	2	18.13	24.48
Tirtar middle level limestone	2	27.41	31.13
Tirtar lower level limestone	2	33.26	39.37

4.1.18 Modified aggregate impact value test

Modified aggregate impact value (MAIV) test is variety of AIV test, but the number of the hammer blows is limited to obtain a yield of between 5 to 20 % fines. For this test, a standard apparatus suggested by BS 812 (BSI, 1990b) is used The samples are first saturated and tested while surface dry. After testing, the sample is oven dried for 12 hours at 105 ^{o}C before sieving (2.36 mm).

Multiplying the percentage fines by 15 and dividing the product by the product by the number of hammer blows then give MAIV:

MAIV = 15.m/ n **(4.7)**

Where;

m is the fines percent

n is the number of hammer blows to which the specimen is subjected

Based on the test results, MAIV of the Degirmencayi, Tirtar upper level, Tirtar middle level and Tirtar lower level limestone are 17.84 %, 21.71 %, 29.94 % and 36.73 % (Table 4.36).

Table 4.36 Average modified aggregate impact values of the Değirmençayı and Tirtar limestones.

Sample Name	# of Samples	Modified Aggregate Impact Value (%)
Değirmençayı limestone	2	17.84
Tirtar upper level limestone	2	21.71
Tirtar middle level limestone	2	29.94
Tirtar lower level limestone	2	36.73

4.1.19 Aggregate crushing value test

In this test, a sample (10 -14 mm size range) of approximately 2 kg is subjected to a continuous load transmitted through a piston, in a compression machine. The test is performed ob both dry and saturated samples in the laboratory. For this test, a standard apparatus suggested by BS 812 (BSI, 1990c) is used A total load of 400 kN is achieved in 10 minutes. As in the AIV, the fines passing 2.36 mm sieve are calculated as a percentage of the initial sample weight. The product is the aggregate crushing value (ACV). Two values are produced for a each test material and values should be within a value of 1. A lower ACV value indicates a more resistant rock (BS 812, 1975). The test results are given in the Table 4.37.

Table 4.37 Average aggregate crushing values of the Değirmençayı and Tirtar limestones.

Sample Name	**# of Samples**	**Dry Aggregate Crushing Value %**	**Saturated Aggregate Crushing Value %**
Değirmençayı limestone	2	18.11	19.62
Tirtar upper level limestone	2	23.05	29.25
Tirtar middle level limestone	2	33.33	36.52
Tirtar lower level limestone	2	37.15	47.21

4.1.20 10 % Fines value test

The ten per cent fines value (TFV) of aggregate /crushed rock presents the load required to produce 10 % fines rather than the amount of crush for a specific load considered in aggregate crushing value test. The test is performed on both and saturated samples. A uniform loading rate is applied to a cause a total penetration of the plunger of 15 mm for gravels, 20 mm for crushed rock and 24 mm for honeycombed aggregates in 10 minutes. The fines less than 2.36 mm should fall within 7.5 % to 12.5 % of the initial weight. The force required to produce ten percent fines can be calculated as follows:

10 % Fines : 14*x/ y+4 (4.8)

Where;

x : the maximum force (kN)

y : the mean percentage fines from two tests at x kN force.

A high value indicates a more resistant rock. When AIV is available, the force required for the first ten percent fines test can be estimated by means of the following equation (BS 812, 1990d):

Force required : 4000 / AIV (4.9)

Where;

AIV : aggregate impact value

4000 : the arbitrary constant number given in BS 812

The results are also given in Table 4.38.

Table 4.38 Average 10 % Fines values of Değirmençayı and Tirtar limestones.

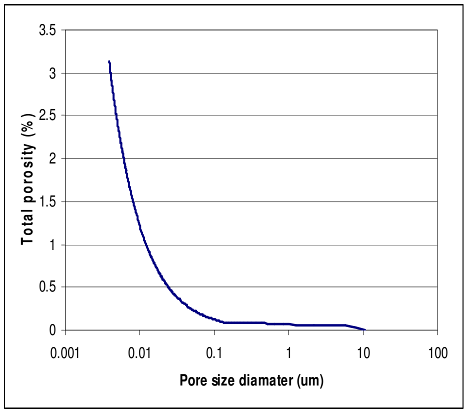
Sample Name	# of Samples	Dry TFV (kN)	Saturated TFV (kN)
Değirmençayı limestone	2	255.52	222.14
Tirtar upper level limestone	2	236.44	171.86
Tirtar middle level limestone	2	169.20	123.09
Tirtar lower level limestone	2	151.57	96.19

In all above methods (Aggregate Impact Value, Aggregate Crushing Value, 10 % Ten Percent Fines), affixed impulsive force is repeatedly applied (using a standard apparatus) to the surface of aggregate specimen. In addition, the weight loss of a certain sieve fraction is measured.

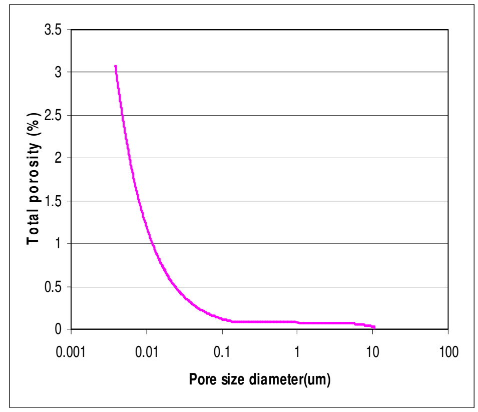
4.1.21 Pore-Size distribution

The measurement of pore size distribution of the Degirmencayi and Tirtar limestone have been carried out with mercury porosimetry (Micromeritics model) at the Central Laboratory of M.E.T.U. Mercury porosimetry is an extensively used technique to enable pore size distribution of rocks. The measurements are performed on four fresh limestone samples each weighing about 1-1.5 g. The tests are designed to perform one stage as . During the intrusion stage, the pressure is raised from 0 to 55 000 psi in 272 steps. This pressure range allows determination of pore sizes of the rocks between 0.003 µm and 10.65 µm. Advancing and receding contact angles of the mercury are taken 140^o . During the tests, a mercury surface tension (γ) value of 480 000 erg / cm ^{2}.

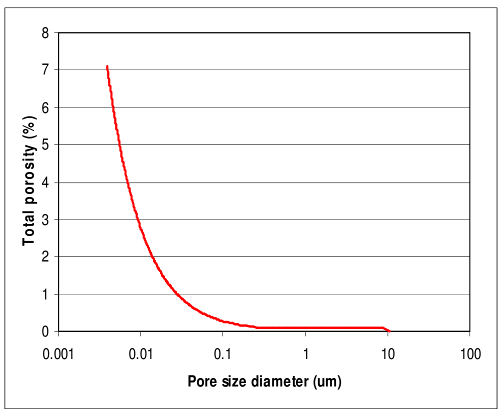
Based on the intrusion data, the average pore diameters of the Değirmençayı limestone, Tirtar upper level limestone, Tirtar middle level limestone and Tirtar lower level limestone are found to be 0.1070 µm, 0.0280 µm, 0.1291 µm and 0.1222 µm. The porosity of the Değirmençayı limestone, Tirtar upper level limestone, Tirtar middle level limestone and Tirtar lower level limestone are found to be 3.14 %, 3.08 %, 7.09 % and 9.78 % according to mercury porosimetry. The effective porosity of the Değirmançayı limestone, Tirtar upper level limestone, Tirtar middle level limestone and Tirtar lower level limestone are found to be 9.62 %, 4.87 %, 13.16 % and 14.56 % according to ISRM (1981). Cumulative intrusion curves for the four limestones are shown in Figure 4.28 and the cumulative intrusion pore-size distribution bar diagrams are shown in Figure 4.29. From Figure 4.29, the maximum peak of the Değirmençayı limestone is in the pore size range from 8 µm to 10 µm. The maximum peak of the Tirtar upper level limestone is in the pore size range from 0.1 µm to 0.3 µm. The maximum peak of the Tirtar middle and lower level limestone are in the pore size range from 10 µm to 11 µm.



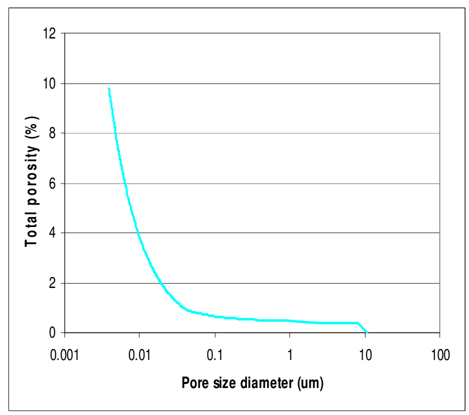
a) Değirmençayı limestone



b) Tirtar upper level limestone



c) Tirtar middle level limestone



d) Tirtar lower level limestone

Figure 4.28 Cumulative intrusion curves of the four fresh limestone samples.

4.1.22 Summary of the properties of the potential armourstones

Due to the fact that several tests are applied on the potential armourstone samples. The test results considering both dry and saturated condition are given in the following summary tables (Tables 4.39, 4.40, 4.41 and 4.42).

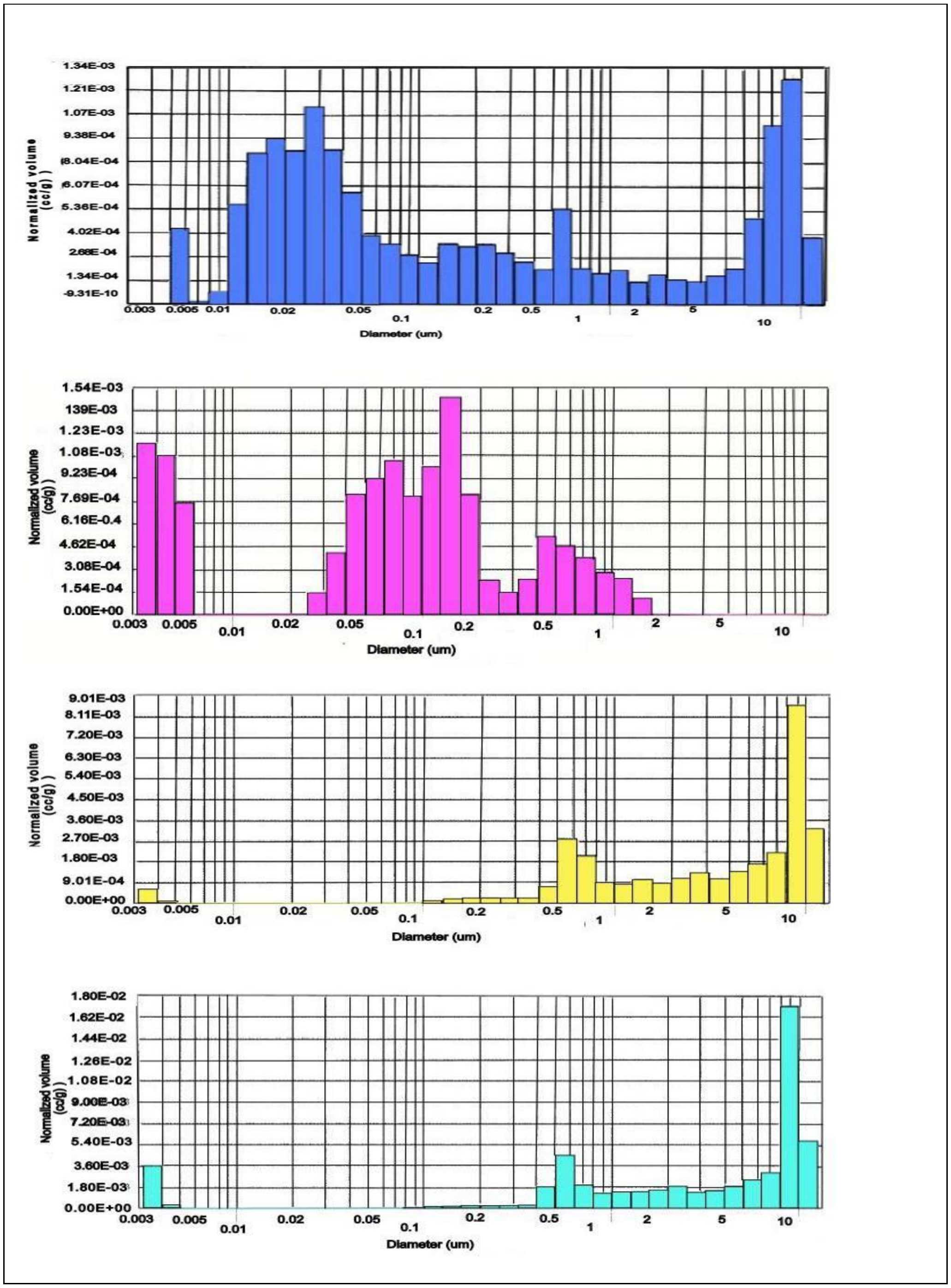


Figure 4.29 Pore size distributions of the four fresh limestone samples.

