QUALITY ASSESSMENT OF THE ARMOURSTONES FOR SOME BLACK SEA RUBBLE MOUND BREAKWATERS

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Approval of the Graduate School of Natural and Applied Sciences.

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ABSTRACT

QUALITY ASSESSMENT OF THE ARMOURSTONES FOR SOME BLACK SEA RUBBLE MOUND BREAKWATERS

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Black Sea coast line is a hazardous region especially in winter due to the dominant wave action. Therefore, rubble mound breakwaters used as ship shelters are vital structures especially for the fishermen. Construction of the breakwater requires good quality durable armourstones. Due to the nature of the rubble mound breakwaters, armourstones having various sizes and types are used in the construction of these structures. The deterioration of these armourstones with time in the form of abrasion and disintegration may result in the failure of the breakwater. Therefore, it is important to investigate the durability and quality of the armourstones to be used in these structures.

In this thesis, the properties of the armourstones taken from five rock quarries and used in the Hisarönü (Bartın), the Tarlaağzı (Bartın) and the Alaplı (Zonguldak) rubble mound breakwaters were studied both in field and laboratory in order to assess their qualities and long term durabilities.

Based on the in-situ observations and laboratory tests, the Kavakdere, Kavukkavlağı and the Tarlaağzı limestones are good (durable) rocks. However, the Çömlekçikuyu andesite is found to be generally marginal rock, and the Kıran sandstone is poor rock. CIRIA/CUR, RDI_d, RERS and Wet-Dry strength ratio classifications are in good agreement with the in-situ observations and the results of the laboratory tests. However RDI_s, Average Pore Diameter and Saturation Coefficient classifications do not fully reflect the reality.

Keywords: Armourstone, Bartın, Durability, Quality, Rubble mound breakwater, Zonguldak

ÖZ

BAZI KARADENİZ KAYA DOLGU DALGAKIRANLARI İÇİN ANROŞMANLARIN KALİTE DEĞERLENDİRMESİ

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Baskın dalga etkisi yüzünden özellikle kış aylarında, Karadeniz kıyı şeridi oldukça tehlikeli bir bölgedir. Bu nedenle, gemi barınağı olarak kullanılan kaya dolgu dalgakıranları özellikle balıkçılar için hayati önem taşıyan yapılardır. Dalgakıranın inşaatı için iyi kalite ve dayanıklı anroşman gerekmektedir. Kaya dolgu dalgakıranlarının doğası gereği, bu yapıların inşasında değişen boylarda ve tipte anroşman kullanılır. Bu anroşmanlarda zaman içinde oluşabilecek önemli miktarda aşınma ve parçalanma, dalgakıranın ciddi hasarlar görmesine neden olabilmektedir. Bu nedenle, dalgakıranlarda kullanılan anroşmanın dayanımının ve kalitesinin belirlenmesi önemlidir.

Bu tezde, kalitelerinin ve uzun dönem dayanımlarının belirlenmesi için beş farklı taş ocağından alınan ve Hisarönü (Bartın), Tarlaağzı (Bartın) ve Alaplı (Zonguldak) kaya dolgu dalgakıranlarında kullanılan anroşmanların özellikleri hem arazi hem de laboratuvar ortamında incelenmiştir.

Yapılan arazi ve laboratuvar çalışmaları sonucunda, Kavakdere, Kavukkavlağı ve Tarlaağzı kireçtaşları iyi (dayanıklı); öte yandan Çömlekçikuyu andezitinin orta derecede, Kıran kumtaşının ise zayıf olduğu bulunmuştur. CIRIA/CUR, RDI_d, RERS ve ıslak-kuru dayanım oranı sınıflandırmalarının arazi gözlemleri ve laboratuar sonuçlarıyla uyumlu olduğu görülmüştür. Öte yandan RDI_s, ortalama gözenek çapı ve donma katsayısı sınıflandırmaları tam olarak gerçeği yansıtmamaktadır.

Anahtar Kelimeler: Anroşman, Bartın, Dayanıklılık, Kalite, Kaya dolgu dalgakıran, Zonguldak

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To my father;

Hasan Özden

CHAPTER 1

INTRODUCTION

1.1. Purpose and Scope

The coast has for many centuries been an area of importance for human development. It is attractive in terms of its flat, fertile land, as base for transport by boat and as a base of fishing (Thomas, 1998). However, in order to benefit from the sources of the coast, the protective coastal engineering structures are needed. Today many coastal engineering structures are being used or being constructed along the coasts of the world. According to Poole (1991), the structures should meet the following three requirements: (a) they must satisfy the objective at the particular location, (b) they must satisfy the local economic constraints, (c) the selected design solution must take account of the construction materials available.

By their nature these typically extensive linear structures involve very large quantities of material hence armourstone (natural quarried rock) is usually the most economical choice. In addition, according to Thomas (1998), there is a strong demand to build environmentally compatible and sustainable coastal defenses and the use of natural materials such as rock and beach-fill (sand and gravel) is one of the potentially environmentally acceptable options.

The armourstones excavated from a quarry as huge blocks are placed to the construction site. The armourstones can be as small as 50 kg where wave energy is low, or as large as 30 ton where the water is deep and wave energy is very large (Erickson, 1993).

The issue of durability of an armourstone relates to the properties of the rock from which it is derived, the environment to which it is exposed, the loads that are applied to it, and the method by which it was extracted from the source and then handled prior to final placement.

The 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 weak planes within the rock and the existence of micro cracks (Magoon and Baird, 1992). In time, depending on these properties and due to the influence of the external forces, the material can loose its quality. This situation directly affects the durability of the coastal structure and in long term the economy of the region. On the other hand, the durability of a single breakwater is not only a result of geo-material properties itself, but also the interaction conditions between the dynamic environment and the rock, based on the selected material. Interaction between the wave, seabed and the breakwater is a vital issue in marine geotechnical engineering (Jeng et al., 2001; US Army Corps of Engineers, 2003)

Similarly in Turkey, harbors, breakwaters and ship shelters that have great importance in navigation and fishery have generally been constructed by using armourstones (natural stones) due to their economic feasibility. Especially in Black Sea region where in winter harsh climatic conditions and dominant wave influence are observed, these kinds of structures are under a great amount of risk.

Alaplı, Hisarönü and Tarlaağzı rubble mound breakwaters are good examples of such structures used as ship shelters. They are all located at Western Black Sea coast between Zonguldak and Bartın, and are subjected to harsh climatic conditions especially in winter (Figure 1.1a). Sometimes these conditions may result in serious damage to the breakwater (Figure 1.1b).

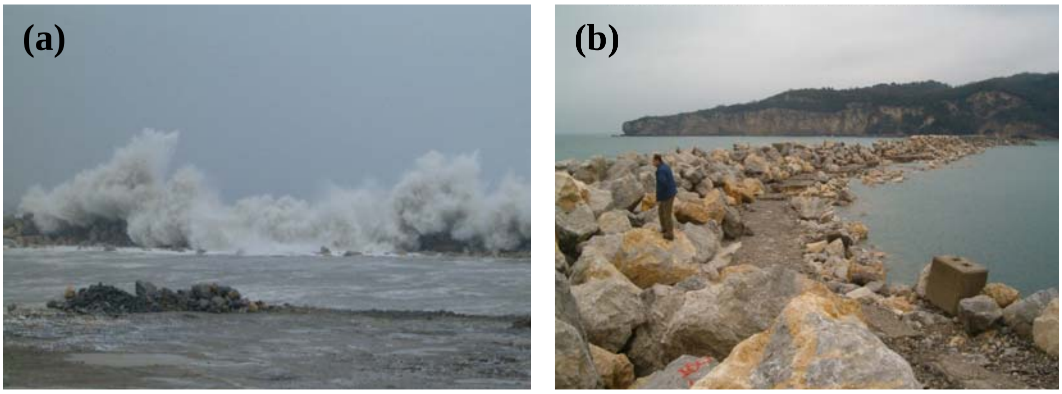


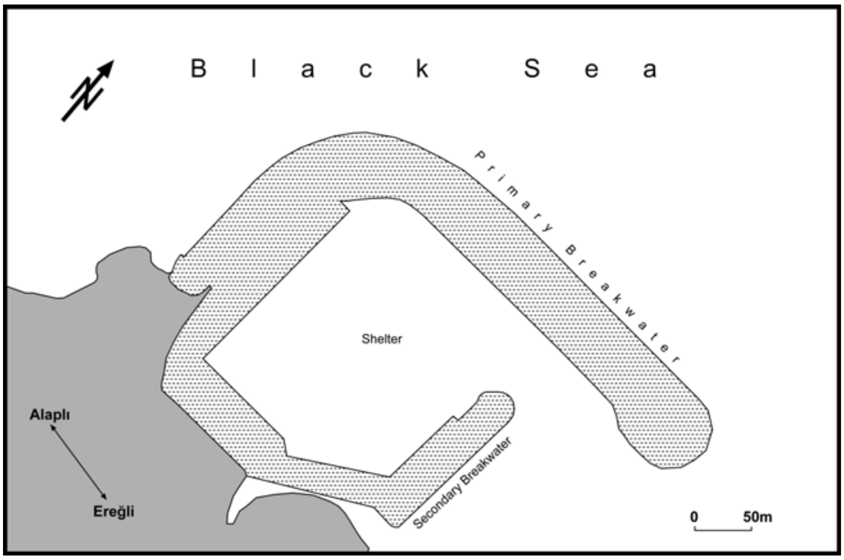
Figure 1.1 A destructive five meter high wave impacting the Tarlaağzı ship shelter as a result of the February 2004 storm (a) and the resulting damage at the shelter (b)

The main component of these three breakwaters is the armourstone; however some cubical concrete blocks weighing between 15-20 tons are also used at the primary armour layer of the breakwaters for additional support (Figure 1.2).

Figure 1.2 The cubical concrete blocks used in Hisarönü ship shelter as additional support.

Alaplı ship shelter which has a 505 m long primary breakwater is one of the latest projects of DLH in Turkey (Figure 1.3 a, b). It is located at Alaplı town of Zonguldak. The armourstones for this shelter are supplied from Kavakdere quarry (Kıyıcak village-Alaplı) (Figure 1.4) and Kavukkavlağı quarry (Ortacı village-Alaplı) (Figure 1.5). The source rock in both of the quarries is limestone.

(a)



(b)

Figure 1.3 Plan sketch of the Alaplı ship shelter (DLH, 2002) (a) and a panoramic view from the shelter (b)

Figure 1.4 Photograph of the Kavakdere quarry

Figure 1.5 Photograph of the Kavukkavlağı quarry

Hisarönü ship shelter is the second breakwater to be investigated. It is located at Hisarönü district of Zonguldak, and has 750 m long primary breakwater (Figure 1.6 a, b). The armourstone for this shelter is supplied from the Çömlekçikuyu quarry (Çömlekçi köyü-Filyos) (Figure 1.7) and is andesite.

(a)

(b)

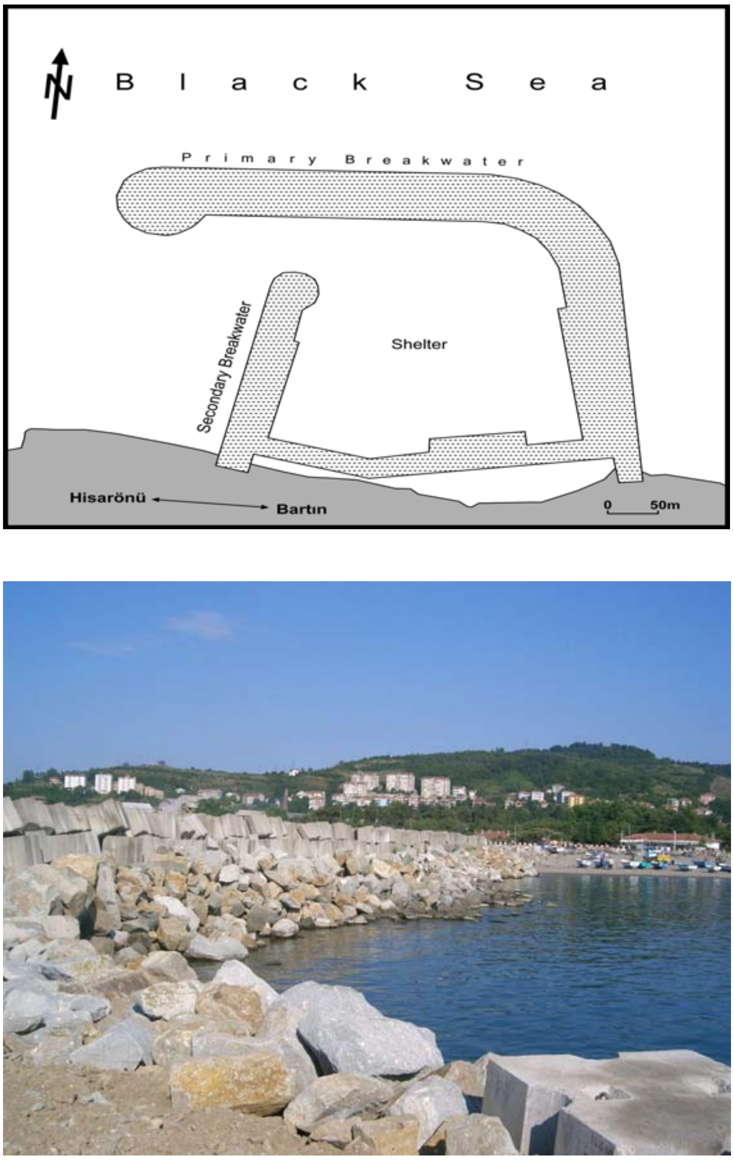
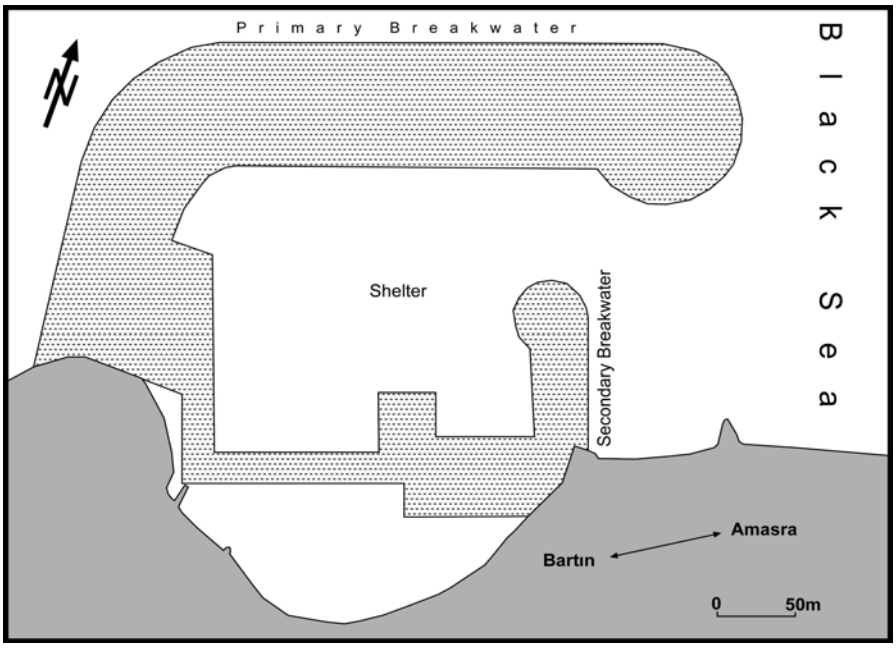


Figure 1.6 Plan sketch of the Hisarönü ship shelter (DLH, 2002) (a) and a panoramic view from the shelter (b)

Figure 1.7 Photograph of the Çömlekçikuyu quarry

Tarlaağzı ship shelter is the last breakwater to be investigated. It is located near Amasra town of Bartın and has 620 m long primary breakwater (Figure 1.8 a, b). The armourstone for this shelter is supplied from Tarlaağzı quarry (Figure 1.9) and is limestone.

(a)



(b)

Figure 1.8 Plan sketch of the Tarlaağzı ship shelter (DLH, 2002) (a) and a panoramic view from the shelter (b)

Figure 1.9 Photograph of the Tarlaağzı quarry

Finally, a potential armourstone quarry which is considered for the ongoing projects is located at Kıran district of Zonguldak. The source rock of this quarry is sandstone (Figure 1.10).

Figure 1.10 Photograph of the Kıran district

The purpose of this thesis is to investigate the above mentioned five quarries and their source rocks and to asses the applicability of the durability methods in order to evaluate the rock quality and durability which will create a guide for the future use of these materials in breakwaters.

In order to accomplish this task detailed field and laboratory studies were carried out. Field studies included detailed discontunity surveys at the quarries, and various laboratory tests were conducted in order to simulate the natural processes acting on the armourstones. As a result, the findings were evaluated on the basis of different classification and rating systems in order to asses the rock quality and durability.

1.2. Location and Physiography

The thesis covers three different study areas. These are Alaplı, Hisarönü (Zonguldak) and Amasra (Bartın) regions (Figure 1.11).

Kavakdere and Kavukkavlağı quarries are located in Alaplı region. The east-west trending coastal highway is the major connection line with the Alaplı breakwater and Zonguldak. The access to the quarries is achieved by stabilized roads that are connecting to the highway. The region is generally covered by high hills trending in East-West direction, and a dense vegetation cover is observed throughout the hills. Alaplı stream is the major streams in the area that discharges to Black Sea from Alaplı.

Çömlekçikuyu quarry and Kıran districts are located in the Hisarönü region. Likely, the east-west trending coastal highway is the major connection line between the Hisarönü breakwater and Zonguldak. The Kıran district is located just a few kilometers away from the highway and access to the Çömlekçikuyu quarry is achieved by a stabilized road connecting to the highway. Topography in the region is generally rough; however some plains exist along the Filyos stream. At these plains, gentle topography which is suitable for agriculture exists. Although the surroundings of the Filyos stream are flat at some localities, mainly undulating topography is observed. Filyos stream is the major stream in the area that discharges to the sea from Hisarönü.

Lastly Tarlaağzı quarry is located in the Amasra region. A stabilized road is the main connection to the Tarlaağzı breakwater. Among the other quarries, Tarlaağzı is the nearest quarry to its breakwater. The stabilized road to the quarry is connected to the Bartın-Amasra road.

Figure 1.11 Location map of the study area

1.3. Climate and Vegetation

Both in Zonguldak and Bartın, temperate climate (Black Sea climate) is observed where summers are hot and the winters are cool. There is dominant rain in the region throughout the year. The meteorological data of Bartın and Zonguldak between the years 1975-2005 are given in Table 1.1 and 1.2.

Table 1.1 Meteorological data of Bartın between the years 1975-2005 (DMİ, 2006)

Average Annual Temperature (°C)	12.5
Average Annual Temperature ≥ 20 °C (days)	177.9
Average Annual Temperature ≤ -0.1 °C (days)	52.0
Average Annual Snow Cover (days)	21.3
Average Annual Frost (days)	37.9
Average Annual Total Precipitation (mm)	1030.0
Average Annual Solar Radiation Time (hr:mnt)	5:42
Average Annual Local Pressure (hPa)	1013.3
Average Annual Vapor Pressure (hPa)	12.3
Average Annual Relative Humidity (%)	78
Average Annual Wind Speed (m/s)	1.4
Avg. Ann. Stormy Days (wind spd ≥ 17.2 m/s)	2.2
Observation Time (years)	31

Table 1.2 Meteorological data of Zonguldak between the years 1975-2005 (DMİ, 2006)

Average Annual Temperature (°C)	13.5
Average Annual Temperature ≥ 20 °C (days)	148.6
Average Annual Temperature ≤ -0.1 °C (days)	16.0
Average Annual Snow Cover (days)	15.9
Average Annual Frost (days)	8.1
Average Annual Total Precipitation (mm)	1246.0
Average Annual Solar Radiation Time (hr:mnt)	5:49
Average Annual Local Pressure (hPa)	1000.1
Average Annual Vapor Pressure (hPa)	11.4
Average Annual Relative Humidity (%)	68.0
Average Annual Wind Speed (m/s)	2.4
Avg. Ann. Stormy Days (wind spd ≥ 17.2 m/s)	8.9
Observation Time (years)	31

1.4 Methods of Study

The study was carried out in five stages. The first stage begins with the literature survey, including the collection of 1/25.000 scaled topographical and geological maps of the study area, and its vicinity with published and unpublished reports and papers. Supplementary documents were also gathered.

In the second stage, the initial field studies were performed in the study area. During this stage, the locations of the five quarries were determined and specific data about these sites were collected.

In the third stage, field studies for detailed discontinuity survey were performed in order to asses the volume and size of the stone blocks at the five different quarries. Meanwhile, a number of rock samples were taken from the 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 subjected into a set of chemical, physical and mechanical tests in both dry and saturated conditions. The properties determined include effective porosity, unit weight, water absorption, uniaxial compressive strength, point load strength index, slake durability, methylene blue adsorption, wet-dry, freeze-thaw, Los Angles abrasion, micro-deval value, magnesium and sodium sulphate soundness, impact resistance, modified impact value, 10 percent fines and crushing value of the stones. Mineralogical and petrographical studies were also 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 the rock armours were identified.

Fifth stage covers the final evaluation of the overall gathered data and durability of the armourstone to asses 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 study area. Most of the studies, except a few, are related to the geology.

Charles (1932, 1933) carried out one of the first paleontological studies at Late Jurassic-Early Cretaceous levels of the İnatlı formation located at Zonguldak region. Tarlaağzı limestone observed in this thesis corresponds to the İnaltı formation.

Arni (1941) carried out geological studies around Zonguldak and Amasra for the determination of the coal deposits. He made detail analysis especially on the Carboniferous rocks of the region and separated them from the general. His definitions about the geology and the stratigraphy of the region were used for the geological interpretations of the five quarries observed in this thesis.

Fratschner (1952, 1953) carried out geology and tectonic studies between Amasra-Cide regions and at Kumluca-Ulus-Eflani-Azdavay districts. In these studies he determined the Jurassic-Cretaceous boundary limestones and investigated the potential coal deposits. His study area includes Tarlaağzı quarry also studied in this thesis.

Wedding (1968, 1969) prepared 1/25.000 scaled geological maps between Amasra-Cide-Ulus regions. Especially during his studies between 1968, 1969 he carried out detailed stratigraphy and tectonic studies at the western parts of the study area. His geological maps also include the rocks exposed in Tarlaağzı quarry.

Akyol et al. (1974) prepared 1/50.000 scaled geological maps of the Cide-Kurucaşile regions and described formations from Precambrian to recent. His geological maps also include the thesis area.

Kaya et al. (1982/1983) carried out a study at Ereğli (Zonguldak) region in order to reevaluate and emphasize the Cretaceous stratigraphy. The age of the rocks observed in Hisarönü, the Kıran, the Kavakdere and the Kavukkavlağı quarries studied in this thesis is Cretaceous.

Kırıcı (1986) performed a detailed bio-stratigraphical study of the İnaltı formation which helped the determination of the age of this formation.

Deveciler (1986) investigated Alaplı, Bartın and Cide regions. He prepared seven 1/25,000 scaled geological maps and described the stratigraphy of these regions. He determined lithologies like calc-arenite, fossiliferous micritic limestone, oolitic and pseudoolotic limestone in the İnaltı formation corresponding to the Tarlaağzı limestone studied in this thesis.

Yergök et al. (1987) prepared 1/50.000 scaled geological maps of the western Black Sea region and revised the stratigraphy of the region. The geological maps prepared by him cover all of the study areas of this thesis and are used for fundamental geological interpretations.

Akman (1992) performed a detailed geology and tectonic studies between Amasra-Arıt regions in order to determine the geological position of the coal bearing Carboniferous rocks under the Mesozoic-Cenozoic successions. He also defined Dinlence formation composed of andesitic lava flows observed in the Hisarönü region in this study.

Derman (1995) carried out detailed studies at the West Black Sea region and divided the İnaltı formation into two new units around Zonguldak. As indicated above, Tarlaağzı quarry observed in this thesis corresponds to the İnaltı formation.

Ergün and Altun (1995) conducted one of the first technical studies in the Tarlaağzı quarry for material supply. In this study, they determined the reserve and usability of the limestone deposits in the quarry.

Bağcı (1995) prepared the construction cross-sections of the Tarlaağzı breakwater and indicated the armourstone distributions in this structure.

İnan (1995) prepared the construction cross-sections of the Alaplı breakwater and indicated the armourstone distributions in this structure.

Demo (2001) prepared the environmental impact assessment report of the Hisarönü quarry studied in this thesis. In this study, location and reserve of the quarry, production method and the effects of the quarry to the environment were described.

Çevretek (2002) prepared the environmental impact assessment report of the Tarlaağzı quarry observed in this thesis. In this study, location and reserve of the quarry, production method and the effects of the quarry on the environment were described.

Serdar (2003) prepared the environmental impact assessment report of the Kavukkavlağı quarry observed in this thesis. In this study, location and reserve of the quarry, production method and the effects of the quarry to the environment were described.

Çıkrıkçı (2004) revised the construction cross-sections of the Hisarönü breakwater and indicated the armourstone distributions in this structure.

Topal and Acır (2004) and Acır and Topal (2005) conducted a study on potential armourstones for the Helaldı (Sinop-Turkey) breakwater. Their findings and methodology enlightened this thesis. They found that sandstone is not a good armourstone for the breakwater.

Ertaş (2006) conducted a study on armourstones used in the Mersin and Kumkuyu harbors. Her findings and methodology enlightened this thesis. She studied four different types of limestone two of which are found to be poor in character as armourstones.

CHAPTER 2

GEOLOGY

2.1. Geology of the Kavakdere Quarry

Compared to the other quarries in this study, the Kavakdere quarry is the largest one where the oldest rocks are exposed. The rocks in the quarry correspond to the Late Cretaceous (Maastrichtian) aged Alaplı formation (Yergök et al., 1987) (Figure 2.1). The Alaplı formation constitutes marl, carbonate sandstone, siltstone, basalt and limestone. The thickness of the formation ranges between 110 meters and 650 meters. The formation has a great extent especially at southern parts of Black Sea Region between Gebze and Kastamonu. The aging of the formation is assessed from the micro-fossil content. The Alaplı formation is also referred as Akveren formation (Ketin and Gümüş, 1963).

The Kavakdere quarry is one of the source quarries for the Alaplı ship shelter. The rocks types exposed in the quarry are generally the limestone which is widely used in the shelter during construction. Therefore, the laboratory samples were taken from this unit and named as Kavakdere limestone (Figure 2.2).

The Kavakdere limestone is gray-pink and beige consists of 0.5-10 cm sized limestone pebbles embedded in a calcareous matrix. The pebbles are angular to sub-angular. Micro-cracks filled with calcite are also observed in the fresh samples of the rock. The rock is slightly weathered with discoloration along the discontinuities. Rock gives strong impulse to hammer blows. Petrographically, the Kavakdere limestone is defined as Limestone Breccia composed of medium crystalline spariclastic limestone fragments. The size of the fragments ranges between a few millimeters to a few centimeters (Figure 2.3).

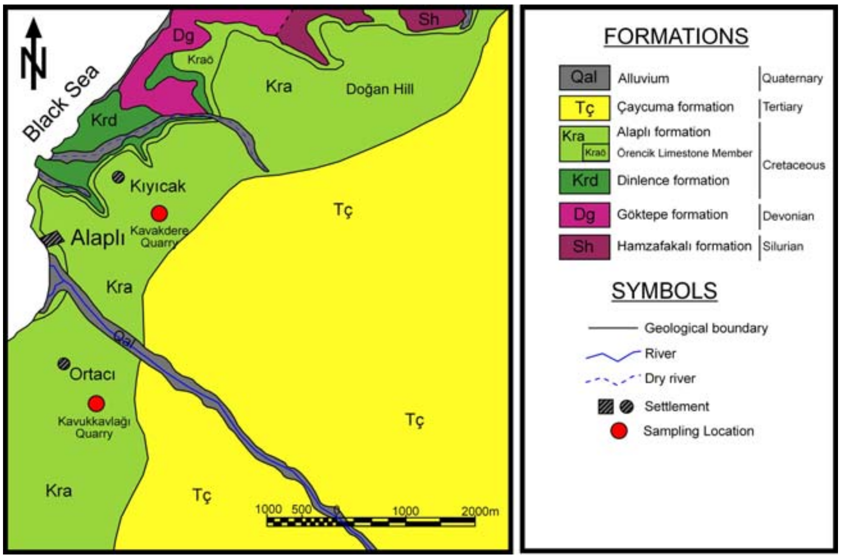


Figure 2.1 Geological map of the Alaplı region (after Yergök et al., 1987)

Figure 2.2 Limestone blocks in the Kavakdere quarry

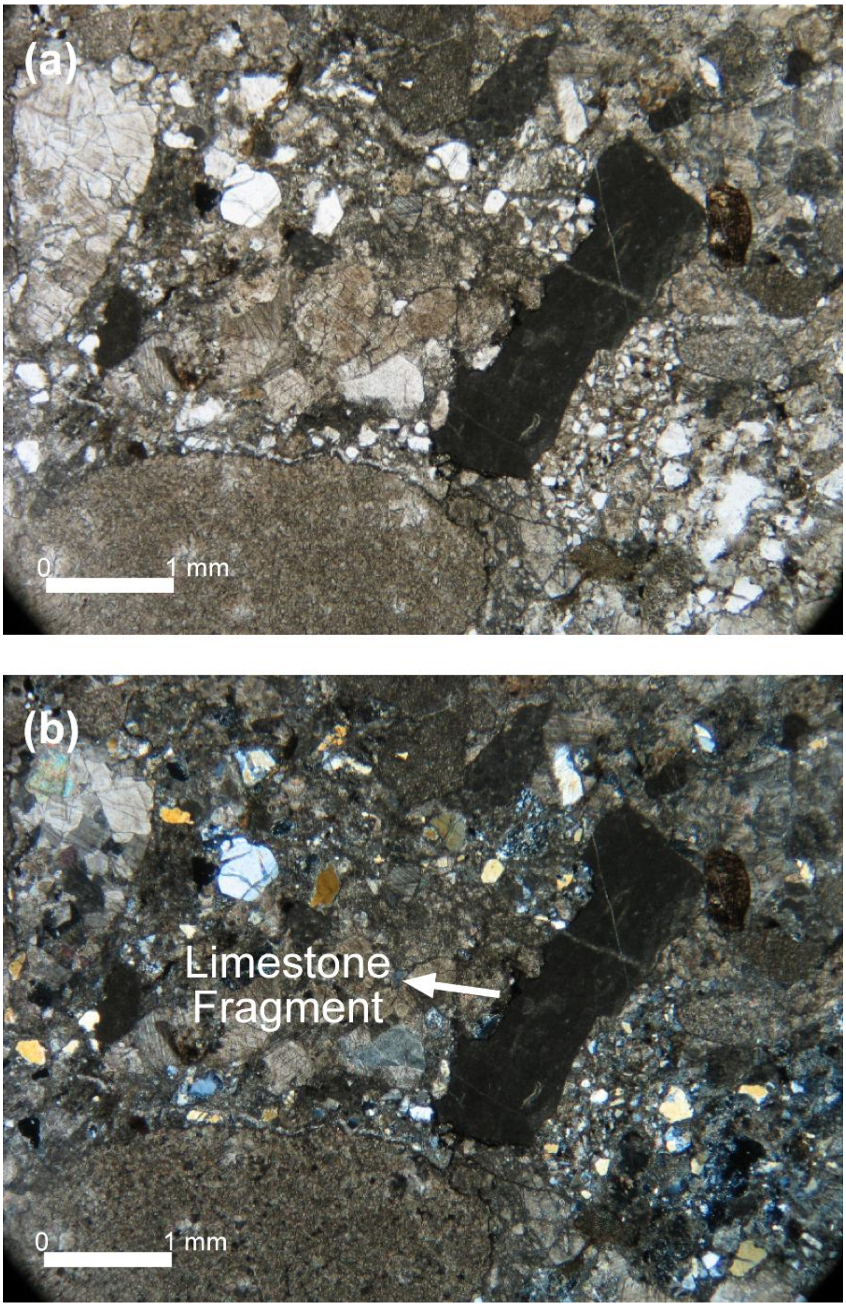


Figure 2.3 Photomicrographs of the Kavakdere limestone (a) plane polarized light (PPL) x5, (b) cross polarized light (CPL) x5

2.2 Geology of the Kavukkavlağı Quarry

The Kavukkavlağı quarry is located just a few kilometers south-east of the Kavakdere quarry, and compared to the Kavakdere quarry it is smaller in extent. The rocks in the quarry correspond to the Late Cretaceous (Maastrichtian) aged Alaplı formation (Yergök et al., 1987) (see Figure 2.1).

Like the Kavakdere quarry, limestone exposes in the Kavukkavlağı quarry, and was widely used during the Alaplı ship shelter construction. Therefore, the laboratory samples were taken from this unit and named as Kavukkavlağı limestone (Figure 2.4).

Figure 2.4 Limestone blocks in the Kavukkavlağı quarry

The Kavukkavlağı limestone is dark gray-black and composed of fine clastics. The rock shows a homogenous character. However, secondary micro-cracks filled with calcite are also observed abundantly in the rock mass. The rock is slightly weathered with discoloration along the discontinuities. The rock gives strong impulse to hammer blows. Petrographically, the Kavukkavlağı limestone is defined as Pelsparite (limestone) composed of highly abundant pellets and trace amount micro crystalline quartz. In addition, it is frequently cut by calcite veins (Figure 2.5).

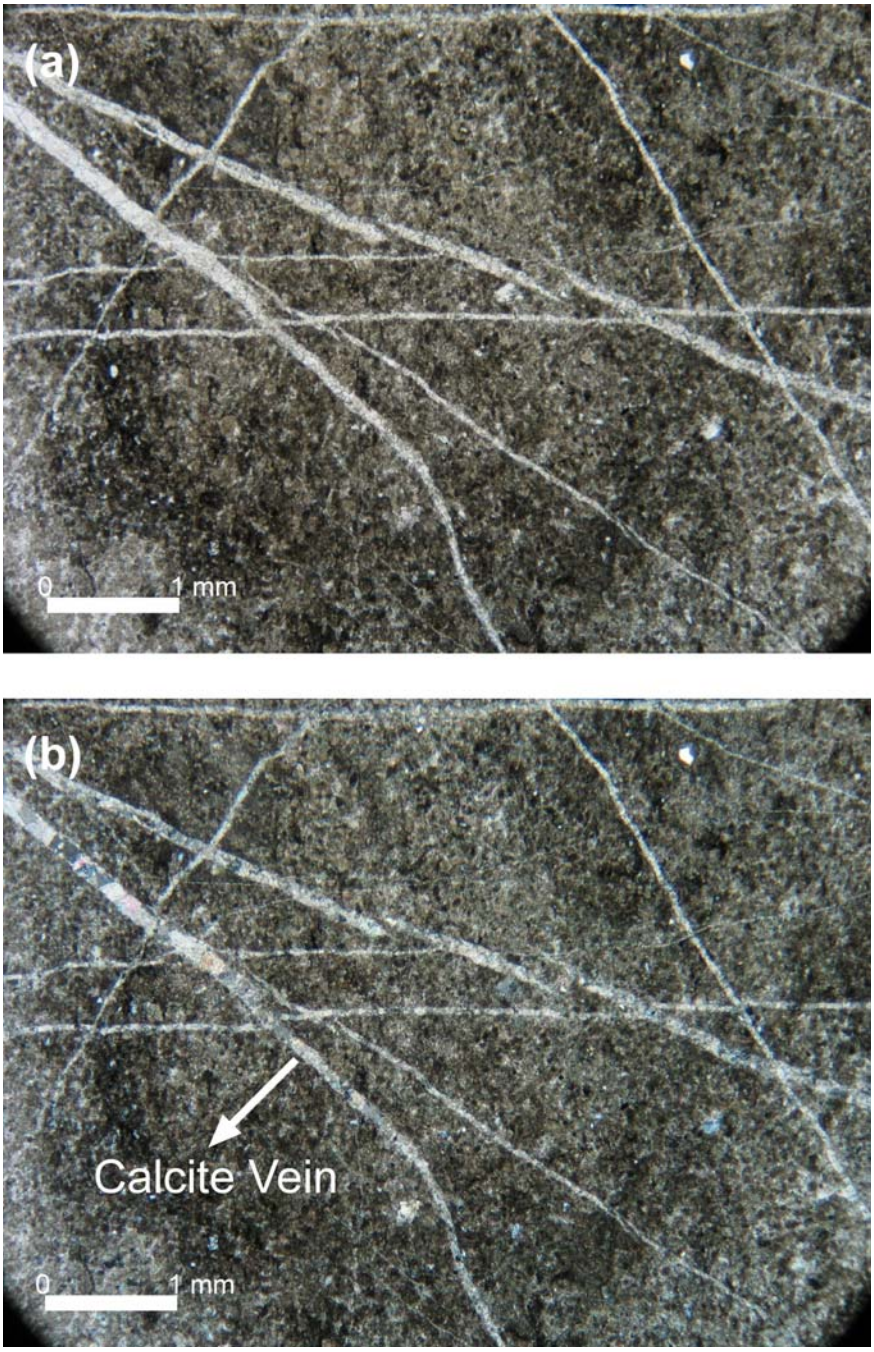


Figure 2.5 Photomicrographs of the Kavukkavlağı limestone (a) plane polarized light (PPL) x5, (b) cross polarized light (CPL) x5

2.3 Geology of the Kıran District

The Kıran district takes its name from the nearby Kıran hill. Unlike the other sample locations, the Kıran district is not an active quarry instead it is a potential armourstone source. Therefore, the analysis about this source is applied on the road cut extending between Zonguldak and Filyos. The rocks exposed at Kıran district correspond to the Cretaceous (Campanian-Santonian) Dinlence formation (Yergök et al., 1987) (Figure 2.6). The Dinlence formation consists mainly of agglomerate and tuff alternations. Andesitic lava flows are also observed in the formation mostly to the north of Bartın. The thickness of the formation shows great variations. Close to Ereğli, the thickness of the formation ranges between 150 and 200 meters, however at some localities about 2000 meters is measured. The ageing of the formation is assessed from the micro-fossil content of rare marl and carbonate levels existing in the formation. The Dinlence formation is also referred to as Sarıkaya formation (Kaya et al., 1981) and Yemişliçay formation (Saner et al., 1981). The samples for laboratory tests were taken from the sandstone succession outcropping on the road cut and named as the Kıran sandstone (Figure 2.7).

The Kıran sandstone is light brown to gray. It is composed of coarse to medium-sized sand grains. No micro-cracks are observed inside the fresh samples. The rock is slightly weathered, and gives medium impulse to hammer blows. Petrographically, the rock is defined as volcanogenic sandstone composed of sand sized detrital material. The rock contains material derived from a pyroxene andesite source. Clastic components are surrounded by their own glassy matrix. The glassy matrix is light brown and the general fabric of the rock is grain-supported (Figure 2.8).