Table 4.39 Index properties of Değirmençayı Limestone

Properties	Standard used for testing	Number of tests	Test results Dry Mean ± SD*	Saturated Mean ± SD*
Unit weight (kN/m^3)	ISRM (1981)	180	23.71 ± 2.00	24.65 ± 1.80
Effective porosity (%)	ISRM (1981)	180	9.62 ± 5.82	
Water absorption under atmospheric pressure-by weight (%)	TS 699 (1987)	180	3.31 ± 2.40	
Water absorption under atmospheric pressure-by volume (%)	TS 699 (1987)	180	7.59 ± 4.83	
Water absorption under pressure-by weight (%)	ISRM (1981)	180	4.13 ± 2.85	
Water absorption under pressure-by volume (%)	ISRM (1981)	180	9.62 ± 5.82	
Saturation coefficient	TS 699 (1987)	180	0.81 ± 0.39	
Methylene blue adsorption value, MBA (g/100g)	AFNOR (1980)	2	0.30 ± 0.05	
Cation exchange capacity, CEC δ (meq./100g)	AFNOR (1980)	2	0.68 ± 0.11	
Wet – dry loss (%)	ASTM (1992)	6	0.57± 0.16	
Freeze – Thaw loss (%)	CIRIA/CUR (1991)	6	1.25 ± 0.66	
Magnesium Sulphate soundness value (%)	ASTM (1990)	6	4.56 ± 1.61	
Sodium Sulphate soundness value (%)	ASTM (1990)	6	2.25 ± 0.87	
Micro-Deval value (%)	TS EN (2002)	2	19.60 ± 0.25	
Mill abrasion resistance index, # ks (%)	CIRIA/CUR (1991)	2	0,0039 ± 0,001	
Point load strength index, $I_{s(50)}$ (MPa)	ISRM (1985)	8	1.86± 0.92	1.43± 0.57
Fracture toughness † (MPa.m$^{1/2}$)	Bearman (1999)	8	0.39± 0.19	0.30± 0.12
Uniaxial compressive strength (MPa)	ISRM (1981)	10	35.70 ± 1.99	26.90 ± 3.51
Sonic Velocity ‡ (m/sec)	ISRM (1981)	180	4806.48 ± 645.70	5219.69 ± 689.14
Schmidt rebound hardness ¥	ISRM (1981	10	61 ± 3.39	58 ± 4.57
Los Angeles abrasion § (%)	ASTM (1989)	2	13.51± 0.005	14.82 ± 0.008
Aggregate impact value (%)	BSI(1990a)	2	16.79 ± 1.75	18.25 ± 0.10
Aggregate crushing value (%)	BSI(1990c)	2	18.11 ± 0.65	19.62 ± 0.51
Modified Aggregate impact value (%)	BSI(1990a)	2	17.84 ± 0.07	
10 % fines value (kN)	BSI(1990b)	1	255.52	222.14

(SD*) standard deviation**, (δ)** determined from methylene blue adsorption test, **(#)** determined from micro-deval test, **(†)** determined from $Is_{(50)}$ using correlation factor
(‡) Pundit-plus 54-kHz transducers are used, **(¥)** L-Type Schmidt hammer is used, **(§)** loss after 1000 revolution

Table 4.40 Index properties of Tirtar upper level Limestone

Properties	**Standard used for testing**	**Number of tests**	**Test results** Dry Mean±SD*	Saturated Mean±SD*
Unit weight (kN/m^3)	ISRM (1981)	155	25.90 ± 1.17	26.38 ± 1.04
Effective porosity (%)	ISRM (1981)	155	4.87 ± 2.68	
Water absorption under atmospheric pressure-by weight (%)	TS 699 (1987)	155	1.38 ± 0.93	
Water absorption under atmospheric pressure- by volume (%)	TS 699 (1987)	155	3.54 ± 2.19	
Water absorption under pressure-by weight (%)	ISRM (1981)	155	1.88 ± 1.13	
Water absorption under pressure- by volume (%)	ISRM (1981)	155	4.87 ± 2.68	
Saturation coefficient	TS 699 (1987)	155	0.73 ± 0.14	
Methylene blue adsorption value, MBA (g/100g)	AFNOR (1980)	2	0.30 ± 0.05	
Cation exchange capacity, CEC δ (meq./100g)	AFNOR (1980)	2	0.68 ± 0.11	
Wet – dry loss (%)	ASTM (1992)	6	1.48 ± 0.58	
Freeze – thaw loss (%)	CIRIA/CUR (1991)	6	1.95± 0.25	
Magnesium Sulphate soundness value (%)	ASTM (1990)	6	8.59 ± 1.18	
Sodium Sulphate soundness value (%)	ASTM (1990)	6	5.06± 4.46	
Micro-Deval index, M_{DE} (%)	TS EN (2002)	2	0,0047± 0	
Point load strength index, $I_{s(50)}$ (MPa)	ISRM (1985)	8	1.78 ± 0.53	1.40 ± 0.41
Fracture toughness † (MPa.m$^{1/2}$)	Bearman (1999)	8	0.37± 0.34	0.29 + 0.16
Uniaxial compressive strength (MPa)	ISRM (1981)	10	32.80 ± 2.94	25.25 ± 3.79
Sonic Velocity ‡ (m/sec)	ISRM (1981)	155	5113.1 + 614.89	5733.8 ± 432.93
Schmidt rebound hardness ¥	ISRM (1981	10	52 + 1.63	48 + 3.23
Los Angeles abrasion § (%)	ASTM (1989)	2	16.2 ± 0.36	16.7 ± 1.13
Aggregate impact value (%)	BSI(1990a)	2	18.13 ± 2.62	24.48± 0.08
Aggregate crushing value (%)	BSI(1990c)	2	23.05 ± 0.28	29.25 ± 0.10
Modified Aggregate impact value (%)	BSI(1990a)	2	21. 71± 0.07	
10 % fines value (kN)	BSI(1990b)	2	236.44	171.86

(**SD***)-standard deviation**, (δ)** determined from Methylene blue adsorption test, **(†)** Assessed from $I_{s(50)}$ using correlation factor,
(‡) Pundit-plus 54-kHz transducers are used, **(¥)** L-Type Schmidt hammer is used, **(§)** Loss after 1000 revolution

Table 4.41 Index properties of Tirtar middle level Limestone

Properties	**Standard used for testing**	**Number of tests**	**Test results** Dry Mean±SD*	Saturated Mean±SD*
Unit weight (kN/m^3)	ISRM (1981)	40	21.74 ± 1.02	23.03 ± 0.71
Effective porosity (%)	ISRM (1981)	40	13.16 ± 4.24	
Water absorption under atmospheric pressure-by weight (%)	TS 699 (1987)	40	4.77 ± 1.72	
Water absorption under atmospheric pressure- by volume (%)	TS 699 (1987)	40	10.44 ± 3.52	
Water absorption under pressure-by weight (%)	ISRM (1981)	40	6.02 ± 2.13	
Water absorption under pressure- by volume (%)	ISRM (1981)	40	13.16 ± 4.24	
Saturation coefficient	TS 699 (1987)	40	0.78 ± 0.13	
Methylene blue adsorption value, MBA (g/100g)	AFNOR (1980)	2	0.43 ± 0.05	
Cation exchange capacity, CEC δ (meq./100g)	AFNOR (1980)	2	0.99 + 0.11	
Wet – dry loss (%)	ASTM (1992)	6	3.54 ± 0.89	
Freeze – thaw loss (%)	CIRIA/CUR (1991)	6	2.06 ± 0.74	
Magnesium Sulphate soundness value (%)	ASTM (1990)	6	9.49± 2.13	
Sodium Sulphate soundness value (%)	ASTM (1990)	6	5.29± 0.20	
Micro-Deval index, M_{DE} (%)	TS EN (2002)	2	0,0079 ± 0.003	
Point load strength index, $I_{s\,(50)}$ (MPa)	ISRM (1985)	8	1.34 ± 0.39	0.94 + 0.37
Fracture toughness † (MPa.m$^{1/2}$)	Bearman (1999)	8	0.28 ± 0.08	0.20 ± 0.08
Uniaxial compressive strength (MPa)	ISRM (1981)	10	21.70 ± 4.3	14.60 ± 3.9
Sonic Velocity ‡ (m/sec)	ISRM (1981)	40	4303.5 ± 277.18	4045.6 ± 289.31
Schmidt rebound hardness ¥	ISRM (1981	10	49 + 2.49	47 + 3.12
Los Angeles abrasion § (%)	ASTM (1989)	2	17.92± 0.16	18.13 ± 0.16
Aggregate impact value (%)	BSI(1990a)	2	27.41 ± 0.07	31.03 ± 0.32
Aggregate crushing value (%)	BSI(1990c)	2	33.33 ± 0.69	36.52 ± 0.78
Modified Aggregate impact value (%)	BSI(1990a)	2	29.94± 0.52	
10 % fines value (kN)	BSI(1990b)	1	169.20	123.09

(SD*)-standard deviation**, (δ)** determined from Methylene blue adsorption test, **(†)** Assessed from $I_{s\,(50)}$ using correlation factor,
(‡) Pundit-plus 54-kHz transducers are used, **(¥)** L-Type Schmidt hammer is used, **(§)** Loss after 1000 revolution

Table 4.42 Index properties of Tirtar lower level Limestone

Properties	Standard used for testing	Number of tests	Test results Dry Mean±SD*	Saturated Mean±SD*
Unit weight (kN/m^3)	ISRM (1981)	110	22.64 ± 1.52	24.07 ± 1.24
Effective porosity (%)	ISRM (1981)	110	14.54 ± 5.74	
Water absorption under atmospheric pressure-by weight (%)	TS 699 (1987)	110	5.58 ± 2.75	
Water absorption under atmospheric pressure- by volume (%)	TS 699 (1987)	110	12.38 ± 5.30	
Water absorption under pressure-by weight (%)	ISRM (1981)	110	6.43 ± 2.84	
Water absorption under pressure- by volume (%)	ISRM (1981)	110	14.54 ± 5.74	
Saturation coefficient	TS 699 (1987)	110	0.95 ± 1.18	
Methylene blue adsorption value, MBA (g/100g)	AFNOR (1980)	2	0.71± 0.22	
Cation exchange capacity, CEC δ (meq./100g)	AFNOR (1980)	2	1.61 ± 0.52	
Wet – dry loss (%)	ASTM (1992)	6	5.14 ± 0.90	
Freeze – thaw loss (%)	CIRIA/CUR (1991)	6	11.60 ± 1.34	
Magnesium Sulphate soundness value (%)	ASTM (1990)	6	23.14 ± 7.88	
Sodium Sulphate soundness value (%)	ASTM (1990)	6	15.23 ± 5.11	
Micro-Deval index, M_{DE} (%)	TS EN (2002)	2	0,00152 ± 0.0012	
Point load strength index, $I_{s(50)}$ (MPa)	ISRM (1985)	8	0.94 ± 0.38	0.65 ± 1.65
Fracture toughness † (MPa.m$^{1/2}$)	Bearman (1999)	8	0.20 ± 0.07	0.14 ± 0.02
Uniaxial compressive strength (MPa)	ISRM (1981)	10	14.70 ± 2.97	9.20 ± 1.39
Sonic Velocity ‡ (m/sec)	ISRM (1981)	110	3868.9 ± 674.38	4287.4 ± 655.45
Schmidt rebound hardness ¥	ISRM (1981	10	43 ± 2.86	41 ± 2.94
Los Angeles abrasion § (%)	ASTM (1989)	2	27.77± 0.01	30.96 ± 0.01
Aggregate impact value (%)	BSI(1990a)	2	33.26 ± 1.44	39.37 ± 2.07
Aggregate crushing value (%)	BSI(1990c)	2	37.15 ± 1.97	47.21 ± 5.24
Modified Aggregate impact value (%)	BSI(1990a)	2	36.73± 0.02	
10 % fines value (kN)	BSI(1990b)	1	151.57	96.19

(**SD***)-standard deviation**, (δ)** determined from Methylene blue adsorption test, **(†)** Assessed from $I_{s(50)}$ using correlation factor,
(‡) Pundit-plus 54-kHz transducers are used, **(¥)** L-Type Schmidt hammer is used, **(§)** Loss after 1000 revolution

4.2 Mass Properties of Degirmencayi and Tirtar Armourstone

Mass properties of the potential and used armourstone were studied during the field trips. Discontinuity properties such as orientation, spacing, persistence, aperture, roughness, wall strength, weathering, infilling, seepage were identified according to ISRM (1981).

4.2.1 Discontinuity survey in the armourstone quarries

Discontinuity measurements of the potential armourstone were carried out in the Mersin and Kumkuyu quarries (Figures 4.30 and 4.31). Scanline surveys with a tape length greater than 10 m were done at different parts of the quarries.

During the scan line survey, orientation of discontinuities (dip and dip direction), spacing, persistence, aperture, roughness, wall strength, weathering, infilling material, groundwater inflow were recorded.

Dip and dip direction records were first evaluated by geological software, "Dips 5.0 (1999)." to represent the relative orientations of discontinuities in quarries. Poles of the data collected data were plotted through Schmidt diagrams using the lower hemisphere projection. The contour diagrams for each quarry were then obtained from the pole plot diagram (Figure 4.32, 4.33 and 4.34).

Based on the scanline survey conducted in both Mersin and Kumkuyu quarries, the properties of the discontinuities are given Tables 4.43, 4.44 and 4.45. Due to the limited number of discontinuities, the Tirtar middle and lower levels are combined in Table 4.45. In addition, the material properties discussed in section 4.1 of the thesis should be evaluated in terms of their suitability for armourstone by considering international acceptance criteria and expected durability.

Figure 4.30 Panoramic view of Degirmencayi quarry.