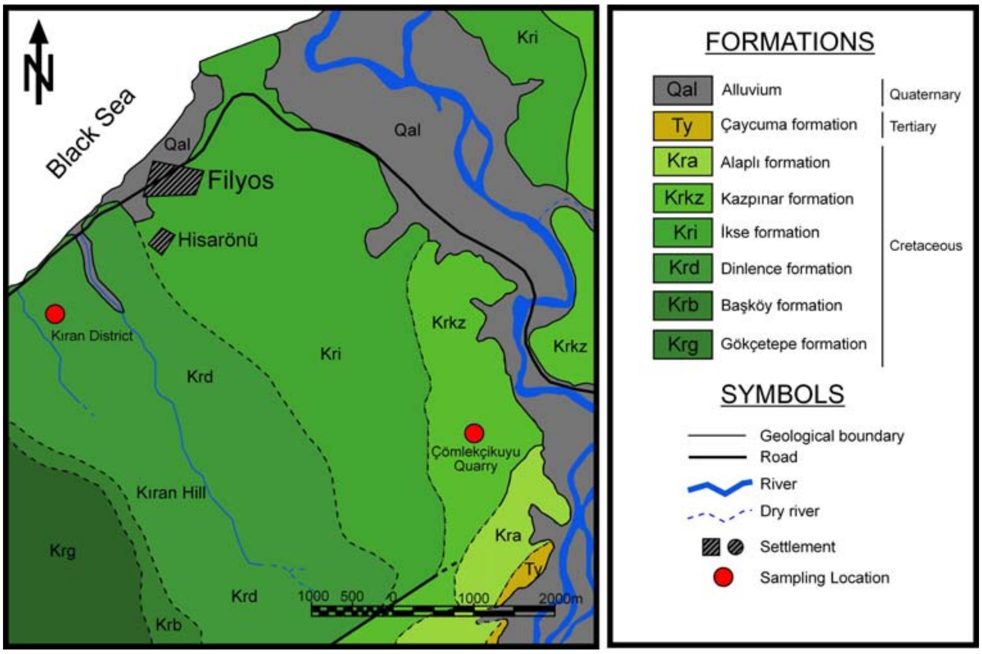


Figure 2.6 Geological map of the Hisarönü region (after Yergök et al., 1987)

Figure 2.7 Sandstone blocks in the Kıran district

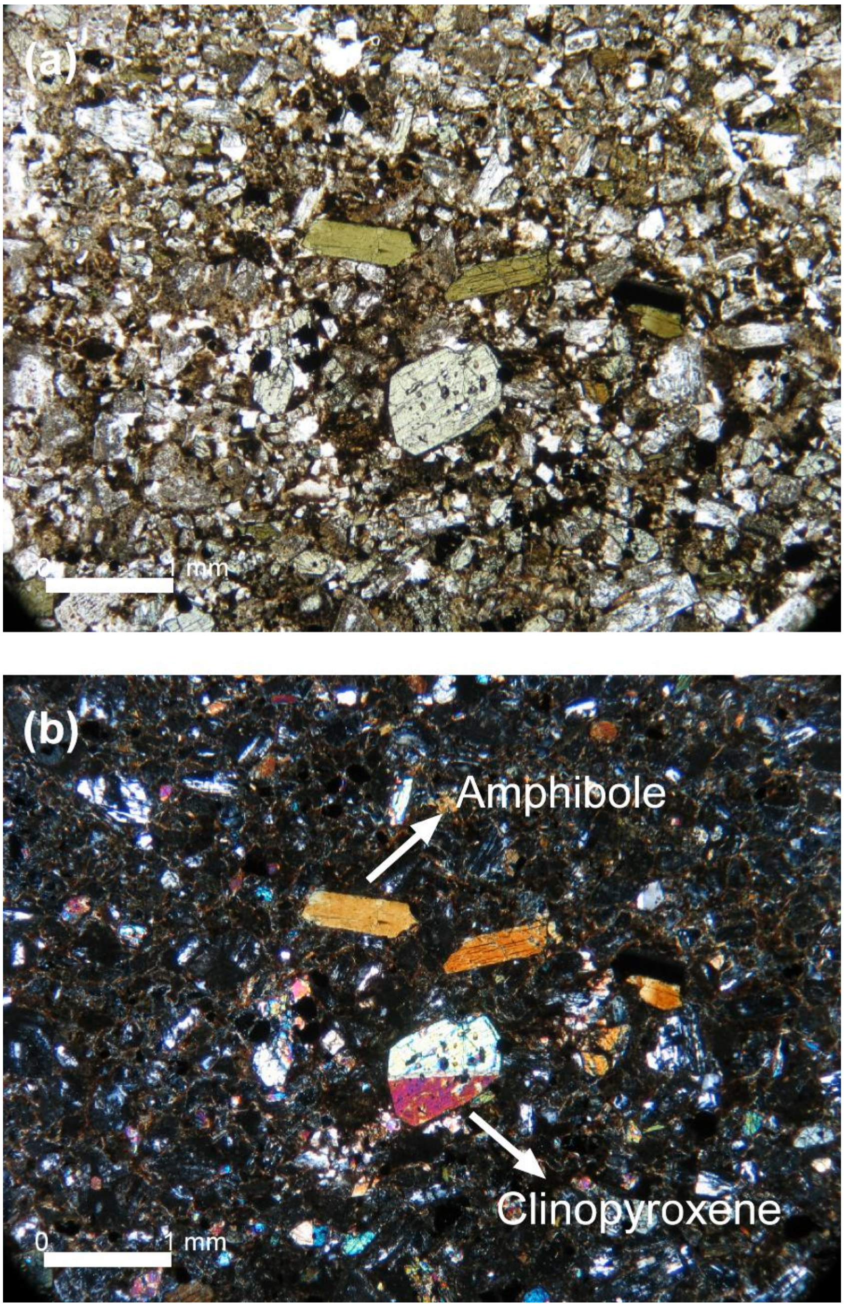


Figure 2.8 Photomicrographs of the Kıran sandstone (a) plane polarized light (PPL) x5, (b) cross polarized light (CPL) x5

2.4 Geology of the Çömlekçikuyu Quarry

The igneous nature of the rocks in the Çömlekçikuyu quarry is easily distinguished from the existence of columnar joints. The rocks in the quarry correspond to the Cretaceous (Campanian) Kazpınar formation (Yergök et al., 1987) (Figure 2.6). The Kazpınar formation constitutes mainly the andezitic lava flows, a few pyroclastics and marl. In these lavas, the columnar cooling joints, radiating cooling structures and basaltic pillow lavas are observed. The thickness of the Kazpınar formation increases to the south reaching 200-600 meters in thickness. Due to the lack of fossil content, the age of the formation is assessed by its stratigraphic position. The Kazpınar formation is widely observed at the regions close to the Black Sea coast (Tüysüz et al., 2004). The Kazpınar formation is also referred as Yemişliçay formation (Ketin and Gümüş, 1963), Kurucaşile formation (Akyol et al., 1974), Lümeran formation (Kaya et al., 1982) and Dinlence formation (Akman, 1992).

The Çömlekçikuyu quarry is the source quarry of the Hisarönü ship shelter. The shelter, except the concrete blocks entirely contains andesite. Therefore, laboratory samples were taken from this unit, and named as Çömlekçikuyu andesite (Figure 2.9).

Figure 2.9 Andesite blocks in the Çömlekçikuyu quarry

The Çömlekçikuyu andesite has a gray matrix with white colored well grown feldspar minerals (as phenocrysts) distributed randomly inside the rock. Gas vesicles and secondary quartz growths are also observed in the Çömlekçikuyu andesite. The upper levels of the succession in the quarry are highly weathered to moderately weathered, however the lower levels are slightly weathered. Rock gives medium impulse to the hammer blows. Petrographically, the Çömlekçikuyu andesite is defined as andesite with hypo-crystalline semi-porphyritic texture and micro-crystalline inter-granular matrix. The glass content of the matrix is considerably low and rich in very fine grained opaque minerals. Abundant phenocrysts are plagioclase, clino-pyroxene and rarely amphibole minerals (Figure 2.10).

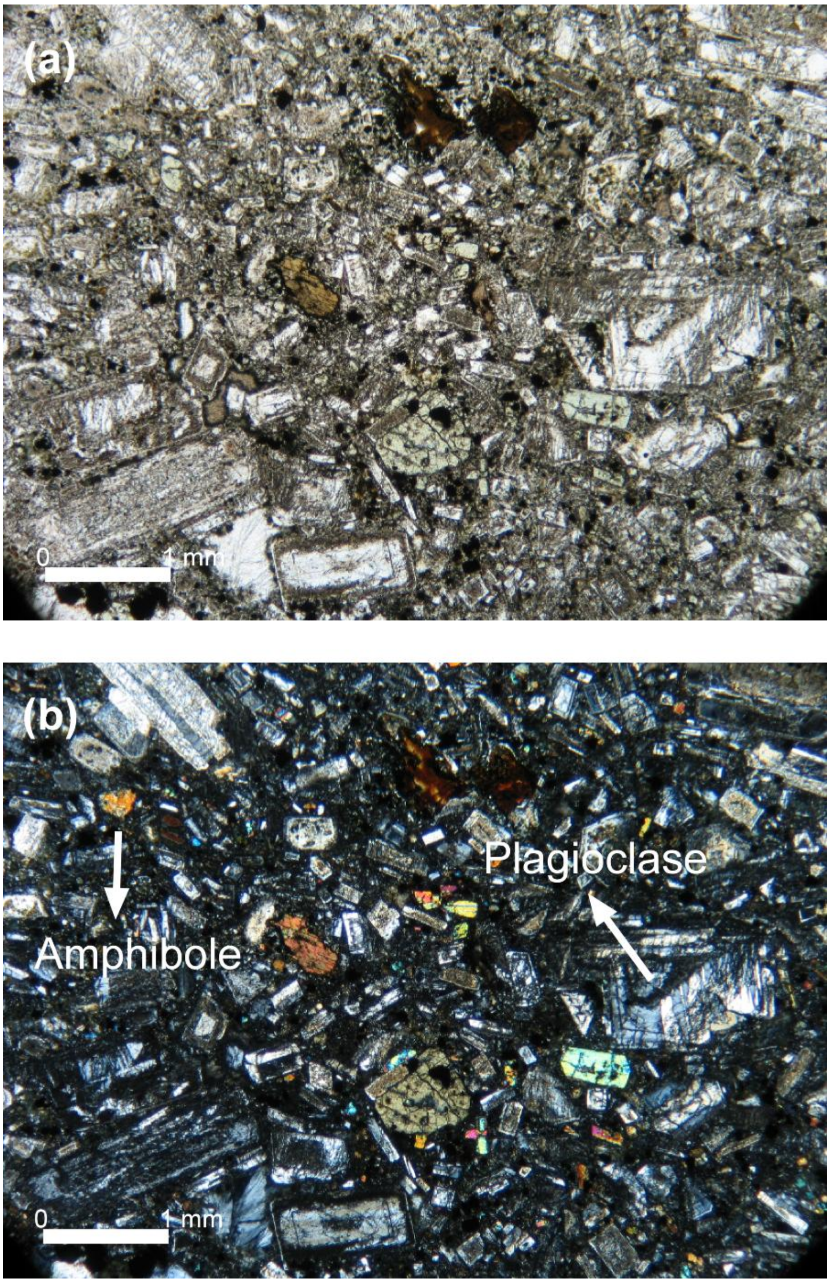


Figure 2.10 Photomicrographs of the Çömlekçikuyu andesite (a) plane polarized light (PPL) x5, (b) cross polarized light (CPL) x5

2.5 Geology of the Tarlaağzı Quarry

The Tarlaağzı quarry is the nearest quarry to its breakwater. The rocks in the Tarlaağzı quarry correspond to Late Jurassic (Barremian-Aptian) aged Zonguldak formation (Yergök et al., 1987) (Figure 2.11), however the name of this formation is later on accepted as İnaltı formation by the Turkish Stratigraphy Committee (Tüysüz et al., 2004). The Zonguldak formation beginning with transgressive shallow marine sediments is mainly composed of shallow marine carbonates. The thickness of the formation ranges between 150 and 1200 meters, and extends in a wide area between south of Sinop to Zonguldak and Black Sea- Ereğli. The age of the formation is assessed from the rich micro-fossil content. The Zonguldak formation is also referred as Kestanedağ formation (Akyol et.al., 1974), Yukanköy formation (Yılmaz, 1979) and Akkaya limestone (Gedik and Korkmaz, 1984).

The Tarlaağzı quarry is entirely consists of limestone which is the major armourstone in the Tarlaağzı ship shelter. Therefore, the laboratory samples were taken from this limestone, and named as Tarlaağzı limestone (Figure 2.12).

The Tarlaağzı limestone is a gray-beige homogeneous rock. Secondary micro-cracks filled with calcite minerals are also observed inside the fresh samples. The rock is slightly weathered and gives strong impulse to hammer blows. Petrographically, the rock is described as Biosparite (limestone) composed of dominantly micro-fossil fragments (Figure 2.13).

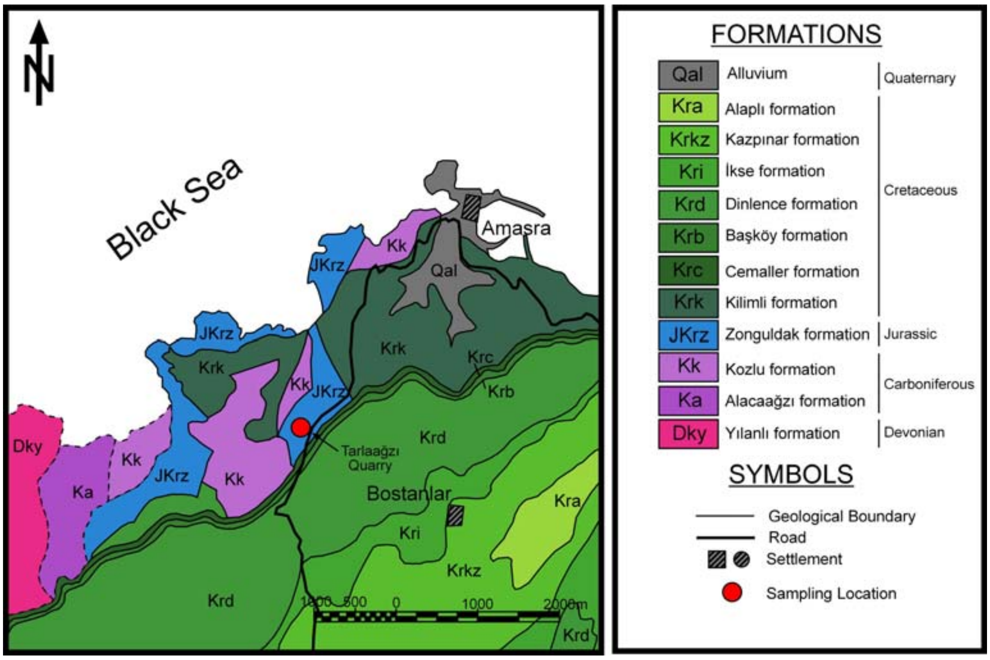


Figure 2.11 Geological map of the Amasra region (after Yergök et al., 1987)

Figure 2.12 Limestone blocks in the Tarlaağzı quarry

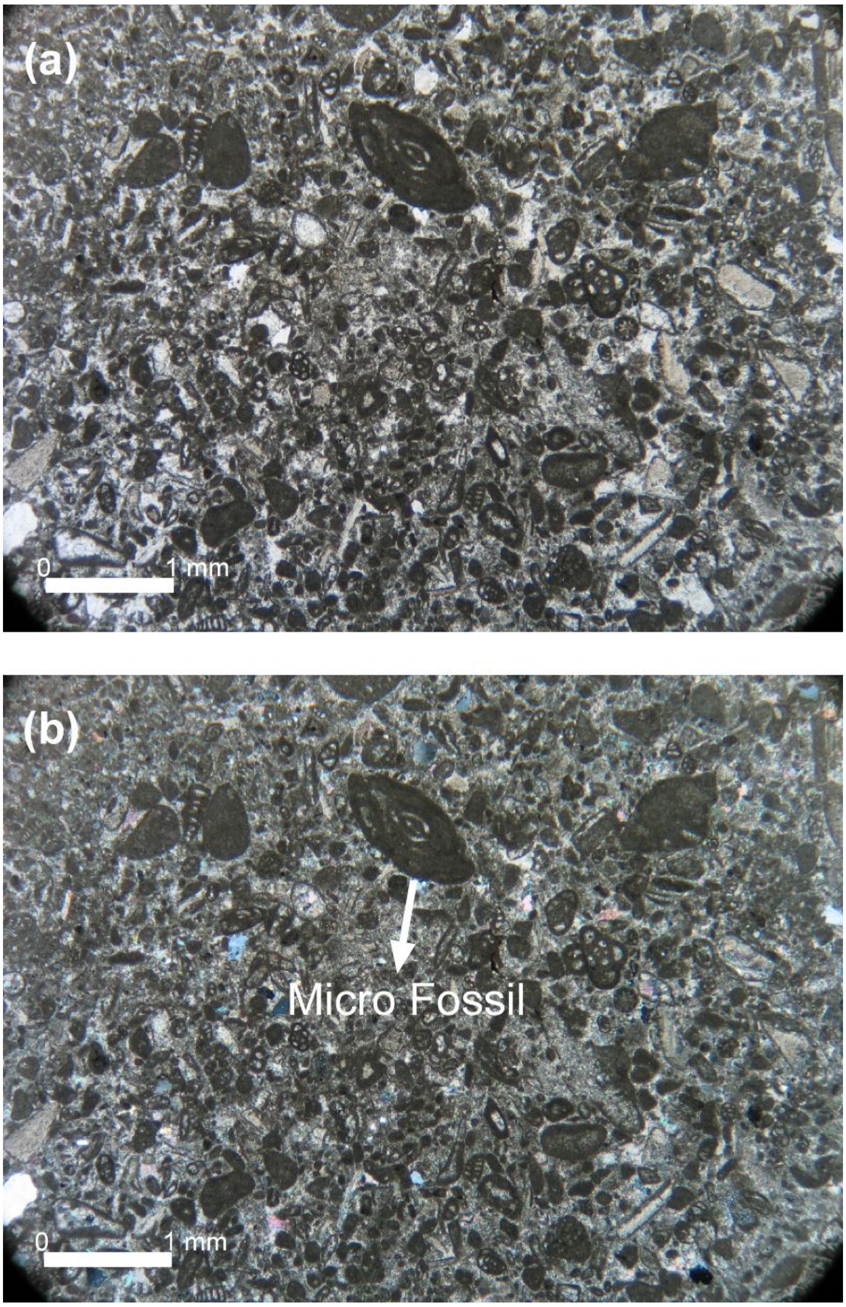


Figure 2.13 Photomicrographs of the Tarlaağzı limestone (a) plane polarized light (PPL) x5, (b) cross polarized light (CPL) x5

CHAPTER 3

RUBBLE-MOUND BREAKWATERS AND ARMOURSTONE

3.1. Rubble-mound Breakwaters

When a harbour is proposed to be established on an exposed coast, whether for naval or commercial purposes, to provide a protected approach to a port or river, or to serve as a refuge for vessels from storms, the necessary shelter, so far as it is not naturally furnished by a bay or projecting headlands, has to be secured by the construction of one or more " breakwaters" (Classic Encyclopedia, 2006). There are various types of breakwaters used as coastal defense structures such as rubble mound breakwaters and reefs, sea walls, groynes, artificial beaches, floating breakwaters, piers and quays (CIRIA/CUR, 1991).

The three breakwaters (Tarlaağzı, Hisarönü and Alaplı) considered in this thesis are rubble mound types. The rubble mound breakwaters are widely used as breakwaters for harbor and coastal protection, and in modified form for coastal defense structures. Their designs make use of a variety of rock grading and require careful specification of block shape, and of physical and mechanical properties (Smith, 1999). The principal function of a rubble mound breakwater is to protect a coastal area from excessive wave action. Incident wave energy is dissipated primarily through turbulent run-up within and over the armour layer (CIRIA/CUR, 1991; Palmer and Christian, 1998).

Some other advantages of these structures defined in CIRIA/CUR (1991) are as follows:

i. Rock (here source rock) can often be supplied from local quarries;
ii. Even with limited equipment, resources and professional skills, structures can be built that perform successfully;
iii. There is only a gradual increase of damage once the design conditions are exceeded (graceful degradation). Design or construction errors can mostly be corrected before complete destruction occurs. If local wave conditions are not well known, this is particularly important;
iv. Repair works are relatively easy, and generally do not require mobilization of very specialized equipment;
v. The structures are not very sensitive to differential settlements, due to their flexibility. Foundation requirements are limited as a result of the sloping faces and wide base.

Rubble mound breakwaters are composed of some distinct layers. A typical cross-section of a rubble mound breakwater is given in Figure 3.1.

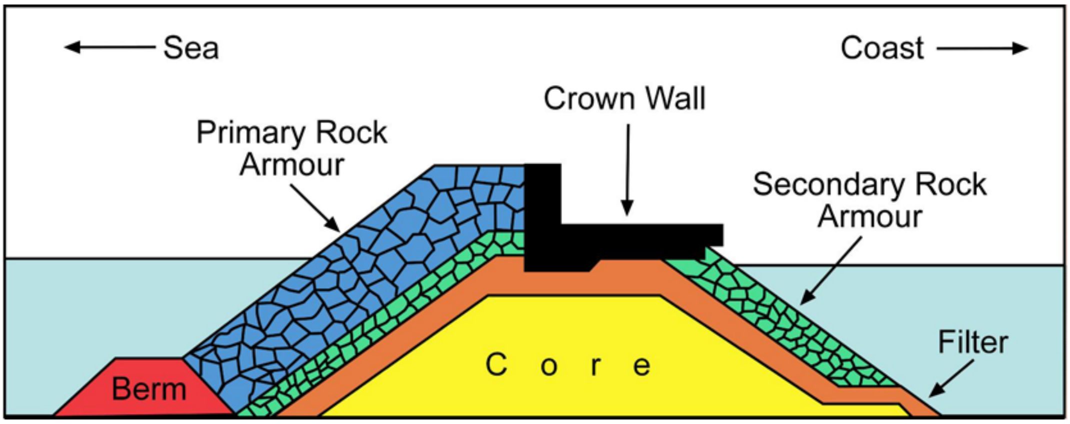


Figure 3.1 Typical cross-section of a conventional rubble mound breakwater (after Smith, 1999)

Crown Wall: The construction of crown wall is optional depending on the project. The crown wall allows easier access to the breakwater structure and can become essential if the breakwater has functions other than simply protection against wave actions. All of the three breakwaters observed in this study have crown wall.

Primary Rock Armour: This layer forms the outer protective layer on the structure and is usually placed in random arrangement in one or two layers. Interlock is maximized by careful placing of the individual blocks during construction since this is important for the potential stability of the layers. The largest and heavier blocks are placed at this layer. Although designs involving primary rock armour blocks up to 25 tons have been constructed, more typically specifications require blocks of 10 tons and smaller as primary armour.

Secondary Rock Armour: This layer is used in rubble mound breakwater structures as a support layer for the primary armour. As with the primary armour, turbulence within voids between blocks in the secondary armour layer helps to dissipate the incident wave energies rather than reflecting the waves back. Since this layer is partly protected by the primary armour, the weight of the secondary armour blocks can be smaller and is typically about one tenth of the primary armour layers.

Filter layer: This layer lies between the armour layers and the core materials of the breakwater. The rock used in this layer must be sufficiently strong and durable for its purpose with low water absorption characteristics. Particle shape must be equant and specifications usually set low limits on the proportions of flaky and elongate particles that are acceptable particularly for filter media. The weight of the armour blocks at this layer is between 0.5 and 2 tons.

Berm: An excess amount of stones are placed in the berm at the seaward slope. In a berm breakwater, the stones are dynamically stable. During more severe storms this material becomes redistributed by the waves to form a natural stable slope. The weight of the armor blocks at this layer is about 0.5 and 2 tons.

Core: The core of rubble mound structures is by far the largest volume of material in most designs. A typical design of breakwater structure may require 80 % by volume of core material with only a 20 % requirement for armour and other materials. In the majority of structures, core material is “quarry run” material, which is material produced by the quarry with a minimum processing. The weight of the core material ranges between 0.1 and 0.4 tons.

According to Smith (1999), the requirements for rock used in marine structures and particularly as armouring to be both strong and durable are quite clear. 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 the primary armour will control many other aspects of the design. Armourstone block sizes are controlled by the natural frequency and spacing of discontinues (joints and bedding) in the quarry. Primary breakwater cross-sections of the Tarlaağzı, Hisarönü and Alaplı ship shelters are given in Figures 3.2-3.4.

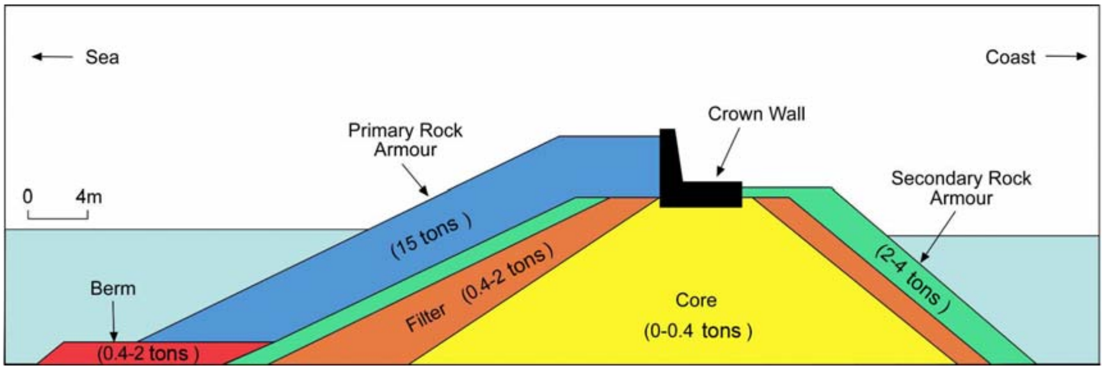


Figure 3.2 Primary breakwater cross-section of the Tarlaağzı ship shelter (after Bağcı, 1995)

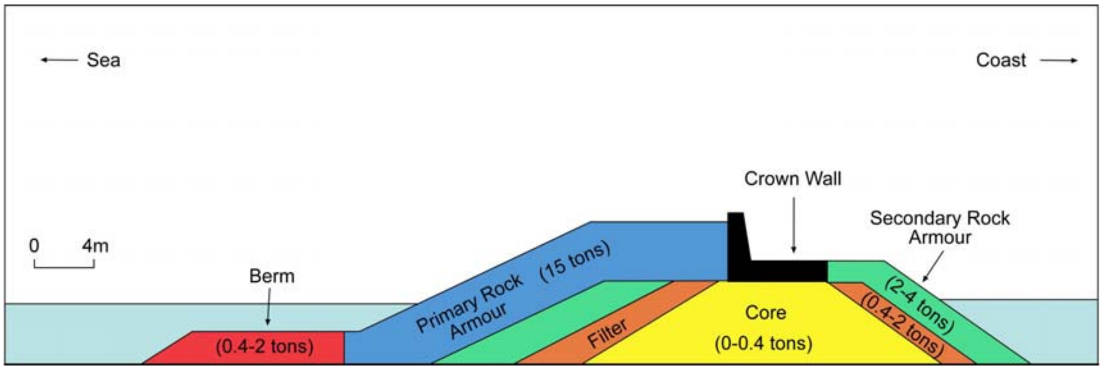


Figure 3.3 Primary breakwater cross-section of the Hisarönü ship shelter (after Çıkrıkçı, 2004)

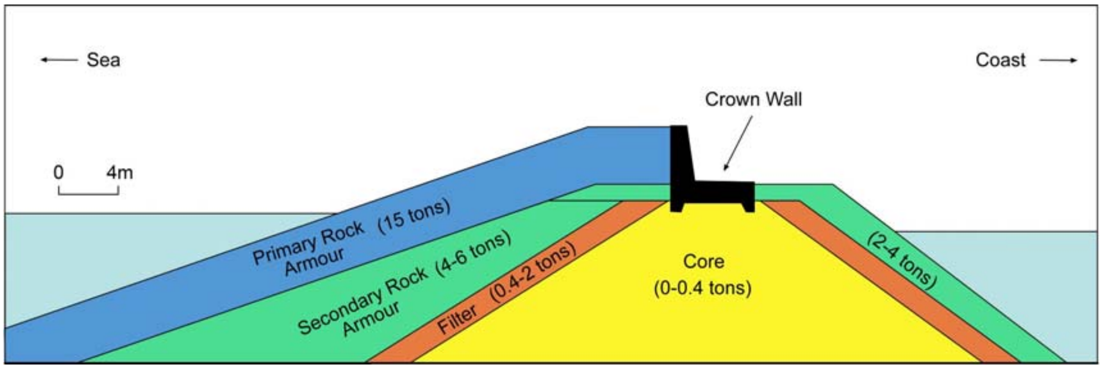


Figure 3.4 Primary breakwater cross-section of the Alaplı ship shelter (after İnan, 1995)

3.2 Armourstone

The armourstone comprises the primary material in rubble-mound breakwaters. As mentioned in the previous section, depending on the area of application, size and amount of the armourstone vary. Fewer amounts of larger blocks are used in the defensive or primary layers, and more amounts of smaller blocks are used in the core or filter layer of the breakwater.

According to Poole (1991), the most important requirement of rock blocks used in the defensive layers is the stability against wave action. In this context, block size and rock density play a vital role which is well described in various armour stability formulae (Van der Meer 1987; Thompson & Shuttler 1975; Hudson 1959). Block angularity is also an important requirement for adequate interlock of the armour layer. Armour blocks must also have sufficient dynamic strength and freedom from the incipient fractures to resist breakage during transportation, placing and while in service.

If the armour blocks are not durable, abrasion from wave-born sand and shingle particles will cause rapid rounding so that the armour layer ceases to function properly because of the change in shape and weight loss. Here, durability may be defined as the ability of a rock to retain its physical and mechanical properties while resisting degradation in engineering service (Smith, 1999). Mineralogical texture, grain size, composition, and degree of weathering all contribute to the durability characteristics of a particular rock (Poole, 1991).

Rocks used in core or filters layers are graded in size so as to prevent the core or sub-soil being drawn through them by the hydraulic forces induced by the wave action. The initial particle shape and grading are important but resistance to degradation of particles in flowing saline water or under cyclic stress is more important. The core material must also resist the complex forces imposed on it during placing and packing. It must support the overlaying primary armour and resist the shearing forces which may develop within the confined pack. The rocks in the core layer are subjected to similar degradation processes to those affecting primary armour layers. Breakage in handling will be important, but abrasion and physical weathering processes may also be important for the primary layers.

It is visible from the above explanations that armourstones whether placed at the primary or core layers are under the influence of various external forces. The material properties; thus the quality of the rock play a vital role in the success of the structure; therefore detailed tests and in-situ observations have to be made for the quality assessment of the armourstones.

CHAPTER 4

ENGINEERING GEOLOGICAL PROPERTIES OF THE ALREADY USED AND POTENTIAL ARMOURSTONES

As mentioned before, the quality of the armourstones is a vital factor for the life span of breakwaters and the quality depends primarily on the engineering geological properties of the rock bodies. In order to designate these properties, detailed field and laboratory studies were conducted. According to Lienhart (1992), the quality of the final stone product hinges on the combination of two factors: rock properties and environmental conditions. The environmental conditions associated with production and final placement cannot be controlled but the rock properties of the final stone product can be. Through careful measurement and analysis of both the environmental conditions and the rock properties, and a proper matching, quality product can be produced. This requires a selection of adequate testing procedures appropriate for the intended environment and the development of a suitable set of acceptance criteria. According to Erickson (1993), laboratory testing is one of the tools one can use to predict the long term durability of the armourstone. In addition to the laboratory tests, in-situ observations like; rock type, bedding, quarrying methods, methods of handling and placement, inclusions void or vugs, saturation of the stone, time of year of production, previous production methods should be used when making a determination of the suitability of an armourstone source. These observations of the armourstones, along with service comparisons of the armourstones produced under similar conditions can be used to improve the selection of a source that produces armourstones that have the highest long term durability.

In this thesis, the field studies were performed in five different quarries where different rock types are exposed. The aim was to assess the mass properties of these rock types by carrying out discontinuity surveys at the rock quarries based on the description of rock material and mass characteristics of Anon (1977), BSI (1981) and ISRM (1981). Several block samples were also taken from the quarries for laboratory studies at the end of the field work.

The laboratory studies were mainly carried out at the Engineering Geology Laboratory of the Department of Geological Engineering (METU). In order to carry out the required tests, various cubic and crushed samples were prepared from the block samples. The cubic samples were prepared in 5cm x 5cm x 5cm dimensions. The strength related tests were performed in both dry and wet conditions due to the field application of the armourstones. Some of the laboratory analyses were carried out at General Directorate of Mineral Research and Exploration (MTA) laboratories.

In order to simulate the natural weathering processes and to determine the index properties of the armourstones, the following rock properties were determined; dry and saturated unit weights, effective porosity, water absorption, saturation coefficient, sonic velocity, methylene blue absorption, wet-dry resistance, freeze-thaw resistance, sulfate soundness (magnesium and sodium), slake durability index, Los Angeles abrasion loss, micro-deval abrasion value, point load strength index, fracture toughness, uniaxial compressive strength, aggregate impact value, modified aggregate impact value, aggregate crushing value and 10 % fines value. The tests were performed according to ISRM (1981), RILEM (1980), TS699 (1987) and TS EN1097-1 (2002) standards.

The tests were applied to Kavakdere, Kavukkavlağı and Tarlaağzı limestones, Çömlekçikuyu andesite and Kıran sandstone. The detailed explanations about the tests and their results are presented within the text.

4.1 Material Properties of the Armourstones

The Kavakdere limestone is gray-pink and beige, composed of 0.5-10 cm sized limestone pebbles embedded in a calcareous matrix. The pebbles are angular to sub-angular. Micro-cracks filled with calcite are also observed in the fresh samples of the rock. The rock is slightly weathered with discoloration along the discontinuities.

The Kavukkavlağı limestone is dark gray-black, composed of fine-grained calcite. The rock shows a homogenous character. However, secondary micro-cracks filled with calcite are also observed abundantly in the rock body. The rock is slightly weathered with discoloration along the discontinuities.

The Tarlaağzı limestone is gray-beige homogenous rock consisting of calcite. Secondary micro cracks filled with calcite minerals are also observed inside the fresh samples. The rock is slightly weathered.

The Çömlekçikuyu andesite is gray, contains white feldspar phenocrysts distributed randomly inside the fine-grained matrix. The rock has well developed cooling joints and flow layering. Gas cavities and secondary quartz growths are also observed in the rock. The upper levels of the succession are highly weathered to moderately weathered. However, the lower levels are slightly weathered.

The Kıran sandstone is light brown to gray, thick bedded, consisting of coarse to medium-sized sand grains. No micro-cracks are observed inside the fresh samples. The rock is slightly weathered.

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. On the other hand, pores also affect the density and unit weight of the rock. Both physical properties can be determined by the same test. Effective porosity, dry and saturated unit weight of the Kavakdere limestone, Kavukkavlağı limestone, Tarlaağzı limestone, Çömlekçikuyu andesite and Kıran sandstone were determined by using saturation and buoyancy techniques according to ISRM (1981). For these tests; 110 Kavakdere limestone samples, 120 Kavukkavlağı limestone samples, 120 Tarlaağzı Limestone samples, 120 Çömlekçikuyu andesite samples and 50 Kıran sandstone samples were used.

Based on the test results, the average effective porosity, dry and saturated unit weights of the samples are given in Table 4.1.

Table 4.1 Average effective porosity and unit weight values of the samples

Sample	The average effective porosity (%)	Engineering Classification for porosity (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)
Kavakdere Limestone	0.45	Very Low	26.91	High	26.94	Very High
Kavukkavlağı Limestone	0.80	Very Low	26.40	High	26.45	High
Tarlaağzı Limestone	2.26	Low	25.95	High	26.17	High
Çömlekçikuyu Andesite	7.20	Medium	23.08	Moderate	23.70	Moderate
Kıran Sandstone	17.32	High	21.56	Low	23.18	Moderate

According to Anon (1979), the effective porosities of the Kavakdere, Kavukkavlağı and Tarlaağzı limestones are very low to low which are desired property for long-term durabilities. In addition, the dry and saturated unit weights of these rocks are high reflecting a dense rock composition suitable for the rubble mound breakwaters. On the other hand, the porosity and dry-saturated unit weights of the Çömlekçikuyu andesite is medium to moderate respectively indicating the necessity of detailed examination on this rock. Finally the Kıran sandstone has the highest porosity and the lowest dry-saturated unit weight values reflecting a weak and very porous rock.

4.1.2 Pore Size Distribution with Mercury Porosimeter

This test is intended to measure effective porosity and pore size distribution of a sample by means of mercury porosimeter (Micromeritics model). For the test, samples weighing 1-1.5 grams were prepared from each of the rock specimens. The test was performed on one sample as one intrusion step. During this step, the pressure is raised from 0 to ~55,000 psi in ~350 steps. By this way, the pore sizes of the rocks ranging between 0.003 μm and 10.65 μm could be detected and stored in computer. Advancing contact angles of the mercury and the surface tension were taken 140° and 480.00 erg / cm^2, respectively. The test was performed at the Central Laboratory of METU. Based on the intrusion data, the effective porosities of the samples are given in Table 4.2.

Table 4.2 Average effective porosity of the samples calculated by mercury porosity

Sample	The average effective porosity (%)	Engineering Classification for porosity Anon (1979)
Kavakdere Limestone	0.02	Very Low
Kavukkavlağı Limestone	0.04	Very Low
Tarlaağzı Limestone	2.09	Low
Çömlekçikuyu Andesite	7.67	Medium
Kıran Sandstone	12.66	Medium

The results are close to the ones calculated by the buoyancy method (ISRM, 1981) in part 4.1.1. The variations in the results are due to the difference in the number and size of samples used in two tests. Nevertheless, the resulting Anon (1979) classification of the samples are unchanged except the Kıran sandstone which is again considerably high compared to the other samples.

The average pore diameters of the Kavakdere, Kavukkavlağı, Tarlaağzı limestone, Çömlekçikuyu andesite and Kıran sandstone are 0.1603 μm, 0.7672 μm, 0.0921 μm, 0.7693 μm and 0.1232 μm, respectively. Cumulative intrusion curves and the pore-size distribution for the samples are given in Figures 4.1, 4.2 and 4.3. The maximum peak pore sizes of the Kavakdere limestone, the Kavukkavlağı limestone, the Tarlaağzı limestone, the Çömlekçikuyu andesite, the Kıran sandstone are in the range 0.003 μm-0.004 μm, 0.003 μm-0.004 μm, 0.02 μm-0.03 μm, 0.06 μm-0.07 μm, and 0.04 μm-0.05 μm, respectively (Figures 4.2 and 4.3).

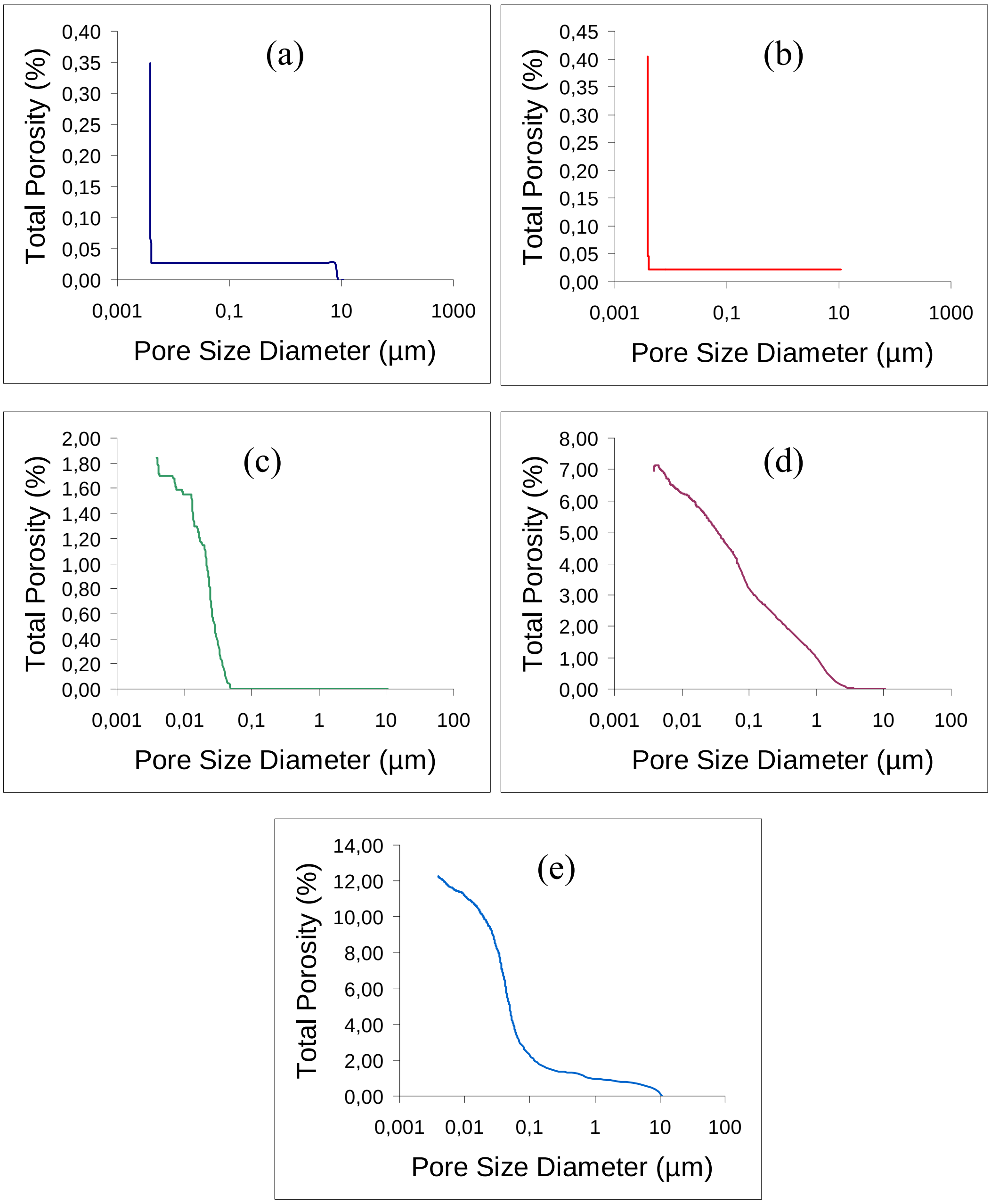


Figure 4.1 Cumulative intrusion curves of the samples (a) Kavakdere limestone (b) Kavukkavlağı limestone (c) Tarlaağzı Limestone (d) Çömlekçikuyu andesite (e) Kıran sandstone

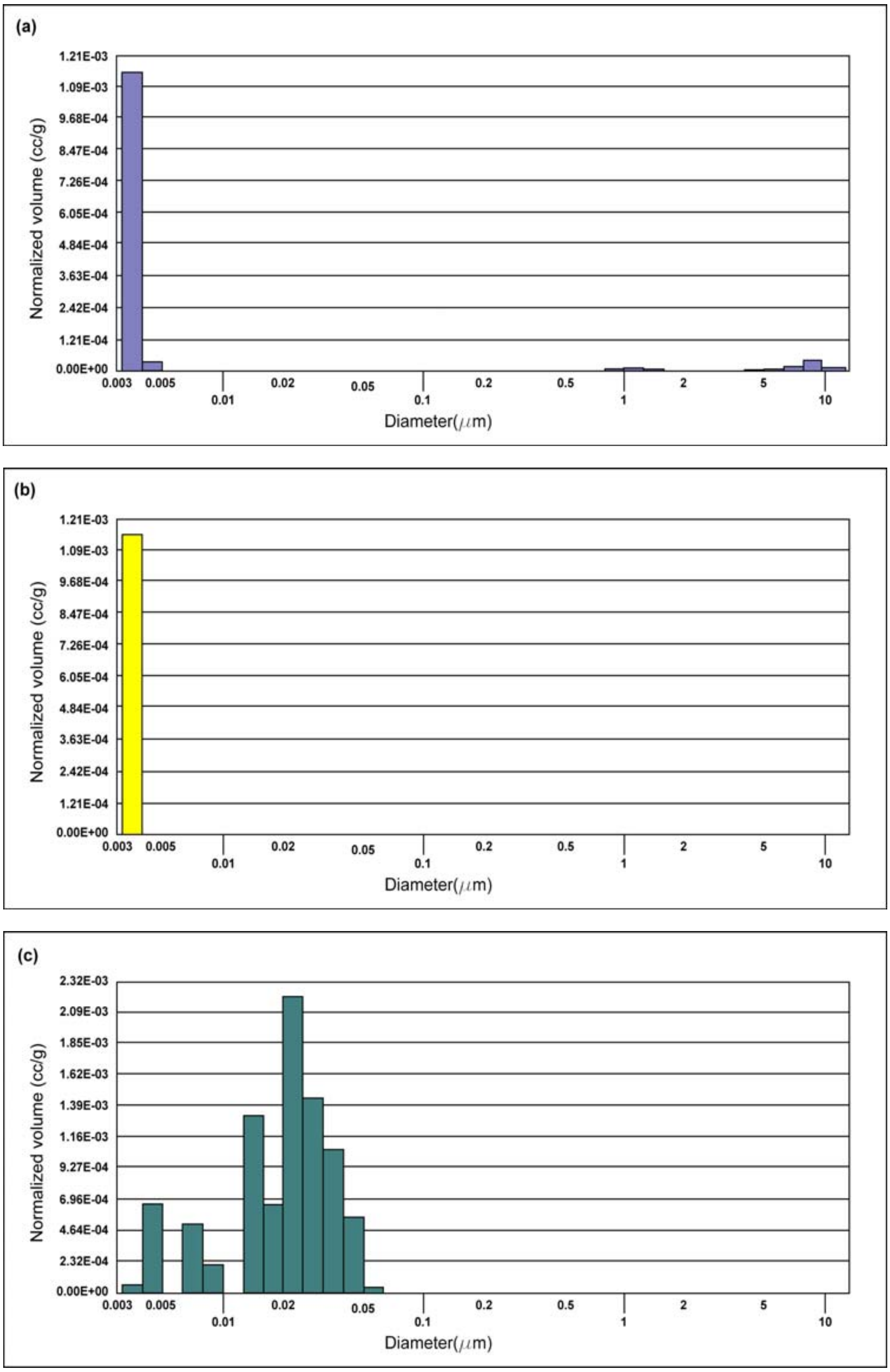
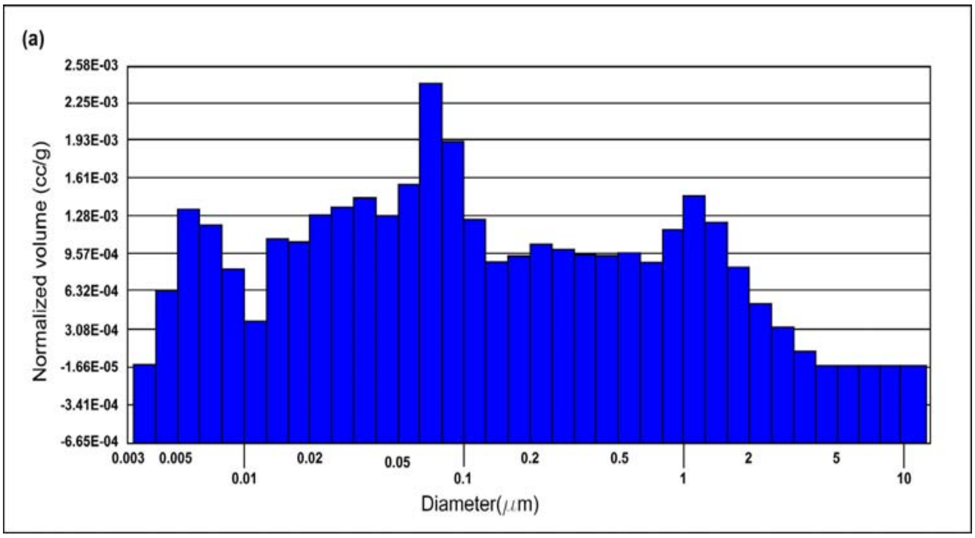


Figure 4.2 Pore size distributions of the samples (a) Kavakdere limestone (b) Kavukkavlağı limestone (c) Tarlaağzı Limestone



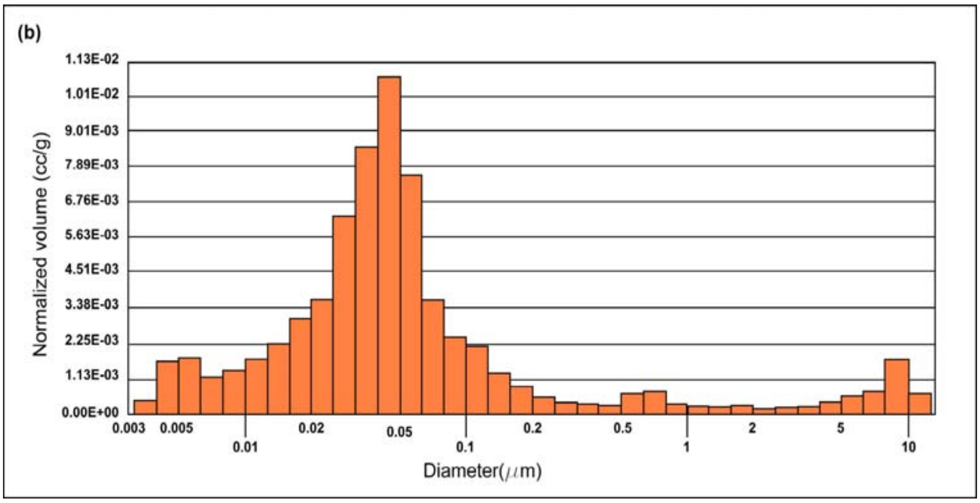


Figure 4.3 Pore size distributions of the samples (a) Çömlekçikuyu andesite (b) Kıran Sandstone

4.1.3 Water Absorption under Atmospheric Pressure

Water absorption under atmospheric pressure is intended to measure the amount of water absorbed by a rock under atmospheric pressure. The test results were evaluated in terms of water absorption by weight and by volume, and expressed in percentages. The tests were performed according to TS699 (1987) and BSI (1975). The corresponding results of the samples are given in Table 4.3.

Table 4.3 Average water absorption values of the samples under atmospheric pressure

Sample	Water Absorption by Weight (%)	Water Absorption by Volume (%)
Kavakdere Limestone	0.10	0.29
Kavukkavlağı Limestone	0.20	0.53
Tarlaağzı Limestone	0.82	2.16
Çömlekçikuyu Andesite	2.70	6.27
Kıran Sandstone	7.54	16.47

According to the test results, the Kavakdere, Kavukkavlağı and Tarlaağzı limestones have considerably low water absorption under atmospheric pressure; on the other hand, the Çömlekçikuyu andesite has moderately high, and the Kıran sandstone has the highest value compared to those from the other samples.

4.1.4 Water Absorption under Pressure

This test is also intended to measure the amount of water absorbed by a rock However, this time, the water absorption occurs under certain vacuum pressure. Similarly, the test results were evaluated in terms of water absorption by weight and by volume, and expressed in percentages. The tests were performed according to TS699 (1987) and BSI (1975). The corresponding results of the samples are given in Table 4.4.

Table 4.4 Average water absorption values of the samples under pressure

Sample	Water Absorption by Weight (%)	Water Absorption by Volume (%)
Kavakdere Limestone	0.16	0.45
Kavukkavlağı Limestone	0.30	0.80
Tarlaağzı Limestone	0.85	2.26
Çömlekçikuyu Andesite	3.10	7.20
Kıran Sandstone	7.96	17.32

According to the test results, the Kavakdere, Kavukkavlağı and Tarlaağzı limestone have considerably low water absorption under pressure; on the other hand, the Çömlekçikuyu andesite has moderately high and the Kıran sandstone has higher values compared to the other samples. As expected, the values are higher than water absorption under atmospheric pressure due to the effect of the vacuum pressure.

4.1.5 Saturation Coefficient

Saturation coefficient is another index property of the intact rocks. It is evaluated from the ratio between the water absorption under atmospheric pressure and pressure tests (TS699, 1987). It is expressed in both weight and volume. The corresponding results of the samples are given in Table 4.5.

Table 4.5 Saturation coefficients of the samples

Sample	Saturation Coefficient-Weight	Saturation Coefficient-Volume
Kavakdere Limestone	0.63	0.64
Kavukkavlağı Limestone	0.66	0.65
Tarlaağzı Limestone	0.96	0.97
Çömlekçikuyu Andesite	0.87	0.87
Kıran Sandstone	0.95	0.95

4.1.6 Sonic Velocity Test

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. Cubic samples of 5cm x 5cm x 5cm dimensions were tested in both dry and saturated states. For the test; 110 Kavakdere limestone samples, 120 Kavukkavlağı limestone samples, 120 Tarlaağzı limestone samples, 120 Çömlekçikuyu andesite samples and 50 Kıran sandstone samples were used.

For the testing, P-wave velocities three directions 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;

$$V = d / t \tag{4.1}$$

where;

V :Velocity,

d : Distance traversed by the wave,

t : Travel time

PUNDIT-PLUS model laboratory 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). For the accuracy of the pulse transmission method, the transmitter and receiver were positioned on the opposite end surfaces of the cubic test specimen. The corresponding test results are given in Table 4.6.

Table 4.6 Dry and saturated sonic velocity values of the samples

Sample	Dry Sonic Velocity (m/s)	Engineering Classification (Anon, 1979)	Saturated Sonic Velocity (m/s)	Engineering Classification (Anon, 1979)
Kavakdere Limestone	5607.13	Very High	5724.31	Very High
Kavukkavlağı Limestone	5593.27	Very High	5843.67	Very High
Tarlaağzı Limestone	5498.99	Very High	5650.11	Very High
Çömlekçikuyu Andesite	3340.66	Low	3516.66	Moderate
Kıran Sandstone	2170.88	Very Low	2556.85	Low

According to the test results, the Kavakdere, Kavukkavlağı and Tarlaağzı limestone have very high sonic velocities both in dry and saturated conditions, these results are in good agreement with their low porosities; on the other hand, due to its moderate porosity the Çömlekçikuyu andesite has low to moderate sonic velocity values in dry and saturated conditions respectively. Finally the Kıran sandstone has very low to low values in dry and saturated conditions respectively which are in good agreement with its very high porosity.

4.1.7 Methylene Blue Test

Methylene blue adsorption test is a reliable and simple method to obtain information on the presence and properties of clay minerals in soils and rocks (Verhoef, 1992; Topal, 1996). This test is mostly used for the determination of smectite group clay minerals (CIRIA/CUR, 1991). If a significant amount of methylene blue is adsorbed by the soil or ground rock material, this may indicate the presence of swelling clay minerals, although there exists other substances that also may adsorb methylene blue (Verhoef, 1992). Low values of adsorption generally indicate low swelling activity (Stapel and Verhoef, 1989).

This test was applied for all of the armourstone samples according to AFNOR (1980). A certain concentration of methylene blue solution is added in definite volumes to a suspension of each rock sample, which was powdered in the laboratory. The methylene blue value (MBA) is calculated through the total amount of methylene blue solution that is adsorbed. Cation exchange capacity value (CEC) of clays can also be expressed by MBA values. Both the MBA and CEC values of the samples are calculated at the end of the test, and the results are given in Table 4.7.

Table 4.7 MBA and CEC values of the samples

Sample	MBA (gr/100 gr)	CIRIA/CUR (1991)	CEC (meq./100 gr)
Kavakdere Limestone	0.53	Good	1.22
Kavukkavlağı Limestone	0.27	Excellent	0.61
Tarlaağzı Limestone	0.27	Excellent	0.61
Çömlekçikuyu Andesite	2.93	Poor	6.69
Kıran Sandstone	2.80	Poor	6.38

According to the test results, the MBA and CEC values of the Kavakdere, Kavukkavlağı and Tarlaağzı limestones are considerably low, therefore, their swelling capacity can be considered as negligible; however the MBA and CEC values of the Çömlekçikuyu andesite and Kıran sandstone are high. Therefore, according to CIRIA/CUR (1991), this indicates the presence of deleterious clay minerals. This property of the two rocks causes serious durability problems especially when the rocks are saturated with water. This affect will be also supported with some other tests throughout the text.

4.1.8 X-Ray diffraction analyses

X-Ray diffraction (XRD) analysis is a test used for identifying the minerals in the rocks. The main purpose of this analysis for this study is to determine the detailed clay content of the samples. As it is seen from the results of the Methylene Blue Test (Part 4.1.7), the Çömlekçikuyu andesite and Kıran sandstone contain considerable amount of clay which may affect their durabilities; therefore, determination of the type of the clay was the main purpose of this analysis. There are various methods and equipments used for this purpose; however, the most practical and widely used one is the X-Ray Powder Diffractometer. This powerful research tool uses essentially monochromatic X-radiation and a finely powdered sample, and records the information about the "reflections" present as an inked trace on a printed strip chart, or as electronic counts (X-Ray counts) that can be stored in a computer (Klein and Hurlbut, Jr., 1999). A RIGAKU diffractometer with CuKα radiation was used in the measurements of this analysis. The measurements were performed at the General Directorate of Mineral Research and Exploration (MTA).

The sample is prepared for powder diffractometer analysis by grinding to a fine powder, which is then spread uniformly over the surface of a glass slide. Two kinds of samples were prepared for the analyses, namely unoriented and oriented. Unoriented samples were prepared for each of the rock samples. From the results of these samples, it was observed that the Kavakdere, Kavukkavlağı and Tarlaağzı limestones are almost completely composed of calcite ($CaCO_3$) with some very few quartz in all of the samples, very few dolomite in the Kavakdere limestone and very few amorphous material in the Kavukkavlağı limestone. This result also showed that there are no considerable amounts of clay materials in all of the limestone samples; however the unoriented samples of the Çömlekçikuyu andesite and the Kıran sandstone indicated some content of clay minerals in those rock samples; therefore the oriented samples of these rocks were prepared and tested after air-drying, glycolation and heating at 300 °C for detailed clay analysis. The result showed that smectite group clay minerals exist in both of the samples together with other minerals (Table 4.8).

The smectite group comprises a number of clay minerals composed of *t-o-t* layers of both dioctahedral and trioctahedral type. The outstanding characteristic of members of this group is their capacity to adsorb water molecules between the sheets, thus producing marked expansion of the structure (Figure 4.4). Especially montmorillonite has the unusual property of expending several times its original volume when placed in water (Klein and Hurlbut, 1999). Although this property of montmorillonite gives rise to advantages uses in industry, it is a defect in the armourstones. The armourstones are mostly in contact with water and; therefore the existence of these minerals results in the structurally weakening and sometimes failing of the material. The resulting XRD patterns for the samples are also given in Figures 4.5 - 4.7.

Table 4.8 Mineralogical content of the rock samples

Sample	Minerals
Kavakdere Limestone	Calcite, dolomite, quartz
Kavukkavlağı Limestone	Calcite, amorphous material, quartz
Tarlaağzı Limestone	Calcite, quartz
Çömlekçikuyu Andesite	Feldspar, biotite, smectite
Kıran Sandstone	Zeolite, smectite, calcite, feldspar

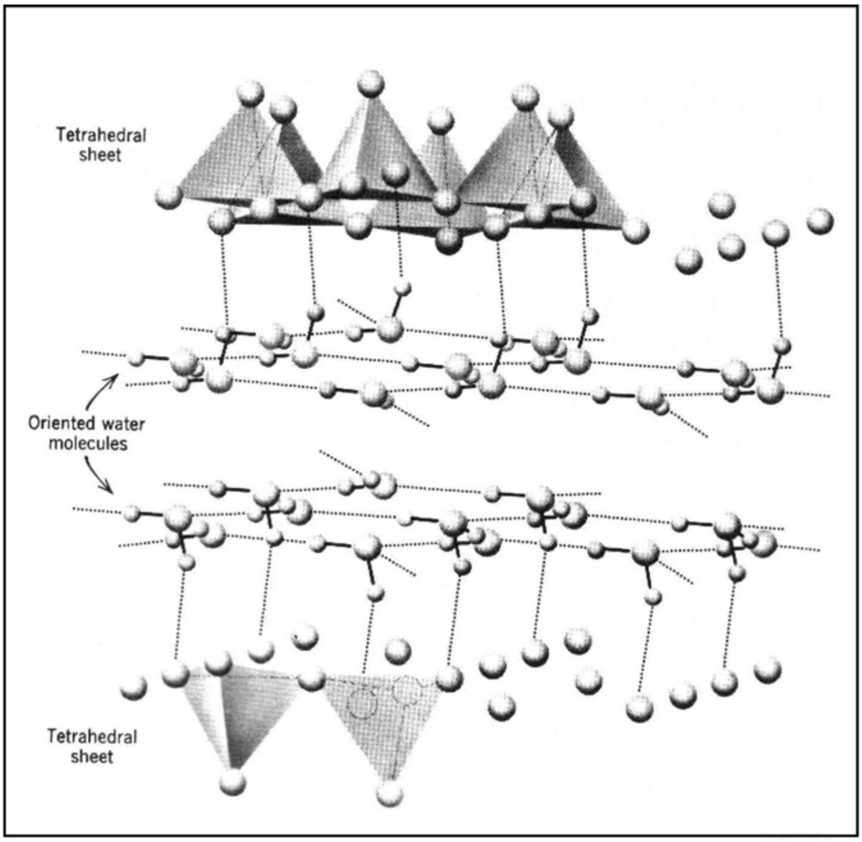


Figure 4.4 Diagrammatic sketch of the smectite group clay minerals, showing layers of water (after Grim, 1968)

The amount of the clay minerals of each sample was determined by using sedimentation method (Craig, 1992). In this method, 10 grams of powdered sample from each of the rock were saturated with pure water and the dissolved material (clay minerals) was separated by removing the water various times. The corresponding test results are given in Table 4.9.

Table 4.9 Clay fraction of the samples

Sample	**Clay Fraction (%)**
Kavakdere Limestone	0.32
Kavukkavlağı Limestone	0.17
Tarlaağzı Limestone	0.23
Çömlekçikuyu Andesite	1.24
Kıran Sandstone	1.20

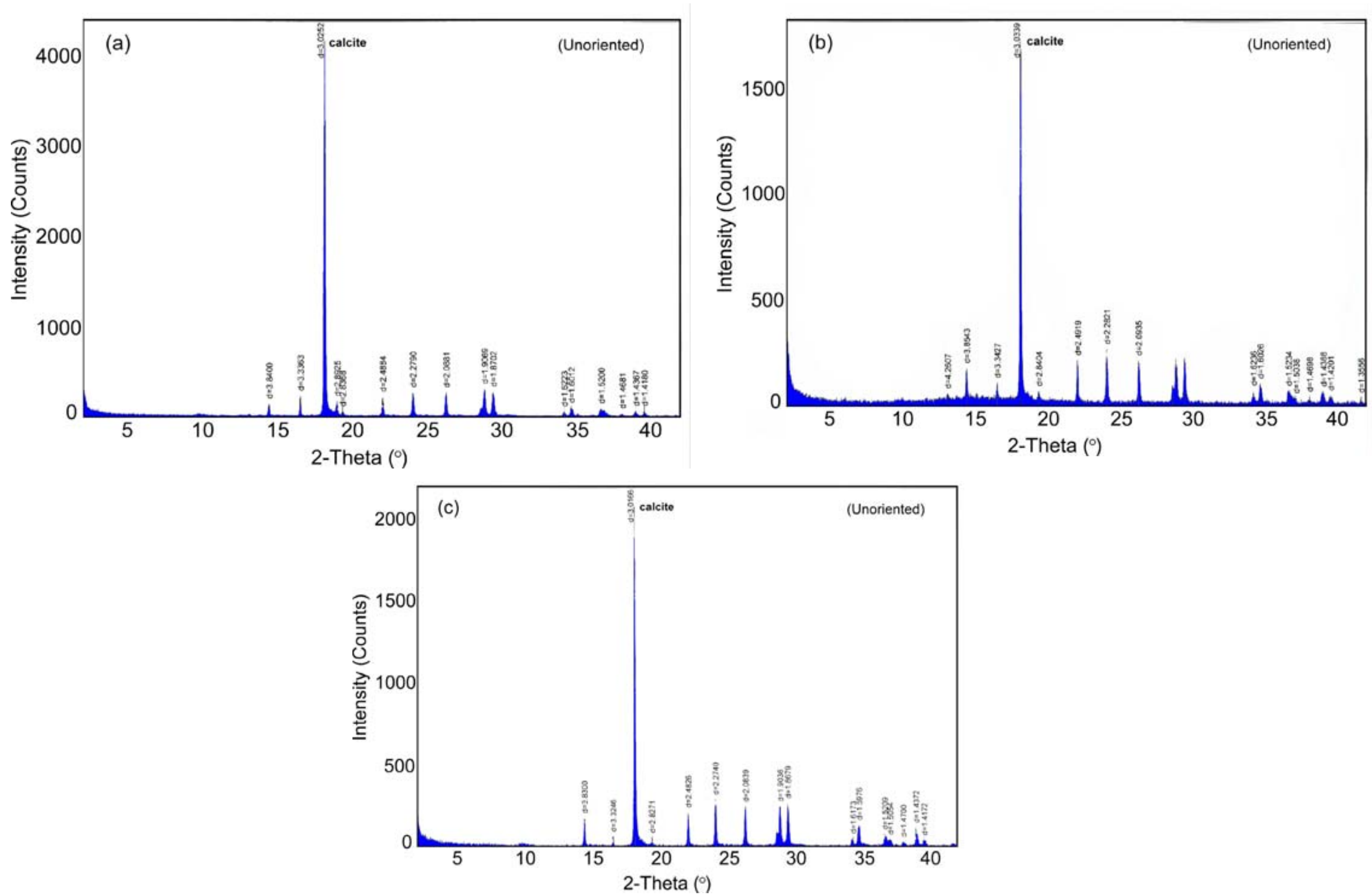


Figure 4.5 X Ray Diffraction patterns of (a) the Kavkadere limestone (b) the Kavukkavlağı limestone (c) the Tarlaağzı Limestone

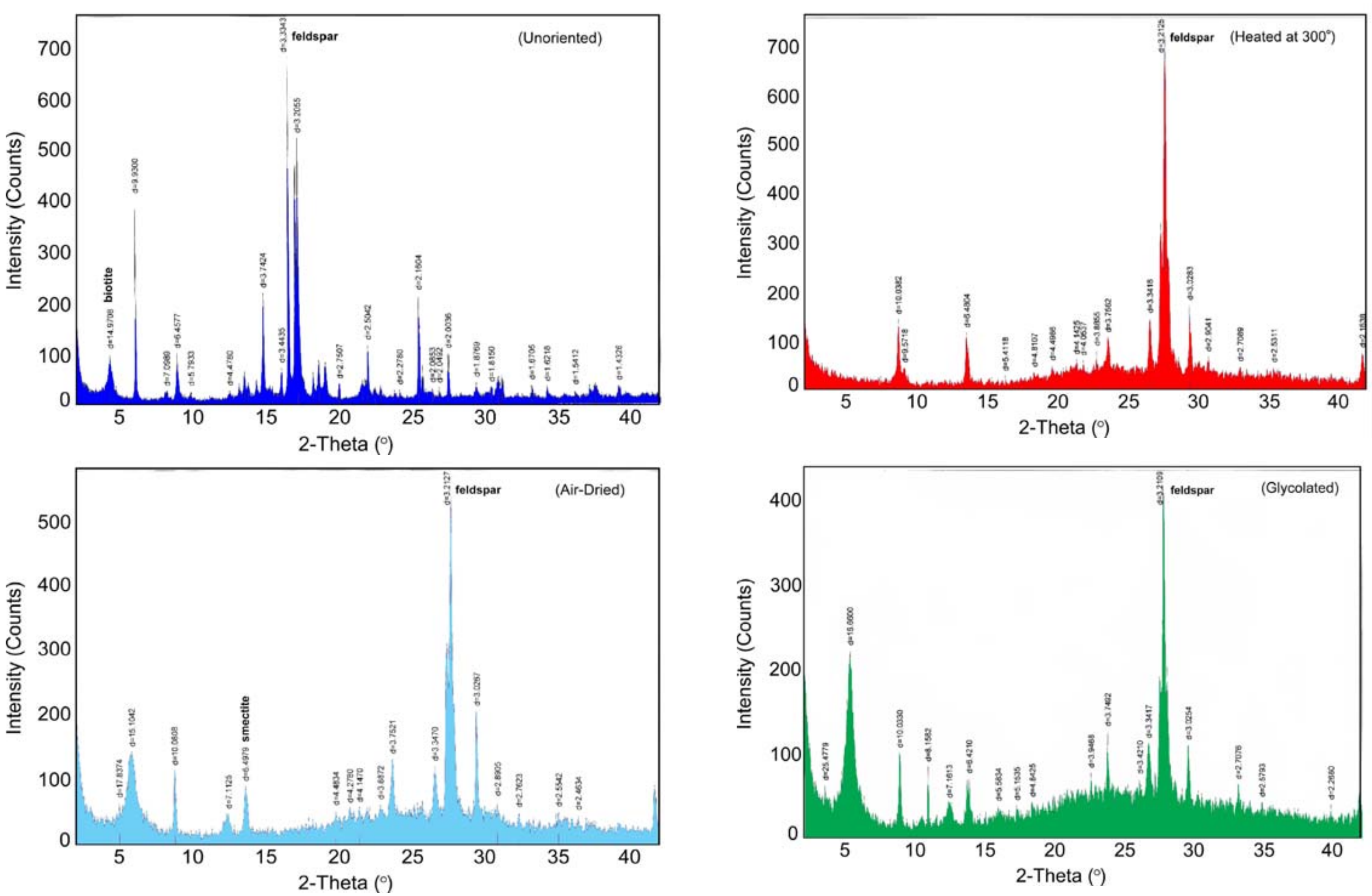


Figure 4.6 X Ray Diffraction patterns of the Çömlekçikuyu andesite

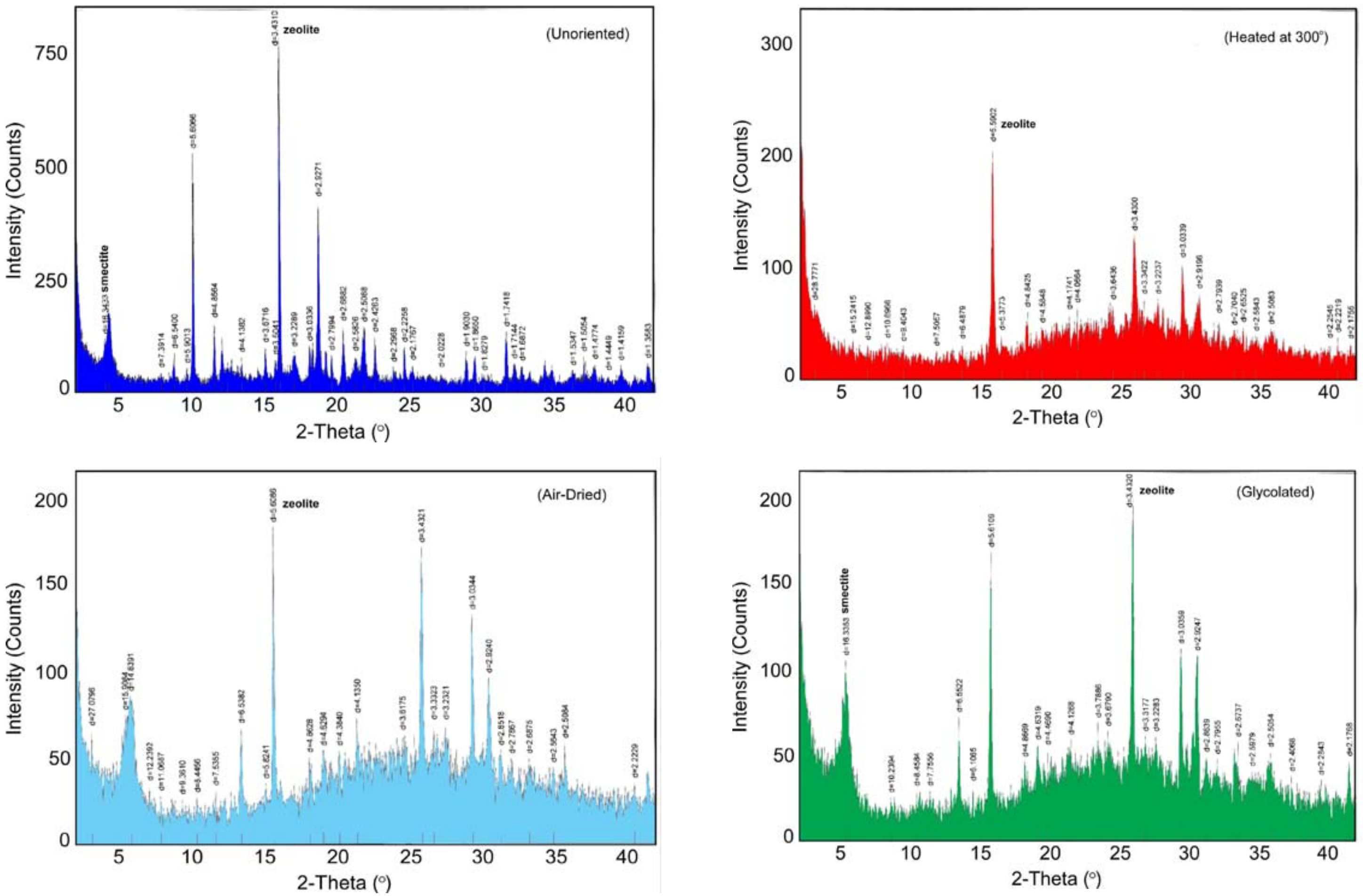


Figure 4.7 X Ray Diffraction patterns of the Kıran Sandstone

4.1.9 Uniaxial Compressive Strength

The Uniaxial Compressive Strength (UCS) is the maximum compressive stress that a sample withstands before failure. This test is intended to measure the uniaxial compressive strength of a rock sample in the form of specimens of regular geometry. The test is mainly intended for strength classification and characterization of intact rock (ISRM, 1981). For this test 5cm x 5cm x 5cm sized cubic samples are used. During the test, motorized hydraulic compression machine with a loading capacity of 1500 kN was used. The pace rate of the machine was adjusted to 1 kN/sec so that the failure takes place in about 5 minutes. The tests were carried out on 10 dry and 10 saturated samples of each armourstone sample. The corresponding test results are given in Table 4.10.

Table 4.10 Average UCS values of the samples

Sample	Dry UCS (MPa)	Engineering Classification Anon (1979)	Saturated UCS (MPa)	Engineering Classification Anon (1979)
Kavakdere Limestone	65.73	Strong	63.93	Strong
Kavukkavlağı Limestone	52.96	Strong	52.80	Strong
Tarlaağzı Limestone	71.17	Strong	70.59	Strong
Çömlekçikuyu Andesite	40.42	Moderately Strong	36.23	Moderately Strong
Kıran Sandstone	28.64	Moderately Strong	19.34	Moderately Strong

4.1.10 Point Load Strength Index Test

The point load strength index test is a fast and convenient way to determine the strength and fracture toughness of an intact rock sample. For the test, a sample of rock is mounted between two pointed platens and pressure is applied until failure of the sample occurs within 60 seconds. The maximum applied load is recorded and used to calculate the point load strength index.

The point load tester consists of a hydraulically powered ram and two pointed platens. One of these platens is stationary while the other is free to move through the application of pressure, delivered via the hydraulically powered ram. The rock specimen to be tested is placed between the two platens, and force is applied to the specimen by activation of the hydraulic ram. The force applied to the rock is increased and eventually causes the rock to fail. The maximum pressure applied is indicated on a pressure gauge.

The force recorded by the instrument to just break the rock (P) is converted to a strength value, equivalent to a 50mm diameter of the rock. This produces the so-called $Is_{(50)}$ value or size-corrected point load index. According to Brook (1985), the formula to convert the force reading to $Is_{(50)}$ value is as follows:

$$I_{s(50)} = F*P / (D_e)^2 \qquad (4.2)$$

Where,

F : size correction factor = $(D_e/50)^{0.45}$
P : applied load
D_e : $(4A/\pi)^{0.5}$
A : minimum cross-sectional area of the specimen (mm^2)

The best possible shape for greatest accuracy is cylindrical (i.e. core). If core samples are not available, square or rectangular samples are preferred (ISRM, 1985). For this test 10 cubic samples of 5cm x 5cm x 5cm dimensions were used for each of the armourstone sample. The test is applied both in dry and saturated states. The corresponding test results are given in Table 4.11.

Table 4.11 Average point load strength indexes of the samples

Sample	**Dry $Is_{(50)}$ (MPa)**	**Engineering Classification Franklin and Broch (1972)**	**Saturated $Is_{(50)}$ (MPa)**	**Engineering Classification Franklin and Broch (1972)**
Kavakdere Limestone	5.84	Very High Strength	5.45	Very High Strength
Kavukkavlağı Limestone	4.60	Very High Strength	4.15	Very High Strength
Tarlaağzı Limestone	6.15	Very High Strength	6.00	Very High Strength
Çömlekçikuyu Andesite	4.14	Very High Strength	3.96	Very High Strength
Kıran Sandstone	1.29	High Strength	0.74	Medium Strength

Point load strength test is an alternative to the Uniaxial Compressive Strength (UCS) test. In most of the ways it is easier and cheaper. The results of the point load strength index test can be converted to UCS test with a conversion factor. Early studies (Bieniawski, 1975; Broch and Franklin, 1972) were conducted on hard, strong rocks, and found that relationship between UCS and the point load strength index could be expressed as:

$$UCS = (K)\ Is50 = 24\ Is50 \tag{4.3}$$

Where K is the "conversion factor". Subsequent studies found that K=24 was not as universal as had been hoped, and that instead there appeared to be a broad range of conversion factors (Broch and Franklin, 1972; Anon, 1972; Bieniawski, 1975; Foster, 1983; ISRM, 1985; Topal, 2000).

However, in this study conversion factors do not fully coincide with the literature. This may be the result of cubic samples that are used for the Uniaxial Compressive Strength.

4.1.11 Fracture Toughness Test

The resistance of the mineral fabric to breakage caused by impact is a strength property that is not sensitive to the possibility of flaws that may partially or fully traverse blocks (i.e. the block integrity). Instead it relates to the 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. This, in turn, may lead to the progressive loss of interlock, size reduction and rounding, and the generation of a large proportion of useless fines and fragments during handling and transportation of the armourstones (Latham, 1998). Fracture toughness is an index text that measures the stress intensity ahead of the crack tip that is required for catastrophic crack propagation (ISRM, 1988). This test is recommended in the CIRIA/CUR (1991) manual as the best test to establish resistance to breakage; however, the necessary equipment for this test is not available neither in universities nor in governmental laboratories in Turkey. Therefore, the fracture toughness of the samples were calculated by a correlation formula of Latham (1998) that is evaluated from a 14 different sedimentary, igneous and metamorphic rocks spanning a wide strength range. The formula is indicated below.

$K_{IC} = 0.164\ I_{S(50)} + 0.340$ (4.4)

where;

K_{IC} : Fracture toughness strength
$I_{S(50)}$: Point load strength index

The corresponding K_{IC} values of the samples calculated by the formula are given in Table 4.12.

Table 4.12 Average fracture toughness values of the samples

Sample	Dry $Is_{(50)}$ (MPa)	Saturated $Is_{(50)}$ (MPa)	Dry K_{IC} (MPA)	Saturated K_{IC} (MPA)
Kavakdere Limestone	5.84	5.70	1.30	1.23
Kavukkavlağı Limestone	4.60	4.15	1.09	1.02
Tarlaağzı Limestone	6.15	6.00	1.35	1.32
Çömlekçikuyu Andesite	4.14	3.96	1.02	0.99
Kıran Sandstone	1.29	0.74	0.55	0.46

4.1.12 Schmidt Hammer Impact Test

One of the important properties of an intact rock is its hardness and the most practical way of determining this property is the Schmidt hammer impact test used to determine the Schmidt Rebound Hardness (ISRM, 1981). The Schmidt hammer is a quantitative extension of the qualitative impression gained from the sound of the geologist's hammer striking a rock in terms of toughness, elasticity and state of freshness (CIRIA/CUR, 1991).

The Schmidt hammer is held tightly against the rock and a spring-loaded hammer or piston, traveling through a fixed distance, applies a known energy input to the rock. The hammer rebounds from the rock, the actual amount being influenced by the elasticity of the rock. This rebound is recorded on a scale as a percentage of the forward travel (Smith and Collis, 2001).

L-type standard schmidt hammer was used for the test. The measurements were repeated 20 times on both dry and saturated samples in the laboratory. The Schmidt rebound value was obtained from the average 10 highest measurements according to ISRM (1981). Table 4.13 gives the average Schmidt rebound values of the samples.

Table 4.13 Average schmidt rebound values of the samples

Sample	**Schmidt rebound hardness value (Dry)**	**Schmidt rebound hardness value (Saturated)**
Kavakdere Limestone	42.60	38.60
Kavukkavlağı Limestone	37.70	37.30
Tarlaağzı Limestone	37.60	35.10
Çömlekçikuyu Andesite	37.00	34.60
Kıran Sandstone	25.40	25.20

4.1.13 Slake Durability Test

This test is a measure of the resistance of a rock to slaking, and was developed as an index test for mud rocks (Franklin, 1970). According to ISRM (1981), this test is intended to asses the resistance offered by a rock sample to weakening and disintegration when subjected to two standard cycles of drying and wetting. Ten samples each weighing about 50 grams from each of the samples was placed in two wire-mesh drum and immersed in water. The drums were rotated for 200 revolutions during a period of 10 minutes for one cycle. After 10 minutes the specimens are dried and weighed, and the remaining material in weight is expressed as a percentage of initial weight, the slake durability index. Average slake durability indexes of the samples are given in Table 4.14.

According to Gamble’s classification (Gamble, 1971), the Kavakdere, Kavukkavlağı, Tarlaağzı limestones and the Çömlekçikuyu andesite have high durability after two successful cycles. On the other hand, the Kıran sandstone has medium-high durability after two successful cycles.