Figure 4.31 Panoramic view of Tirtar quarry from right side (a) and from left side (b).

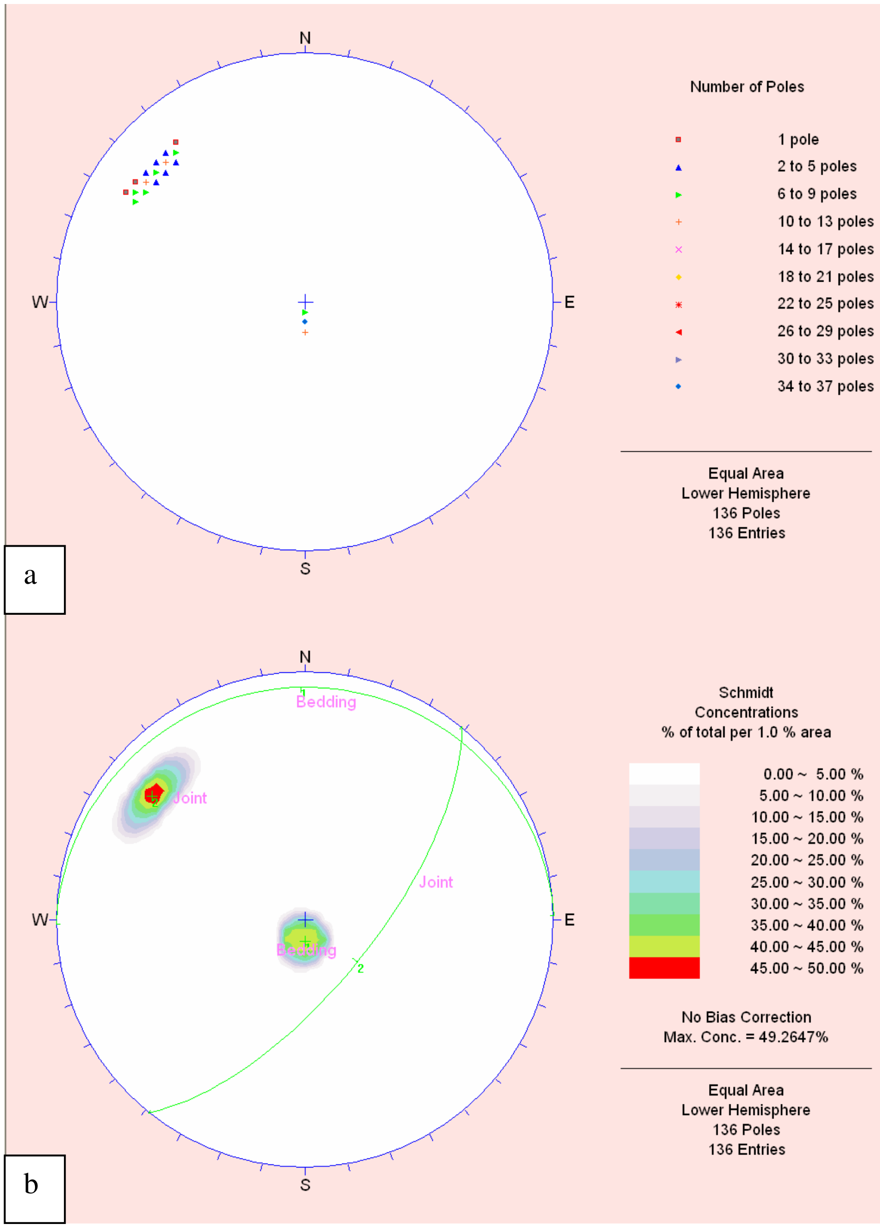


Figure 4.32 Pole plot (a) and contour plot (b) of the discontinuities in the Değirmençayı quarry.

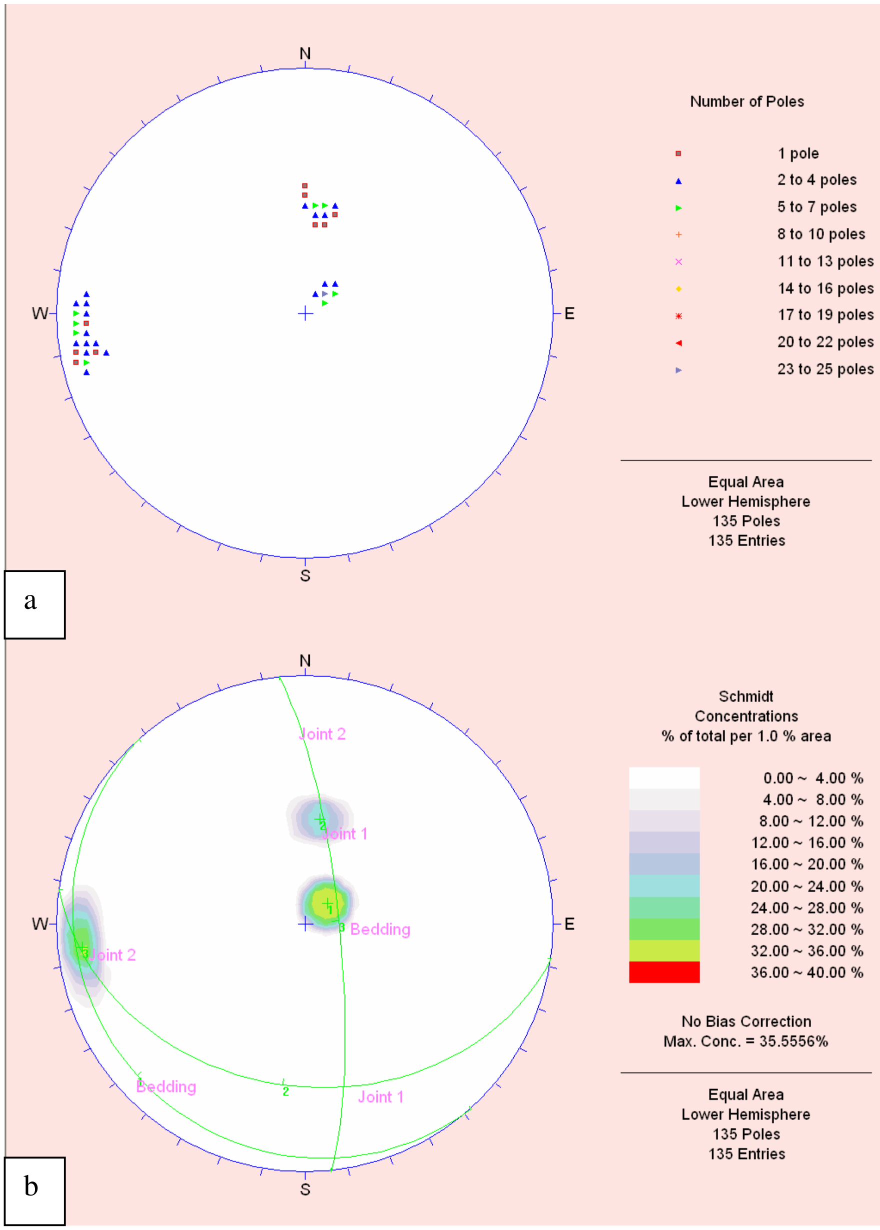


Figure 4.33 Pole plot (a) and contour plot (b) of the discontinuities in the Tirtar upper level quarry.

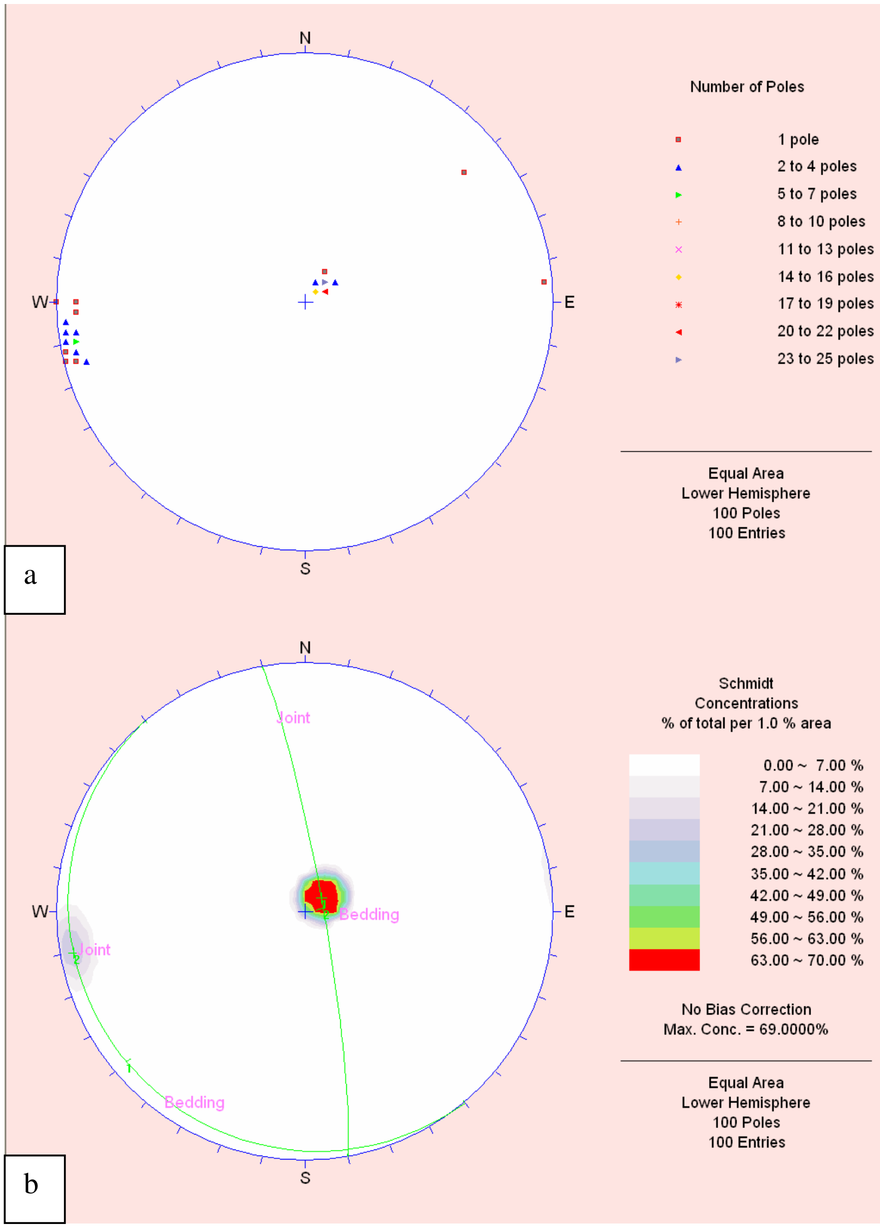


Figure 4.34 Pole plot (a) and contour plot (b) of the discontinuities in the Tirtar middle and lower level quarry.

Table 4.43 Properties of the discontinuities in the Değirmençayı limestone based on 136 measurements

DISCONTINUITY PROPERTIES	DEĞİRMENÇAYI LIMESTONE	
	Bedding Plane	**Joint 1**
Orientation	005/5	130/68
Spacing	60 cm-2 m (wide spacing)	2 m-10 m (very wide to extremely wide spacing)
Persistence	> 20 m (Very high persistence)	10 m -20 m (High persistence)
Aperture	0.1 mm-0.25 mm (Tight)	0.1 mm-0.25 mm (Tight)
Roughness	Rough planar	
Wall Strength	Strong	
Weathering	Slightly weathered	
Infilling	Clay	
Seepage	None	
Number of sets	2	
Block size (Max), (Min), (V_{80})*	(6) (0.6)(4.8)	
Volumetric joint count (J_v) (joints/ m^3)	Not applicable due to two discontinuity sets	
Block shape	Not applicable due to two discontinuity sets	

* assessed

Table 4.44 Properties of the discontinuities in the Tirtar upper level limestone based on 136 measurements

DISCONTINUITY PROPERTIES	**TIRTAR UPPER LEVEL LIMESTONE**		
	Bedding Plane	**Joint 1**	**Joint 2**
Orientation	225/10	190/36	085/80
Spacing	60 cm-2 m (wide spacing)	2 m-6 m (very wide spacing)	20 cm-2 m (moderate to wide spacing)
Persistence	> 20 m (Very high persistence)	10 m-20 m (High persistence)	3 m-10 m (Medium persistence)
Aperture	0.1 mm-3 m (Tight)	0.1 mm-3 m (Tight)	0.1 mm-3 m (Tight)
Roughness	Rough planar	Smooth planar	Rough planar
Wall Strength	Strong		
Weathering	Slightly to moderately to weathered		
Infilling	Clay		
Seepage	None		
Number of sets	3		
Block size (Max), (Min), (V_{80})*	(5) (0.5)(4.6)		
Volumetric joint count (J_v) (joints/ m^3)	0.7 very large blocks		
Block shape	blocky		

* assessed

Table 4.45 Properties of the discontinuities in the Tirtar miidle- lower level limestone based on 100 measurements

DISCONTINUITY PROPERTIES	**TIRTAR MIDDLE-LOWER LEVEL LIMESTONE**	
	Bedding Plane	**Joint 1**
Orientation	228/8	083/85
Spacing	20 cm-2 m (Moderate to wide spacing)	60 cm-2 m (Wide spacing)
Persistence	10 m- 20 m (High persistence)	1 m-3 m (Low persistence)
Aperture	<0.1 mm- 0.25 mm (Tight)	10 cm- > 1m (Extremely wide to cavernous)
Roughness	Rough planar	
Wall Strength	Medium strong	
Weathering	Slightly to moderately weathered	
Infilling	Clay	
Seepage	None	
Number of sets	2	
Block size (Max), (Min), (V_{80})*	(2.4) (0.07)(1.8)	
Volumetric joint count (J_v) (joints/ m^3)	Not applicable due to two discontinuity sets	
Block shape	Not applicable due to two discontinuity sets	

* assessed

4.3 Correlation of Physical and Mechanical Parameters After Durability Tests

In this part, effect of the durability tests on the physical and mechanical properties of the Değirmançayı and Tirtar limestone will be discussed. In order to correlate them, variation of each property of the Değirmençayı and Tirtar limestones after salt crystallization ($MgSO_4$) and freeze-thaw test and wet-dry tests are drawn (Figures 4.35, 4.36, 4.37 and 4.38).