Multiple cycles of wetting and drying are suggested by Gökçeoğlu et al, (2000) for the determination of the long term changes in the rocks. So, the test is repeated 20 times for each sample. However based on the test results (Figure 4.8), the reduction in slake durability index is rather significant at 2 test cycles.

Table 4.14 Average slake durability indexes of the samples

Sample	% Retained 1st Cycle	Gamble's Engineering Classification	% Retained 2nd Cycle	Gamble's Engineering Classification	% Retained 20th Cycle
Kavakdere Limestone	99.47	High Durability	98.98	High Durability	97.24
Kavukkavlağı Limestone	99.46	High Durability	98.89	High Durability	96.57
Tarlaağzı Limestone	99.63	High Durability	99.22	High Durability	97.98
Çömlekçikuyu Andesite	98.92	High Durability	98.04	High Durability	92.78
Kıran Sandstone	97.97	Medium-High Durability	95.66	Medium-High Durability	85.29

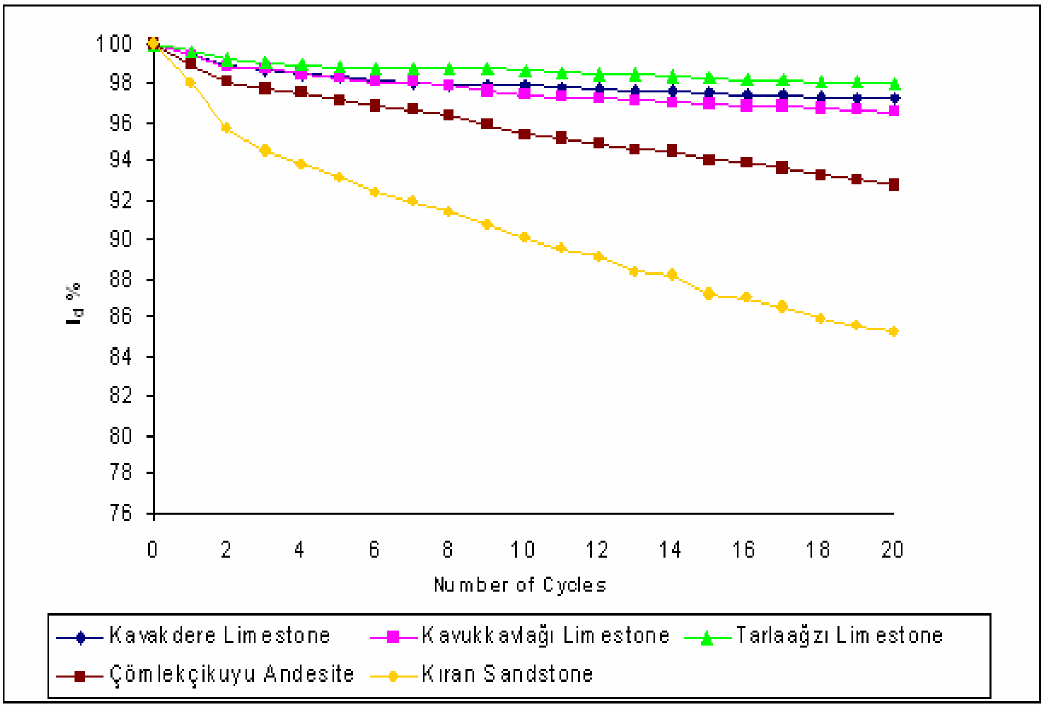


Figure 4.8 The variation of slake durability indexes of the samples for 20 test cycles.

4.1.14 Micro Deval Test

The micro-Deval test is often used as the method of determining the resistance of an aggregate to abrasion. The procedure used in this research is firstly given in French Standard NF P 18-572 (AFNOR, 1978). The test is also referred as wet Deval test for assessing wear resistance of armourstone (LCPC, 1989). This test was applied according to TSE 1097-1 (2002). According to the test procedure, 500±5 grams of aggregate passing 14 mm and retaining at 10 mm sieve was prepared using a certain fraction. Then the aggregates are placed into the steel cylinders of micro-Deval machine with 2.5 liters of water and 5000 grams of equal sized stainless steel balls. The abrasion of the aggregate is produced by the charge of stainless steel balls in the rotating cylinder.

Two tests were applied to each sample, and the average value is used for the calculations. The Micro-Deval value is calculated as (500-m)/5, where m is the weight of the material which passes through the 1.6 mm sieve after the test. The result obtained is identified as coefficient of Micro Deval (M_{DE}). The corresponding MDE values of the samples are given in Table 4.15.

Table 4.15 Average slake durability of the samples

Sample	M_{DE} (gr)	CIRIA/CUR (1991)	LCPC (1989)
Kavakdere Limestone	23.02	Good	Upper Marginal
Kavukkavlağı Limestone	19.33	Good	Good
Tarlaağzı Limestone	15.15	Good	Excellent
Çömlekçikuyu Andesite	45.76	Lower marginal	-
Kıran Sandstone	92.54	Poor	-

According to the test results, the Tarlaağzı limestone has the highest M_{DE} value. The Kavakdere and Kavukkavlağı limestones have also high test results which show their high resistance to abrasion; on the other hand, the Çömlekçikuyu andesite has low value indicating a low resistance to abrasion. Finally, the Kıran sandstone has an extremely low value reflecting a very week rock to abrasion. The physical changes of the samples before and after the test are given in Figure 4.9.

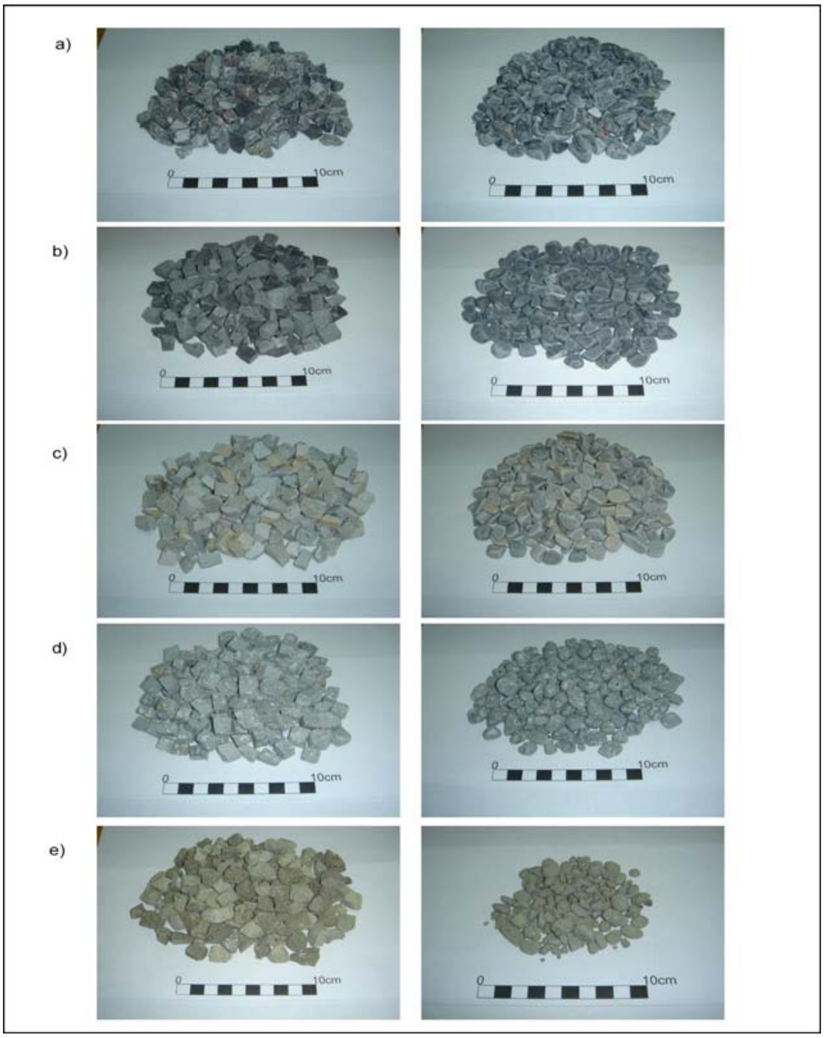


Figure 4.9 Physical changes of the samples after the micro-deval test. Fresh samples are given on the left. (a: Kavakdere limestone, b: Kavukkavlağı limestone, c: Tarlaağzı limestone, d: Çömlekçikuyu andesite, e: Kıran sandstone)

4.1.15 QMW Mill Abrasion Test

The QMW mill abrasion test is designed to indicate the resistance of a rock to mutual attrition and grinding of water-saturated coarse-aggregate size rock fragments. The mutual wear of rock fragments takes place as the pieces roll across the diametral free surface of the horizontally rotating cylindrical mill. The gentle rolling action is similar to that on a shingle beach, and does not result in whole-lump impact breakages typical of the Los Angeles test (CIRIA/CUR, 1991). Unfortunately this mandatory test could not be assed due to the lack of necessary equipment; however a correlation factor between wet micro-deval vs. QMW mill abrasion value (MAV) defined by Latham (1998) was used for the calculation of MAV. The formula is:

$$M_{DE} : -0.00115 + 0.000283MAV \quad (4.5)$$

where,

M_{DE} : Wet micro-deval value

MAV : QMW mill abrasion value

The corresponding calculations are given in Table 4.16.

Table 4.16 QMW mill abrasion values of the samples

Sample	MAV (gr)	CIRIA/CUR (1991)
Kavakdere Limestone	0.0065	Upper Marginal
Kavukkavlağı Limestone	0.0055	Upper Marginal
Tarlaağzı Limestone	0.0043	Good
Çömlekçikuyu Andesite	0.0130	Lower Marginal
Kıran Sandstone	0.0262	Poor

According to the test results, the Tarlaağzı limestone has the highest MAV value. The Kavakdere and Kavukkavlağı limestones have also high test results which show their high resistance to mill abrasion; on the other hand, the Çömlekçikuyu andesite and the Kıran sandstone have low values reflecting their low resistance to mill abrasion.

4.1.16 Los Angeles Abrasion Test

The Los Angeles test is a measure of degradation of mineral aggregates of standard gradings resulting from a combination of actions including abrasion or attrition, impact and grinding in a rotating steel drum containing a specified number of steel spheres, the number depending upon the grading of the test sample. As the drum rotates, a shelf plate picks up the sample and the steel spheres, carrying them around until they are dropped to the opposite side of the drum, creating an impact-crushing effect. After the prescribed number of revolutions, the samples and the steel balls are removed from the drum, and the aggregate portion is sieved to measure the degradation as percent loss (ASTM, 1989).

For this test, 2.5 kg of sample passing 75 mm sieve and retaining at 63 mm sieve, 2.5 kg of sample passing 63 mm sieve and retaining at 50 mm sieve and 5 kg of sample passing 50 mm sieve and retaining at 37.5 mm sieve were prepared from each rock. The amount of fines passing 1.70 mm sieve after 200 and 1000 revolutions for both dry and saturated rock samples were recorded. The corresponding Los Angeles Abrasion values (LAV) of the samples after 1000 revolutions is given in Table 4.17 According to ASTM C 535 (1989), the ratio of the loss after 200 revolutions to the loss after 1000 revolutions should not greatly exceed 0.20 for material of uniform hardness. For the saturated samples of

Kavakdere, Kavukkavlağı and Tarlaağzı limestone 0.27, 0.34 and 0.26 values were calculated respectively reflecting almost uniform hardness; on the other hand for the saturated samples of Çömlekçikuyu andesite and Kıran sandstone 0.41 and 0.53 values were calculated reflecting non-uniform hardness.

Table 4.17 Los Angeles abrasion values (LAV) of the samples

Sample	LAV % (Dry)	LAV % (Saturated)
Kavakdere Limestone	30.43	30.52
Kavukkavlağı Limestone	23.54	23.73
Tarlaağzı Limestone	27.19	28.49
Çömlekçikuyu Andesite	29.12	32.16
Kıran Sandstone	55.78	61.74

4.1.17 Aggregate Impact Test

This test also referred as dynamic crushing test (CIRIA/CUR, 1991) gives relative measure of the resistance of an aggregate to sudden shock or impact. The final value obtained from the test is referred as aggregate impact value (AIV). In this test a standard sample in the size ranging from 14 mm to 10 mm is subjected to a discontinuous loading in the form of 15 blows from a hammer or piston (13.5 kg) falling through 381 ± 6.5 mm (BSI, 1990a). The sample suffers degradation to a graded assemblage of fines. An arbitrary sieve size, 2.36 mm, is chosen as the diagnostic cut-off level, and the percentage of material passing relative to initial weight, gives the aggregate impact value, and is used as the measure of granulation.

This test is applied according to BSI (1990a) on both dry and saturated samples. The corresponding test results are given in Table 4.18.

Table 4.18 Average aggregate impact values (AIV) of the samples

Sample	Dry AIV (%)	CIRIA/CUR (1991)	Wet AIV (%)	CIRIA/CUR (1991)
Kavakdere Limestone	14.16	Good	15.31	Good
Kavukkavlağı Limestone	17.08	Good	19.29	Good
Tarlaağzı Limestone	14.43	Good	15.29	Good
Çömlekçikuyu Andesite	18.83	Good	22.96	Marginal
Kıran Sandstone	24.96	Marginal	37.44	Poor

According to the test results, the Kavakdere, Kavukkavlağı and Tarlaağzı limestones have lower AIV values which are classified as good in CIRIA/CUR (1991). On the other hand, the Çömlekçikuyu andesite has good classification in dry condition. However, with saturation its rating drops to marginal. Finally, the Kıran sandstone can be classified as the weakest rock according to the test results. Especially when saturated, the rating of the rock drops to poor.

4.1.18 Modified Aggregate Impact Value Test

The test procedure is similar to that of the standard aggregate impact test (BSI, 1990b) except that the number of hammer blows is limited to that which will yield between 5% and 20% fines. For this test, the samples were saturated, although surface dry. After testing, the samples were oven-dried (12 hours at 105 ºC). The modified Aggregate Impact Value (modified AIV) is obtained by multiplying the percentage finer than 2.36 mm by 15/X where X is the actual number of blows. The corresponding test results of the samples are given Table 4.19.

Table 4.19 Average modified aggregate impact values of the samples

Sample	Wet modified AIV (%)
Kavakdere Limestone	14.78
Kavukkavlağı Limestone	14.72
Tarlaağzı Limestone	12.61
Çömlekçikuyu Andesite	18.52
Kıran Sandstone	66.42

According to the test results the Kavkadere, Kavukkavlağı, Tarlaağzı limestones and the Çömlekçikuyu andesite have low modified AIV values indicating their good resistance to impact; on the other hand, the Kıran sandstone's considerably high value indicates very low resistance to impact.

4.1.19 Aggregate Crushing Value Test

The aggregate crushing value gives a relative measure of the resistance of an aggregate to crushing under a gradually applied compressive load (BSI, 1975). In this test, a sample of approximately 2 kg is subjected to a continuous load transmitted through a piston, in a compression test machine. A total load of 400 kN is achieved in 10 minutes. As in the aggregate impact test, the fines passing 2.36 mm sieve are calculated as a percentage of the initial weight. This is the aggregate crushing value (ACV). The test was performed on both dry and saturated samples. The corresponding test results are given in Table 4.20.

Table 4.20 Average aggregate crushing values of the samples

Sample	Dry ACV (%)	Saturated ACV (%)
Kavakdere Limestone	22.82	23.98
Kavukkavlağı Limestone	22.45	22.72
Tarlaağzı Limestone	18.55	20.19
Çömlekçikuyu Andesite	23.84	25.26
Kıran Sandstone	27.91	32.28

According to the BSI (1990c), a lower ACV value indicates more resistance to crushing. Based on this approach, the Kavakdere, Kavukkavlağı, Tarlaağzı limestones and the Çömlekçikuyu andesite are found to be more resistant rocks whereas the Tarlaağzı limestone is the most resistant; on the other hand, the Kıran sandstone is the least resistant rock.

4.1.20 10 % Fines Test

The variation of the aggregate crushing value (ACV) presents the load required to produce 10 % fines rather than the amount of crush for a specific load (Smith and Collis, 2001). The ten percent fines value gives a measure of the resistance of an aggregate to crushing which is applicable to both weak and strong rocks. A preliminary test is used to ensure that the load is recorded when between 7.5% and 12.5% fines are produced in the aggregate specimen by compression in a standard machine at a displacement rate of 20 mm in 10 min. The force required to produce ten per cent fines = 14x / (y+4) where x is the maximum force (kN) and y is the mean percentage fines from two tests at x force (kN) (BSI, 1975). The corresponding test results are given in Table 4.21.

Table 4.21 Average 10 % fines values of the samples

Sample	Dry 10 % Fines Value (kN)	Saturated 10 % Fines Value (kN)
Kavakdere Limestone	277.70	263.19
Kavukkavlağı Limestone	231.51	226.91
Tarlaağzı Limestone	248.24	231.90
Çömlekçikuyu Andesite	175.92	160.67
Kıran Sandstone	149.65	96.74

According to the BSI (1990d), a high 10 % fines value indicates more resistance to crushing. Based on this approach, the Kavakdere, Kavukkavlağı, Tarlaağzı limestones have close and high values reflecting more resistant rock whereas the Kavakdere Limestone has the highest value; on the other hand, the Çömlekçikuyu andesite and the Kıran sandstone have moderate and low values reflecting a low resistant rock.

4.1.21 Freeze-Thaw Test

Freeze-thaw test is a recommended test for the determination of weathering resistance of armourstones (CIRIA/CUR 1991). The idea behind the test is to simulate the harsh climatic conditions that would create stresses inside the stone due to ice crystallization. Those effects are generally obtained by varying temperature under and above 0 ^{o}C on samples containing a known amount of water. Freeze-thaw test is usually performed for rocks having water absorption under atmospheric pressure values greater than 1 % according to Clark (1988), and greater than 0.5 % according to CIRIA/CUR (1991). Although the Kavakdere, Kavukkavlağı and Tarlaazğzı limestones have very low water absorptions, the test was applied on those samples too for comparison.

For this test, 25 cubic samples from the Kavakdere, Kavukkavlağı, Tarlaağzı limestones and the Çömlekçikuyu andesite, and 10 cubic samples for the Kıran sandstone were used. All of the samples were saturated for 24 hours in distilled water at 15 to 20 °C, and were tested in an automated freeze-thaw machine. The machine automatically changes the heat from -15 to 2°C for 12 hours period of freezing. At the end of 25 freeze-thaw cycles, the total weight losses of the samples in terms of their initial sizes were calculated. The corresponding test results are given in Table 4.22.

Table 4.22 Freeze-Thaw loss values of the samples

Sample	Weight Loss Value (%)
Kavakdere Limestone	0.11
Kavukkavlağı Limestone	0.04
Tarlaağzı Limestone	0.23
Çömlekçikuyu Andesite	8.65
Kıran Sandstone	15.74

According to the above results, the weight loss in the Kavakdere, Kavukkavlağı and Tarlaağzı limestones are considerably low indicating a perfect weathering resistance which would be expected from their very low water absorption values. On the other hand, the weight loss in the Çömlekçikuyu andesite is higher showing a good correlation with its water absorption. Finally, the Kıran sandstone has the highest weight loss reflecting a low weathering resistance.

In addition, dry unit weight, saturated unit weight, effective porosity, weight, water absorption by weight, water absorption by volume, sonic velocity and UCS of the samples were also recorded at 5, 10, 15, 20 and 25 freeze-thaw test cycles and compared with those of the fresh samples. However mechanical disintegration of the Kıran sandstone occurred very early at the fifth cycle; therefore in order to assess the necessary physico-mechanical properties, the samples having relatively good end surfaces were used for testing. Corresponding measurements are given in Tables 4.23-4.27 as average normalized values.

Table 4.23 Normalized average physical and mechanical properties of the Kavakdere limestone during freeze-thaw cycles

Cycle #	Weight (%)	Porosity (%)	Dry Unit Weight (%)	Saturated Unit Weight (%)	Water abs. By weight (%)	Water abs. By Volume (%)	Sonic Velocity (%)	UCS (%)
0	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
5	100.00	98.11	100.04	100.00	95.00	98.11	99.80	99.98
10	99.99	100.00	100.00	99.96	100.00	100.00	99.07	100.06
15	99.98	100.00	99.92	99.92	100.00	100.00	98.41	99.36
20	99.97	103.77	99.89	99.85	105.00	103.77	98.72	98.52
25	99.96	107.55	99.81	99.81	105.00	107.55	98.38	95.32

Table 4.24 Normalized average physical and mechanical properties of the Kavukkavlağı limestone during freeze-thaw cycles

Cycle #	Weight (%)	Porosity (%)	Dry Unit Weight (%)	Saturated Unit Weight (%)	Water abs. By weight (%)	Water abs. By Volume (%)	Sonic Velocity (%)	UCS (%)
0	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
5	99.96	100.00	100.00	100.00	110.00	100.00	99.84	99.41
10	99.94	103.45	99.96	99.96	110.00	100.00	99.50	99.77
15	99.92	103.45	99.93	99.89	110.00	103.45	99.15	99.12
20	99.92	110.34	99.89	99.89	120.00	110.34	98.62	99.65
25	99.89	106.90	99.85	99.85	110.00	106.90	98.28	99.10

Table 4.25 Normalized average physical and mechanical properties of the Tarlaağzı limestone during freeze-thaw cycles

Cycle #	Weight (%)	Porosity (%)	Dry Unit Weight (%)	Saturated Unit Weight (%)	Water abs. By weight (%)	Water abs. By Volume (%)	Sonic Velocity (%)	UCS (%)
0	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
5	99.93	101.39	99.92	99.92	102.47	101.39	98.61	99.11
10	99.91	101.85	99.88	99.89	102.47	101.39	98.21	98.72
15	99.85	101.85	99.81	99.81	102.47	101.39	98.32	99.90
20	99.84	102.78	99.77	99.77	103.70	102.31	98.07	98.52
25	99.77	106.02	99.69	99.73	106.17	105.09	98.11	98.76

Table 4.26 Normalized average physical and mechanical properties of the Çömlekçikuyu andesite during freeze-thaw cycles

Cycle #	Weight (%)	Porosity (%)	Dry Unit Weight (%)	Saturated Unit Weight (%)	Water abs. By weight (%)	Water abs. By Volume (%)	Sonic Velocity (%)	UCS (%)
0	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
5	98.76	102.87	99.09	99.16	102.59	102.87	100.21	98.42
10	95.43	127.43	98.40	99.16	127.78	127.43	99.06	99.26
15	94.17	132.85	95.15	96.12	137.78	132.85	93.35	97.43
20	92.85	142.58	90.73	92.07	155.19	142.58	89.74	78.75
25	91.35	143.70	87.00	88.44	162.96	143.70	83.46	77.51

Table 4.27 Normalized average physical and mechanical properties of the Kıran sandstone during freeze-thaw cycles

Cycle #	Weight (%)	Porosity (%)	Dry Unit Weight (%)	Saturated Unit Weight (%)	Water abs. By weight (%)	Water abs. By Volume (%)	Sonic Velocity (%)	UCS (%)
0	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
5	84.26	144.20	81.73	86.07	176.39	144.20	74.61	42.88

The weight losses observed in the Kavakdere, Kavukkavlağı and Tarlaağzı limestones are 0.11 %, 0.04 % and 0.23 %, respectively. These values indicate very minor (almost negligible) losses in weight for the limestone samples. On the other hand, at the end of the test the weight loss in the Çömlekçikuyu andesite is calculated as 8.65 %. The weight loss in the andesite follows an almost linear path throughout the cycles. Finally, the weight loss in the Kıran sandstone is the maximum, and calculated as 15.74 % at the fifth cycle (Figure 4.10).

The increase in effective porosity of the Kavakdere, Kavukkavlağı and Tarlaağzı limestone is 6.90 %, 7.55 % and 7.90 %, respectively. On the other hand, the increase in the Çömlekçikuyu andesite and Kıran sandstone is 43.70 % and 44.20 %, respectively. The increase in the effective porosity of the andesite and sandstone are pretty high compared to the other samples (Figure 4.10).

Dry and saturated unit weights of the limestones are almost unchanged. The decrease in saturated unit weights of the Kavakdere, Kavukkavlağı and Tarlaağzı limestones are 0.15 %, 0.19 %, and 0.27 %, respectively. The change in the Hisarönü andesite and Kıran sandstone are 11.56 % and 13.93 %, respectively which are considerably high compared to the other samples (Figure 4.10).

Water absorption of the Kavakdere, Kavukkavlağı and Tarlaağzı limestone is again very low compared to the other samples as expected from the minor changes in their effective porosities. Water absorption by weight and volume are both calculated for the samples and for the Kavakdere, Kavukkavlağı and Tarlaağzı limestones, the increase in water absorption by weight are 6.90 %, 7.55 %, 5.09 %, respectively. On the other hand, the increase in the water absorption by weight for the Çömlekçikuyu andesite and Kıran sandstone are 43.70 % and 44.20 %, respectively (Figure 4.10).

The decreases in the sonic velocities of the samples are in good correlation with the increasing effective porosity values. 1.72 %, 1.62 % and 1.89 % decrease in sonic velocities are calculated for the Kavakdere, Kavukkavlağı and Tarlaağzı limestones, respectively and 16.54 % and 25.39 % decrease in sonic velocity are calculated for the Çömlekçikuyu andesite and Kıran sandstone. The decrease in the sonic velocities of the andesite and the sandstone samples are in good agreement with the increasing effective porosity of the samples (Figure 4.10).

The decreases in the UCS values of the Kavakdere, Kavukkavlağı and Tarlaağzı limestones are again considerably low. 0.9 %, 4.68 % and 1.24 % decreases are calculated respectively for these samples. On the other hand, the decrease in the Çömlekçikuyu andesite and Kıran sandstone are significant. 22.49 % decrease for the andesite and 57.12 % decrease for the sandstone are calculated in the end of the test (Figure 4.10).

In general, the decrease in weight, dry weight, saturated weight, sonic velocity and UCS of the Kavakdere, Kavukkavlağı and Tarlaağzı limestones is negligible, and minor increase is observed in the water absorption and porosity of the samples; therefore it can be concluded that these rocks are nearly unaffected from the freeze-thaw test retaining their initial physico-mechanical properties. On the other hand, especially after cycle 15, a major decrease in the dry unit weight, saturated unit weight, sonic velocity and UCS, and a major increase in the porosity and water absorption occurred in the samples of the Çömlekçikuyu andesite reflecting the destructive effect of the ice crystallization in the rock. The Çömlekçikuyu andesite is mostly disintegrated from the sides and the corners. Finally, the Kıran sandstone can be referred as the weakest rock compared to the others. Only 5 cycles could be applied to this specimen. Nevertheless, the maximum decrease in weight, dry weight, saturated weight, sonic velocity and UCS, and the maximum increase in water absorption and porosity is observed at this sample reflecting a considerably low resistance to thawing and freezing.

During the test in order to reflect the changes in the shape, the samples are photographed at the end of cycles 5, 10, 15, 20 and 25. The corresponding pictures are given in Figures 4.11-4.15.

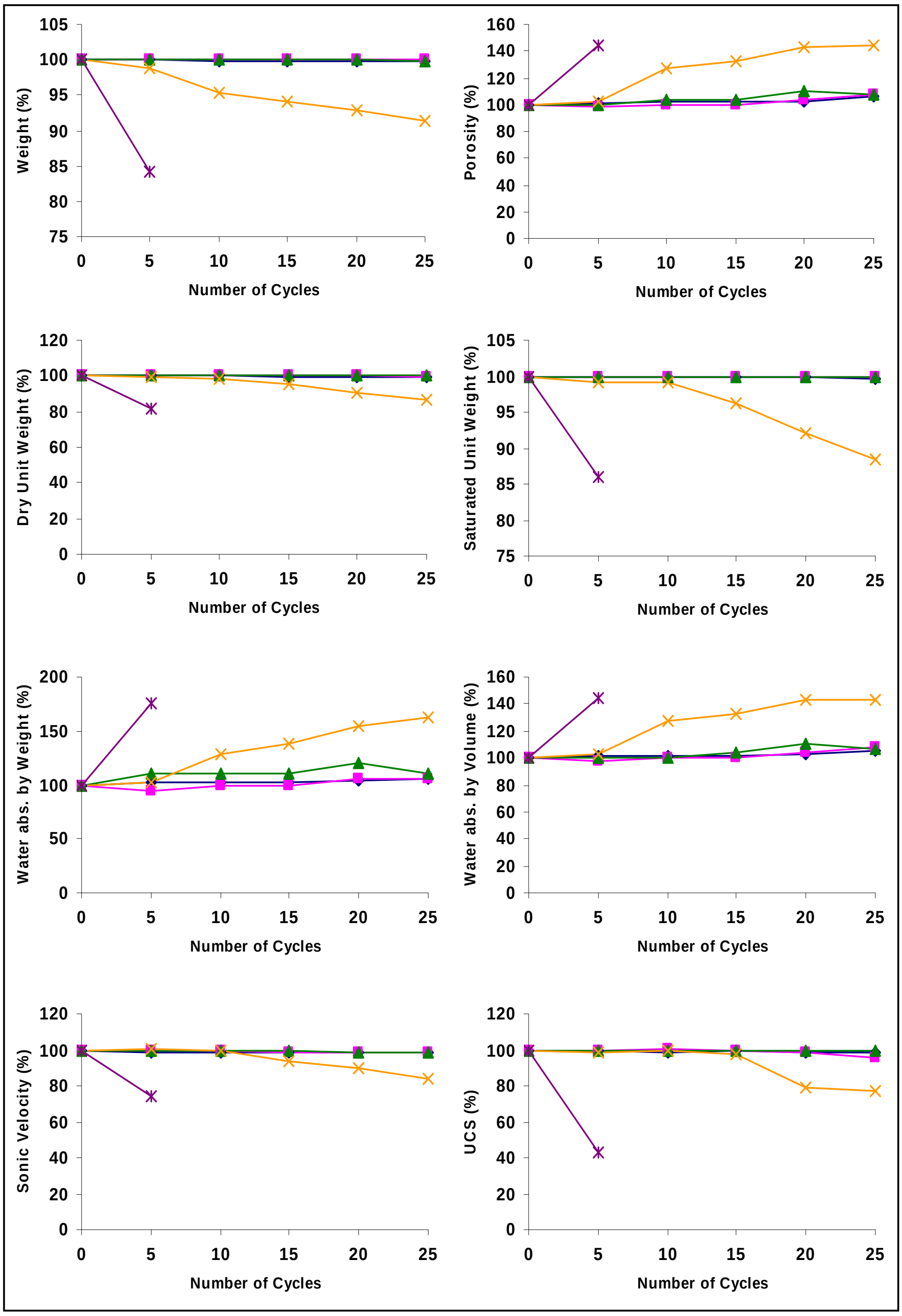


Figure 4.10 Variation of the physico-mechanical properties of the samples after freeze-thaw test (green line indicates the Kavakdere limestone, pink line indicates the Kavukkavlağı limestone, blue line indicates the Tarlağzı limestone, orange line indicates the Çömlekçikuyu andesite and purple line indicates the Kıran sandstone)

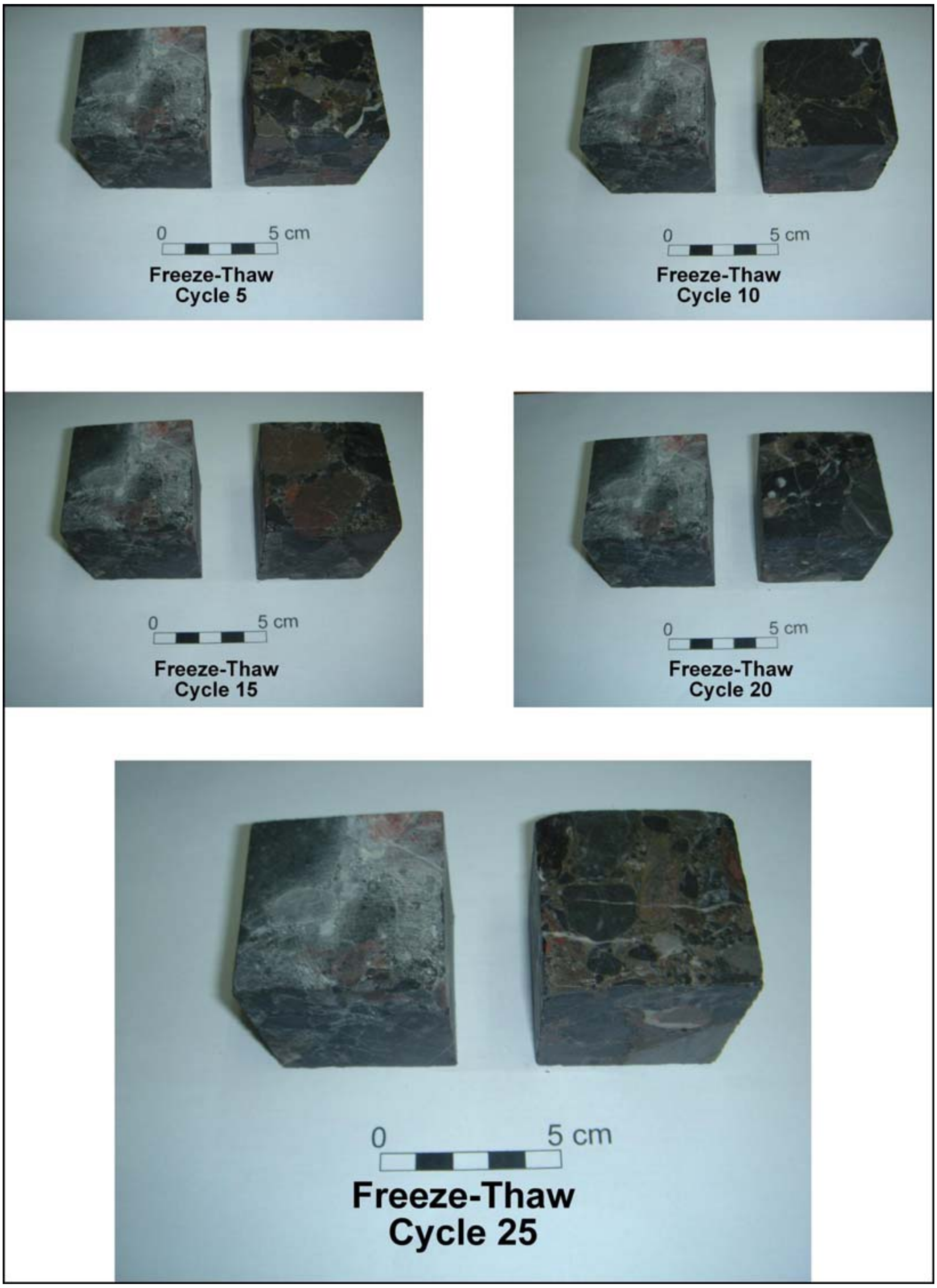


Figure 4.11 Physical appearances of the Kavakdere limestone during the freeze-thaw test. The sample on the left side of the photographs indicates a fresh reference sample.

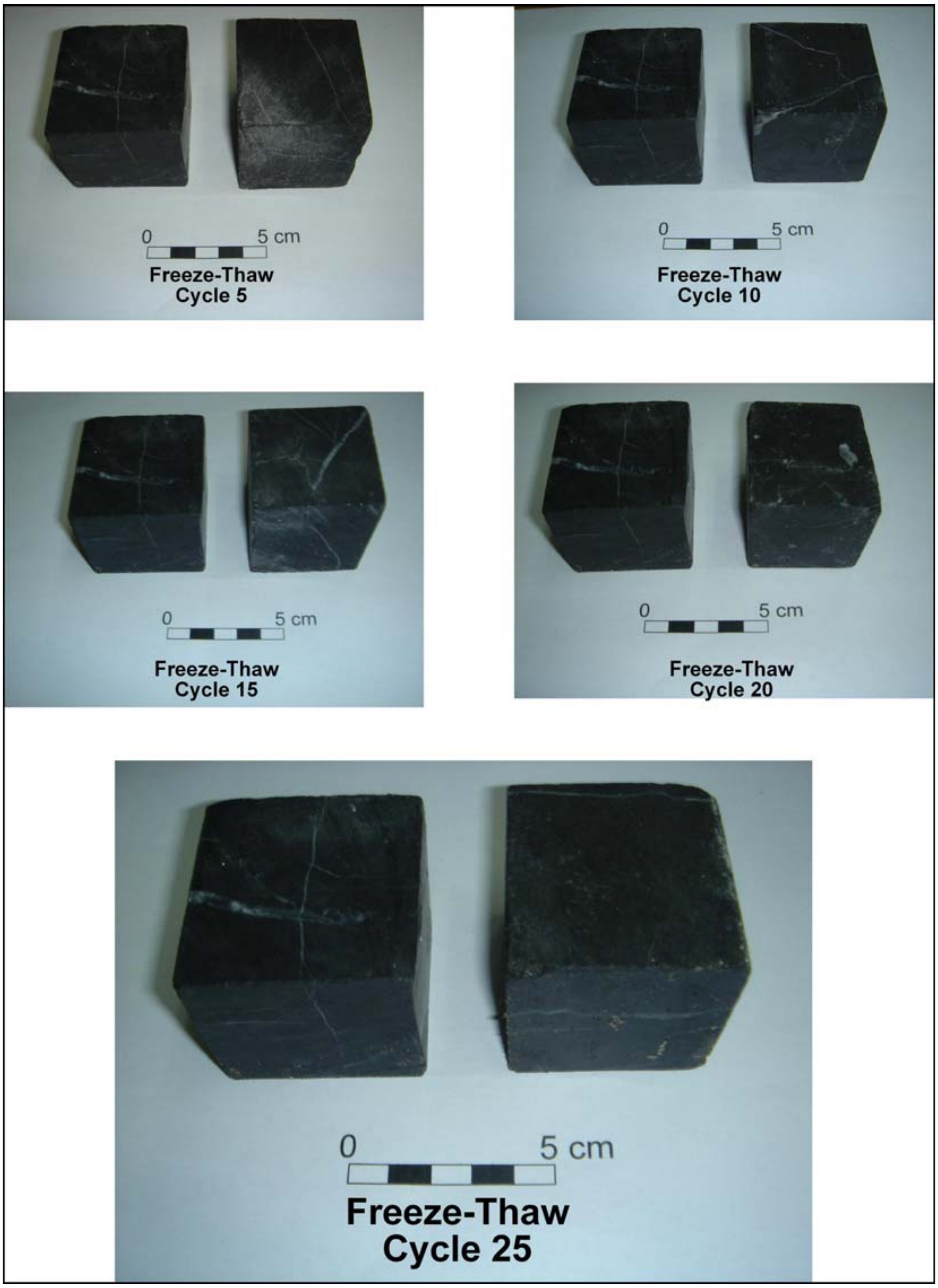


Figure 4.12 Physical appearances of the Kavukkavlağı limestone during the freeze-thaw test. The sample on the left side of the photographs indicates a fresh reference sample.

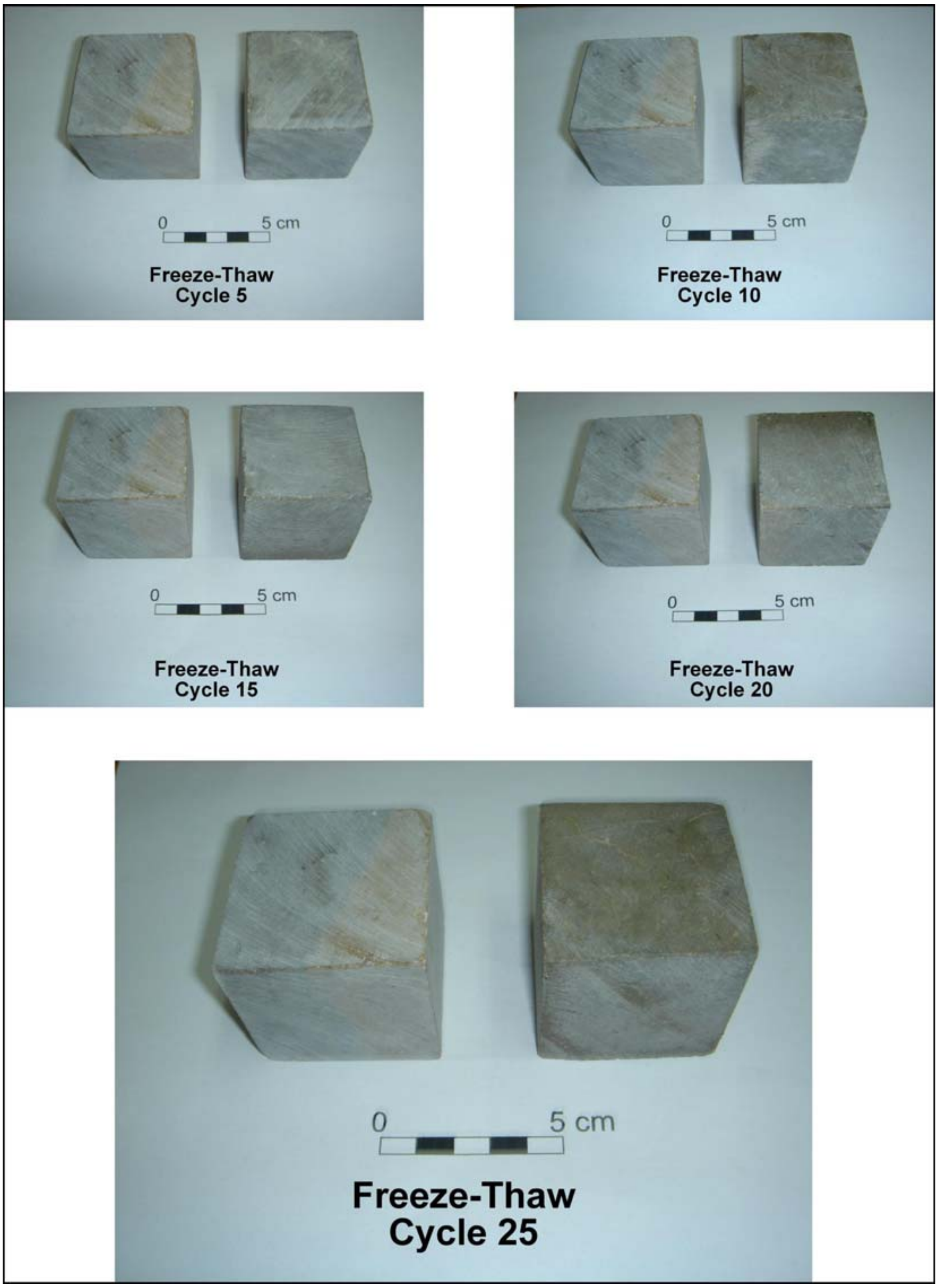


Figure 4.13 Physical appearances of the Tarlaağzı limestone during the freeze-thaw test. The sample on the left side of the photographs indicates a fresh reference sample.

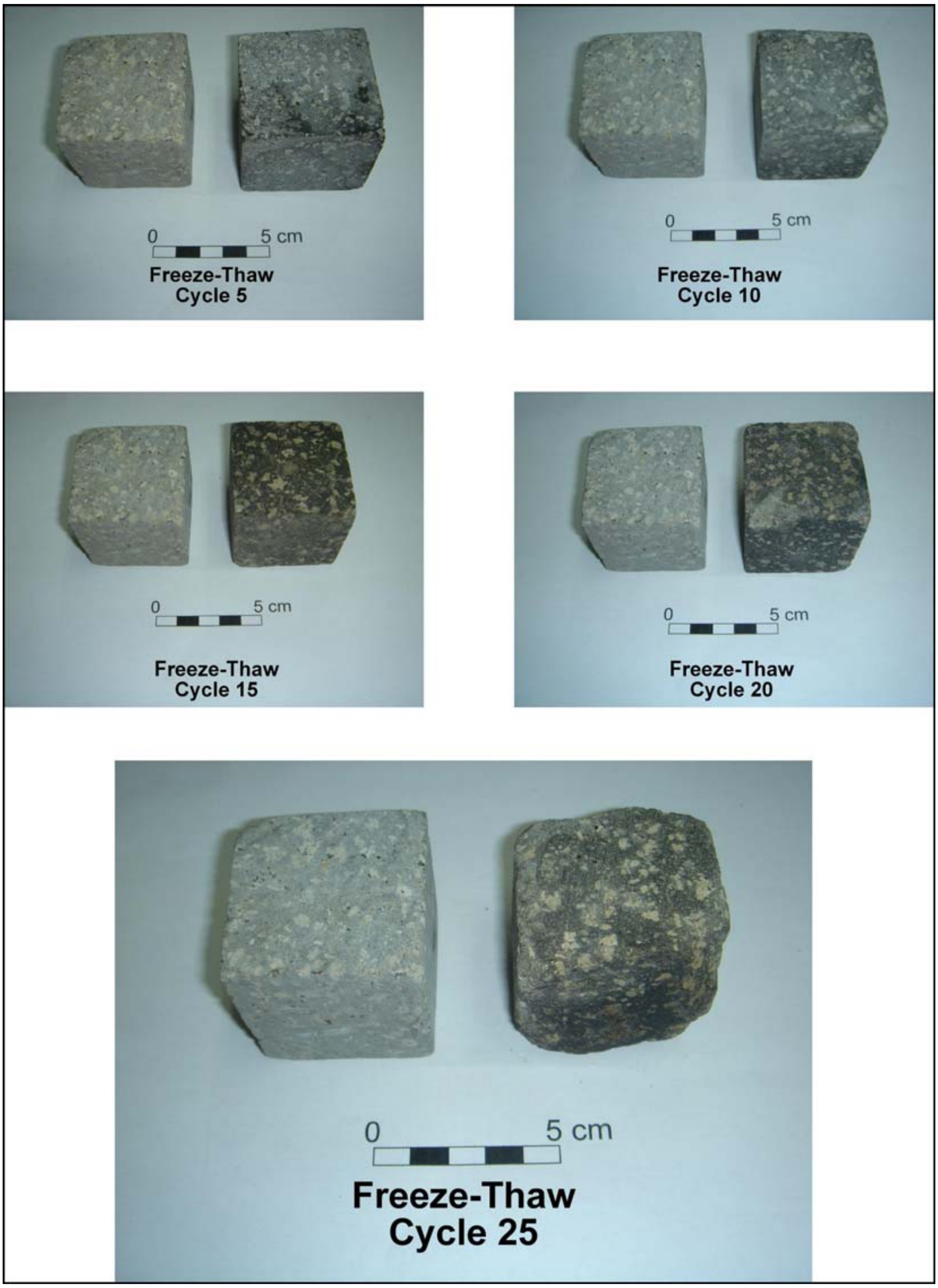


Figure 4.14 Physical appearances of the Çömlekçikuyu andesite during the freeze-thaw test. The sample on the left side of the photographs indicates a fresh reference sample.

Figure 4.15 Physical appearance of the Kıran sandstone during the freeze-thaw test. The sample on the left side of the photographs indicates a fresh reference sample

4.1.22 Wetting-Drying Test

Wetting-drying is another test that is used for the determination of weathering resistance of the rock material especially for the armourstones that are frequently subjected to this kind of process.

Stone expands when it absorbs water and shrinks as it dries. This expansion and contraction produces internal stresses at the grain boundaries. When the stone heats up a "baking effect" occurs, which will eventually lead to surface flaking.

Frequently, the exposed surfaces of the stones are covered by a film of water that is too thin to allow the water to run down, over the surface. Water in this form may cause more damage than the direct action of rain, because, it is often acidic, and transports all particulate pollutants present in the atmosphere such as soot, dust, etc. The water may penetrate into the stone through pores or cracks, but it returns to the surface to be evaporated when drying conditions prevail. Thus, wetting-drying process can cause damage during the wetting phase because of acid attack, and during the drying phase because of crystallization of pollutants and reaction products (Torraca, 1998).

For this test, 25 cubic samples from the Kavakdere, Kavukkavlağı, Tarlaağzı limestone and the Çömlekçikuyu andesite, and 10 samples for the Kıran sandstone were used. All of the 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. The corresponding test results are given in Table 4.28.

Table 4.28 Wetting-drying loss values of the samples

Sample	Weight Loss Value (%)
Kavakdere Limestone	0.02
Kavukkavlağı Limestone	0.04
Tarlaağzı Limestone	0.14
Çömlekçikuyu Andesite	6.79
Kıran Sandstone	12.38

According to the above results, the weight losses in the Kavakdere, Kavukkavlağı, Tarlaağzı limestones are considerably low indicating a perfect weathering resistance which would be expected due to their low water absorption values. On the other hand, weight loss in the Çömlekçikuyu andesite is higher showing a good correlation with its water absorption. Finally, the Kıran sandstone has the highest weight loss reflecting a low weathering resistance.

In addition, dry unit weight, saturated unit weight, effective porosity, weight, water absorption by weight, water absorption by volume, sonic velocity and UCS of the samples were also recorded at 20, 40, 60 and 80 wetting-drying test cycles and compared with those of the fresh samples. However, mechanical disintegration of the Kıran sandstone occurred very early at the twentieth stage. Therefore in order to assess necessary physico-mechanical properties, most intact Kıran sandstone samples were removed from the test after the twentieth cycle. Corresponding measurements are given in Tables 4.29-4.33 as normalized average values.

Table 4.29 Normalized average physical and mechanical properties of the Kavakdere limestone during wetting-drying cycles

Cycle #	Weight (%)	Porosity (%)	Dry Unit Weight (%)	Saturated Unit Weight (%)	Water abs. By weight (%)	Water abs. By Volume (%)	Sonic Velocity (%)	UCS (%)
0	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
20	100.00	100.00	100.00	100.00	110.00	100.00	99.22	99.38
40	99.99	100.00	99.96	99.96	110.00	100.00	98.68	98.65
60	99.98	103.45	99.96	99.93	110.00	103.45	98.49	98.95
80	99.98	103.45	99.93	99.93	110.00	103.45	98.32	98.81

Table 4.30 Normalized average physical and mechanical properties of the Kavukkavlağı limestone during wetting-drying cycles

Cycle #	Weight (%)	Porosity (%)	Dry Unit Weight (%)	Saturated Unit Weight (%)	Water abs. By weight (%)	Water abs. By Volume (%)	Sonic Velocity (%)	UCS (%)
0	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
20	99.99	101.89	99.96	99.92	100.00	101.89	98.79	98.94
40	99.99	103.77	99.92	99.89	100.00	103.77	98.75	99.98
60	99.97	103.77	99.92	99.89	100.00	103.77	98.27	98.07
80	99.96	105.66	99.85	99.81	105.00	105.66	98.31	98.71

Table 4.31 Normalized average physical and mechanical properties of the Tarlaağzı limestone during wetting-drying cycles

Cycle #	Weight (%)	Porosity (%)	Dry Unit Weight (%)	Saturated Unit Weight (%)	Water abs. By weight (%)	Water abs. By Volume (%)	Sonic Velocity (%)	UCS (%)
0	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
20	99.99	99.54	99.96	99.92	100.00	99.54	98.37	99.79
40	99.98	101.39	99.81	99.77	102.47	101.39	98.40	98.51
60	99.98	101.39	99.77	99.73	101.23	100.93	98.15	99.28
80	99.96	102.78	99.69	99.70	103.70	102.31	97.44	98.45

Table 4.32 Normalized average physical and mechanical properties of the Çömlekçikuyu andesite during wetting-drying cycles

Cycle #	Weight (%)	Porosity (%)	Dry Unit Weight (%)	Saturated Unit Weight (%)	Water abs. By weight (%)	Water abs. By Volume (%)	Sonic Velocity (%)	UCS (%)
0	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
20	98.45	107.50	99.61	99.79	107.04	107.50	99.62	97.43
40	97.70	114.19	98.70	99.07	114.44	114.19	95.10	99.38
60	95.56	124.40	94.06	94.85	125.19	124.40	91.22	96.29
80	93.21	125.68	93.93	94.73	126.67	125.68	88.07	86.32

Table 4.33 Normalized average physical and mechanical properties of the Kıran sandstone during wetting-drying cycles

Cycle #	Weight (%)	Porosity (%)	Dry Unit Weight (%)	Saturated Unit Weight (%)	Water abs. By weight (%)	Water abs. By Volume (%)	Sonic Velocity (%)	UCS (%)
0	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
20	84.30	120.52	96.80	98.40	125.46	120.52	88.30	63.55

The weight losses observed in the Kavakdere, Kavukkavlağı and Tarlaağzı limestones are 0.02 %, 0.04 % and 0.14 %, respectively. These values indicate a very minor almost negligible loss in weight for the limestone samples. On the other hand, at the end of the test weight loss in the Çömlekçikuyu andesite is calculated as 6.79 %. The weight loss in the andesite follows an almost linear path through out the cycles. Finally the weight loss in the Kıran sandstone is the maximum, and calculated as 12.38 % at the twentieth cycle (Figure 4.16).

The increases in effective porosities of the Kavakdere, Kavukkavlağı and Tarlaağzı limestones are 3.45 %, 5.66 % and 2.78 %, respectively. On the other hand, the increase in the Çömlekçikuyu andesite and Kıran sandstone is 25.68 % and 20.52 %, respectively. The increase in the effective porosity of the andesite seems to be the maximum, however it must be pointed that the sandstone achieved a high value at early stages of the test (Figure 4.16).

Dry and saturated unit weights of the limestones are almost unchanged. The decrease in saturated unit weights of the Kavakdere, Kavukkavlağı and Tarlaağzı limestones are 0.07 %, 0.19 %, and 0.30 %. The change in the Çömlekçikuyu andesite and Kıran sandstone are 5.27 % and 1.6 %, respectively which are high compared to the other samples (Figure 4.16).

Water absorptions of the Kavakdere, Kavukkavlağı and Tarlaağzı limestones are again very low compared to the other samples as expected from the minor change in their effective porosities. Water absorption by weight and volume are both calculated for the samples and for the Kavakdere, Kavukkavlağı and Tarlaağzı limestones, the increases in water absorptions by weight are 3.45 %, 5.66 %, 2.31 %, respectively. On the other hand, increases in water absorptions by weight for the Çömlekçikuyu andesite and Kıran sandstone are 25.68 % and 20.52 %, respectively (Figure 4.16).

The decreases in the sonic velocities of the samples are in good correlation with the increases in effective porosity values. 1.68 %, 1.69 % and 2.56 % decreases are calculated for the Kavakdere, Kavukkavlağı and Tarlaağzı limestones, respectively and 11.93 % and 11.70 % decreases are calculated for the Çömlekçikuyu andesite and Kıran sandstone. The decrease in the sonic velocity of the andesite and sandstone samples is in good correlation with the increasing effective porosity of the samples (Figure 4.16).

The decrease in the UCS values of the Kavakdere, Kavukkavlağı and Tarlaağzı limestones is again considerably low. 1.19%, 1.29 % and 1.55 % decreases are calculated respectively for these samples. On the other hand, the decrease in the Çömlekçikuyu andesite and Kıran sandstone is significant. 13.68 % decrease for the andesite and 36.45 % decrease for the sandstone are calculated in the end of the test (Figure 4.16).

In general, the decrease in weight, dry weight, saturated weight, sonic velocity and UCS of the Kavakdere, Kavukkavlağı and Tarlaağzı limestones is negligible, and minor increase is observed in the water absorption and porosity of the samples; therefore it can be concluded that these rocks are nearly unaffected from the wetting-drying test retaining their initial physico-mechanical properties. On the other hand especially after cycle 40, a decrease in the dry weight, saturated weight, sonic velocity and UCS, and an increase in the porosity and water absorption occurred in the samples of the Çömlekçikuyu andesite. These results reflect that the Çömlekçikuyu andesite is affected from the wetting-drying test, however the loss in the UCS shows a minor disintegration in the physical behavior of the rock. The Çömlekçikuyu andesite is mostly disintegrated from the sides and the corners. Finally, the Kıran sandstone can be referred as the weakest rock compared to the others. Only 20 cycles could be applied to this specimen. Nevertheless, considerable decreases in weight, dry weight, saturated weight, sonic velocity and UCS, and considerable increases in water absorption and porosity are observed at this sample reflecting a low resistance to wetting-drying.

During the test in order to reflect the changes in the shape, the samples are photographed at the end of cycles 20, 40, 60 and 80. The corresponding pictures are given in Figures 4.17-4.21.

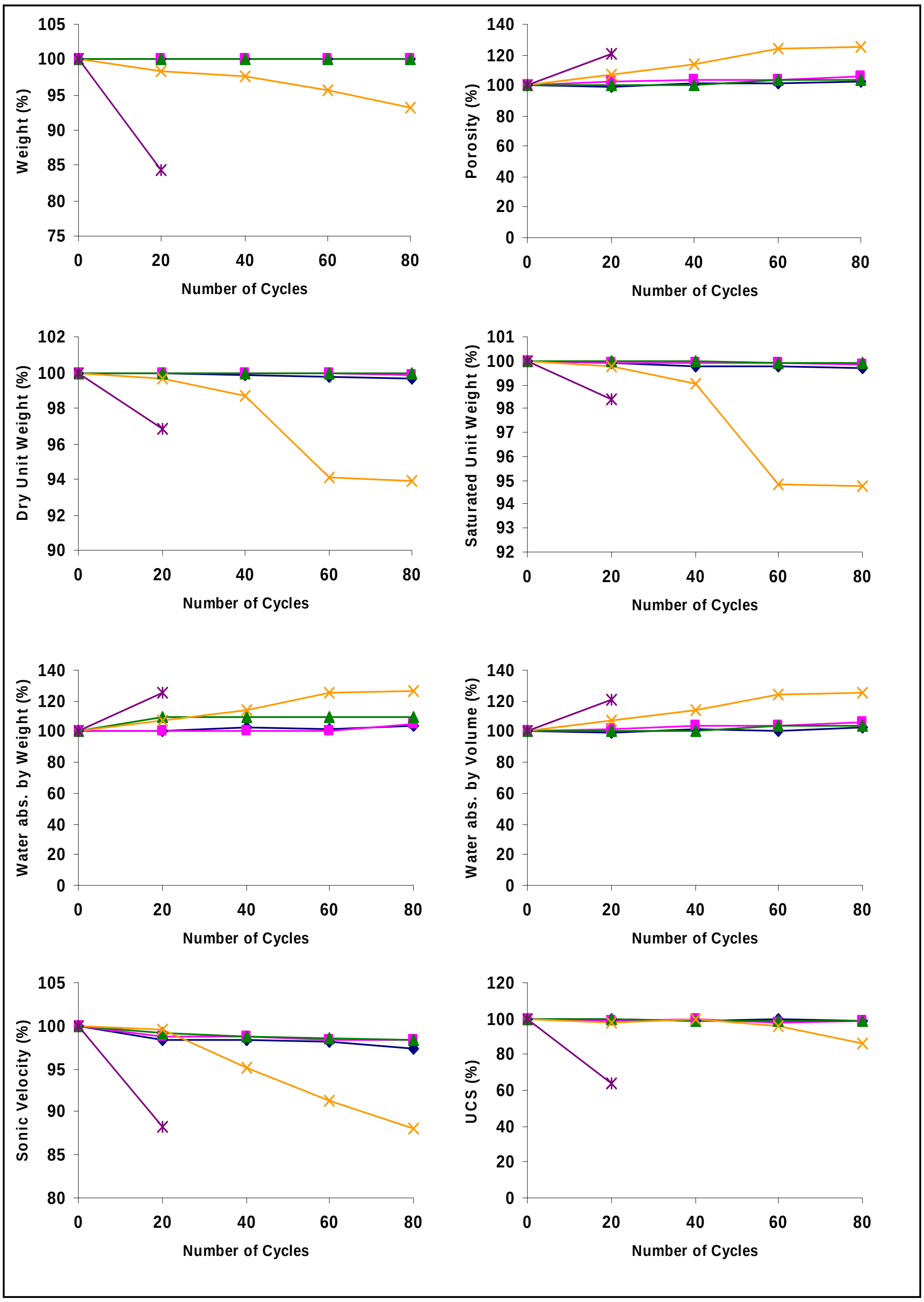


Figure 4.16 Variation of the physico-mechanical properties of the samples after wetting-drying test (green line indicates the Kavakdere limestone, pink line indicates the Kavukkavlağı limestone, blue line indicates the Tarlağzı limestone, orange line indicates the Çömlekçikuyu andesite, and purple line indicates the Kıran sandstone)

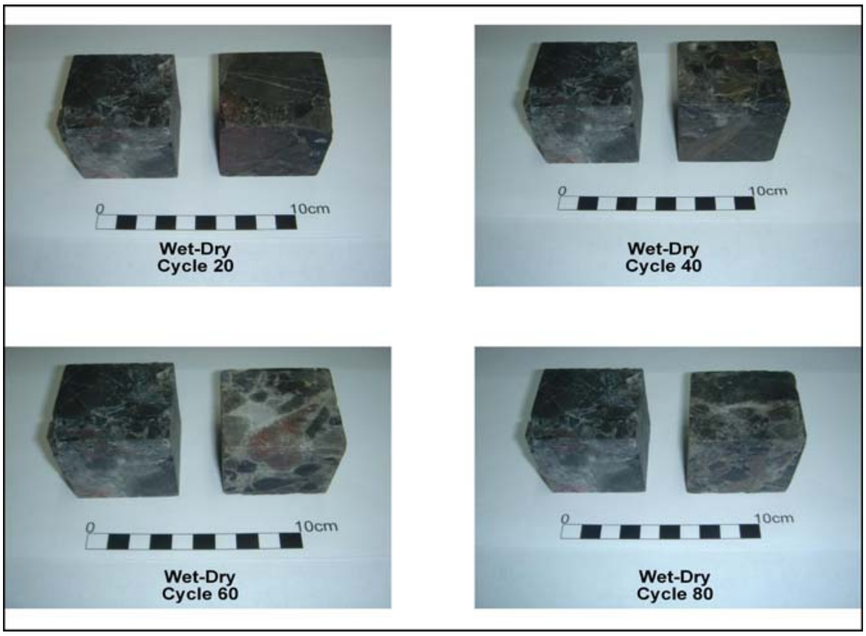


Figure 4.17 Physical appearances of the Kavakdere limestone during the wetting-drying test. The sample on the left side of the photographs indicates a fresh reference sample

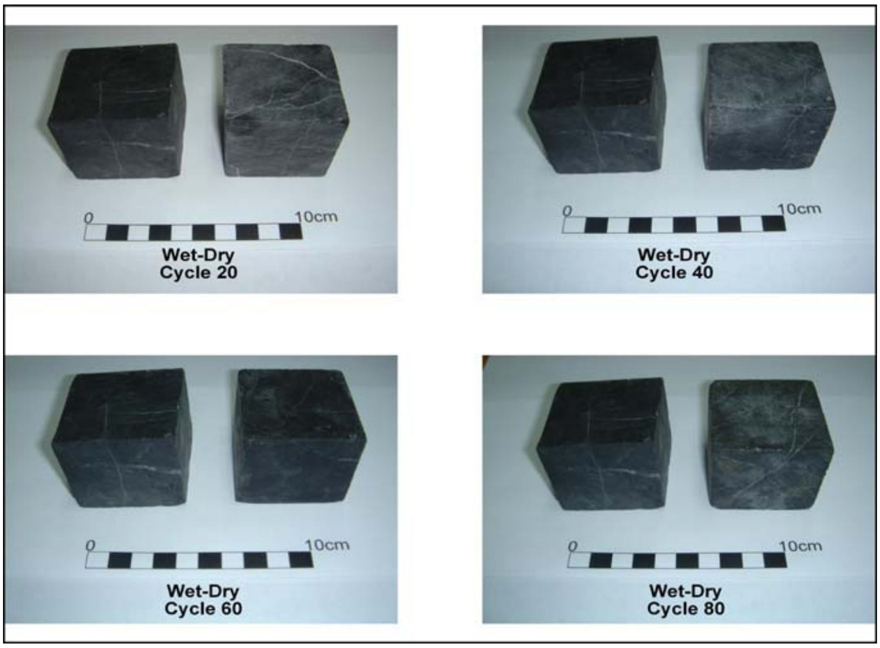


Figure 4.18 Physical appearances of the Kavukkavlağı limestone during the wetting-drying test. The sample on the left side of the photographs indicates a fresh reference sample

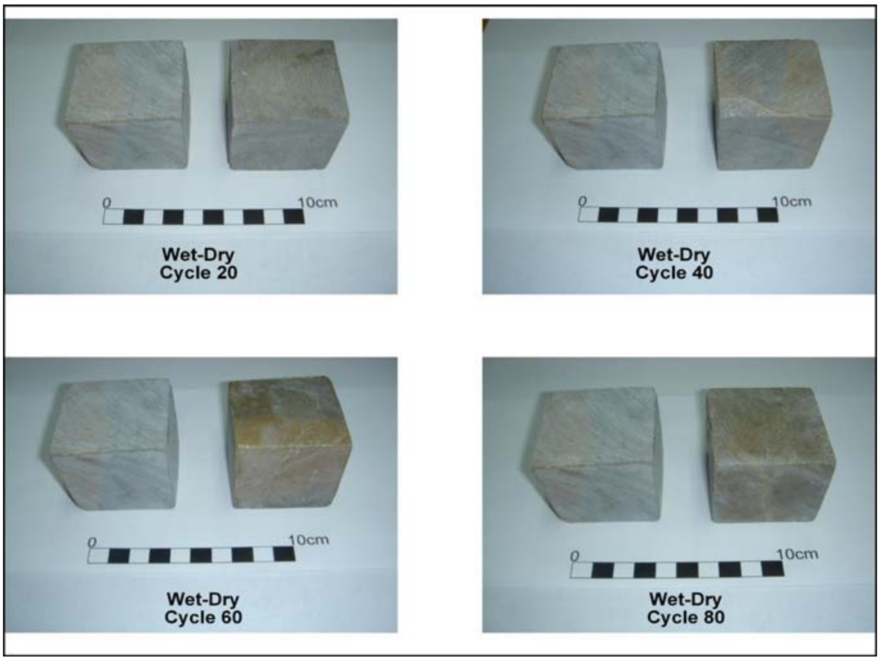


Figure 4.19 Physical appearances of the Tarlaağzı limestone during the wetting-drying test. The sample on the left side of the photographs indicates a fresh reference sample

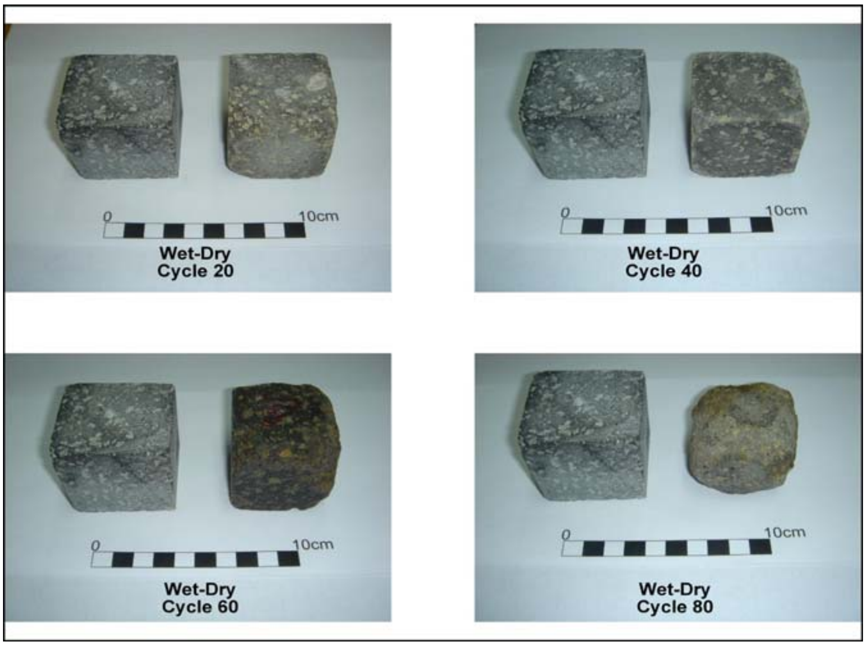


Figure 4.20 Physical appearances of the Çömlekçikuyu andesite during the wetting-drying test. The sample on the left side of the photographs indicates a fresh reference sample

Figure 4.21 Physical appearance of the Kıran sandstone during the wetting-drying test. The sample on the left side of the photographs indicates a fresh reference sample

4.1.23 Sulphate Soundness Tests

4.1.23.1 Magnesium sulphate ($MgSO_4$) soundness test

This test is intended to measure the resistance of an aggregate sample to disintegration by saturated solution of magnesium sulphate. The test method subjects the sample of aggregate to disruptive effects of the repeated crystallization and rehydration of magnesium sulphate within the pores of the aggregate (Smith and Collis, 2001).

Firstly, $MgSO_4$ solution was prepared in the laboratory according to the ASTM (1990). Following that step, samples were immersed into the solution for 16 hours and oven dried for a complete cycle. 25 successful cycles where conducted during the test except the Kıran sandstone. Due to the early failure of the samples, the test was completed at the fifth cycle for the Kıran sandstone.

For this test 25 cubic samples from the Kavakdere, Kavukkavlağı, Tarlaağzı limestones and the Çömlekçikuyu andesite, and 10 samples for the Kıran sandstone were used. At the end of 25 cycles, the total weight loss in terms of the initial values was calculated. The corresponding test results are given in Table 4.34.

Table 4.34 Magnesium sulphate soundness values of the samples

Sample	Weight Loss Value (%)
Kavakdere Limestone	0.08
Kavukkavlağı Limestone	0.11
Tarlaağzı Limestone	0.33
Çömlekçikuyu Andesite	11.64
Kıran Sandstone	25.12

According to the above results, the weight losses in the Kavakdere, Kavukkavlağı and Tarlaağzı limestones are considerably low indicating a perfect magnesium sulphate soundness which would be expected due to their low porosity values. On the other hand, the weight loss in the Çömlekçikuyu andesite is considerably high, reflecting a good correlation with its porosity. Finally, the Kıran sandstone has the highest weight loss reflecting low magnesium sulphate soundness.

In addition, dry unit weight, saturated unit weight, effective porosity, weight, water absorption by weight, water absorption by volume, sonic velocity and UCS of the samples were also recorded at 5, 10, 15, 20 and 25 test cycles, and compared with those of the fresh samples. Corresponding measurements are given in Tables 4.35-4.39 as normalized average values.

Table 4.35 Normalized average physical and mechanical properties of the Kavakdere limestone during $MgSO_4$ cycles

Cycle #	Weight (%)	Porosity (%)	Dry Unit Weight (%)	Saturated Unit Weight (%)	Water abs. By weight (%)	Water abs. By Volume (%)	Sonic Velocity (%)	UCS (%)
0	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
5	99.98	96.55	99.96	99.96	100.00	96.55	98.25	98.97
10	99.96	106.90	99.93	99.93	110.00	106.90	99.62	99.07
15	99.95	113.79	99.89	99.89	120.00	113.79	98.73	98.60
20	99.94	124.14	99.78	99.78	130.00	124.14	98.22	98.97
25	99.92	127.59	99.55	99.59	140.00	127.59	96.75	96.59

Table 4.36 Normalized average physical and mechanical properties of the Kavukkavlağı limestone during $MgSO_4$ cycles

Cycle #	Weight (%)	Porosity (%)	Dry Unit Weight (%)	Saturated Unit Weight (%)	Water abs. By weight (%)	Water abs. By Volume (%)	Sonic Velocity (%)	UCS (%)
0	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
5	99.96	111.32	99.89	99.89	110.00	111.32	99.00	100.70
10	99.94	115.09	99.89	99.89	115.00	115.09	98.28	98.20
15	99.93	115.09	99.73	99.74	115.00	115.09	98.37	97.03
20	99.90	124.53	99.47	99.47	125.00	124.53	97.87	97.42
25	98.89	126.42	99.39	99.43	125.00	126.42	98.25	96.27

Table 4.37 Normalized average physical and mechanical properties of the Tarlaağzı limestone during $MgSO_4$ cycles

Cycle #	Weight (%)	Porosity (%)	Dry Unit Weight (%)	Saturated Unit Weight (%)	Water abs. By weight (%)	Water abs. By Volume (%)	Sonic Velocity (%)	UCS (%)
0	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
5	99.93	101.85	99.69	99.70	102.47	101.85	98.25	98.99
10	99.86	102.31	99.50	99.50	103.70	102.31	98.64	99.14
15	99.82	105.09	99.42	99.43	106.17	105.09	96.98	97.33
20	99.78	116.67	98.81	98.89	118.52	116.67	97.84	98.23
25	99.67	120.83	98.54	98.70	123.46	120.83	96.94	97.91

Table 4.38 Normalized average physical and mechanical properties of the Çömlekçikuyu andesite during $MgSO_4$ cycles

Cycle #	Weight (%)	Porosity (%)	Dry Unit Weight (%)	Saturated Unit Weight (%)	Water abs. By weight (%)	Water abs. By Volume (%)	Sonic Velocity (%)	UCS (%)
0	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
5	98.23	111.48	99.44	99.75	110.74	111.48	98.56	95.50
10	95.26	134.77	98.27	99.20	135.56	134.77	93.31	94.78
15	92.17	150.40	97.10	98.44	152.96	150.40	85.07	67.49
20	90.82	159.97	87.39	89.24	181.85	159.97	80.77	49.75
25	88.36	164.59	82.02	84.14	195.93	164.59	74.77	26.37

Table 4.39 Normalized average physical and mechanical properties of the Kıran sandstone during $MgSO_4$ cycles

Cycle #	Weight (%)	Porosity (%)	Dry Unit Weight (%)	Saturated Unit Weight (%)	Water abs. By weight (%)	Water abs. By Volume (%)	Sonic Velocity (%)	UCS (%)
0	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
5	74.88	171.10	61.41	69.03	279.58	171.10	53.82	20.98

The weight losses observed in the Kavakdere, Kavukkavlağı and Tarlaağzı limestones are 0.08 %, 0.11 % and 0.33 %, respectively. These values indicate a very minor almost negligible loss in weight for the limestone samples. On the other hand, at the end of the test, the weight loss in the Çömlekçikuyu andesite is calculated as 11.64 %. The weight loss in the andesite follows an almost linear path throughout the cycles. Finally, the weight loss in the Kıran sandstone is the maximum, and calculated as 25.12 % at the fifth cycle (Figure 4.22).

The increases in effective porosity of the Kavakdere, Kavukkavlağı and Tarlaağzı limestones are 27.59 %, 26.42 % and 20.83 %, respectively. On the other hand, the increases in the Çömlekçikuyu andesite and Kıran sandstone are 64.59 % and 71.10 %, respectively. The increases in the effective porosity of the andesite and sandstone are pretty high compared to the other samples (Figure 4.22).

Dry and saturated unit weights of the limestones are almost unchanged. The decreases in saturated unit weights of the Kavakdere, Kavukkavlağı and Tarlaağzı limestones are 0.41 %, 0.57 %, and 1.3 %, respectively. The changes in the Çömlekçikuyu andesite and Kıran sandstone are 15.86 % and 30.97 %, respectively which are considerably high compared to the other samples (Figure 4.22).

Water absorptions of the Kavakdere, Kavukkavlağı and Tarlaağzı limestones are again low compared to the other samples. The water absorptions by weight and volume are both calculated for the samples and for the Kavakdere, Kavukkavlağı and Tarlaağzı limestones, the increase in water absorptions by weight are 27.59 %, 26.42 %, 20.83 %, respectively. On the other hand, the increases in water absorption by weight for the Çömlekçikuyu andesite and Kıran sandstone are 64.59 % and 71.10 %, respectively (Figure 4.22).

The decreases in the sonic velocities of the samples are in good correlation with the increasing effective porosity values. 3.25 %, 1.75 % and 3.06 % decreases are calculated for the Kavakdere, Kavukkavlağı and Tarlaağzı limestones, respectively, and 25.23 % and 46.18 % decreases are calculated for the Çömlekçikuyu andesite and Kıran sandstone. The decreases in the sonic velocity of the andesite and sandstone sample are in good correlation with the increasing effective porosity of the samples (Figure 4.22).

The decreases in the UCS values of the Kavakdere, Kavukkavlağı and Tarlaağzı limestones are again considerably low. 3.41 %, 3.73 % and 2.09 % decreases are calculated, respectively for these samples. On the other hand, the decreases in the Çömlekçikuyu andesite and Kıran sandstone are significant. 73.63 % decrease for the andesite and 79.02 % decrease for the sandstone are calculated in the end of the test (Figure 4.22).

In general, the decrease in weight, dry weight, saturated weight, and the increase in the water absorption and porosity of the Kavakdere, Kavukkavlağı and Tarlaağzı limestones seem to be high. The resulting average effective porosity and water absorption values of these samples are again considerably low; therefore, the decreases in sonic velocity and UCS of the samples are in good agreement with these values. Therefore, it can be concluded that these rocks are slightly affected from the magnesium sulphate test retaining their initial physico-mechanical properties. On the other hand the decrease in the dry unit weight, saturated unit weight, sonic velocity and UCS, and a major increase in the porosity and water absorption occurred in the samples of the Çömlekçikuyu andesite reflecting the destructive effect of the salt crystals in the rock. The Çömlekçikuyu andesite is mostly disintegrated from the sides and the corners, and some of the samples are completely failed in the end of the test. Finally, the Kıran sandstone can be referred as the weakest rock compared to the others. Only 5 cycles could be applied to this specimen. Nevertheless, the maximum decrease in weight, dry weight, saturated weight, sonic velocity and UCS and the maximum increases in water absorption and porosity are observed at this sample reflecting a considerably low resistance to magnesium sulphate.

During the test in order to reflect the changes in the shape, the samples were photographed at the end of cycles 5, 10, 15, 20 and 25. The corresponding pictures are given in Figures 4.23-4.27.