In Degirmencayi limestone, if the weight (%) versus the number of each cycles test is drawn, it can be easily seen that similar changes are occurred at each cycle. weight (%), dry unit weight and saturated unit weight are not significantly affected from the durability tests. Porosity is increased as a similar order in each case. Nevertheless, salt crystallization gives rise to slightly higher weight losses although the samples are failed at earlier cycles compared to the other tests. Both water absorptions under atmospheric pressure and pressure increase as the number of the test cycles increases. However, the increase of water absorptions in salt crystallization ($MgSO_4$) is the highest. The UCS is significantly affected from the durability tests. The salt crystallization gives the highest reduction in strength if compared with the other tests. If sonic velocity versus the number of cycles for each durability test is drawn, noticeable changes are occurred at each cycle. In both salt crystallization and freeze-thaw test, sonic velocity values decrease by parallel to each other. It is clearly observed that salt crystallization is the most effective test, the freezing-thawing is the next most effective and wetting-drying is the least effective durability test for the Değirmençayı limestone (Figure 4.35).

In Tirtar upper level limestone, similar order is shown in the case of the weight (%), porosity, dry unit weight, saturated unit weight, water absorptions under atmospheric pressure and pressure after freeze-thaw and salt crystallization tests. On the other hand, if sonic velocities versus the number of cycles for each durability test is drawn, significant change in sonic velocity after all the tests is easily realized. The salt crystallization test gives higher damage to the limestone rather than freeze-thaw test. Freeze-thaw and wet-dry give almost equal damage to the Tirtar upper level limestone as reveal by the decrease in UCS and the increase in water absorptions under atmospheric pressure and pressure (Figure 4.36).

In Tirtar middle level limestone, except weight, dry unit weight and saturated unit weight , all the other properties are notably influenced from the durability tests. Through the porosity, water absorption values, the damage mostly occurred at the last cycles. Moreover, all the changes increase parallel to each other in two tests. Sonic velocity values are decreased in both tests. In addition, the damage is similar to each other. However, the salt crystallization gives more damage to the limestone in sonic velocity. It is quite interesting that similar reduction in the UCS of the limestone is recorded after the freeze-thaw and salt crystallization test. However, almost in last cycles salt crystallization gives more apparent damage to the limestone (Figure 4.37).

In Tirtar lower level limestone, if the weight (%) versus the number of each cycles test is drawn, it may be concluded that the salt crystallization gives slightly higher rise rather than freeze-thaw test. In the case of porosity, similar conclusions may be drawn. Dry and saturated densities are not significantly affected from the durability tests.

Nevertheless, the UCS is significantly affected from the durability tests. The salt crystallization gives highest reduction at the last cycles in strength if compared with the freezing-thawing and wetting-drying test. In sonic velocity, the similar reduction order is clearly observed. However, the salt crystallization test is again the most effective test to decrease the sonic velocity. The salt crystallization gives the most apparent damage to the stone in strength and in sonic velocity. The salt crystallization test deteriorates the limestone significantly whereas the wet-dry test gives no apparent damage to the limestone (Figure 4.38).

As a result, except dry unit weight and saturated unit weight all the other parameters are affected from the durability tests. It is clearly observed that weight, porosity, water absorption values, sonic velocity and uniaxial compressive strength values are changed through the cycle of the durability tests. They are mostly increased after 5 test cycles. Therefore, the weight losses and damages are increase as in similar order through the cycles. One can conclude that the order of damage to the limestone from the most effective to the least one is the salt crystallization, freeze-thaw and wet-dry tests. The sonic velocities and uniaxial compressive strength values indicate that the salt crystallization process is the most destructive test.

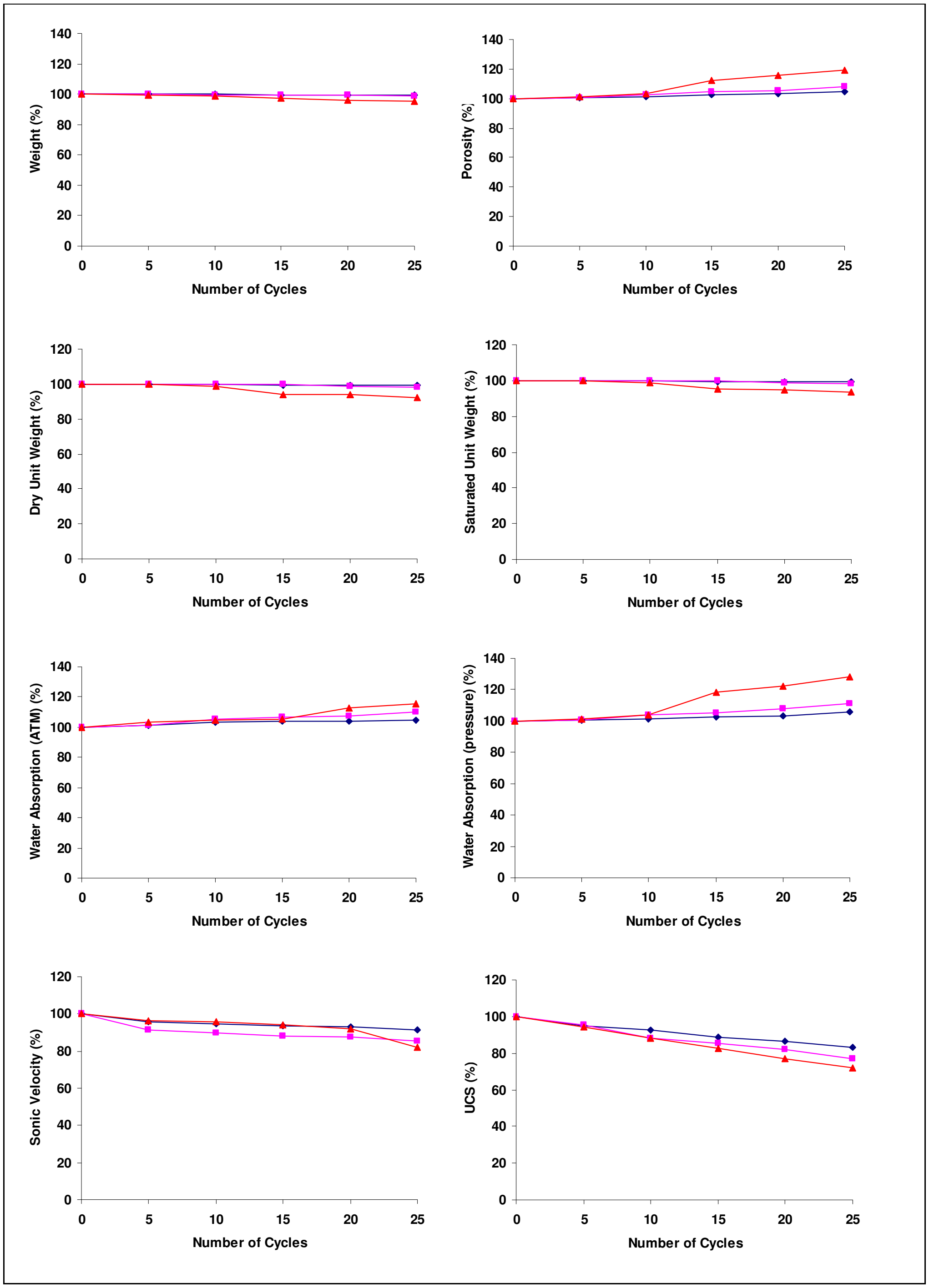


Figure 4.35 Effect of durability tests on the physical and mechanical properties of the Değirmançayı limestone (blue line shows wet-dry; pink line shows freeze-thaw and the red line shows salt crystallization test).

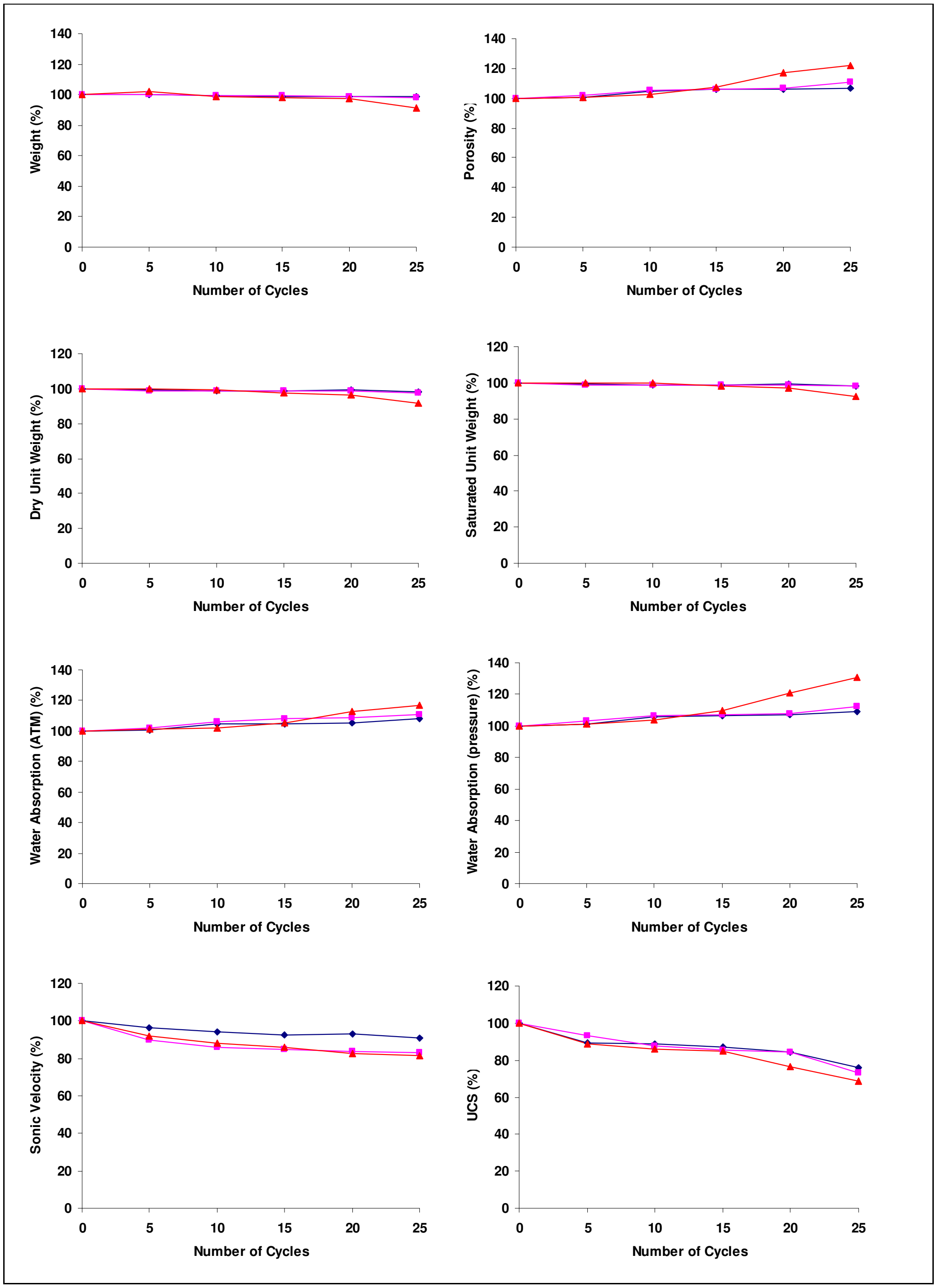


Figure 4.36 Effect of durability tests on the physical and mechanical properties of the Tirtar upper level limestone (blue line shows wet-dry; pink line shows freeze-thaw and the red line shows salt crystallization test).