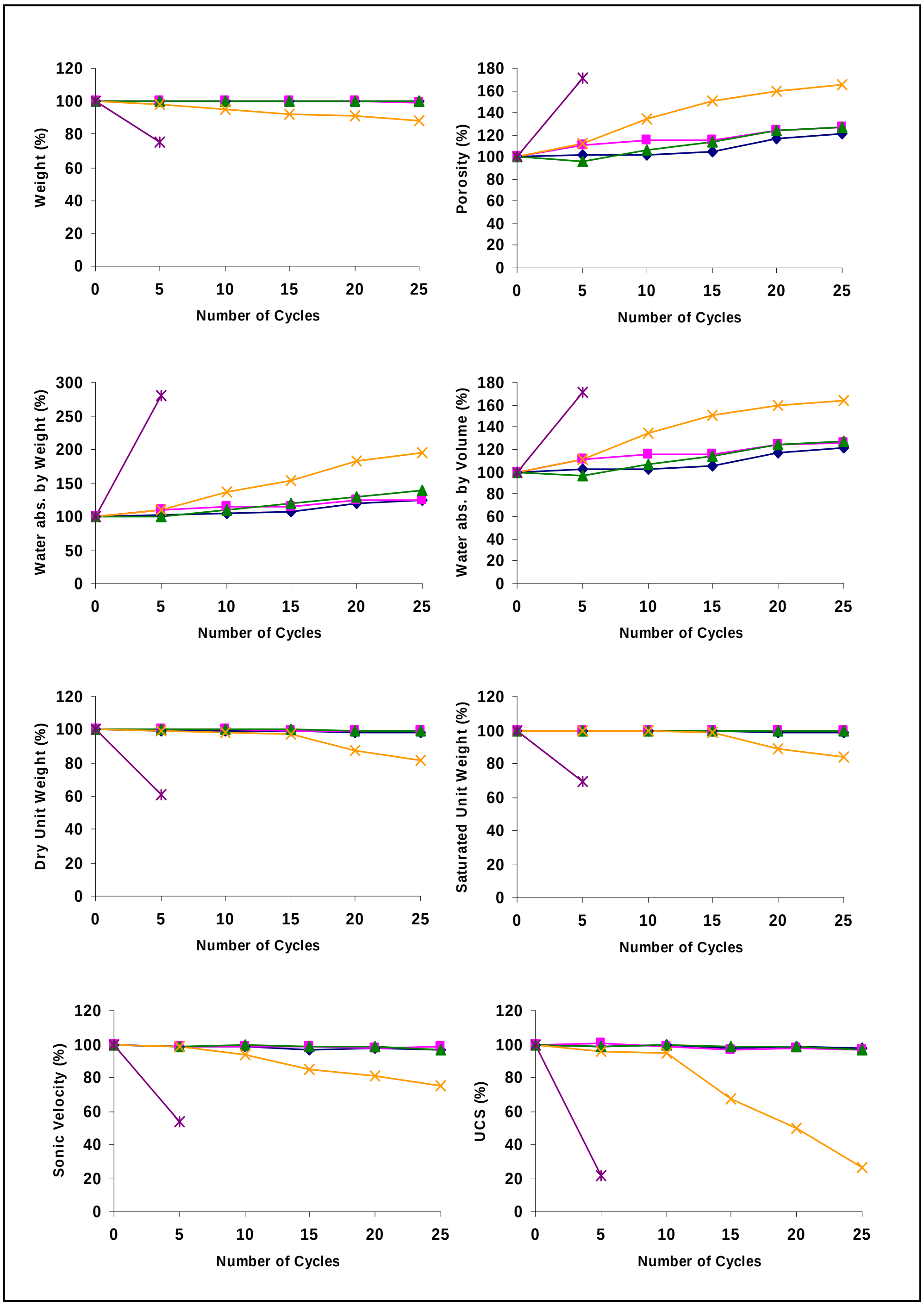


Figure 4.22 Variation of the physico-mechanical properties of the samples after magnesium sulphate soundness test (green line indicates the Kavakdere limestone, pink line indicates the Kavukkavlağı limestone, blue line indicates the Tarlaağzı limestone, orange line indicates the Çömlekçikuyu andesite, and purple line indicates the Kıran sandstone)

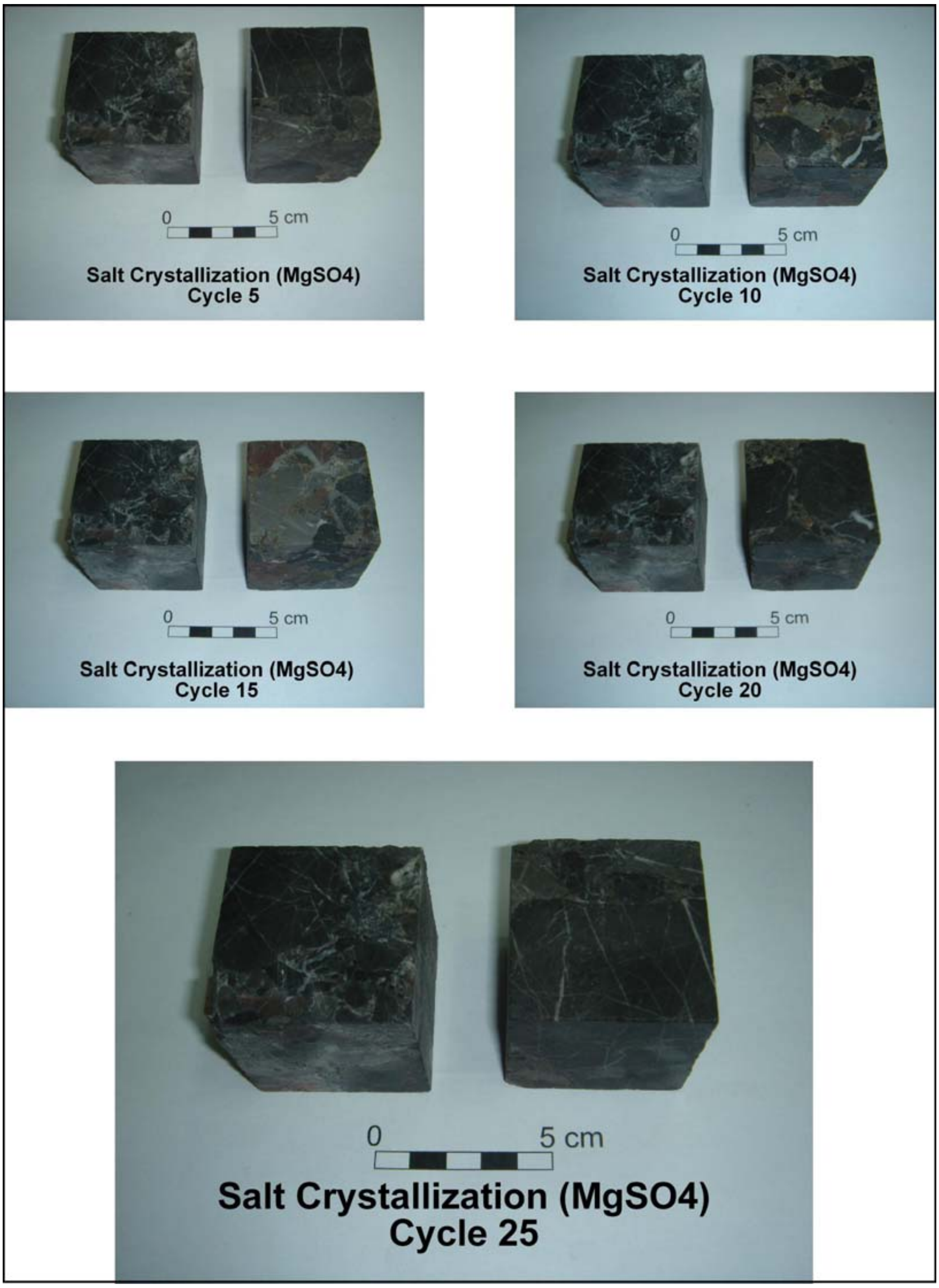


Figure 4.23 Physical appearances of the Kavakdere limestone during the magnesium sulphate soundness test. The sample on the left side of the photographs indicates a fresh reference sample

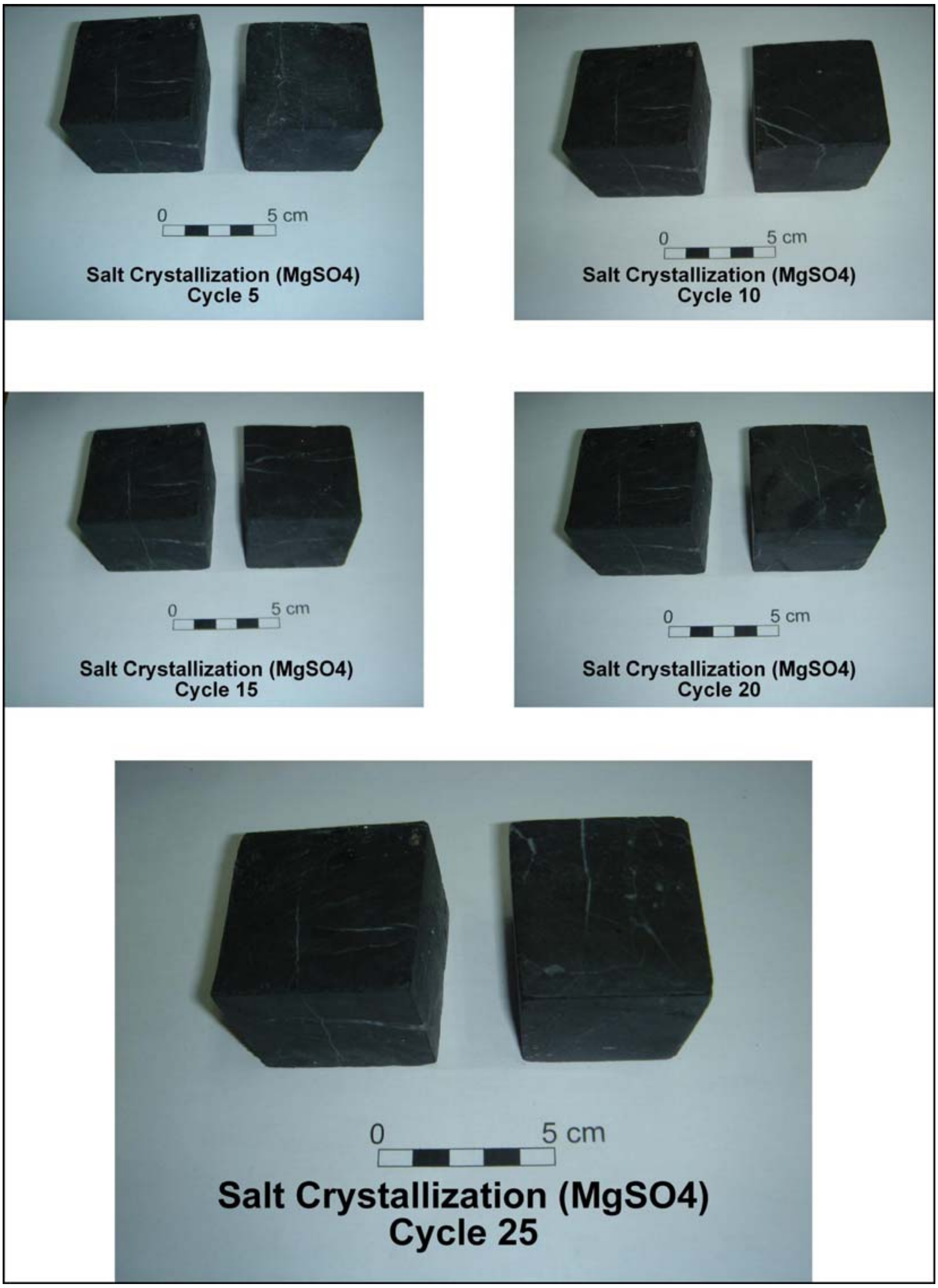


Figure 4.24 Physical appearances of the Kavukkavlağı limestone during the magnesium sulphate soundness test. The sample on the left side of the photographs indicates a fresh reference sample

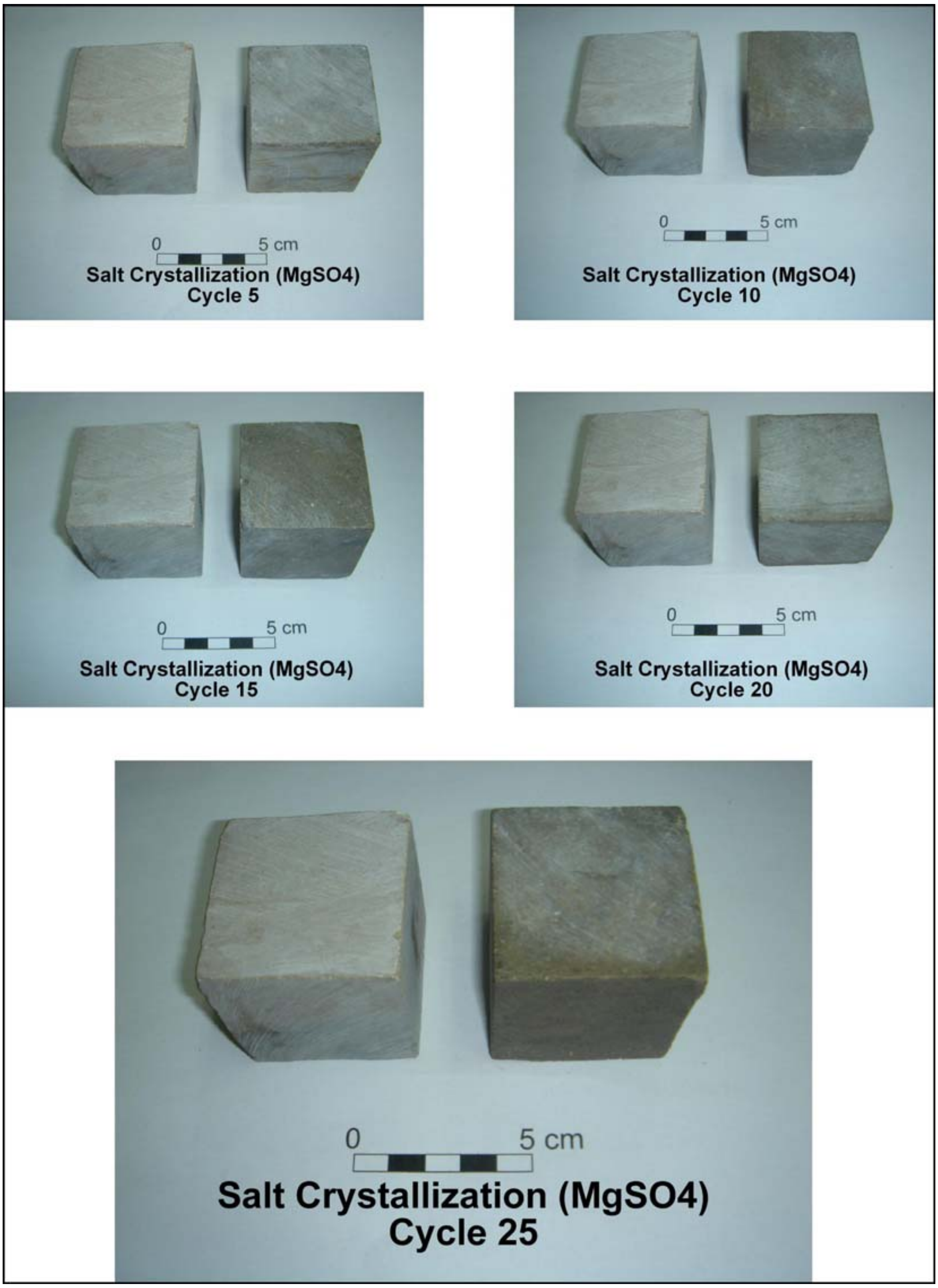


Figure 4.25 Physical appearances of the Tarlaağzı limestone during the magnesium sulphate soundness test. The sample on the left side of the photographs indicates a fresh reference sample

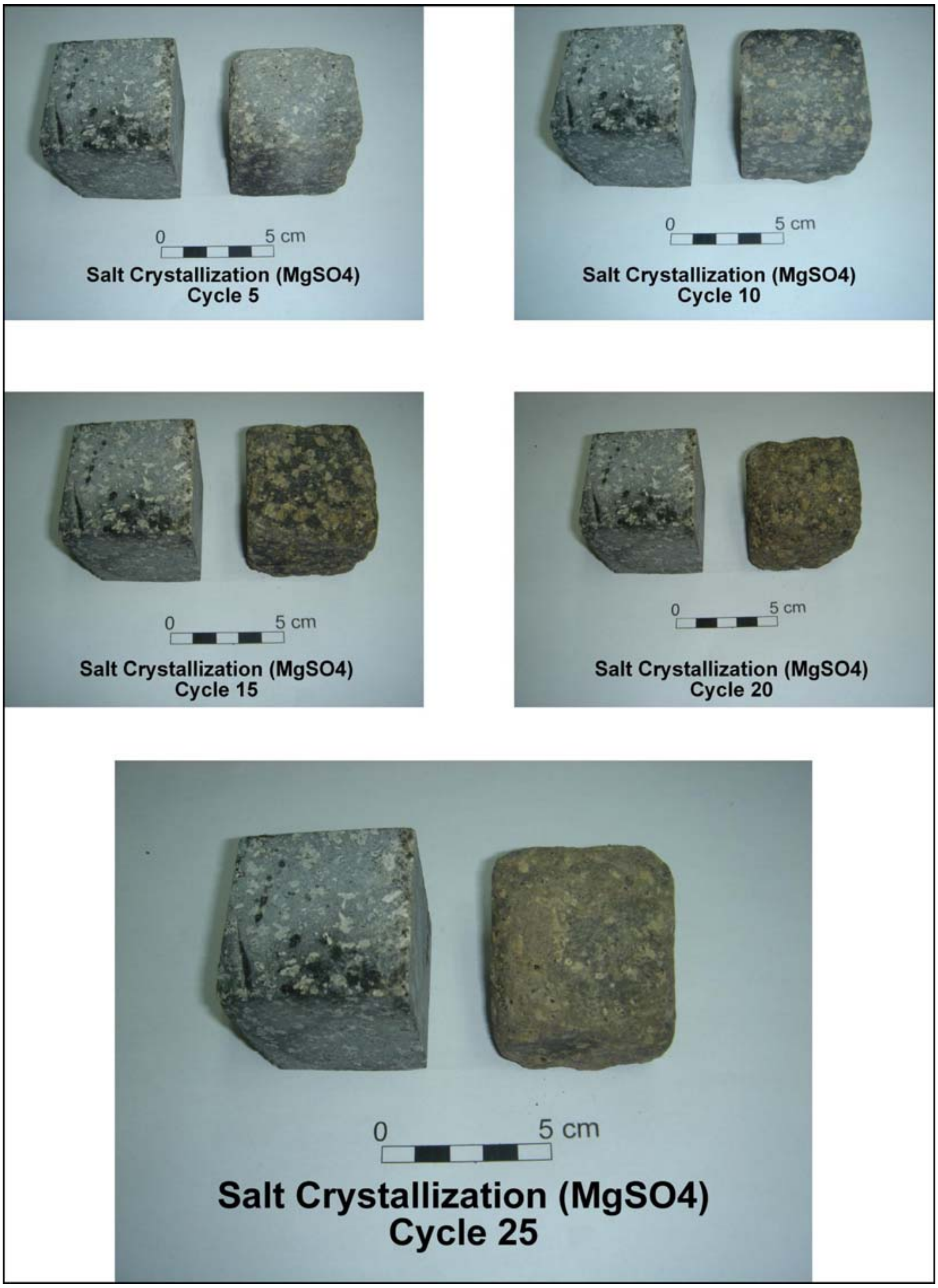


Figure 4.26 Physical appearances of the Çömlekçikuyu andesite during the magnesium sulphate soundness test. The sample on the left side of the photographs indicates a fresh reference sample

Figure 4.27 Physical appearance of the Kıran sandstone during the magnesium sulphate soundness test. The sample on the left side of the photographs indicates a fresh reference sample

4.1.23.2 Sodium sulphate (Na_2SO_4) soundness test

Sodium sulphate is another salt used in the sulphate soundness test. Like the magnesium sulphate soundness test, this test is also intended to measure the resistance of an aggregate sample to disintegration by saturated solution of sodium sulphate.

Firstly, Na_2SO_4 solution was prepared in the laboratory according to the ASTM (1990). Following that step, samples were immersed into the solution for 16 hours and oven dried for a complete cycle. 25 successful cycles were conducted during the test, except the Kıran sandstone. Due to the early failure of the samples, the test was completed at the fifth cycle for the Kıran sandstone.

For this test, 25 cubic samples from the Kavakdere, Kavukkavlağı, Tarlaağzı limestones and the Çömlekçikuyu andesite, and 10 samples for the Kıran sandstone were used. At the end of 25 cycles, the total weight loss in terms of the initial weights was calculated. The corresponding test results are given in Table 4.40.

Table 4.40 Sodium sulphate soundness values of the samples

Sample	Weight Loss Value (%)
Kavakdere Limestone	0.06
Kavukkavlağı Limestone	0.06
Tarlaağzı Limestone	0.25
Çömlekçikuyu Andesite	10.01
Kıran Sandstone	23.24

According to the above results, the weight loss in the Kavakdere, Kavukkavlağı, Tarlaağzı limestones are considerably low indicating a perfect sulphate soundness which would be expected due to their low porosity values. On the other hand, the weight loss in the Çömlekçikuyu andesite is considerably high, reflecting a good correlation with its porosity. Finally, the Kıran sandstone has the highest weight loss reflecting low magnesium sulphate soundness.

In addition, dry unit weight, saturated unit weight, effective porosity, weight, water absorption by weight, water absorption by volume, sonic velocity and UCS of the samples were also recorded at 5, 10, 15, 20 and 25 test cycles and compared with those of the fresh samples. Corresponding measurements are given in Tables 4.41-4.45 as normalized average values.

Table 4.41 Normalized average physical and mechanical properties of the Kavakdere limestone during Na_2SO_4 cycles

Cycle #	Weight (%)	Porosity (%)	Dry Unit Weight (%)	Saturated Unit Weight (%)	Water abs. By weight (%)	Water abs. By Volume (%)	Sonic Velocity (%)	UCS (%)
0	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**
5	**100.00**	**103.45**	**99.96**	**99.96**	**110.00**	**103.45**	**99.83**	**99.39**
10	**99.98**	**103.45**	**99.96**	**99.96**	**110.00**	**103.45**	**99.28**	**99.53**
15	**99.96**	**110.34**	**99.85**	**99.89**	**120.00**	**110.34**	**98.72**	**98.55**
20	**99.95**	**110.34**	**99.85**	**99.85**	**120.00**	**110.34**	**98.53**	**98.17**
25	**99.94**	**113.79**	**99.81**	**99.81**	**120.00**	**113.79**	**97.45**	**98.89**

Table 4.42 Normalized average physical and mechanical properties of the Kavukkavlağı limestone during Na_2SO_4 cycles

Cycle #	Weight (%)	Porosity (%)	Dry Unit Weight (%)	Saturated Unit Weight (%)	Water abs. By weight (%)	Water abs. By Volume (%)	Sonic Velocity (%)	UCS (%)
0	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**
5	**99.98**	**109.43**	**99.96**	**99.96**	**110.00**	**109.43**	**99.33**	**99.92**
10	**99.97**	**109.43**	**99.89**	**99.89**	**110.00**	**109.43**	**98.78**	**99.22**
15	**99.97**	**113.21**	**99.77**	**99.77**	**115.00**	**113.21**	**99.02**	**99.28**
20	**99.96**	**116.98**	**99.51**	**99.51**	**115.00**	**116.98**	**97.18**	**98.37**
25	**99.94**	**116.98**	**99.47**	**99.47**	**115.00**	**116.98**	**96.74**	**98.11**

Table 4.43 Normalized average physical and mechanical properties of the Tarlaağzı limestone during Na_2SO_4 cycles

Cycle #	Weight (%)	Porosity (%)	Dry Unit Weight (%)	Saturated Unit Weight (%)	Water abs. By weight (%)	Water abs. By Volume (%)	Sonic Velocity (%)	UCS (%)
0	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**
5	**96.40**	**106.06**	**99.05**	**99.20**	**106.67**	**106.06**	**101.35**	**99.63**
10	**95.38**	**120.26**	**98.92**	**99.45**	**120.37**	**120.26**	**95.18**	**98.34**
15	**93.63**	**127.43**	**98.61**	**99.32**	**127.78**	**127.43**	**91.15**	**95.65**
20	**91.18**	**150.88**	**89.17**	**90.76**	**167.41**	**150.88**	**85.33**	**86.07**
25	**89.99**	**162.52**	**85.18**	**87.17**	**188.52**	**162.52**	**77.81**	**48.05**

Table 4.44 Normalized average physical and mechanical properties of the Çömlekçikuyu andesite during Na_2SO_4 cycles

Cycle #	Weight (%)	Porosity (%)	Dry Unit Weight (%)	Saturated Unit Weight (%)	Water abs. By weight (%)	Water abs. By Volume (%)	Sonic Velocity (%)	UCS (%)
0	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**
5	**99.95**	**104.63**	**99.54**	**99.54**	**106.17**	**104.63**	**97.41**	**99.69**
10	**99.93**	**107.87**	**99.46**	**99.50**	**108.64**	**107.87**	**99.02**	**98.17**
15	**99.87**	**108.80**	**99.35**	**99.39**	**109.88**	**108.33**	**98.31**	**98.88**
20	**99.83**	**112.96**	**99.12**	**99.20**	**113.58**	**111.57**	**97.57**	**98.44**
25	**99.75**	**114.81**	**98.92**	**99.01**	**116.05**	**113.43**	**97.33**	**97.39**

Table 4.45 Normalized average physical and mechanical properties of the Kıran sandstone during Na_2SO_4 cycles

Cycle #	Weight (%)	Porosity (%)	Dry Unit Weight (%)	Saturated Unit Weight (%)	Water abs. By weight (%)	Water abs. By Volume (%)	Sonic Velocity (%)	UCS (%)
0	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**
5	**76.76**	**155.31**	**72.22**	**78.00**	**219.89**	**155.31**	**60.89**	**24.41**

The weight losses observed in the Kavakdere, Kavukkavlağı and Tarlaağzı limestones are 0.06 %, 0.06 % and 0.25 %, respectively. These values indicate a very minor almost negligible loss in weight for the limestone samples. On the other hand, at the end of the test the weight loss in the Çömlekçikuyu andesite is calculated as 10.01 %. The weight loss in the andesite follows an almost linear path through out the cycles. Finally, the weight loss in the Kıran sandstone is the maximum and calculated as 23.24 % at the fifth cycle (Figure 4.28).

The increase in effective porosity of the Kavakdere, Kavukkavlağı and Tarlaağzı limestones are 13.79 %, 16.98 % and 14.81 %, respectively. On the other hand, the increases in the Çömlekçikuyu andesite and Kıran sandstone are 65.52 % and 55.31 %, respectively. The increase in the effective porosities of the andesite and sandstone are pretty high compared to the other samples (Figure 4.28).

Dry and saturated unit weights of the limestones are almost unchanged. The decreases in saturated unit weights of the Kavakdere, Kavukkavlağı and Tarlaağzı limestone are 0.19 %, 0.53 %, and 0.99 %, respectively. The changes in the Çömlekçikuyu andesite and Kıran sandstone are 12.83 % and 22.00 %, respectively which are considerably high compared to the other samples (Figure 4.28).

Water absorptions of the Kavakdere, Kavukkavlağı and Tarlaağzı limestones are again low compared to the other samples. Water absorptions by weight and volume are both calculated for the samples, and for the Kavakdere, Kavukkavlağı and Tarlaağzı limestones the increases in water absorptions by weight are 13.79 %, 16.98 %, 13.43 %, respectively. On the other hand, the increases in water absorptions by weight for the Çömlekçikuyu andesite and Kıran sandstone are 62.52 % and 55.31 %, respectively (Figure 4.28).

The decreases in the sonic velocities of the samples are in good correlation with the increasing effective porosities values. 2.55 %, 3.26 % and 2.67 % decreases are calculated for the Kavakdere, Kavukkavlağı and Tarlaağzı limestones, respectively and 22.19 % and 39.11 % decreases are calculated for the Çömlekçikuyu andesite and Kıran sandstone. The decreases in the sonic velocity of the andesite and sandstone samples are in good correlation with the increasing effective porosity of the samples (Figure 4.28).

The decreases in the UCS values of the Kavakdere, Kavukkavlağı and Tarlaağzı limestones are again considerably low. 1.11 %, 1.89 % and 2.61 % decreases are calculated, respectively for these samples. On the other hand, the decreases in the Çömlekçikuyu andesite and Kıran sandstone are significant. 51.95 % decrease for the andesite and 75.86 % decrease for the sandstone are calculated in the end of the test (Figure 4.28).

In general, the decreases in weight, dry weight, saturated weight and the increases in the water absorption and porosity of the Kavakdere, Kavukkavlağı and Tarlaağzı limestones seem to be high. The resulting average effective porosity and water absorption values of these samples are again considerably low therefore the decreases in sonic velocity and UCS of the samples are in good correlation with these values; therefore it can be concluded that these rocks are slightly affected from the magnesium sulphate test retaining their initial physico-mechanical properties. On the other hand, the decreases in the dry unit weight, saturated unit weight, sonic velocity and UCS, and a major increase in the porosity and water absorption occurred in the samples of the Çömlekçikuyu andesite reflecting the destructive effect of the salt crystals in the rock. The Çömlekçikuyu andesite is mostly disintegrated from the sides and the corners and some of the samples are completely failed in the end of the test. Finally, the Kıran sandstone can be referred as the weakest rock compared to the others. Only 5 cycles could be applied to this specimen. Nevertheless the maximum decreases in weight, dry weight, saturated weight, sonic velocity and UCS, and the maximum increases in water absorption and porosity are observed at this sample reflecting a considerably low resistance to magnesium sulphate.

During the test in order to reflect the changes in the shape, the samples are photographed at the end of cycles 5, 10, 15, 20 and 25. The corresponding pictures are given in Figures 4.29-4.33.

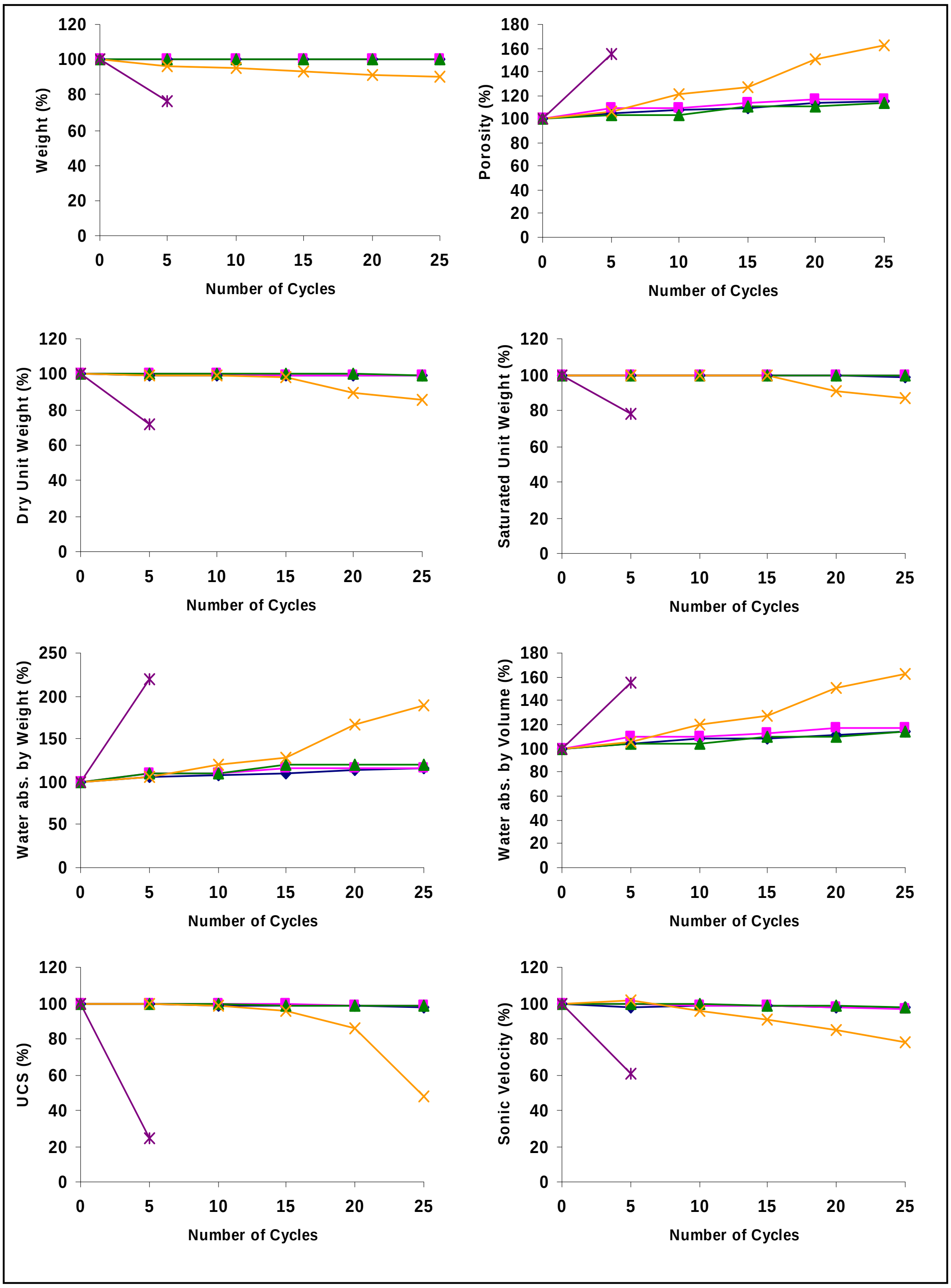


Figure 4.28 Variation of the physico-mechanical properties of the samples after sodium sulphate soundness test (green line indicates the Kavakdere limestone, pink line indicates the Kavukkavlağı limestone, blue line indicates the Tarlağzı limestone, orange line indicates the Çömlekçikuyu andesite and purple line indicates the Kıran sandstone)

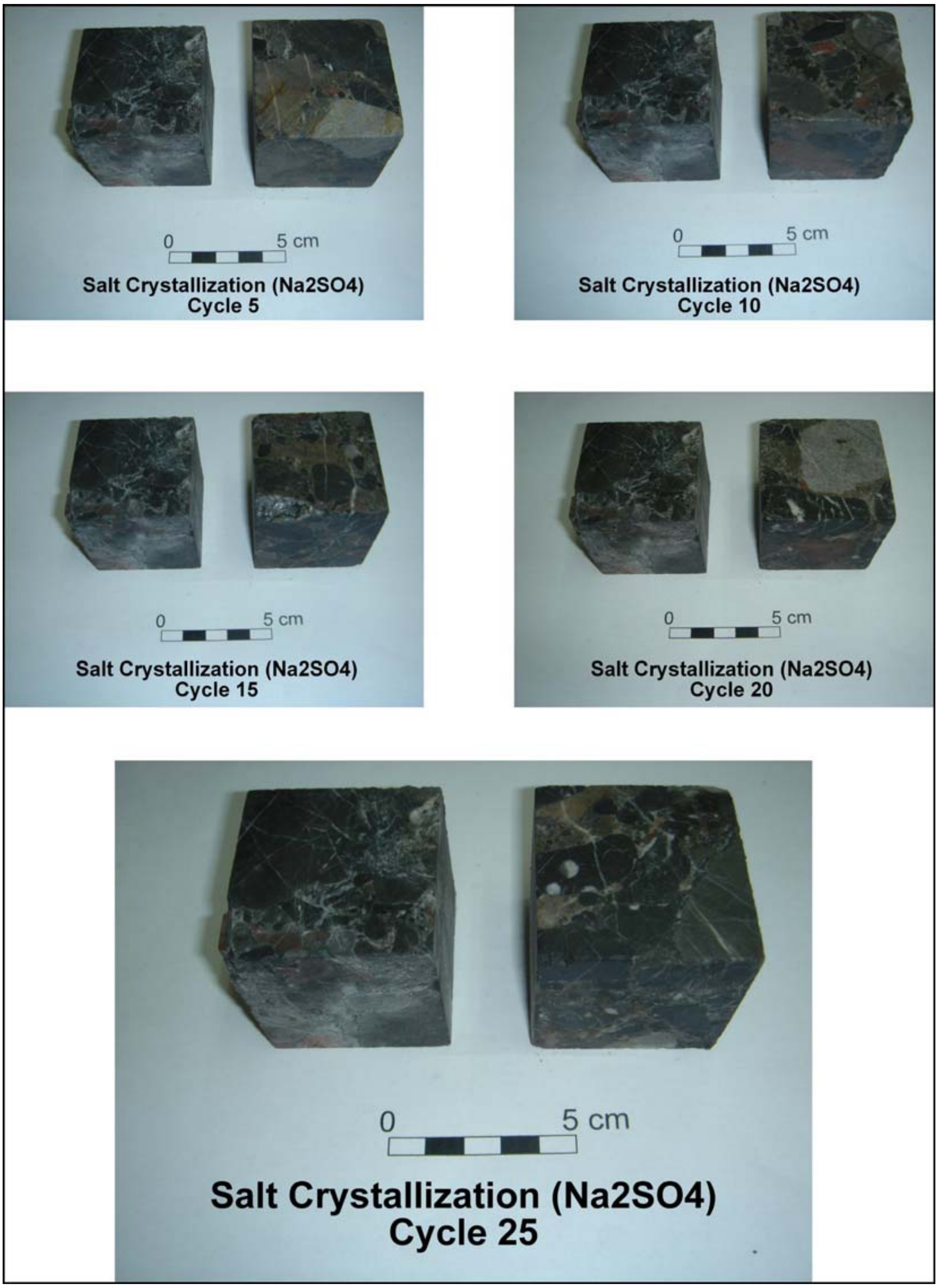


Figure 4.29 Physical appearances of the Kavakdere limestone during the sodium sulphate soundness test. The sample on the left side of the photographs indicates a fresh reference sample

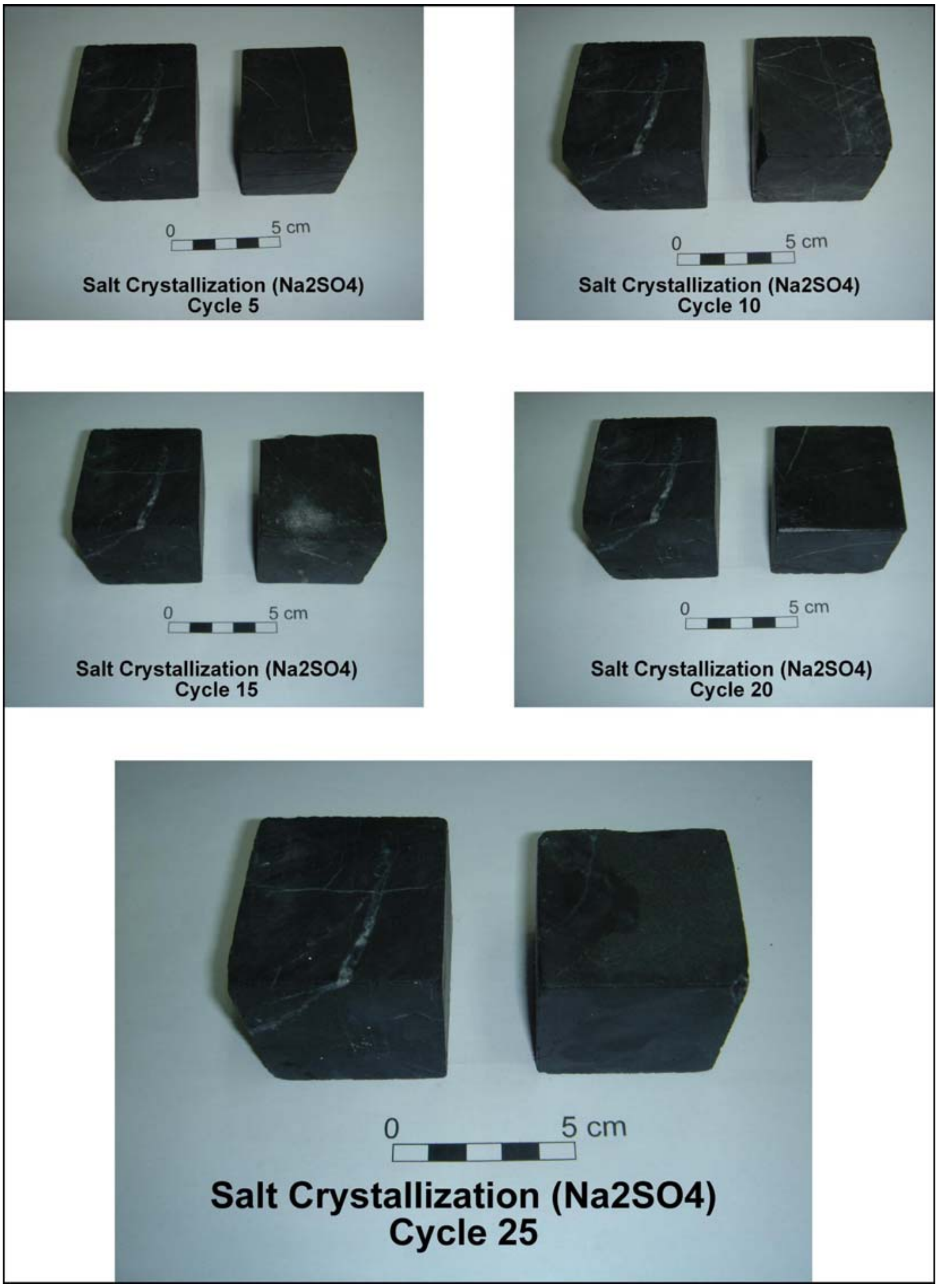


Figure 4.30 Physical appearances of the Kavukkavlağı limestone during the sodium sulphate soundness test. The sample on the left side of the photographs indicates a fresh reference sample

Figure 4.31 Physical appearances of the Tarlaağzı limestone during the sodium sulphate soundness test. The sample on the left side of the photographs indicates a fresh reference sample

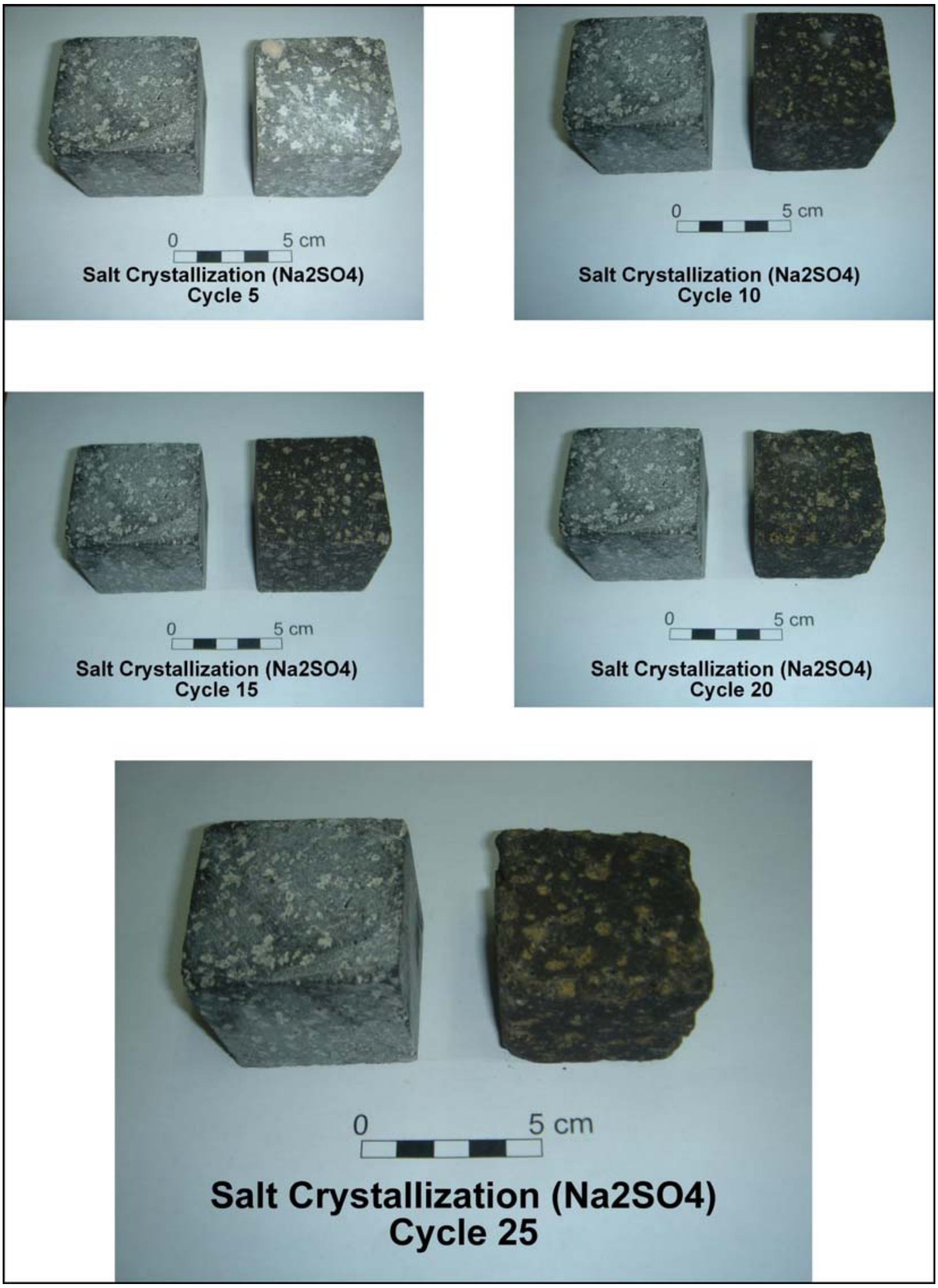


Figure 4.32 Physical appearances of the Çömlekçikuyu andesite during the sodium sulphate soundness test. The sample on the left side of the photographs indicates a fresh reference sample

Figure 4.33 Physical appearance of the Kıran sandstone during the sodium sulphate soundness test. The sample on the left side of the photographs indicates a fresh reference sample

4.1.24 Block Integrity Drop Test

This test is used to determine the percentage of stone loss from heavy gradings of quarried stone in a standard drop test, this percentage being described as the drop test breakage index (CIRIA/CUR, 1991).

In the application of the test, fresh samples are dropped from a height of 3 meters onto the bed of rocks and the number and type of visible flaws in blocks and the number and type of blocks resulting are recorded. Drop test breakage index, I_d is calculated by the following formula:

$$I_d = [(W_{50i} - W_{50f}) / W_{50i}] * 100 \%$$

where,

W_{50i}: Median sample weight before testing
W_{50f}: Median sample weight after testing

The standard application of this test could not be applied because the quarrying was already completed. Instead, the results of this test are obtained from the field observations at the quarries. The corresponding test results are given in Table 4.46.

Table 4.46 Drop test breakage index values of the samples

Sample	I_d (%)
Kavakdere Limestone	2
Kavukkavlağı Limestone	4
Tarlaağzı Limestone	2
Çömlekçikuyu Andesite	3
Kıran Sandstone	7

4.1.25 Summary of the Laboratory Test Results

According to the test results, limestones are generally classified as strong and resistant rocks; on the other hand Çömlekçikuyu andesite was found to be a moderate rock in most of the tests. Finally, the Kıran sandstone is classified as a weak and non-resistant rock in most of the tests. The tests results considering both dry and saturated conditions are also given in Tables 4.47-4.51.

Table 4.47 Laboratory test results of the Kavakdere 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	26.91 ± 0.21	26.94 ± 0.21
Effective porosity (%)	ISRM (1981)	110	0.45 ± 0.23	
Water absorption under atmospheric pressure-by weight (%)	TS 699 (1987)	110	0.10 ± 0.08	
Water absorption under atmospheric pressure-by volume (%)	TS 699 (1987)	110	0.29 ± 0.23	
Water absorption under pressure-by weight (%)	ISRM (1981)	110	0.16 ± 0.08	
Water absorption under pressure-by volume (%)	ISRM (1981)	110	0.45 ± 0.23	
Saturation coefficient	TS 699 (1987)	110	0.64 + 0.50	
Methylene blue adsorption value, MBA (g/100g)	AFNOR (1980)	2	0.53 ± 0.00	
Cation exchange capacity, CEC δ (meq./100g)	AFNOR (1980)	2	1.22 ± 0.00	
Wet – dry loss (%)	ASTM (1992)	5	0.02 ± 0.001	
Freeze – Thaw loss (%)	CIRIA/CUR (1991)	5	0.11 ± 0.02	
Magnesium Sulphate soundness value (%)	ASTM (1990)	5	0.08 ± 0.003	
Sodium Sulphate soundness value (%)	ASTM (1990)	5	0.06 ± 0.005	
Micro-Deval value (%)	TS EN (2002)	2	23.02 ± 0.087	
Mill abrasion resistance index, # ks (%)	CIRIA/CUR (1991)	2	0,0065 ± 0,00002	
Point load strength index, $I_{s\,(50)}$ (MPa)	ISRM (1985)	6	5.84 ± 1.74	5.45± 0.39
Fracture toughness † (MPa.m$^{1/2}$)	Latham (1998)	6	1.30± 0.29	1.23± 0.06
Uniaxial compressive strength (MPa)	ISRM (1981)	10	65.73 ± 10.05	63.93 ± 14.03
Sonic Velocity ‡ (m/sec)	ISRM (1981)	110	5607.13 ± 465.65	5724.31 ± 351.56
Schmidt rebound hardness ¥	ISRM (1981	10	42.60 ± 3.35	38.60 ± 0.66
Los Angeles abrasion § (%)	ASTM (1989)	1	30.43	30.52
Aggregate impact value (%)	BSI(1990a)	2	14.16 ± 0.15	15.31 ± 0.07
Aggregate crushing value (%)	BSI(1990c)	2	22.82 ± 0.02	23.98 ± 0.03
Modified Aggregate impact value (%)	BSI(1990a)	2	14.78 ± 0.11	
10 % fines value (kN)	BSI(1990b)	1	277.70	263.19

(SD*) standard deviation**, (δ)** determined from methylene blue adsorption test, **(#)** determined from micro-deval test, **(†)** determined from $Is_{(50)}$ using correlation factor
(‡) Pundit-plus 500-kHz transducers are used, **(¥)** L-Type Schmidt hammer is used, **(§)** loss after 1000 revolutions

Table 4.48 Laboratory test results of the Kavukkavlağı Limestone

Properties	Standard used for testing	Number of tests	Test results Dry Mean ± SD*	 Saturated Mean ± SD*
Unit weight (kN/m^3)	ISRM (1981)	120	26.40 ± 0.33	26.45 ± 0.32
Effective porosity (%)	ISRM (1981)	120	0.80 ± 0.26	
Water absorption under atmospheric pressure-by weight (%)	TS 699 (1987)	120	0.20 ± 0.11	
Water absorption under atmospheric pressure-by volume (%)	TS 699 (1987)	120	0.53 ± 0.28	
Water absorption under pressure-by weight (%)	ISRM (1981)	120	0.30 ± 0.10	
Water absorption under pressure-by volume (%)	ISRM (1981)	120	0.80 ± 0.26	
Saturation coefficient	TS 699 (1987)	120	0.65 ± 0.36	
Methylene blue adsorption value, MBA (g/100g)	AFNOR (1980)	2	0.27 ± 0.00	
Cation exchange capacity, CEC δ (meq./100g)	AFNOR (1980)	2	0.61 ± 0.00	
Wet – dry loss (%)	ASTM (1992)	5	0.04 ± 0.001	
Freeze – Thaw loss (%)	CIRIA/CUR (1991)	5	0.04 ± 0.002	
Magnesium Sulphate soundness value (%)	ASTM (1990)	5	0.11 ± 0.03	
Sodium Sulphate soundness value (%)	ASTM (1990)	5	0.06 ± 0.003	
Micro-Deval value (%)	TS EN (2002)	2	19.33 ± 0.090	
Mill abrasion resistance index, # ks (%)	CIRIA/CUR (1991)	2	0,0055 ± 0,00003	
Point load strength index, $I_{s(50)}$ (MPa)	ISRM (1985)	6	4.60 ± 1.16	4.15 ± 0.60
Fracture toughness † ($MPa.m^{1/2}$)	Latham (1998)	6	1.09 ± 0.19	1.02 ± 0.10
Uniaxial compressive strength (MPa)	ISRM (1981)	8	52.96 ± 5.93	52.80 ± 11.03
Sonic Velocity ‡ (m/sec)	ISRM (1981)	120	5593.27 ± 568.45	5843.67 ± 354.42
Schmidt rebound hardness ¥	ISRM (1981	10	37.70 ± 1.10	37.30 ± 2.57
Los Angeles abrasion § (%)	ASTM (1989)	1	23.54	23.73
Aggregate impact value (%)	BSI(1990a)	2	17.08 ± 0.17	19.29 ± 0.08
Aggregate crushing value (%)	BSI(1990c)	2	22.45 ± 0.02	22.72 ± 0.06
Modified Aggregate impact value (%)	BSI(1990a)	2	14.72 ± 0.08	
10 % fines value (kN)	BSI(1990b)	1	231.51	226.91

(SD*) standard deviation, **(δ)** determined from methylene blue adsorption test, **(#)** determined from micro-deval test, **(†)** determined from $Is_{(50)}$ using correlation factor
(‡) Pundit-plus 500-kHz transducers are used, **(¥)** L-Type Schmidt hammer is used, **(§)** loss after 1000 revolutions

Table 4.49 Laboratory test results of the Tarlaağzı Limestone

Properties	Standard used for testing	Number of tests	Test results: Dry Mean ± SD*	Test results: Saturated Mean ± SD*
Unit weight (kN/m^3)	ISRM (1981)	120	25.95 ± 0.28	26.17 ± 0.27
Effective porosity (%)	ISRM (1981)	120	2.26 ± 0.39	
Water absorption under atmospheric pressure-by weight (%)	TS 699 (1987)	120	0.82 ± 0.13	
Water absorption under atmospheric pressure-by volume (%)	TS 699 (1987)	120	2.16 ± 0.35	
Water absorption under pressure-by weight (%)	ISRM (1981)	120	0.85 ± 0.15	
Water absorption under pressure-by volume (%)	ISRM (1981)	120	2.26 ± 0.39	
Saturation coefficient	TS 699 (1987)	120	0.97 ± 0.16	
Methylene blue adsorption value, MBA (g/100g)	AFNOR (1980)	2	0.27 ± 0.00	
Cation exchange capacity, CEC δ (meq./100g)	AFNOR (1980)	2	0.61 ± 0.00	
Wet – dry loss (%)	ASTM (1992)	5	0.14 ± 0.03	
Freeze – Thaw loss (%)	CIRIA/CUR (1991)	5	0.23 ± 0.02	
Magnesium Sulphate soundness value (%)	ASTM (1990)	5	0.33 ± 0.03	
Sodium Sulphate soundness value (%)	ASTM (1990)	5	0.25 ± 0.06	
Micro-Deval value (%)	TS EN (2002)	2	15.15 ± 0.06	
Mill abrasion resistance index, # ks (%)	CIRIA/CUR (1991)	2	0,0043 ± 0,00002	
Point load strength index, $I_{s(50)}$ (MPa)	ISRM (1985)	6	6.15 ± 0.72	6.00± 0.96
Fracture toughness † ($MPa.m^{1/2}$)	Latham (1998)	6	1.35± 0.12	1.32± 0.16
Uniaxial compressive strength (MPa)	ISRM (1981)	8	71.17 ± 10.20	70.59 ± 9.02
Sonic Velocity ‡ (m/sec)	ISRM (1981)	120	5498.99 ± 403.95	5650.11 ± 207.09
Schmidt rebound hardness ¥	ISRM (1981	10	37.60 ± 1.02	35.10 ± 2.39
Los Angeles abrasion § (%)	ASTM (1989)	1	27.19	28.49
Aggregate impact value (%)	BSI(1990a)	2	14.43 ± 0.20	15.29 ± 0.18
Aggregate crushing value (%)	BSI(1990c)	2	18.55 ± 0.13	20.19 ± 0.17
Modified Aggregate impact value (%)	BSI(1990a)	2	12.61 ± 0.04	
10 % fines value (kN)	BSI(1990b)	1	248.24	231.90

(SD*) standard deviation**, (δ)** determined from methylene blue adsorption test, **(#)** determined from micro-deval test, **(†)** determined from $Is_{(50)}$ using correlation factor
(‡) Pundit-plus 500-kHz transducers are used, **(¥)** L-Type Schmidt hammer is used, **(§)** loss after 1000 revolutions

Table 4.50 Laboratory test results of the Çömlekçikuyu andesite

Properties	Standard used for testing	Number of tests	Test results Dry Mean ± SD*	 Saturated Mean ± SD*
Unit weight (kN/m^3)	ISRM (1981)	120	23.08 ± 0.86	23.70 ± 0.66
Effective porosity (%)	ISRM (1981)	120	7.20 ± 2.55	
Water absorption under atmospheric pressure-by weight (%)	TS 699 (1987)	120	2.70 ± 1.10	
Water absorption under atmospheric pressure-by volume (%)	TS 699 (1987)	120	6.27 ± 2.35	
Water absorption under pressure-by weight (%)	ISRM (1981)	120	3.10 ± 1.20	
Water absorption under pressure-by volume (%)	ISRM (1981)	120	7.20 ± 2.55	
Saturation coefficient	TS 699 (1987)	120	0.87 ± 0.05	
Methylene blue adsorption value, MBA (g/100g)	AFNOR (1980)	2	2.93 ± 0.13	
Cation exchange capacity, CEC δ (meq./100g)	AFNOR (1980)	2	6.69 ± 0.30	
Wet – dry loss (%)	ASTM (1992)	5	6.79 ± 1.16	
Freeze – Thaw loss (%)	CIRIA/CUR (1991)	5	8.65 ± 1.08	
Magnesium Sulphate soundness value (%)	ASTM (1990)	5	11.64 ± 1.20	
Sodium Sulphate soundness value (%)	ASTM (1990)	5	10.01 ± 1.43	
Micro-Deval value (%)	TS EN (2002)	2	45.76 ± 2.63	
Mill abrasion resistance index, # ks (%)	CIRIA/CUR (1991)	2	0,0130 ± 0,0074	
Point load strength index, $I_{s\,(50)}$ (MPa)	ISRM (1985)	6	4.14 ± 0.53	3.96± 0.73
Fracture toughness † (MPa.m$^{1/2}$)	Latham (1998)	6	1.02± 0.09	0.99± 0.12
Uniaxial compressive strength (MPa)	ISRM (1981)	8	40.42 ± 4.58	36.23 ± 5.26
Sonic Velocity ‡ (m/sec)	ISRM (1981)	120	3340.66 ± 560.93	3516.66 ± 428.56
Schmidt rebound hardness ¥	ISRM (1981	10	37.00 ± 1.55	34.60 ± 1.56
Los Angeles abrasion § (%)	ASTM (1989)	1	29.12	32.16
Aggregate impact value (%)	BSI(1990a)	2	18.83 ± 0.95	22.96 ± 1.04
Aggregate crushing value (%)	BSI(1990c)	2	23.84 ± 0.18	25.26 ± 0.04
Modified Aggregate impact value (%)	BSI(1990a)	2	18.52 ± 0.04	
10 % fines value (kN)	BSI(1990b)	1	175.92	160.67

(SD*) standard deviation**, (δ)** determined from methylene blue adsorption test, **(#)** determined from micro-deval test, **(†)** determined from $Is_{(50)}$ using correlation factor
(‡) Pundit-plus 500-kHz transducers are used, **(¥)** L-Type Schmidt hammer is used, **(§)** loss after 1000 revolutions

Table 4.51 Laboratory test results of the Kıran sandstone

Properties	Standard used for testing	Number of tests	Test results Dry Mean ± SD*	 Saturated Mean ± SD*
Unit weight (kN/m^3)	ISRM (1981)	50	21.56 ± 1.12	23.18 ± 1.07
Effective porosity (%)	ISRM (1981)	50	17.32 ± 1.67	
Water absorption under atmospheric pressure-by weight (%)	TS 699 (1987)	50	7.54 ± 1.07	
Water absorption under atmospheric pressure-by volume (%)	TS 699 (1987)	50	16.47 ± 1.69	
Water absorption under pressure-by weight (%)	ISRM (1981)	50	7.96 ± 1.08	
Water absorption under pressure-by volume (%)	ISRM (1981)	50	17.32 ± 1.67	
Saturation coefficient	TS 699 (1987)	50	0.95 ± 0.01	
Methylene blue adsorption value, MBA (g/100g)	AFNOR (1980)	2	2.80 ± 0.13	
Cation exchange capacity, CEC δ (meq./100g)	AFNOR (1980)	2	6.38 ± 0.30	
Wet – dry loss (%)	ASTM (1992)	5	12.38 ± 1.56	
Freeze – Thaw loss (%)	CIRIA/CUR (1991)	5	15.74 ± 1.46	
Magnesium Sulphate soundness value (%)	ASTM (1990)	5	25.12 ± 3.64	
Sodium Sulphate soundness value (%)	ASTM (1990)	5	23.24 ± 2.83	
Micro-Deval value (%)	TS EN (2002)	2	92.54 ± 0.92	
Mill abrasion resistance index, # ks (%)	CIRIA/CUR (1991)	2	0,0262 ± 0,00026	
Point load strength index, $I_{s\,(50)}$ (MPa)	ISRM (1985)	6	1.29 ± 0.37	0.74± 0.39
Fracture toughness † ($MPa.m^{1/2}$)	Latham (1998)	6	0.55± 0.06	0.46± 0.06
Uniaxial compressive strength (MPa)	ISRM (1981)	8	28.64 ± 7.06	19.34 ± 3.87
Sonic Velocity ‡ (m/sec)	ISRM (1981)	50	2170.88 ± 266.98	2556.85 ± 261.11
Schmidt rebound hardness ¥	ISRM (1981	10	25.40 ± 1.20	25.20 ± 2.44
Los Angeles abrasion § (%)	ASTM (1989)	1	55.78	61.74
Aggregate impact value (%)	BSI(1990a)	2	24.96 ± 0.98	37.44 ± 1.58
Aggregate crushing value (%)	BSI(1990c)	2	27.91 ± 0.22	32.28 ± 0.04
Modified Aggregate impact value (%)	BSI(1990a)	2	66.42 ± 1.70	
10 % fines value (kN)	BSI(1990b)	1	149.65	96.74

(SD*) standard deviation**, (δ)** determined from methylene blue adsorption test, **(#)** determined from micro-deval test, **(†)** determined from $Is_{(50)}$ using correlation factor
(‡) Pundit-plus 500-kHz transducers are used, **(¥)** L-Type Schmidt hammer is used, **(§)** loss after 1000 revolutions

4.2 Mass Properties of the Armourstone

4.2.1 Discontinuity Survey in the Armourstone Sources

Discontinuity measurements of the potential armourstones were carried out in Kavakdere, Kavukkavlağı, Çömlekçikuyu, Tarlaağzı quarries and Kıran district. Scanline surveys with a tape length greater than 10 m were done at different parts of the source localities. Discontinuity properties such as orientation, spacing, persistence, aperture, roughness, wall strength, weathering, infilling, seepage were identified according to ISRM (1981). The panoramic views of the quarries are given in Figures 4.34-4.38.

For the general evaluation of the dip and dip direction records, “Dips 5.0 (1999)” software was used. From the software, the poles of the measurements were plotted through equal area diagrams using the lower hemisphere projection. The contour diagrams for each of the source locality were also obtained. From the contour concentrations, the most suitable major planes for the discontinuity sets were calculated and plotted on the diagrams (Figures 4.39-4.43).

Based on the scanline survey conducted in the Kavakdere quarry, three major sets of discontinues including bedding planes and two systematic joint sets are distinguished. Spacings of the discontinuities show normal distribution (Figure 4.44). In the Kavukkavlağı quarry, similar sets are also determined. However in Kavukkavlağı quarry, the spacing of the beds decreases towards the upper levels. Here spacings of the discontinuities show negative exponential distribution (Figure 4.45). In the Kıran district, also three sets of discontinuities, including bedding and two systematic joint sets are distinguished. Spacings of the discontinuities show negative exponential distribution at this locality (Figure 4.46). In the Çömlekçikuyu quarry, seven sets of discontinues composed of flow layering and six systematic columnar joint sets are distinguished. Spacings of the columns are large at the lower levels; however decrease towards the upper levels and normal distribution is observed (Figure 4.47). Finally in the Tarlaağzı quarry, three joint sets containing bedding planes and two joint sets are also determined. Spacings of the discontinuities show negative exponential distribution However, the joint sets in this quarry are not mostly systematic and many randomly distributed non-systematic joints are also observed in the quarry (Figure 4.48). The properties of the discontinuities are also given in Tables 4.52-4.56.

Figure 4.34 Panoramic view of the Kavakdere quarry

Figure 4.35 Panoramic view of the Kavukkavlağı quarry

Figure 4.36 Panoramic view of the Kıran district

Figure 4.37 Panoramic view of the Çömlekçikuyu quarry

Figure 4.38 Panoramic view of the Tarlaağzı quarry

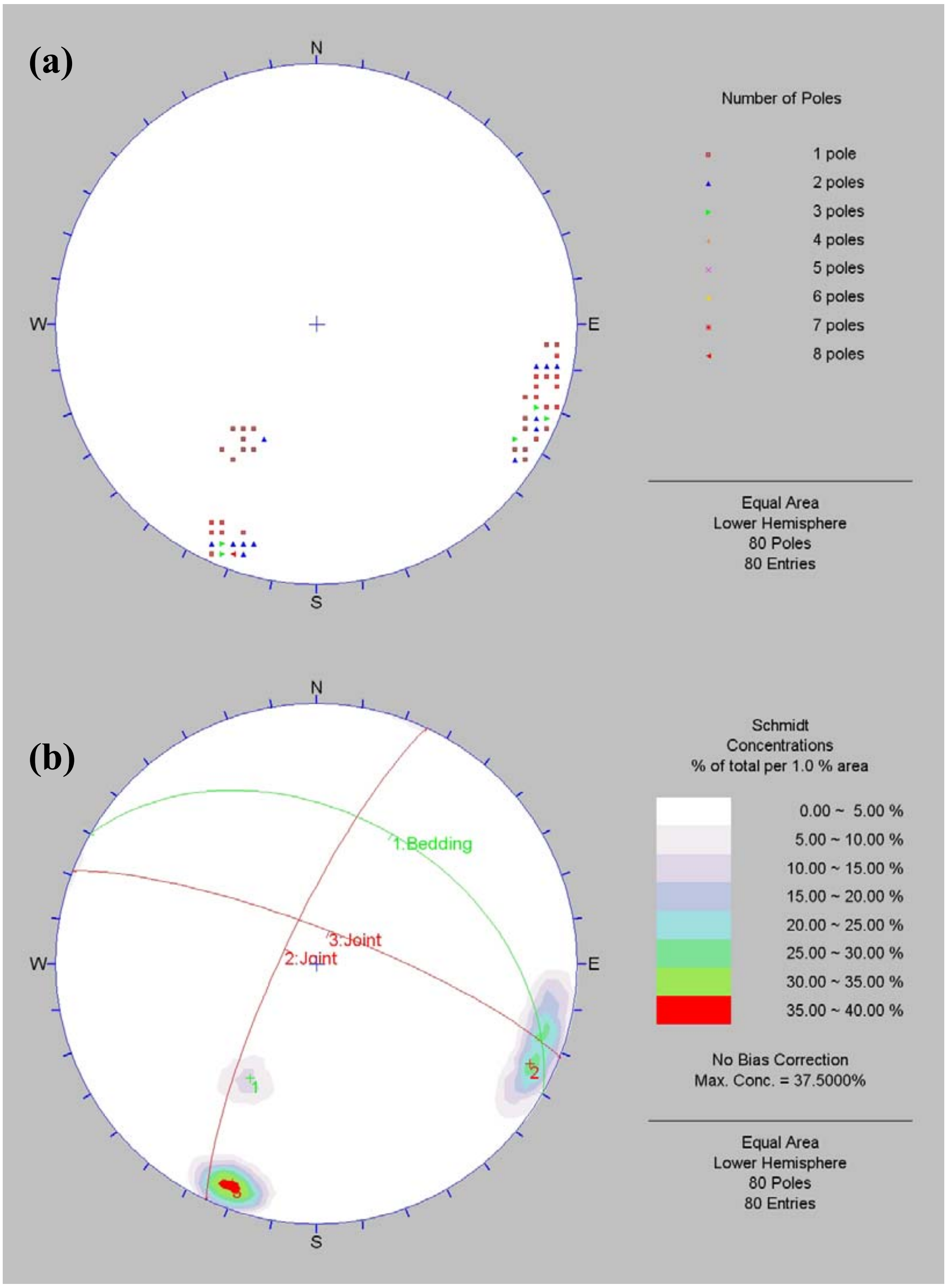


Figure 4.39 Pole plot (a) and contour plot (b) of the discontinuities in the Kavakdere quarry

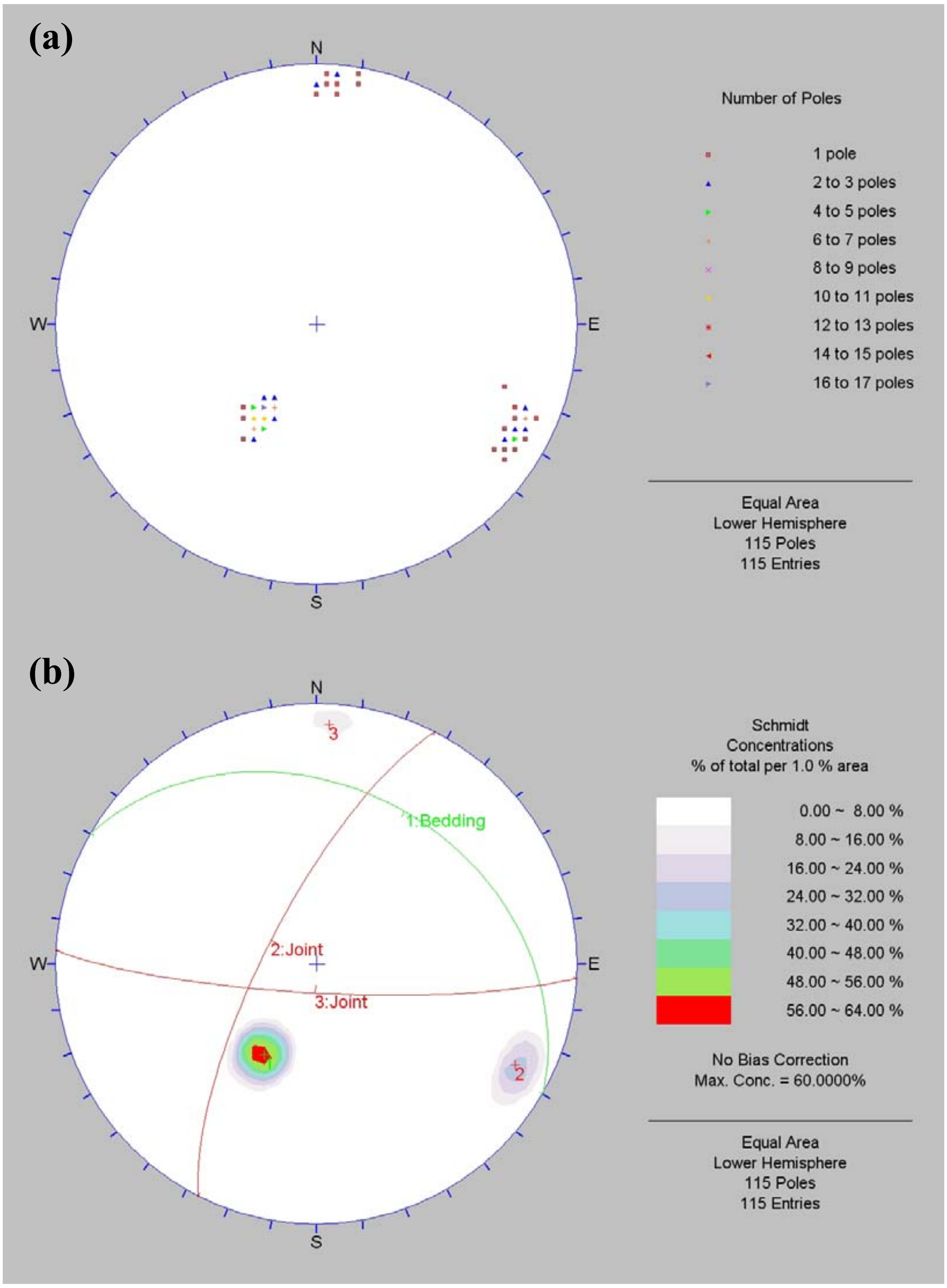


Figure 4.40 Pole plot (a) and contour plot (b) of the discontinuities in the Kavukkavlağı quarry

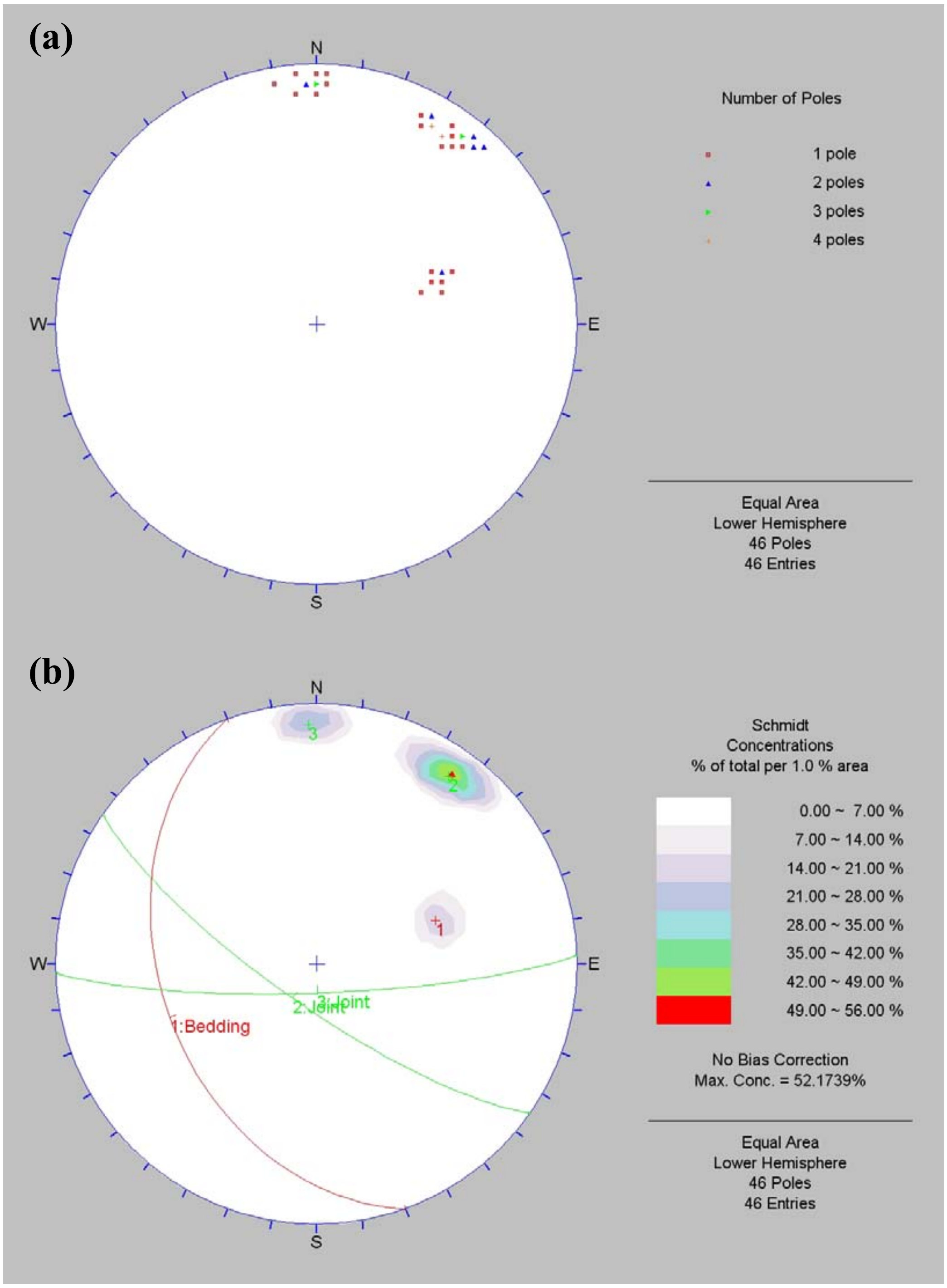


Figure 4.41 Pole plot (a) and contour plot (b) of the discontinuities in the Kıran District

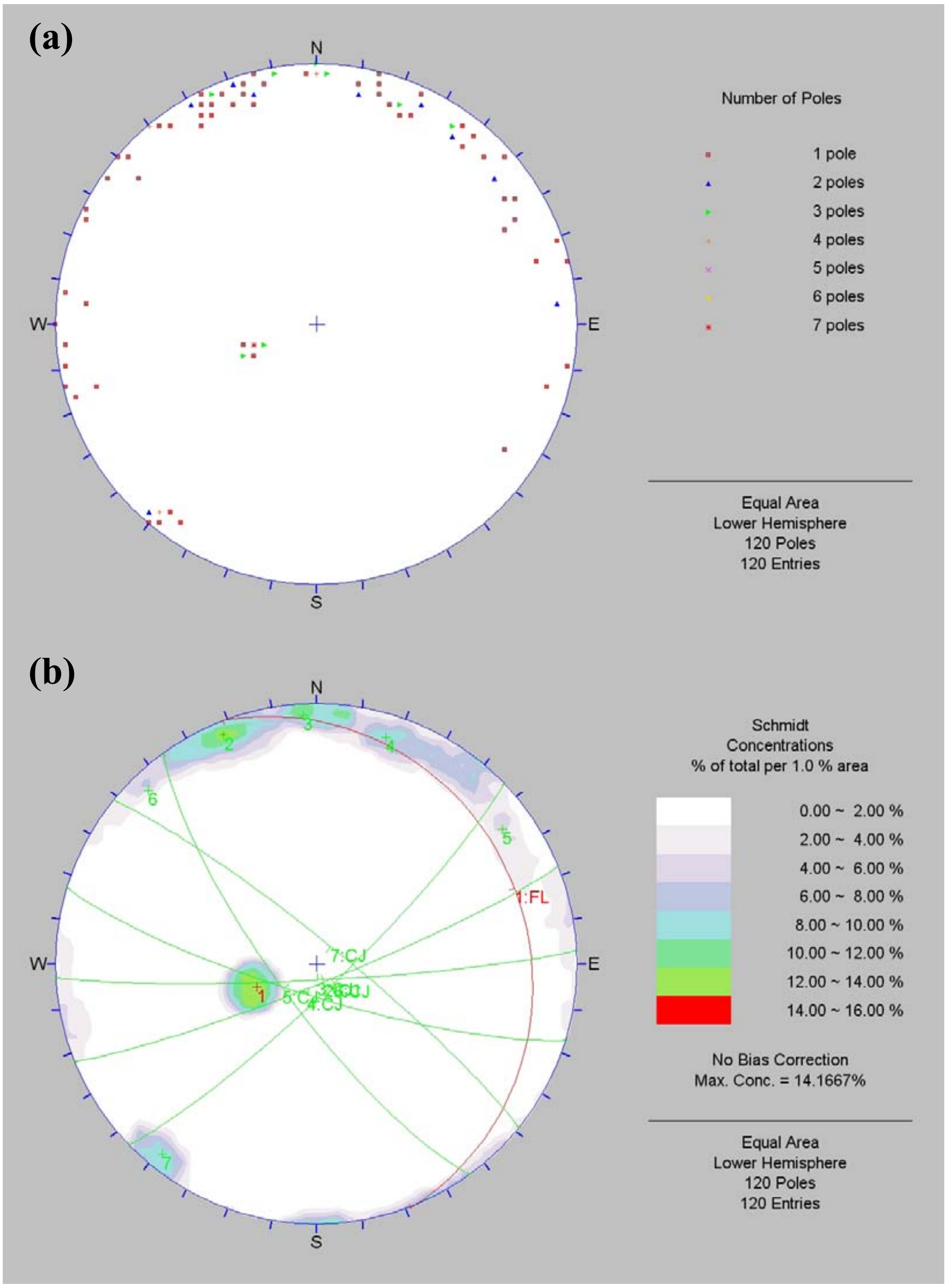


Figure 4.42 Pole plot (a) and contour plot (b) of the discontinuities in the Çömlekçikuyu quarry

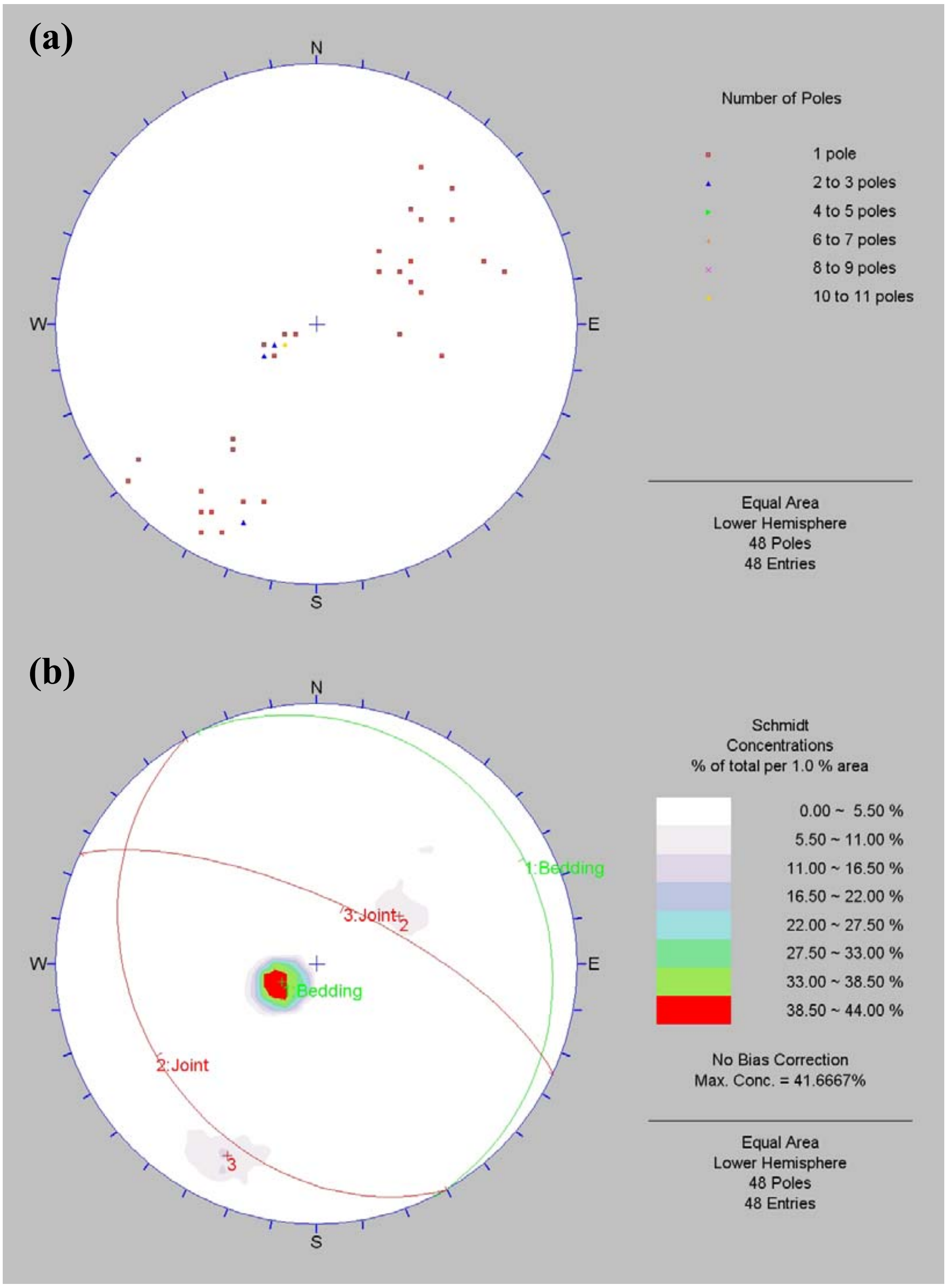


Figure 4.43 Pole plot (a) and contour plot (b) of the discontinuities in the Tarlaağzı quarry