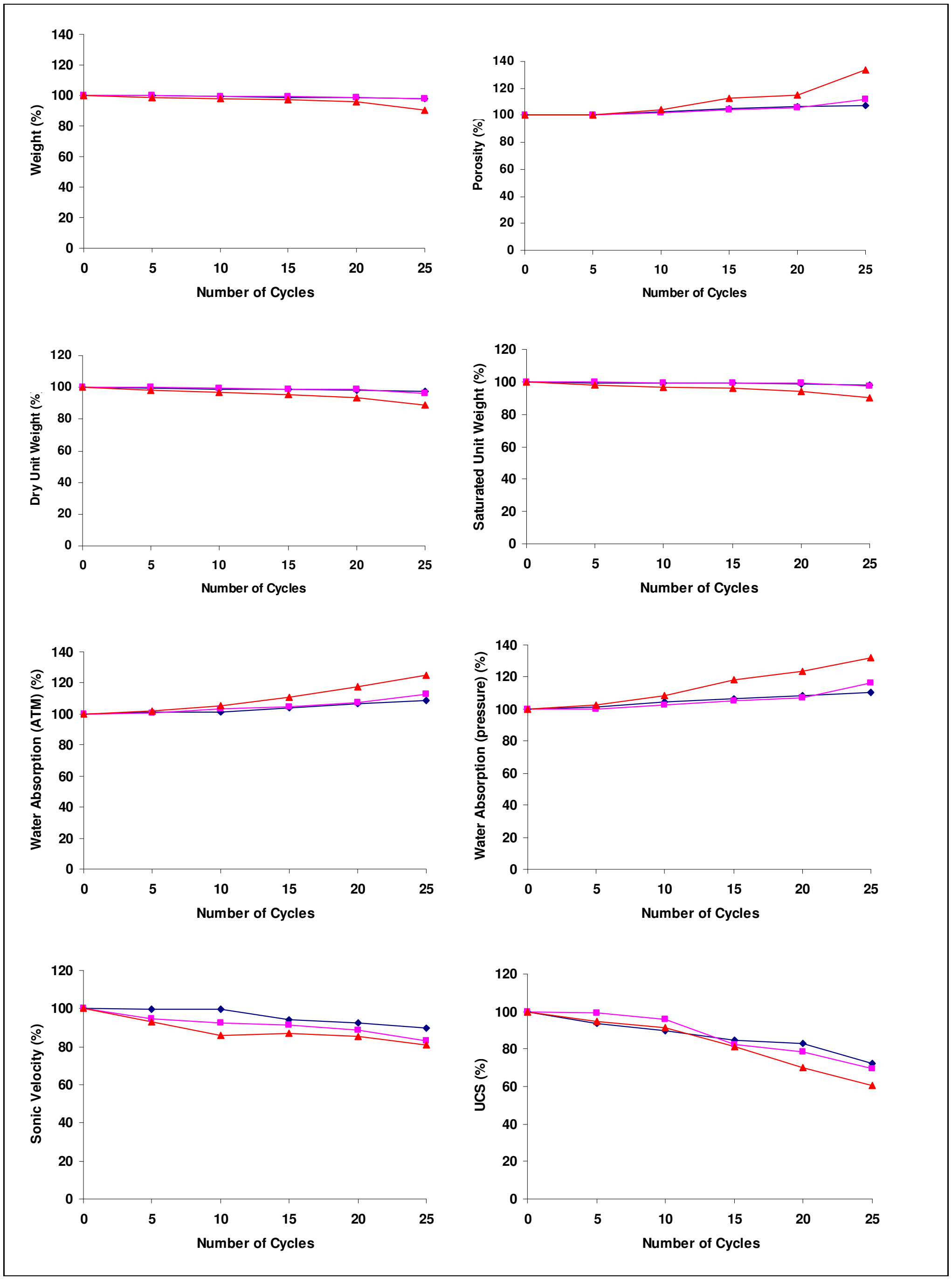


Figure 4.37 Effect of durability tests on the physical and mechanical properties of the Tirtar middle level limestone (blue line shows wet-dry; pink line shows freeze-thaw and the red line shows salt crystallization test).

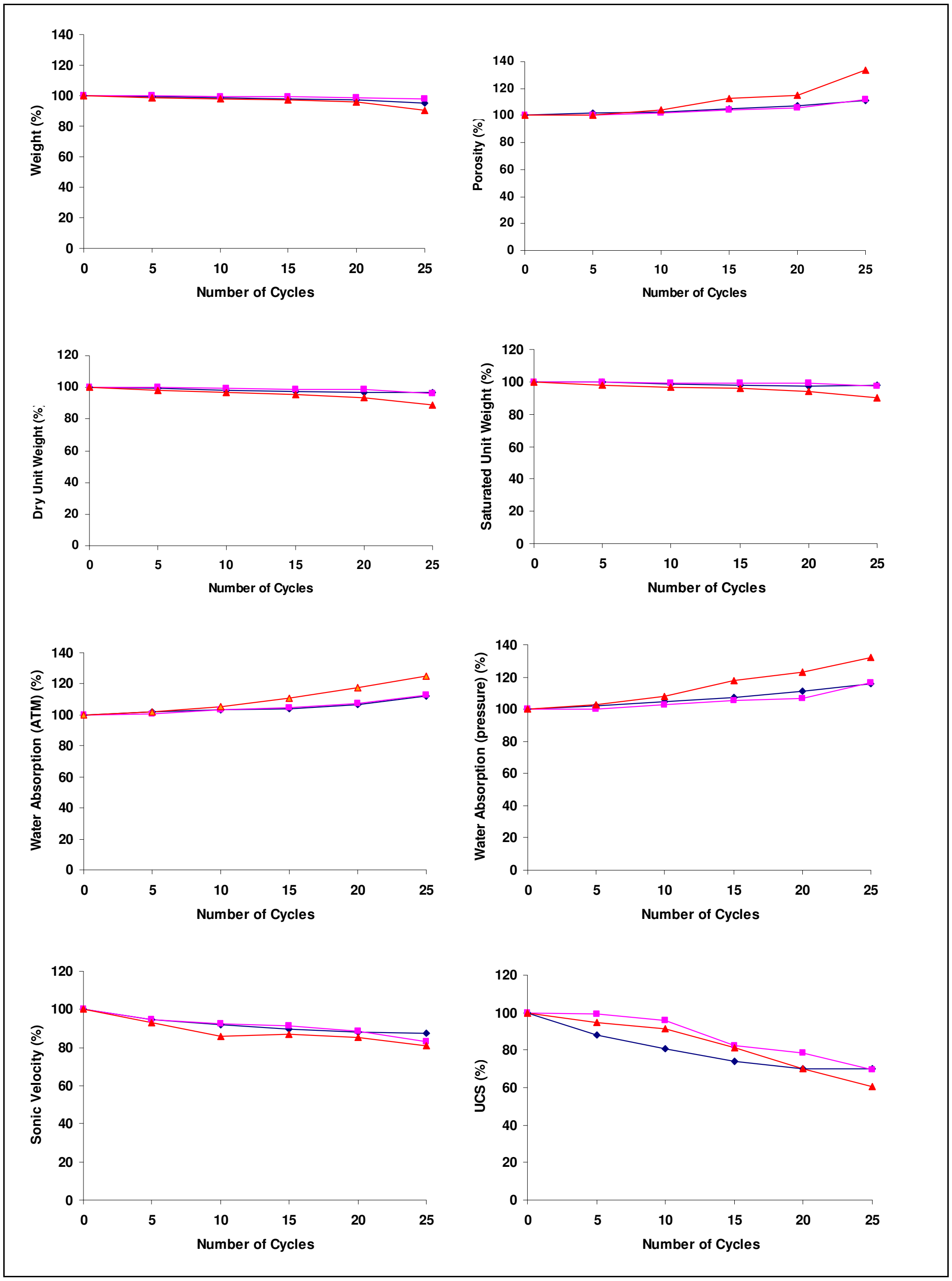


Figure 4.38 Effect of durability tests on the physical and mechanical properties of the Tirtar lower level limestone (blue line shows wet-dry; pink line shows freeze-thaw and the red line shows salt crystallization test).

CHAPTER V

QUALITY EVALUATION OF THE LIMESTONES AS ARMOURSTONE

It is important to establish the availability and quality of rock materials for a particular site at an early stage when considering design options. The requirements for rock, used in marine structures and particularly as armoring, are being both strong and durable. There are general reasons to find out its durability (Poole, 1991):

a) Assess the size, quality and usefulness of a new source of stone,

b) Ascertain whether the rock from a given source is changing or constant,

c) Compare the size and quality of stone from different sources,

d) Assess sample variability from within one source,

e) Predict the performance of material in service,

f) Ascertain that the rock characteristics satisfy a specification.

No single test can fulfill all these functions. The possible criteria for selecting a suitable suite of tests for material source evaluation and contract specification include. Quality assessment of an armourstone is the key point in order to confirm the long-term durability and the functionality of a rubble mound breakwater for various reasons:

a) Good quality armourstone should serve the sufficient amount of homogeneous rock blocks with requested size, geometry and strength parameters during the construction period. All of these mainly physical and less frequently chemical properties of the rocks are directly related to the geological setting.

b) One of the missing properties in the mentioned ideal armourstone can easily result in a major breakdown in the project. Neither the geometry nor the strength parameters would lead the project alone.

For this point of view, rock properties of armourstones are very important cases to assess the quality of the rock.

There is a different evaluation method for different types of natural stones used in industry. However, the performance of a rubble mound breakwater is directly related to the long-term structural durability of the used armourstone in coastal protection (Clark, 1988). This long-term durability is indicated based on both field observations and experimental laboratory data (CIRIA/CUR, 1991; Hoş, 1999; Smith, 1999 ; Şiş, 2000 ; Topal and Acır 2004). There are various methods and classification systems for geomaterials used in construction purposes however, a few of them are originally developed for coastal engineering structures (Lienhart and Stransky, 1981; Lienhart, 1994). Since coastal structures such as breakwaters are affected by long-term dynamic environmental conditions, their structural performances and durability classifications are peculiar (CIRIA/CUR, 1991).

In this thesis, the Değirmençayı limestone and the Tirtar upper, middle and lower limestones were investigated in terms of quality and durability. The quality and the durability of the armourstones are evaluated in detail on the basis of CIRIA/CUR (1991) criteria, the recently developed rating system for coastal engineering structures suggested by (Lienhart, 1998), the rock durability index of Fookes et al. (1998), saturation coefficient of Schaffer (1972), and wet-to-dry strength ratio of Winkler (1986). The results obtained are compared with the field performances of the four armourstones.

The Değirmençayı limestone was used for the construction of the Mersin harbour. Both upper and lower levels of the Tirtar limestone were used for the Kumkuyu breakwater. Among these, both Değirmençayı and Tirtar upper level limestones showed good performances in practice. However, the Tirtar middle and lower level limestones were almost totally disintegrated in the Kumkuyu breakwater.

5.1 CIRIA/CUR Classification

CIRIA/CUR (1991) classification is based on the laboratory and field tests of the armourstone. This system represents the outlines of the marginal values of rocks for different tests. In this study, the index properties of the armourstones are studied because the stone blocks are generally massive. Therefore, the comparison is only based on the laboratory test results. The strength-related parameters used for the classification belong to the saturated conditions. The CIRIA/CUR (1991) classification for the Değirmençayı limestone, Tirtar upper level limestone, Tirtar middle level limestone and Tirtar lower level limestone are given in Table 5.1, 5.2, 5.3 and 5.4. The CIRIA/CUR (1991) classification for the four limestones belonging to two quarries indicates that both the Değirmençayı and Tirtar upper level limestones are generally "**marginal to good** " in quality, whereas the Tirtar middle level limestone is **"poor to good"** and the Tirtar lower level limestone is **"poor to marginal".** These findings are in good agreement with the field performance of the armourstones.

Table 5.1 Quality evaluation system of the Değirmençayı limestone by (CIRIA/CUR, 1991)

Properties	CIRIA/CUR CRITERIA				
	Excellent	Good	Marginal	Poor	Değirmençayı limestone
Dry density (t/m^3)	≥2.9	2.6-2.9	2.3-2.6	≤2.3	2.42
Water absorption (%)	≤0.5	0.5-2.0	2.0-6.0	≥6.0	3.31
Magnesium sulphate soundness (%)	≤2	2-12	12-30	≥30	4.56
Freeze- Thaw (%)	≤0.1	0.1-0.5	0.5-2.0	≥2.0	1.25
Methylene blue absorption (g/100g)	≤0.4	0.4-0.7	0.7-1.0	≥1.0	0.30
Fracture toughness (MPa.m$^{1/2}$)	≥2.2	1.4-2.2	0.8-1.4	≤0.8	0.33
Point load strength index (MPa)	≥8.0	4.0-8.0	1.5-4.0	≤1.5	1.56
Saturated dynamic crushing value (%)	≤12.0	12-20	20-30	≥30	19.62
Mill abrasion resistance, k_s (%)	≤0.002	0.002-0.004	0.004-0.015	≥0.015	0.0039*
Block integrity drop test, I_d (%)	≤2	2-5	5-15	≥15	2-5**

* assessed from micro-deval test
** assessed from point load strength index test.

Table 5.2 Quality evaluation system of the Tirtar upper level limestone by (CIRIA/CUR, 1991)

Properties	CIRIA/CUR CRITERIA				Tirtar upper level limestone
	Excellent	Good	Marginal	Poor	
Dry density (t/m^3)	≥2.9	2.6-2.9	2.3-2.6	≤2.3	2.64
Water absorption (%)	≤0.5	0.5-2.0	2.0-6.0	≥6.0	3.54
Magnesium sulphate soundness (%)	≤2	2-12	12-30	≥30	8.59
Freeze- Thaw (%)	≤0.1	0.1-0.5	0.5-2.0	≥2.0	1.50
Methylene blue absorption (g/100g)	≤0.4	0.4-0.7	0.7-1.0	≥1.0	0.30
Fracture toughness ($MPa.m^{1/2}$)	≥2.2	1.4-2.2	0.8-1.4	≤0.8	0.32
Point load strength index (MPa)	≥8.0	4.0-8.0	1.5-4.0	≤1.5	1.52
Saturated dynamic crushing value (%)	≤12.0	12-20	20-30	≥30	29.25
Mill abrasion resistance, k_s (%)	≤0.002	0.002-0.004	0.004-0.015	≥0.015	0.0045*
Block integrity drop test, I_d (%)	≤2	2-5	5-15	≥15	2-5**

* assessed from micro-deval test
** assessed from point load strength index test.

Table 5.3 Quality evaluation system of the Tirtar middle level limestone by (CIRIA/CUR, 1991)

Properties	CIRIA/CUR CRITERIA				Tirtar middle level limestone
	Excellent	Good	Marginal	Poor	
Dry density (t/m^3)	≥2.9	2.6-2.9	2.3-2.6	≤2.3	2.22
Water absorption (%)	≤0.5	0.5-2.0	2.0-6.0	≥6.0	4.77
Magnesium sulphate soundness (%)	≤2	2-12	12-30	≥30	9.49
Freeze- Thaw (%)	≤0.1	0.1-0.5	0.5-2.0	≥2.0	1.95
Methylene blue absorption (g/100g)	≤0.4	0.4-0.7	0.7-1.0	≥1.0	0.43
Fracture toughness (MPa.m$^{1/2}$)	≥2.2	1.4-2.2	0.8-1.4	≤0.8	0.20
Point load strength index (MPa)	≥8.0	4.0-8.0	1.5-4.0	≤1.5	0.95
Saturated dynamic crushing value (%)	≤12.0	12-20	20-30	≥30	36.52
Mill abrasion resistance, k_s (%)	≤0.002	0.002-0.004	0.004-0.015	≥0.015	0.0079*
Block integrity drop test, I_d (%)	≤2	2-5	5-15	≥15	5-15**

* assessed from micro-deval test
** assessed from point load strength index test.

Table 5.4 Quality evaluation system of the Tirtar lower level limestone by (CIRIA/CUR, 1991)

Properties	CIRIA/CUR CRITERIA				
	Excellent	Good	Marginal	Poor	Tiratr lower level limestone
Dry density (t/m^3)	≥2.9	2.6-2.9	2.3-2.6	≤2.3	2.31
Water absorption (%)	≤0.5	0.5-2.0	2.0-6.0	≥6.0	5.58
Magnesium sulphate soundness (%)	≤2	2-12	12-30	≥30	23.14
Freeze- Thaw (%)	≤0.1	0.1-0.5	0.5-2.0	≥2.0	11.51
Methylene blue absorption (g/100g)	≤0.4	0.4-0.7	0.7-1.0	≥1.0	0.71
Fracture toughness ($MPa.m^{1/2}$)	≥2.2	1.4-2.2	0.8-1.4	≤0.8	0.14
Point load strength index (MPa)	≥8.0	4.0-8.0	1.5-4.0	≤1.5	0.65
Saturated dynamic crushing value (%)	≤12.0	12-20	20-30	≥30	47.21
Mill abrasion resistance, k_s (%)	≤0.002	0.002-0.004	0.004-0.015	≥0.015	0.00152*
Block integrity drop test, I_d (%)	≤2	2-5	5-15	≥15	5-15**

* assessed from micro-deval test
** assessed from point load strength index test.

5.2 Rock Durability Index

The factors affecting the rock durability in marine environments are mainly originated by the physical structure of the armourstone (Dibb et al., 1983). Rock durability index is one of the most commonly used approaches for analyzing the performance of geomaterials to be used in a coastal structure. The durability index is suggested by Fookes et al. (1988), and is included in CIRIA/CUR (1991). The method can be applied for both static and dynamic conditions that are valid for breakwaters. The static rock durability index (RDI_s) is better suite to under layer and core, whereas the dynamic rock durability index (RDI_d) is applied for armour layer. Static and Dynamic Rock Durability Indicators are both based on some of the laboratory parameters (Fookes, et al., 1998).

5.2.1 Static rock durability indicator

Static rock durability indicator RDI_s is expressed by (Fookes et al. (1988) as follows:

$$\mathbf{RDI_s = Is_{(50)} - 0.1(SST + 5\,W_{ab})\rho_{ssd}} \qquad \textbf{(5.1)}$$

Where;

Is $_{(50)}$: average of dry and saturated point-load strength index (ISRM, 1985)

SST : magnesium sulphate soundness test (Hosking and Tubey, 1969)

W $_{ab}$:water absorption (atm. pressure) (BSI, 1975; TS699 (1987)

ρ_{ssd} : saturated surface dry relative density (BSI, 1975; ISRM, 1981)

The water absorption test result is multiplied by an arbitrary factor of 5 in the above equation to bring the magnitudes of the variables into equivalent terms, and to emphasize its importance in assessing the durability of the rock. The point load strength index is used to give an assessment of the static strength of the material, and is especially useful where material is not subject to dynamic loading.

The magnesium sulphate soundness test is included to assess the ability of the material to resist some of the cyclic physical weathering processes, such as salt crystallization, heating-cooling, and possibly freezing-thawing (Fookes, et al., 1998). A tentative estimation of the potential durabilities of rocks based on the static rock quality index is given in Table 5.5.

Table 5.5 Tentative estimation of static rock durability (Fookes et al., 1988)

RDI_s value	**Durability**
> 2.5	**Excellent**
2.5 to (-1)	**Good**
(-1) to (-3)	**Marginal**
< (-3)	**Poor**

Based on the static rock durability classification (Table 5.5) and the calculated RDI_s values of the Değirmençayı limestone, Tirtar upper level limestone, Tirtar middle level limestone and Tirtar lower level limestone are – 3.63 (poor), - 2.56 (Marginal), - 6.69 (Poor), -11.69 (Poor), respectively (Table 5.6).

Table 5.6 Quality evaluation of the limestones according to RDI_s values.

Sample Name	**RDI_s value**	**Durability Class**
Değirmençayı limestone	-3.63	Poor
Tirtar upper level limestone	- 2.56	Marginal
Tirtar middle level limestone	- 6.69	Poor
Tirtar lower level limestone	- 11.69	Poor

5.2.2 Dynamic rock durability indicator

Dynamic rock durability indicator RDI_d is expressed by Fookes et al. (1988) as follows:

$$\mathbf{RDI_d = 0.1\ (MAIV + 5W_{ab}) / (\rho_{ssd})} \qquad \mathbf{(5.2)}$$

Where;

MAIV : modified aggregate impact value (Hosking and Tubey, 1969)
$\mathbf{W_{ab}}$: water absorption (atm.pressure) (BSI, 1975; TS699 (1987)
$\boldsymbol{\rho}_{\mathbf{ssd}}$: saturated surface dry relative density(BSI, 1975; ISRM, 1981)

In this equation, modified aggregate impact value is included. This is because the dynamic action of seawater causes impact to the stones. A tentative estimation of the potential durability of rocks based on the dynamic rock quality index is given Table 5.7.

Table 5.7 Tentative estimation of dynamic rock durability (Fookes et al., 1988)

RDI_d values	**Durability**
< 0.5	Excellent
0.5-2.0	Good
2.0-4.0	Marginal
> 4.0	Poor

Based on the dynamic rock durability classification (Table 5.7) and the calculated RDI_d values of the Degirmencayi limestone, Tirtar upper level limestone, Tirtar middle level limestone and Tirtar lower level limestone are 1.37 (Good), 1.06(Good), 2.28 (Marginal), 2.63 (Marginal), respectively (Table 5.8).

Table 5.8 Quality evaluation of the limestones according to RDI_d values.

Sample Name	**RDI $_d$ value**	**Durability**
Değirmençayı limestone	1.37	Good
Tirtar upper level limestone	1.06	Good
Tirtar middle level limestone	2.28	Marginal
Tirtar lower level limestone	2.63	Marginal

5.3 Rock Engineering Rating System

The recently suggested evaluation of armourstones is a straight- forward rating system, which contains various processes affecting armourstones (Lienhart, 1998). These processes are simply defined as decision matrix, which was created by Lienhart (1998) depending on his previous long-term professional experience and data. The author suggests that each matrix and their calculated values can be recreated depending on the site – specific conditions and the experience of the researcher. However, due to the worldwide acceptance of this method and availability of data on limited number of limestones in this thesis, the matrix-based values of the rating system are not modified.

To develop a specification system for the assessment of the potential quality of armourstone, the following criteria must be established:

a) Specific information related to the geology of the quarry and quarry operations that may affect rock quality
b) Specific information related to rock properties
c) Related to rock properties that may affect performance

d) Limits for the various qualities (excellent, good, marginal, poor) of rock.

Lienhart (1998) suggests that evaluation of quality of an armourstones consists of various complex processes. These processes consider inspection, production methods and testing steps with their related sub-factors. However, the entire process may be viewed as a combination of rock engineering matrices, in which the sum of all corresponded values is accepted as the overall rating. These are three main matrix groups (processes) that affect the quality of armourstones as follows:

Geological processes: Discontinuity geometry, hydraulic conditions, rock mass properties, in-situ stress, intact rock quality,

Production / Construction processes: Block integrity, degree of saturation, release of stored stress, quarried stone quality,

In-service processes: Petrological features, strength properties, density properties, rock durability.

The parameters used for these three processes are given in Tables 5.9, 5.10 and 5.11. In these tables, quality classes are divided into four classes. Cause–effect rating and index numbers for different parameters to be used for the rock engineering rating system of armourstones are given Table 5.12. For the use of rock engineering rating system, the quality specifications from Tables 5.9-5.13 should be evaluated, ranked such as “excellent, good, marginal or poor” are noted under the appropriate quality rating.

A numerical rating 4 (excellent), 3 (good), 2 (marginal), 1 or 0 (poor or less) should be entered into appropriate column of a worksheet. Here, a “0” rating means less than poor quality, may be assigned for a particular specification that the criterion will be especially detrimental to the long-term performance of armourstones produced from a potential source. The rating system suggests the use of average values of the ratings for strength, density and durability- related rock property criteria.

Depending on the performed laboratory test results with their weighted quality rating values and the calculated "index numbers" (these numbers are accepted as assigned constant values for this thesis), the overall rating value of the rock armour is calculated as follows;

Overall rating = ∑ (Quality rating* Index number) /n (5.3)

Where;

Quality rating is a value between 0-4 for each parameter, evaluated from Tables 5.9-5.11

Index number is obtained from Table 5.12 and n is the number of weighted rating. The overall rating is evaluated using the classification suggested in Table 5.13.

Table 5.9 Geological criteria affecting the performance of armourstones (Lienhart, 1998)

Criteria	Quality Specification			
	Excellent	Good	Marginal	Poor
Lithological classification	Unfoliated, coarsely crystalline igneous and metamorphic rocks, quartzite and highly silica cemented sandstone	Crystalline dolomite, limestone moderately well-cemented sandstone	Argillaceous limestones and sandstones, very vuggy dolomite reef rock, rhyolite and andesite	Shaly limestones, reef breccia, shale, schist, obsidian, pumice and gypsiferous carbonates
Regional *in situ* stress	Low stress, no folds or faults $\sigma_c/\sigma_1 > 200$	Medium stress. Unloading features may be present $\sigma_c/\sigma_1 = 200- 10$	High stress. Release fractures parallel to face may be present $\sigma_c/\sigma_1 = 10 - 5$	Very high stress. Faults may be present in quarry face. Rock bursts may be present in floor $\sigma_c/\sigma_1 = 5- 2.5$
Weathering grade	IA- fresh, unweathered	IB-faintly weathered (staining on major discontinuity surfaces)	II- slightly weathered (staining persists throughout a greater part of the rock mass)	III-moderately weathered (less than half the rock mass is decomposed)
Discontinuity analysis (in situ block size distribution)	$V_{80} < 7 ,> 4.5$ m^3	$V_{80} = 3 - 4.5$ m^3	$V_{80} = 0.6- 3$ m^3	$V_{80} < 0.6$ m^3
Groundwater conditions	Dry	Moist	Seepage from quarry walls	Water flowing from walls and pooling on floor

Table 5.10 Production and service criteria affecting the performance of armourstones (Lienhart, 1998)

Criteria	Quality Specification			
	Excellent	Good	Marginal	Poor
Production method	Cutting, challing or rock piercing methods – non-blasted	Specifically tailored blast using a single roe of blastholes (low specific charge using explosive with low shock energy, high gas energy; Bench height/burden = 2-3 Spacing/burden = < 1 Stemming/burden = >1 Blastholes diameter =50-76 mm	Conventional blasting using anfo and multiple rows of blastholes (bench height / burden = 1-2 ; Spacing/burden = 1- 1.5 Stemming/burden = 0.75-1 Blasthole diameter =76 -127 mm	Aggregate blasting with large size stone as a by product
Set -aside	Quarried stone is stockpiled for three months for curing and release of stored stress	Quarried stone is stockpiled for two months	Quarried stone is stockpiled for one months	Freshly quarried stone is transported directly to project site for placement
Quarried rock quality	Less than 5 % of blocks have a length to thickness ratio greater than 3 : 1.95 % of the blocks are weathering grade IA, dense, free of vugs and cavities and extremely high strength	5-10 % blocks have a length to thickness ratio greater than 3 : 1.95 % of the blocks are weathering grade IB or better , dense, free draining , very high strength	10-15 % blocks have a length to thickness ratio greater than 3 : 1.95 % of the blocks are at least weathering grade II,either microporous or vuggy with cavities dense, high strength	15 % blocks have a length to thickness ratio greater than 3 : 1.95 % of the blocks are at least weathering grade III, argillaceous or micaceous
Block integrity	> 95 % of blocks are free of incipient fractures, flaws or cracks due to stress relief, rough handling, overblasting or other causes after two months set-aside in stockpile	90-95 % of blocks are fracture- free after two months set-aside in stockpile	85- 90 % of blocks are fracture-free after two months set-aside in stockpile	< 85 % of blocks are fracture-free after two months set-aside in stockpile

Table 5.11 In-service criteria affecting the performance of armourstones (Lienhart, 1998).

PROPORTIES	**Quality Specification**			
	Excellent 4	Good 3	Marginal 2	Poor 1
Petrographic evaluation	*	*	*	*
Sonic velocity (km/s)	>6	4.5-6	3-4.5	<3
Point load strength(MPa)	>8.0	4.0-8.0	1.5-4.0	<1.5
Schmidt impact resistance	>60	50-60	40-50	<40
Los Angeles abrasion loss (%)	<15	15-25	25-35	>35
Specific gravity	>2.9	2.60-2.90	2.50-2.60	<2.50
Water absorption (%)	<0.5	0.5-2.0	2.0-6.0	>6.0
Adsorption/absorption	<0.1	0.1-0.3	0.3-0.45	>0.45
$MgSO_4$ soundness loss (%)	<2	2-10	10-30	>30
Freeze - thaw loss (%)	<0.1	0.1-0.5	0.5-2.0	>2.0
Wet-dry loss (%)	<0.1	0.1-0.5	0.5-2.0	>2.0

* assessed on the basis clay content, degree of fracturing and mineralogy

Table 5.12 Cause-effect rating and index numbers used in the rock-engineering rating system of armourstones (Lienhart, 1998).

Criteria	Cause-Effect Rating	Index number
Lithological classification	11.31	0.74
Regional in-situ stress	14.14	0.93
Weathering grade	14.14	0.93
Discontinuity analysis	18.38	1.20
Groundwater conditions	14.14	0.93
Production method	15.56	1.02
Rock quality	15.56	1.02
Set aside	13.43	0.88
Block integrity	15.56	1.02
Petrographic evaluation	18.38	1.20
Sonic velocity (km/s)	16.97	1.11
Point load strength(MPa)		
Schmidt impact resistance		
Los Angeles abrasion loss (%)		
Specific gravity	15.56	1.02
Water absorption (%)		
Adsorption/absorption		
$MgSO_4$ soundness loss (%)	15.56	1.02
Freeze - thaw loss (%)		
Wet-dry loss (%)		

Table 5.13 Rock armour classification based on rating system

Rating by proposed system	Class
4	Excellent
3	Good
2	Marginal
1	Poor

In this thesis, the in-situ stress and V_{80} values are assessed. Nevertheless, the other parameters are measured. In addition, the adsorption/absorption ratio is obtained from Mercury porosimetry test data. Based on the rock engineering rating system of Lienhart (1998), the overall ratings of the Değirmançayı limestone, Tirtar upper level limestone, Tirtar middle level limestone and Tirtar lower level limestone are given in Tables 5.14, 5.15, 5.16 and 5.17.

Based on rock engineering rating system of Lienhart (1998), the overall rating of the Degirmencayi limestone is 3.19 (good), the Tirtar upper level limestone 3.20 (good), the Tirtar middle level limestone 2.71 (marginal) and the Tirtar lower level limestone 2.48 (marginal), respectively.

Table 5.14 Quality rating assessment of the Değirmançayı limestone

Criteria	b) Quality rating Excellent = 4	Good = 3	Marginal = 2	Poor = 1	c) Rating value	d) Cause-effect rating	e) Index (d/d mean)	f) Weighted rating (c x e)
Lithological classification		√			3	11.31	0.74	2.22
Regional *in situ* stress	√				4	14.14	0.93	3.72
Weathering grade		√			3	14.14	0.93	2.79
Discontinuity analysis	√				4	18.38	1.20	4.8
Groundwater conditions	√				4	14.14	0.93	3.72
Production method		√			3	15.56	1.02	3.06
Rock quality		√			3	15.56	1.02	3.06
Set-aside		√			3	13.43	0.88	2.64
Block integrity		√			3	15.56	1.02	3.06
Petrographic evaluation	√				4	18.38	1.20	4.8
Sonic velocity		√			3	16.97	1.11	3.60
Point load strength		√			3			
Schmidt impact resistance		√			3			
LA abrasion	√				4			
Specific gravity				√	1	15.56	1.02	1.69
Water Absorption				√	1			
Adsorption/absorption		√			3			
MgSo4		√			3			
Freeze-thaw loss			√		2	15.56	1.02	2.37
Wet-dry loss			√		2	Mean = 15.28		**Overall rating =3.19**

Table 5.15 Quality rating assessment of the Tirtar upper level limestone

Criteria	b) Quality rating Excellent = 4	Good = 3	Marginal = 2	Poor = 1	c) Rating value	d) Cause –effect rating	e) Index (d/d mean)	f) Weighted rating (c x e)
Lithological classification		√			3	11.31	0.74	2.22
Regional *in situ* stress	√				4	14.14	0.93	3.72
Weathering grade		√			3	14.14	0.93	2.79
Discontinuity analysis	√				4	18.38	1.20	4.8
Groundwater conditions	√				4	14.14	0.93	3.72
Production method		√			3	15.56	1.02	3.06
Rock quality		√			3	15.56	1.02	3.06
Set-aside		√			3	13.43	0.88	2.64
Block integrity		√			3	15.56	1.02	3.06
Petrographic evaluation	√				4	18.38	1.20	4.8
Sonic velocity		√			3	16.97	1.11	2.75
Point load strength			√		2			
Schmidt impact resistance			√		2			
LA abrasion		√			3			
Specific gravity		√			3	15.56	1.02	2.71
Water Absorption			√		2			
Adsorption/absorption		√			3			
MgSo4		√			3			
Freeze-thaw loss			√		2	15.56	1.02	2.37
Wet –dry loss			√		2	Mean = 15.28		**Overall rating =3.20**

Table 5.16 Quality rating assessment of the Tirtar middle level limestone

Criteria	b) Quality rating							
	Excellent = 4	Good = 3	Marginal = 2	Poor = 1	c) Rating value	d) Cause-effect rating	e) Index (d/d mean)	f) Weighted rating (c x e)
Lithological classification		√			3	11.31	0.74	2.22
Regional *in situ* stress	√				4	14.14	0.93	3.72
Weathering grade			√		2	14.14	0.93	1.86
Discontinuity analysis		√			3	18.38	1.20	3.6
Groundwater conditions	√				4	14.14	0.93	3.72
Production method		√			3	15.56	1.02	3.06
Rock quality			√		2	15.56	1.02	3.06
Set-aside		√			3	13.43	0.88	2.64
Block integrity			√		2	15.56	1.02	2.04
Petrographic evaluation	√				4	18.38	1.20	3.6
Sonic velocity			√		2	16.97	1.11	2.49
Point load strength			√		2			
Schmidt impact resistance			√		2			
LA abrasion		√			3			
Specific gravity				√	1	15.56	1.02	2.04
Water Absorption				√	1			
Adsorption/absorption	√				4			
MgSo4		√			3	15.56	1.02	2.14
Freeze-thaw loss			√		2			
Wet –dry loss				√	1	Mean = 15.28		**Overall rating = 2.71**

Table 5.17 Quality rating assessment of the Tirtar lower level limestone

Criteria	b) Quality rating							
	Excellent = 4	Good = 3	Marginal = 2	Poor = 1	c) Rating value	d) Cause –effect rating	e) Index (d/d mean)	f) Weighted rating (c x e)
Lithological classification		√			3	11.31	0.74	
Regional *in situ* stress	√				4	14.14	0.93	3.72
Weathering grade			√		2	14.14	0.93	1.86
Discontinuity analysis			√		2	18.38	1.20	2.4
Groundwater conditions	√				4	14.14	0.93	3.72
Production method		√			3	15.56	1.02	1.02
Rock quality			√		2	15.56	1.02	1.02
Set-aside		√			3	13.43	0.88	0.88
Block integrity			√		2	15.56	1.02	1.02
Petrographic evaluation		√			3	18.38	1.20	2.4
Sonic velocity			√		2	16.97	1.11	1.6
Point load strength				√	1			
Schmidt impact resistance			√		2			
LA abrasion			√		2			
Specific gravity				√	1	15.56	1.02	2.37
Water Absorption				√	1			
Adsorption/absorption	√				4			
MgSo4			√		2	15.56	1.02	1.02
Freeze-thaw loss				√	1			
Wet –dry loss				√	1	Mean = 15.28		**Overall rating = 2.48**

5.4 Average Pore Diameter

Average pore diameter is considered to be an important parameter for the freeze-thaw durability of stones (Larsen and Candy, 1969). They stated that the critical pore size is 5 µm below which pore water can not be drained out of the stone. Therefore, stones having average pore size less than 5 µm are susceptile to frost damage.

The average pore diameters of the Değirmançayı and the Tirtar limestones are obtained from the intrusion data of the mercury porosimeter. They are 0.10 µm for the Değirmençayı limestone, 0.02 µm for the Tirtar upper level limestone, 0.13 µm for the Tirtar middle level limestone and 0.12 µm for the Tirtar lower level limestone. These results are showed that all samples are susceptile to frost damage.

5.5 Saturation Coefficient

Saturation coefficient (S) of a stone is the ratio between the natural capacity of a stone to absorb water after complete immersion under atmospheric pressure for a definite time, and its total volume of the pores that is accessible to water.

S = (water absorption / effective porosity) (5.4)

A stone with very high saturation coefficient may be deteriorated by freeze-thaw activity (RILEM, 1980). Therefore, this value will be helpful to evaluate the durability of the stone in freeze-thaw situation. The value of saturation coefficient can mostly vary between 0.4 and 0.95 (BRE, 1983). A saturation coefficient greater than 0.8, indicates low durability “susceptible to frost activity” (Hirschwald in Schaffer, 1912 and TSE, 1977). However, many stones have saturation coefficient in the range of 0.66 to 0.77. In this range, the saturation coefficient gives an unreliable guide (Anon, 1975 and BRE, 1983).

The saturation coefficient of the Degirmencayi limestone is 0.82. This value indicates that the Degirmencayi limestone has a low durability (susceptible to frost activity). The saturation coefficient of the Tirtar upper level limestone is

0.73. This value indicates that the Tirtar upper level limestone has a high durability (susceptible to frost activity). The saturation coefficient of the Tirtar middle limestone is 0.78, which is almost in the unreliable range and also in or near to frost susceptibility boundary corresponding to a value of 0.8. The saturation coefficient of the Tirtar lower level limestone is 0.95. This value indicates that the Tirtar lower level limestone has a low durability (susceptible to frost activity). Therefore, by a conservative approach, except the Tirtar upper level limestone, the Değirmançayı, Tirtar middle and lower level limestone may be considered to be frost susceptile based on the saturation coefficient. Especially, the Tirtar lower level limestone is effected from the freeze-thaw activity and has the highest saturation coefficient value corresponding to a low durability.

However, saturation coefficient by itself is not considered to be a reliable guide for durability (Schaffer, 1972; Robinson, 1984; Winslow, 1991 et al., 1988).

5.6 Wet –to- Dry Strength Ratio

Swelling and non-swelling clay in stone tends to attract water when exposed to moisture. The strength of the stone can be reduced significantly due to the presence of moisture. Winkler (1986 and 1993) suggested that the wet-to-dry strength ratio based on the modulus rupture or the uniaxial compressive strength or the tensile strength is a good and rapid method of testing the durability of a stone in use as a durability index. Approximate evaluation of the stone durability as a function of the wet-to-dry strength ratio is given in Figure 5.1.

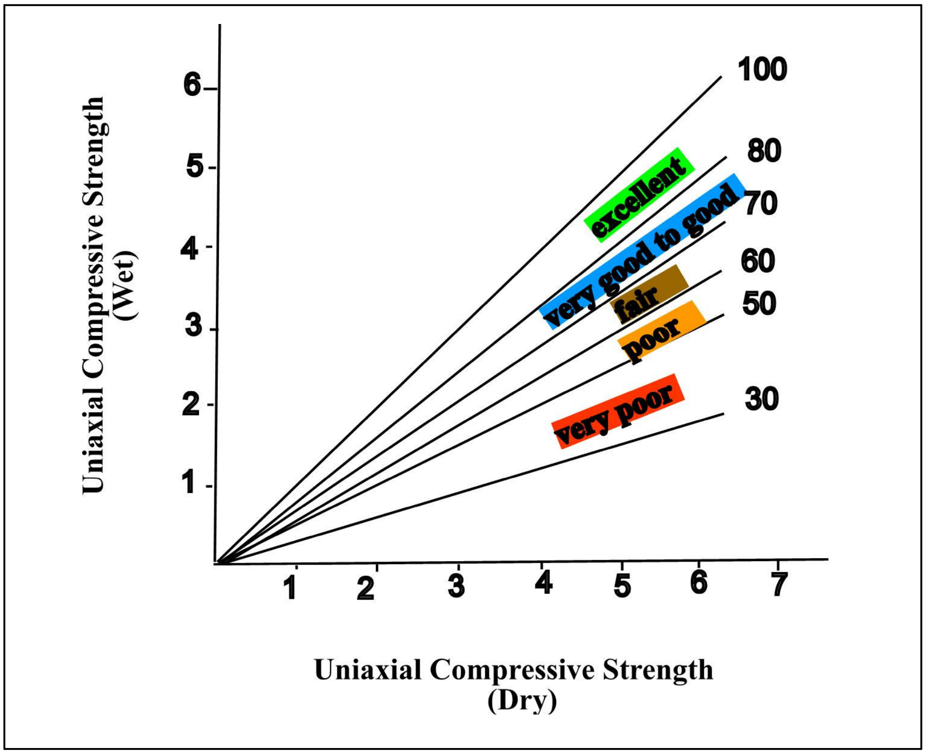


Figure 5.1 Durability evaluations of stone based on the wet-to-dry strength ratio (after Winkler, 1986).

In this study, the durability index of the Değirmançayı and the Tirtar limestones is evaluated based on the saturated and dry uniaxial compressive strength of the rocks. The wet wet-to-dry strength ratio of the Değirmançayı limestone, Tirtar upper level limestone, Tirtar middle level limestone and Tirtar lower level limestone is 0.75, 0.76, 0.67 and 0.62, respectively. This reveals that the Değirmençayı limestone has very good to good durability, Tirtar upper level limestone has very good to good durability, Tirtar middle level limestone has good durability and Tirtar lower level limestone has poor durability.

CHAPTER 6

GENERAL EVALUATION

In this section, the laboratory and field tests are overviewed to better understanding the quality and the expected behavior of the armourstones during their engineering life. In order to determine the index and mechanical properties of four limestones (Değirmançayı, Tirtar upper, Tirtar middle, Tirtar lower), effective porosity and unit weight, water absorption under atmospheric pressure and pressure, uniaxial compressive strength, point load strength index, Schmidt hammer rebound hardness, sonic velocity, slake durability index, methylene blue absorption test, wetting-drying test, freezing-thawing test, $MgSO_4$ sulphate soundness test Na_2SO_4 sulphate soundness test, Los Angeles test, Micro-Deval test, aggregate impact value test, modified aggregate impact value test, aggregate crushing value test, 10 % Fines value test, pore–size distribution test, are performed.

The Değirmançayı limestone is beige, thick bedded to massive, slightly weathered. The rock fragments embedded within calcareous matrix. The Değirmançayı limestone has one dominant joint set and a bedding plane. It is slightly weathered and no seepage is observed. Based on the test results, Değirmançayı limestone has medium porosity (9.62 %) and moderate dry density (2.42 Mg/m^3). Its water absorptions under atmospheric pressure and pressure averages are 3.31 % and 4.13 %. The limestone has moderately strong uniaxial compressive strength (35.70 MPa). Based on the slake durability index, this limestone has high durability after two cycles. The dry sonic velocity is in high class (4806.48 m/sec) and the saturated sonic velocity belongs to very high class (5219.69 m/sec). The schmidt rebound hardness value of dry and saturated specimens are 61 and 58. Calculated M.B.A value of the Degirmencayi limestone is 0.30 g r/100 gr. Dry and saturated LAV of the Degirmencayi limestone after 1000 revolutions, is recorded as 13.51 % and 14.82 %, respectively. Dry and saturated AIV of the Değirmançayı limestone after 1000 revolutions, is recorded as 16.79 % and 18.25 %, respectively.MAIV of the Değirmançayı limestone is 17. 84 % . Dry and saturated ACV is 18.11 % and 19.62 %. The average of % 10 Values of the Değirmançayı limestone in dry and saturated conditions are 255.52 kN and 222.14 kN.

The Tirtar upper level limestone is light brown, fine grained, thick bedded, slightly weathered. The limestone contains local solution cavities for the upper 1-2 m of the quarry. No dissolution effect can be observed below this level. The total thickness of the upper limestone level ranges between 4-6 m. It has two joint sets and one bedding plane. It is slightly to moderately weathered and no seepage is observed. Based on the test results, the Tirtar upper level limestone has low porosity (4.87 %) and high dry density (2.64 Mg/m^3). Its water absorptions under atmospheric pressure and pressure averages are 1.38 % and 1.88 %, respectively. The limestone has moderately strong uniaxial compressive strength (32.80 MPa). Based on the slake durability index, the limestone has medium high durability after two tests cycles. The dry sonic velocity is in very high class (5113.1m/sec) and the saturated sonic velocity belongs to very high class (5733.8 m/sec). The schmidt rebound hardness value of dry and saturated specimens are 52 and 48. Calculated M.B.A value of the Tirtar upper level limestone is 0.30 g r/100 gr. Dry and saturated LAV of the Tirtar upper level limestone after 1000 revolutions, is recorded as 16.2 % and 16.7 %, respectively. Dry and saturated AIV of the Tirtar upper level limestone after 1000 revolutions, is recorded as 18.13 % and 24.48 %, respectively.MAIV of the Tirtar upper level limestone is 21.71 %.

Dry and saturated ACV is 23.05 % and 29.25 %. The average of % 10 Values of the Tirtar upper level limestone in dry and saturated conditions are 236.44 kN and 171.86 kN.

The middle level limestone is beige to light brown. It is also fine grained. It is biomicritic limestone containing with nummilites. Microsparitic-sparitic limestone contains nummilites in the carbonate calcareous matrix. This level has one joint set and a bedding plane. Based on the test results, Tirtar middle level limestone has medium porosity (13.16 %) and moderate dry density (2.22 Mg/m^3). Its water absorptions under atmospheric pressure and pressure averages are 4.77 % and 6.02 %. The limestone has moderately strong uniaxial compressive strength (21.70 MPa). Based on the slake durability index, the limestone has medium high durability after two tests cycles. The dry sonic velocity is in moderate class (4303.5 m/sec) and the saturated sonic velocity belongs to high class (4045.6 m/sec). The schmidt rebound hardness value of dry and saturated specimens are 49 and 47. Calculated M.B.A value of the Tirtar middle level limestone is 0.43 g r/100 gr. Dry and saturated LAV of the Tirtar middle level limestone after 1000 revolutions, is recorded as 17.92 % and 18.13 %, respectively. Dry and saturated AIV of the Tirtar upper level limestone after 1000 revolutions, is recorded as 27.41 % and 31.13 %, respectively.MAIV of the Tirtar upper level limestone is 21.71 % . Dry and saturated ACV is 33.33 % and 36.52 %. The average of % 10 Values of the Tirtar upper level limestone in dry and saturated conditions are 169.20 kN and 123.09 kN.

Although the lower level of the quarry also consists of limestone, it is weaker than the upper level. It is light brown to beige, fine grained, slightly weathered, biomicritic limestone with some fossil fragments. Mainly it contains oolite and pisolite in sparitic calcite matrix. Tirtar lower level limestone has one dominant joint set and a bedding plane. It is slightly to moderately weathered and has no seepage. Based on the test results, the Tirtar lower level limestone has medium porosity (14.54 %) and moderate dry density (2.31 Mg/m^3). Its water absorptions under atmospheric pressure and pressure averages are 5.58 % and 6.43 %, respectively. The limestone has weak uniaxial compressive strength (14.70 MPa). Based on the slake durability index, the limestone has high durability after two tests cycles. The dry sonic velocity is in moderate class (3868.9m/sec) and the saturated sonic velocity belongs to high class (4287.4 m/sec). The schmidt rebound hardness value of dry and saturated specimens are 43 and 41. Calculated M.B.A value of the Tirtar lower level limestone is 0.71 g r/100 gr. Dry and saturated LAV of the Tirtar upper level limestone after 1000 revolutions, is recorded as 27.77 % and 32.8 %, respectively. Dry and saturated AIV of the Tirtar upper level limestone after 1000 revolutions, is recorded as 33.26 % and 39.37 %, respectively.MAIV of the Tirtar upper level limestone is 21.71 % . Dry and saturated ACV is 37.15 % and 47.21 %. The average of % 10 Values of the Tirtar upper level limestone in dry and saturated conditions are 151.57 kN and 96.19 kN.

The ageing tests (wet-dry, freeze-thaw, $MgSO_4$) performed on four different limestones reveal that $MgSO_4$ gives the most damage, followed by freeze-thaw. Nevertheless, wet-dry gives the least damage to the samples. Among the limestones, the Değirmançayı and Tirtar upper limestones are more resistant to the ageing tests than the Tirtar middle and lower limestones.

The results of the durability assessments based on laboratory test results are summarized in Table 6.1. As can be seen from Table 6.1, different durability assessment methods give different results. However, the field observations by checking the performances of the armourstones in two harbours indicate that Tirtar middle and lower limestones were readily disintegrated after a few months. For this reason, they are not used anymore. Therefore, they have poor performances. On the other hand, the Değirmançayı and Tirtar upper level limestones showed rather good performances. They are still in use.

Table 6.1 Durability assessment of the limestones using various methods

Armourstone	CIRIA/ CUR*	RDI_s *	RDI_d*	RERS*	Average Pore Diameter*	Sat. Coef.*	Wet-to-Dry Strength Ratio*
Değirmençayı	**M-G**	**P**	**G**	**G**	**P**	**P**	**VG-G**
Tırtar Upper	**M-G**	**M**	**G**	**G**	**P**	**M**	**VG-G**
Tırtar Middle	**P-G**	**P**	**M**	**M**	**P**	**M**	**M**
Tırtar Lower	**P-M**	**P**	**M**	**M**	**P**	**P**	**P**

*VG-very good; G-good; M-marginal; P-poor

The comparison between varies laboratory-based durability and field performances reveal that CIRIA/CUR, RDI_d, RERS, and wet to dry strength ratio predict the armourstone durability better than $RDI_{s,}$ Average pore diameter and saturation coefficient.

As a general evaluation, CIRIA/CUR, RDI_d, RERS, and wet to dry strength ratio are in good agreement with the field performance of the armourstones (Figures 6.1, 6.2, 6.3, 6.4 and 6.5). No significant further deterioration is expected for the Değirmançayı and Tirtar upper level limestones in the harbors. However, Tirtar middle and lower level armourstones with poor field and laboratory performances should not be used for the protection of any marine structures. This study reveals that systematic testing and quality evaluation procedures are very useful in predicting the long-term performances of the armourstones.

Figure 6.1 A close-up view of the Değirmençayı limestone samples in Mersin harbour.

Figure 6.2 Limesstone blocks used in the Mersin harbour with wetting-drying effects after 1 year.

Figure 6.3 A close-up view of the Tirtar upper level limestone used in Kumkuyu harbour.

Figure 6.4 Limestone blocks used in Kumkuyu harbour with dissolution effects after 1 year.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

Four limestones were used as armourstones in Mersin and Kumkuyu harbours. However, the Değirmançayı and Tirtar upper level limestones showed good performances whereas the Tirtar middle and lower level limestone presented rather poor performances in the field. Some index tests performed in this study were used to assess the quality of the armourstones and to compare field and laboratory performances of the rocks. Based on the test results, the following conclusions are drawn:

1. The Değirmançayı limestone is beige, thick bedded to massive, slightly weathered. Under the microscope, locally clayey lenses or veins are observed within the rock. The limestone also contains solution cavities near the surface. The Tirtar upper level limestone is light brown, fine grained, thick bedded, slightly weathered. The limestone contains local solution cavities. The Tirtar middle level middle level limestone is beige to light brown. It is also fine grained. It is microsparitic-sparitic limestone. The Tirtar lower level limestone is light brown to beige, fine grained, slightly weathered, biomicritic limestone with some fossil fragments. Mainly it contains oolite and pisolite in sparitic calcite matrix with light yellowish beige fresh surface color.
2. All limestones yield block sizes suitable for the use as armourstone.
3. The Değirmançayı limestone is considered as having medium porosity and moderate unit weight. However, the Tirtar upper level limestone has low porosity and high unit weight; the Tirtar middle level has medium porosity

and moderate unit weight; and the Tirtar lower level has medium porosity and moderate unit weight**.**

4. The Değirmançayı, the Tirtar upper level and the Tirtar middle level limestones are moderately strong in both dry and saturated state. However, the Tirtar lower level limestone is weak strength in both dry state and saturated states.
5. The ageing test results indicate that the Değirmançayı and Tirtar upper level limestones are more resistant to salt crystallization, freezing-thawing and wetting-drying than the Tirtar middle and lower level limestones.
6. Among the durability assessment methods, CIRIA/CUR, RDI_d, RERS, and wet to dry strength ratio give better results if compared with their field performances of the limestones. However, RDIs, average pore diameter, and saturation coefficient are not.

Based on the test results and the expreince gained in this study, the followings are recommended:

1. There is a need to have more systematic tests results on varies rock types with their field performances from all over the world. Therefore, further studies on other rock types with known performances may help the engineers to suggest new durability evaluation methods which may better predict the long term stone durabity.
2. In Turkey, the density (2.2 g/cm^3) is the only parameter to use for the selection of the armourstone. As can be seen from this study, may parameters should be used together. Otherwise, one can come up with misleading information. Therefore, the armourstone selection criterion in Turkey should be revised and systematic testing and evaluation should be considered.

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