Table 4.52 Properties of the discontinuities in the Kavakdere quarry

DISCONTINUITY PROPERTIES	**KAVAKDERE QUARRY**		
	Bedding Plane	Joint 1	Joint 2
Orientation	030/42	295/79	021/79
Spacing	2 m – 4 m (Very wide spacing)	0.5 m – 4 m (Moderate to very wide spacing)	0.3 m – 2 m (Moderate to wide spacing)
Persistence	10 m – 20 m (High persistence)	10 m – 20 m (High persistence)	10 m – 20 m (High persistence)
Aperture	0.1 mm – 0.25 mm (Tight)	0.1 mm – 0.25 mm (Tight)	0.1 mm – 0.25 mm (Tight)
Roughness	Rough-planar	Rough-undulating	Rough-undulating
Wall Strength	Strong		
Weathering	Slightly weathered		
Infilling	Clay, limonitization		
Seepage	No		
Number of Sets	3		
Block Size (Max), (Min), (V_{80})	(3.3), (0.9), (3.0)		
Volumetric Joint Count (J_v) (joints/m^3)	2.8 (Large blocks)		
Block Shape	Blocky		

Table 4.53 Properties of the discontinuities in the Kavukkavlağı quarry

DISCONTINUITY PROPERTIES	**KAVUKKAVLAĞI QUARRY**		
	Bedding Plane	Joint 1	Joint 2
Orientation	030/33	297/74	183/81
Spacing	0.1 m – 2 m (Close to wide spacing)	0.6 m – 1 m (Wide spacing)	0.5 m – 2 m (Moderate to wide spacing)
Persistence	10 m – 20 m (High persistence)	10 m – 20 m (High persistence)	10 m – 20 m (High persistence)
Aperture	0.1 mm – 0.25 mm (Tight)	0.1 mm – 0.25 mm (Tight)	0.1 mm – 0.25 mm (Tight)
Roughness	Rough-undulating		
Wall Strength	Strong		
Weathering	Slightly weathered		
Infilling	Clay, imonitization		
Seepage	Yes		
Number of Sets	3		
Block Size (Max), (Min), (V_{80})	(1.6), (0.4), (1.2)		
Volumetric Joint Count (J_v) (joints/m^3)	4.1 – 12.6 (Medium-sized blocks to small blocks)		
Block Shape	Blocky		

Table 4.54 Properties of the discontinuities in the Kıran district

DISCONTINUITY PROPERTIES	KIRAN DISTRICT		
	Bedding Plane	Joint 1	Joint 2
Orientation	250/40	215/77	178/81
Spacing	1 m – 3 m (Wide spacing)	0.5 m – 3 m (Moderate to wide spacing)	0.5 m – 1 m (Moderate to wide spacing)
Persistence	10 m – 20 m (High persistence)	10 m – 20 m (High persistence)	10 m – 20 m (High persistence)
Aperture	0.1 mm – 0.25 mm (Tight)	0.1 mm – 0.25 mm (Tight)	0.1 mm – 0.25 mm (Tight)
Roughness	Rough-undulating		
Wall Strength	Moderate		
Weathering	Slightly weathered		
Infilling	Sand, calcite		
Seepage	No		
Number of Sets	3		
Block Size (Max), (Min), (V_{80})	(2.3), (0.7), (2.1)		
Volumetric Joint Count (J_v) (joints/m^3)	2.2 – 3.4 (Large blocks to medium sized blocks)		
Block Shape	Blocky		

Table 4.55 Properties of the discontinuities in the Çömlekçikuyu quarry

DISCONTINUITY PROPERTIES	**ÇÖMLEKÇİKUYU QUARRY**	
	Flow Layering	Columnar Joints
Orientation	069/20	C1) 158/84 C2) 177/85 C3) 197/80 C4) 234/77 C5) 136/82 C6) 039/83
Spacing	0.1 m -1 m (Close to wide spacing)	0.3 m – 1.4 m (Moderate to wide spacing)
Persistence	10 m – 20 m (High persistence)	10 m – 20 m (High persistence)
Aperture	0.1 mm – 0.25 mm (Tight)	0.1 mm – 0.25 mm (Tight)
Roughness	Smooth to rough-undulating	
Wall Strength	Moderate	
Weathering	Slightly weathered to weathered	
Infilling	Quartz (locally)	
Seepage	Yes	
Number of Sets	7	
Block Size (Max), (Min), (V_{80})	(1.2), (0.2), (1.0)	
Volumetric Joint Count (J_v) (joints/m^3)	2.5 – 4.8 (Large blocks to medium-sized blocks)	
Block Shape	Columnar	

Table 4.56 Properties of the discontinuities in the Tarlaağzı quarry

DISCONTINUITY PROPERTIES	**TARLAAĞZI QUARRY**		
	Bedding Plane	Joint 1	Joint 2
Orientation	063/12	240/30	025/70
Spacing	0.6 m – 2 m (Wide spacing)	0.5 m – 2 m (Moderate to wide spacing)	0.5 m – 1 m (Moderate to wide spacing)
Persistence	10 m – 20 m (High persistence)	0.1 m – 3 m (Very low to low persistence)	3 m – 5 m (Medium persistence)
Aperture	0.1 mm – 0.25 mm (Tight)	0.1 mm – 0.25 mm (Tight)	0.1 mm – 0.25 mm (Tight)
Roughness	Rough undulating		
Wall Strength	Strong		
Weathering	Slightly weathered		
Infilling	Calcite (locally)		
Seepage	No		
Number of Sets	3 + Random sets		
Block Size (Max), (Min), (V_{80})	(1.7), (0.53), (1.6)		
Volumetric Joint Count (J_v) (joints/m^3)	2.0 – 6.9 (Large blocks to medium sized blocks)		
Block Shape	Irregular		

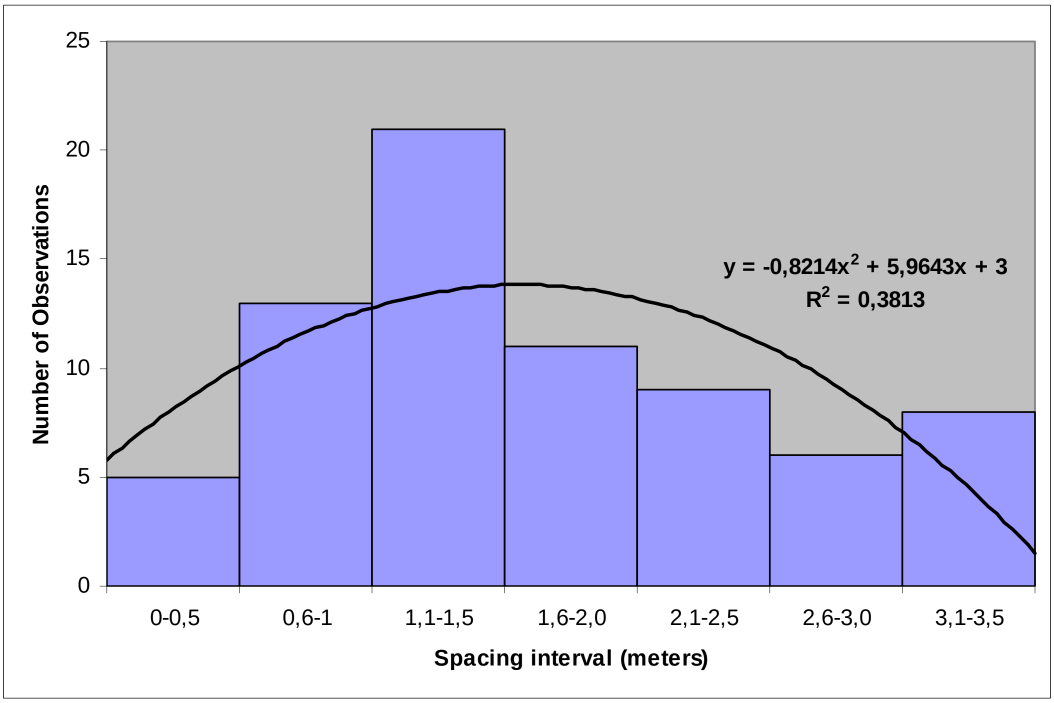


Figure 4.44 Distributions of the joint spacing in the Kavakdere quarry

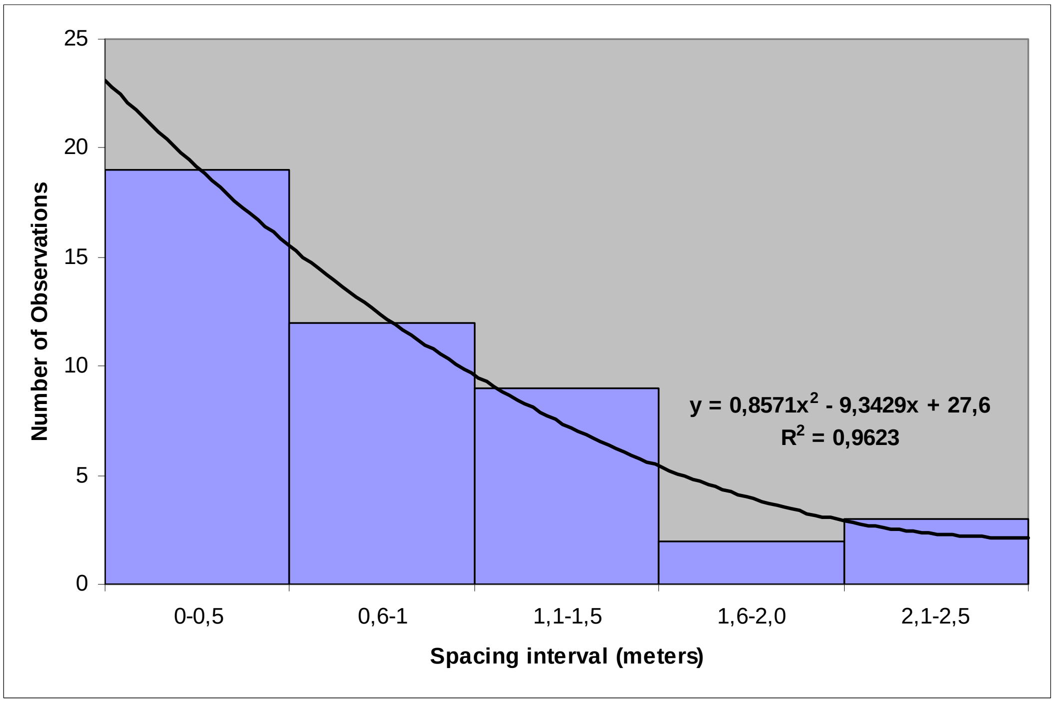


Figure 4.45 Distributions of the joint spacing in the Kavukkavlağı quarry

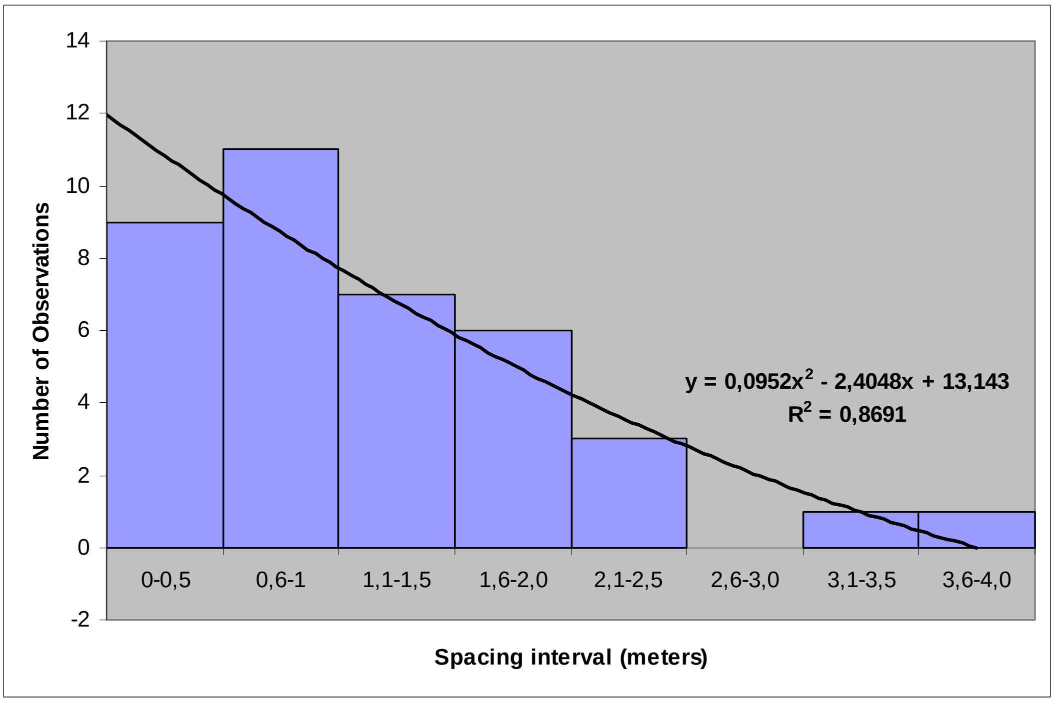


Figure 4.46 Distributions of the joint spacing in the Kıran district

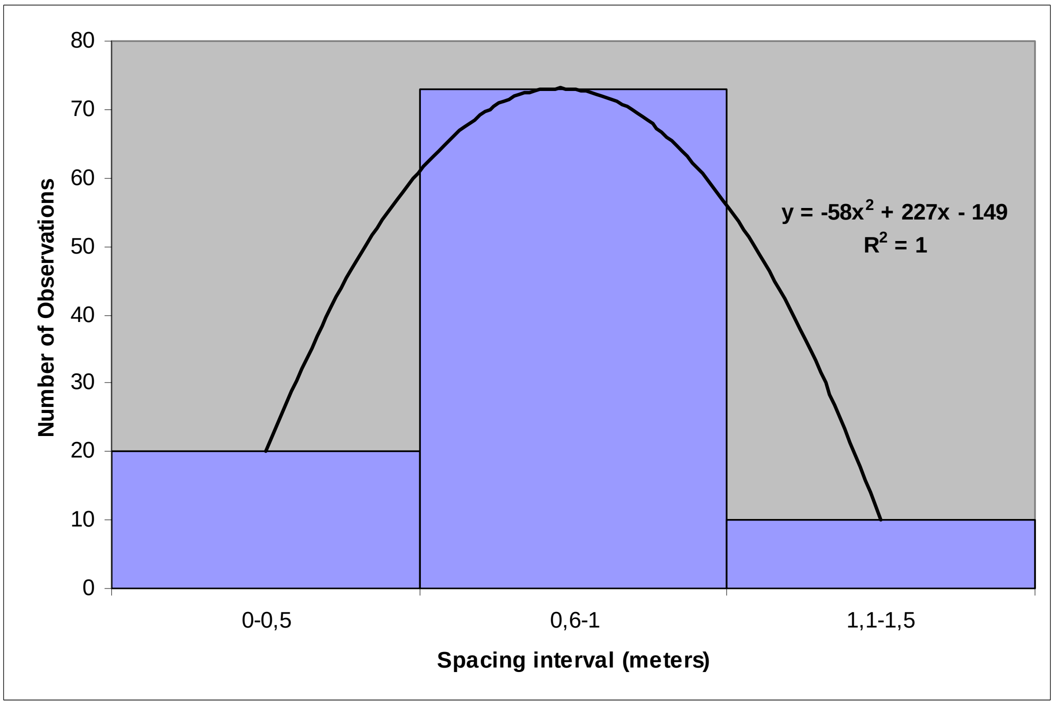


Figure 4.47 Distributions of the joint spacing in the Çömlekçikuyu quarry

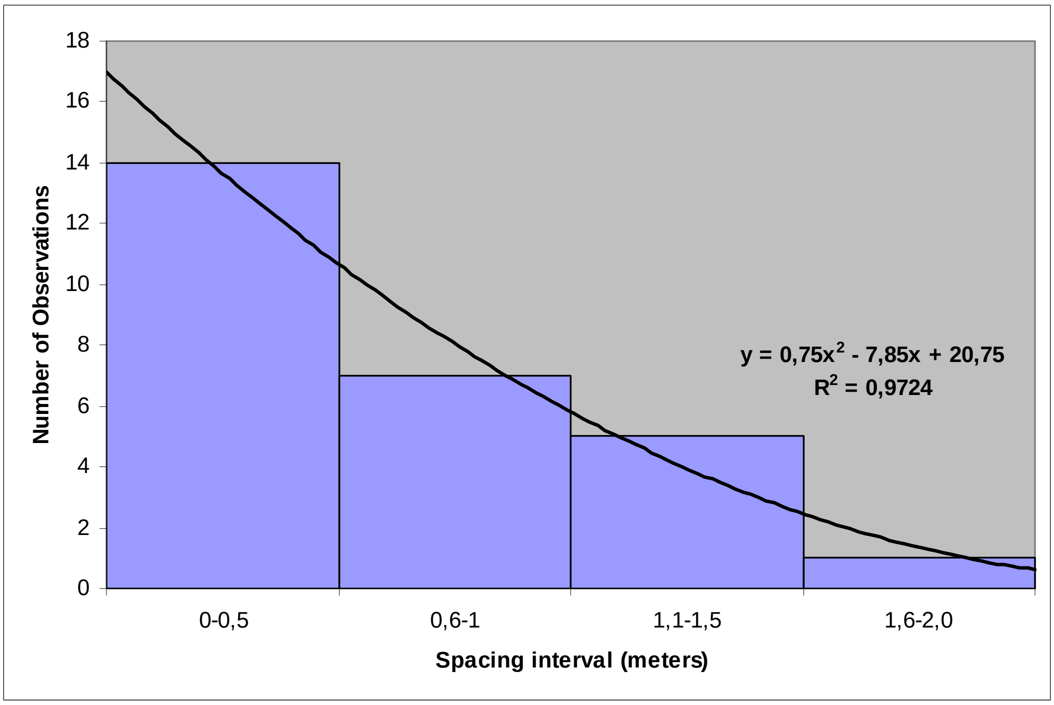


Figure 4.48 Distributions of the joint spacing in the Tarlaağzı quarry

CHAPTER 5

QUALITY EVALUATION OF THE ARMOURSTONES

After various laboratory test and field observations on the armourstones; a huge quantity of data were produced. Therefore in order to organize this data under a general frame, a need for a classification system occurred. There are various classification systems described in literature all aiming to select the suitable materials for the construction of costal structures. According to Erickson (1993), the overall goal of a stone source evaluation is to assure the permanence in the structure and not have to perform maintenance for the design life of the project. If deterioration of the stone occurs, repairs can be very costly. By considering this fact, the necessary classification methods are applied with great care.

For the quality evaluation of the Kavkadere, Kavukkavlağı, Tarlaağzı limestones, the Çömlekçikuyu andesite and Kıran sandstone CIRIA/CUR (1991), the rock durability index of Fookes et al. (1988), rock engineering rating system of Lienhart (1998), saturation coefficient classification suggested by Schaffer (1972) and wet-dry strength ratio of Winkler (1986) were used in this thesis.

5.1 CIRIA/CUR Classification

CIRIA/CUR (1991) classification is a simple classification system for the general evaluation of the laboratory and field data. Rather than quantitative descriptions, the system uses qualitative descriptions for the results of the laboratory and field tests. As an overall, CIRIA/CUR (1991) can be referred as a summary table for the visualization of the various properties of the source rock. The CIRIA/CUR (1991) considers rock density (p_r), water absorption (W_{ab}), magnesium sulphate soundness (MSS), freeze/thaw resistance (FT), methylene blue absorption (MBA), fracture toughness (K_{IC}), point load strength index ($I_{S(50)}$), wet dynamic crushing value (WDCV), mill abrasion resistance index (k_s) and the block integrity drop test (I_d) values of the samples. The strength-related parameters used for the classification belong to the saturated conditions. The CIRIA/CUR (1991) classification for the Kavakdere, Kavukkavlağı, Tarlaağzı limestones, the Çömlekçikuyu andesite and Kıran sandstone are given in Tables 5.1-5.4.

According to the CIRIA/CUR classification, the Kavakdere limestone is excellent-marginal in quality. Similarly values of the Kavukkavlağı and Tarlaağzı limestones are in the range of excellent-marginal; on the other hand, values for the Çömlekçikuyu andesite are distributed in between good and poor, and for the Kıran sandstone they are distributed between marginal and poor.

Table 5.1 Quality evaluation of the Kavakdere limestone by CIRIA/CUR (1991)

Properties	CIRIA/CUR CRITERIA				Kavakdere Limestone
	Excellent	Good	Marginal	Poor	
Dry density – p_r (t/m$^{3)}$	≥2.9	2.6-2.9	2.3-2.6	≤2.3	2.74
Water absorption – W_{ab} (%)	≤0.5	0.5-2.0	2.0-6.0	≥6.0	0.10
Magnesium sulphate soundness – MSS (%)	≤2	2-12	12-30	≥30	0.08
Freeze- Thaw – FT (%)	≤0.1	0.1-0.5	0.5-2.0	≥2.0	0.11
Methylene blue absorption – MBA (g/100g)	≤0.4	0.4-0.7	0.7-1.0	≥1.0	0.53
Fracture toughness – K_{IC} (MPa.m$^{1/2}$)	≥2.2	1.4-2.2	0.8-1.4	≤0.8	1.23*
Point load strength index – $I_{S(50)}$ (MPa)	≥8.0	4.0-8.0	1.5-4.0	≤1.5	5.45
Wet dynamic crushing value – WDCV (%)	≤12.0	12-20	20-30	≥30	23.98
Mill abrasion resistance – k_s (%)	≤0.002	0.002-0.004	0.004-0.015	≥0.0 15	0.0065**
Block integrity drop test – I_d (%)	≤2	2-5	5-15	≥15	2-5

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

Table 5.2 Quality evaluation of the Kavukkavlağı limestone by CIRIA/CUR (1991)

Properties	CIRIA/CUR CRITERIA				Kavukkavlağı Limestone
	Excellent	Good	Marginal	Poor	
Dry density – p_r (t/m$^{3)}$	≥2.9	2.6-2.9	2.3-2.6	≤2.3	2.69
Water absorption – W_{ab} (%)	≤0.5	0.5-2.0	2.0-6.0	≥6.0	0.20
Magnesium sulphate soundness – MSS (%)	≤2	2-12	12-30	≥30	0.11
Freeze- Thaw – FT (%)	≤0.1	0.1-0.5	0.5-2.0	≥2.0	0.04
Methylene blue absorption – MBA (g/100g)	≤0.4	0.4-0.7	0.7-1.0	≥1.0	0.27
Fracture toughness – K_{IC} (MPa.m$^{1/2}$)	≥2.2	1.4-2.2	0.8-1.4	≤0.8	1.02*
Point load strength index – $I_{S(50)}$ (MPa)	≥8.0	4.0-8.0	1.5-4.0	≤1.5	4.15
Wet dynamic crushing value – WDCV (%)	≤12.0	12-20	20-30	≥30	22.72
Mill abrasion resistance – k_s (%)	≤0.002	0.002-0.004	0.004-0.015	≥0.015	0.0055**
Block integrity drop test – I_d (%)	≤2	2-5	5-15	≥15	2-5

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

Table 5.3 Quality evaluation of the Tarlaağzı limestone by CIRIA/CUR (1991)

Properties	CIRIA/CUR CRITERIA				Tarlaağzı Limestone
	Excellent	Good	Marginal	Poor	
Dry density – p_r ($t/m^{3)}$	≥2.9	2.6-2.9	2.3-2.6	≤2.3	2.65
Water absorption – W_{ab} (%)	≤0.5	0.5-2.0	2.0-6.0	≥6.0	0.82
Magnesium sulphate soundness – MSS (%)	≤2	2-12	12-30	≥30	0.33
Freeze- Thaw – FT (%)	≤0.1	0.1-0.5	0.5-2.0	≥2.0	0.23
Methylene blue absorption – MBA (g/100g)	≤0.4	0.4-0.7	0.7-1.0	≥1.0	0.27
Fracture toughness – K_{IC} (MPa.$m^{1/2}$)	≥2.2	1.4-2.2	0.8-1.4	≤0.8	1.32*
Point load strength index – $I_{S(50)}$ (MPa)	≥8.0	4.0-8.0	1.5-4.0	≤1.5	6.00
Wet dynamic crushing value – WDCV (%)	≤12.0	12-20	20-30	≥30	20.19
Mill abrasion resistance – k_s (%)	≤0.002	0.002-0.004	0.004-0.015	≥0.0 15	0.0043**
Block integrity drop test – I_d (%)	≤2	2-5	5-15	≥15	2-5

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

Table 5.4 Quality evaluation of the Çömlekçikuyu andesite by CIRIA/CUR (1991)

Properties	CIRIA/CUR CRITERIA				Çömlekçikuyu andesite
	Excellent	Good	Marginal	Poor	
Dry density – p_r (t/m^3)	≥2.9	2.6-2.9	2.3-2.6	≤2.3	2.35
Water absorption – W_{ab} (%)	≤0.5	0.5-2.0	2.0-6.0	≥6.0	2.70
Magnesium sulphate soundness – MSS (%)	≤2	2-12	12-30	≥30	11.64
Freeze- Thaw – FT (%)	≤0.1	0.1-0.5	0.5-2.0	≥2.0	8.65
Methylene blue absorption – MBA (g/100g)	≤0.4	0.4-0.7	0.7-1.0	≥1.0	2.93
Fracture toughness – K_{IC} ($MPa.m^{1/2}$)	≥2.2	1.4-2.2	0.8-1.4	≤0.8	0.99*
Point load strength index – $I_{S(50)}$ (MPa)	≥8.0	4.0-8.0	1.5-4.0	≤1.5	3.96
Wet dynamic crushing value – WDCV (%)	≤12.0	12-20	20-30	≥30	25.26
Mill abrasion resistance – k_s (%)	≤0.002	0.002-0.004	0.004-0.015	≥0.015	0.013**
Block integrity drop test – I_d (%)	≤2	2-5	5-15	≥15	2-5

* assessed from point load strength index test

** assessed from micro-deval test

Table 5.5 Quality evaluation of the Kıran sandstone by CIRIA/CUR (1991)

Properties	CIRIA/CUR CRITERIA				Kıran Sandstone
	Excellent	Good	Marginal	Poor	
Dry density – p_r (t/m$^{3)}$	≥2.9	2.6-2.9	2.3-2.6	≤2.3	2.20
Water absorption – W_{ab} (%)	≤0.5	0.5-2.0	2.0-6.0	≥6.0	7.54
Magnesium sulphate soundness – MSS (%)	≤2	2-12	12-30	≥30	25.12
Freeze- Thaw – FT (%)	≤0.1	0.1-0.5	0.5-2.0	≥2.0	15.74
Methylene blue absorption – MBA (g/100g)	≤0.4	0.4-0.7	0.7-1.0	≥1.0	2.80
Fracture toughness – K_{IC} (MPa.m$^{1/2}$)	≥2.2	1.4-2.2	0.8-1.4	≤0.8	0.46*
Point load strength index – $I_{S(50)}$ (MPa)	≥8.0	4.0-8.0	1.5-4.0	≤1.5	0.74
Wet dynamic crushing value – WDCV (%)	≤12.0	12-20	20-30	≥30	32.28
Mill abrasion resistance – k_s (%)	≤0.002	0.002-0.004	0.004-0.015	≥0.015	0.262**
Block integrity drop test – I_d (%)	≤2	2-5	5-15	≥15	5-15

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

5.2 Rock Durability Index

Another most commonly used classification is the Rock Durability Index suggested by Fookes et al. (1988). According to Dibb et al. (1983), the factors affecting the rock durability in marine environments are mainly originated by the physical structure of the armourstone. Therefore, application of a durability index is important on those sources. 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 applied to under layer and core parts of the breakwater, whereas the dynamic rock durability index (RDI_d) is applied for armour layer. Unlike CIRIA/CUR (1991) classification, in rock durability index various laboratory test results are correlated with empirical formulas for a generalized qualitative classification.

5.2.1 Static Rock Durability Indicator

Static rock durability indicator RDI_s is expressed by the following formula (Fookes et al., 1988):

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

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 formula correlates four mandatory laboratory tests and depending on the result of the formula, rock is classified as excellent, good, marginal or poor. A tentative estimation of the potential durability of rocks based on the static rock quality index is given in Table 5.6.

Table 5.6 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 5.6) and the calculated RDI_s values, the Kavakdere, Kavukkavlağı and Tarlaağzı limestones are classified as excellent; on the other hand the Çömlekçikuyu andesite and the Kıran sandstone are classified as poor. The corresponding RDI_S results of the samples are also given in Table 5.7.

Table 5.7 Quality evaluation of the samples according to RDI_s values

Sample Name	RDI $_s$ value	Durability Class
Kavakdere limestone	5.22	Excellent
Kavukkavlağı limestone	3.63	Excellent
Tarlaağzı limestone	3.10	Excellent
Çömlekçikuyu andesite	-6.35	Poor
Kıran sandstone	-24.35	Poor

5.2.2 Dynamic Rock Durability Indicator

Dynamic rock durability indicator RDI_d is expressed by the following formula (Fookes et al., 1988):

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

Where;

MAIV : modified aggregate impact value (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 formula correlates three mandatory laboratory tests and depending on the result of the formula, rock is classified as excellent, good, marginal or poor. A tentative estimation of the potential durability of rocks based on the dynamic rock quality index is given in Table 5.8.

Table 5.8 Tentative estimation of dynamic rock durability (Fookes et al., 1988)

RDI_d value	**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 5.8) and the calculated RDI_d values, the Kavakdere, Kavukkavlağı and Tarlaağzı limestones are classified as good but they are almost in the excellent range; on the other hand, the Çömlekçikuyu andesite is classified as marginal and the Kıran sandstone is classified as poor. The corresponding RDI_d results of the samples are also given in Table 5.9.

Table 5.9 Quality evaluation of the samples according to RDI_d values

Sample Name	**RDI_d value**	**Durability Class**
Kavakdere limestone	0.59	Good
Kavukkavlağı limestone	0.64	Good
Tarlaağzı limestone	0.88	Good
Çömlekçikuyu andesite	2.06	Marginal
Kıran sandstone	6.30	Poor

5.3 Rock Engineering Rating System

Rock Engineering Rating System (RERS) is another classification method described by Lienhart (1998). According to Lienhart (1998), the process involved in assessing and selecting a potential source of armourstone of suitable quality is one of great complexity. The process involves the inspection and evaluation of the quarry and its production methods, testing of the processed stone, evaluation of the quality of both intact and processed stone, and consideration of both the transportation methods and placement techniques. The entire process from quarry selection to placement at the project may be viewed as rock engineering system.

Compared to the other classification methods RERS considers and correlates a wider range of data about the source rock. Those data are classified under certain criteria and an interaction matrix is created by Lienheart (1998) for each of these criteria. He 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.

The three important criteria in RERS and their sub contents are: geological factor criteria, production process criteria and rock property criteria. In geological factor criteria, data related to lithology, regional in-situ stress, weathering grade, discontinuity analysis and groundwater conditions are evaluated. In production process criteria; production method, rock quality, set-aside time and block integrity are evaluated and finally in rock property criteria; petrography, sonic velocity, point load strength, Schmidt impact resistance, Los Angeles abrasion, specific gravity, water absorption under atmospheric pressure, adsorption/absorption, magnesium sulphate soundness, freeze-thaw loss and wet-dry loss are evaluated.

The parameters used for these three criteria are given in Tables 5.10-5.12. 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 5.13. For the use of rock engineering rating system, the quality specifications from Tables 5.10-5.12 should be evaluated, ranked such as “excellent, good, marginal or poor” 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 the 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;

$$\text{Overall rating} = \sum (\text{Quality rating} * \text{Index number}) / n \qquad (5.3)$$

Where;

Quality rating is a value varying between 0 and 4 for each parameter, evaluated from Tables 5.10-5.12.

Index number is obtained from Table 5.13 and n is the number of weighted rating. The overall rating is evaluated using the classification suggested in Table 5.14.

Table 5.10 Geological criteria affecting the performance of armourstones (Lienhart, 1998).

Criteria	Quality Specification			
	Excellent	Good	Marginal	Poor
Lithological classification	Un-foliated, 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 5.11 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; Blasthole 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

Table 5.12 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 rebound value	>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 5.13 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 5.14 Rock armour classification based on the rating system

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

Based on the rock engineering rating system of Lienhart (1998), the overall ratings and related calculations of the samples are given in Tables 5.15-5.19. During the evaluation of the overall ratings, V_{80} value for the discontinuity analysis section of the geological criteria was assessed in the field, and the adsorption/absorption ratio was obtained from Mercury porosimetry test data whereas the other parameters were measured.

According to the calculations in Tables 5.15-5.19, the overall rating of the Kavakdere limestone is 3.37 (good), the Kavukkavlağı limestone is 2.90 (marginal), the Tarlaağzı limestone is 3.07 (good), the Çömlekçikuyu andesite is 2.60 (good - marginal) and finally the overall rating of the Kıran sandstone is 2.34 (marginal).

Table 5.15 Quality rating assessment of the Kavakdere limestone

Kavakdere Limestone									
Criteria Type	**Criteria**	**Quality Rating**							
		Excellent = 4	Good = 3	Marginal = 2	Poor = 1	a) Rating Value	b) Cause-effect rating	c) Index (b/b mean)	d) Weighted rating (a x c)
Geological Factor	Lithological Classification	✓				4	11.31	0.74	2.96
	Regional in situ stress		✓			3	14.14	0.93	2.79
	Weathering grade		✓			3	14.14	0.93	2.79
	Discontinuity analysis		✓			3	18.38	1.20	3.60
	Groundwater conditions	✓				4	14.14	0.93	3.72
Production Process	Production method	✓				4	15.56	1.02	4.08
	Set-aside		✓			3	15.56	1.02	3.06
	Quarried rock quality		✓			3	13.43	0.88	2.64
	Block integrity		✓			3	15.56	1.02	3.06
Rock Property	Petrographic evaluation	✓				4	18.38	1.20	4.80
	Sonic velocity		✓			2.25	16.97	1.11	2.50
	Point Load strength		✓						
	Schmidt impact resistance				✓				
	LA abrasion			✓					
	Specific gravity		✓			3.67	15.56	1.02	3.74
	Water absorption	✓							
	Adsorption / absorption	✓							
	Magnesium Sulphate Soundness	✓				4.00	15.56	1.02	4.08
	Freeze-thaw loss	✓							
	Wet-dry loss	✓							
						Mean	15.28	**Overall Rating**	**3.37 (Good)**

Table 5.16 Quality rating assessment of the Kavukkavlağı limestone

Kavukkavlağı Limestone									
Criteria Type	**Criteria**	**Quality Rating**							
		Excellent = 4	Good = 3	Marginal = 2	Poor = 1	a) Rating Value	b) Cause-effect rating	c) Index (b/b mean)	d) Weighted rating (a x c)
Geological Factor	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			✓		2	18.38	1.20	2.40
	Groundwater conditions			✓		2	14.14	0.93	1.86
Production Process	Production method			✓		2	15.56	1.02	2.04
	Set-aside		✓			3	15.56	1.02	3.06
	Quarried rock quality		✓			3	13.43	0.88	2.64
	Block integrity		✓			3	15.56	1.02	3.06
Rock Property	Petrographic evaluation		✓			3	18.38	1.20	3.60
	Sonic velocity		✓			2.50	16.97	1.11	2.78
	Point Load strength		✓						
	Schmidt impact resistance				✓				
	LA abrasion		✓						
	Specific gravity		✓			3.33	15.56	1.02	3.40
	Water absorption		✓						
	Adsorption / absorption	✓							
	Magnesium Sulphate Soundness	✓				4.00	15.56	1.02	4.08
	Freeze-thaw loss	✓							
	Wet-dry loss	✓							
						Mean	15.28	**Overall Rating**	**2.90 (Good-Marginal)**

Table 5.17 Quality rating assessment of the Tarlaağzı limestone

Tarlaağzı Limestone										
Criteria Type	**Criteria**	**Quality Rating**								
		Excellent = 4	Good = 3	Marginal = 2	Poor = 1	a) Rating Value	b) Cause-effect rating	c) Index (b/b mean)	d) Weighted rating (a x c)
Geological Factor	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			✓		2	18.38	1.20	2.40
	Groundwater conditions	✓				4	14.14	0.93	3.72
Production Process	Production method			✓		2	15.56	1.02	2.04
	Set-aside	✓				4	15.56	1.02	4.08
	Quarried rock quality		✓			3	13.43	0.88	2.64
	Block integrity		✓			3	15.56	1.02	3.06
Rock Property	Petrographic evaluation		✓			3	18.38	1.20	3.60
	Sonic velocity		✓			2.50	16.97	1.11	2.78
	Point Load strength		✓						
	Schmidt impact resistance				✓				
	LA abrasion		✓						
	Specific gravity		✓			3.33	15.56	1.02	3.40
	Water absorption		✓						
	Adsorption / absorption	✓							
	Magnesium Sulphate Soundness	✓				3.33	15.56	1.02	3.40
	Freeze-thaw loss		✓						
	Wet-dry loss		✓						
						Mean	15.28	**Overall Rating**	**3.07 (Good)**

Table 5.18 Quality rating assessment of the Çömlekçikuyu andesite

Çömlekçikuyu Andesite									
Criteria Type	**Criteria**	**Quality Rating**							
		Excellent = 4	Good = 3	Marginal = 2	Poor = 1	a) Rating Value	b) Cause-effect rating	c) Index (b/b mean)	d) Weighted rating (a x c)
Geological Factor	Lithological Classification	✓				4	11.31	0.74	2.96
	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	2.40
	Groundwater conditions			✓		2	14.14	0.93	1.86
Production Process	Production method			✓		2	15.56	1.02	2.04
	Set-aside	✓				4	15.56	1.02	4.08
	Quarried rock quality		✓			3	13.43	0.88	2.64
	Block integrity		✓			3	15.56	1.02	3.06
Rock Property	Petrographic evaluation		✓			3	18.38	1.20	3.60
	Sonic velocity			✓		2.00	16.97	1.11	2.22
	Point Load strength		✓						
	Schmidt impact resistance				✓				
	LA abrasion			✓					
	Specific gravity				✓	2.00	15.56	1.02	2.04
	Water absorption				✓				
	Adsorption / absorption	✓							
	Magnesium Sulphate Soundness			✓		1.33	15.56	1.02	1.36
	Freeze-thaw loss				✓				
	Wet-dry loss				✓				

Mean	15.28	**Overall Rating**	**2.60 (Marginal)**

Table 5.19 Quality rating assessment of the Kıran sandstone

Kıran Sandstone									
Criteria Type	**Criteria**	**Quality Rating**							
		Excellent = 4	Good = 3	Marginal = 2	Poor = 1	a) Rating Value	b) Cause-effect rating	c) Index (b/b mean)	d) Weighted rating (a x c)
Geological Factor	Lithological Classification			✓		2	11.31	0.74	1.48
	Regional in situ stress	✓				4	14.14	0.93	3.72
	Weathering grade		✓			3	14.14	0.93	2.79
	Discontinuity analysis			✓		2	18.38	1.20	2.40
	Groundwater conditions	✓				4	14.14	0.93	3.72
Production Process	Production method			✓		2	15.56	1.02	2.04
	Set-aside		✓			3	15.56	1.02	3.06
	Quarried rock quality		✓			3	13.43	0.88	2.64
	Block integrity			✓		2	15.56	1.02	2.04
Rock Property	Petrographic evaluation			✓		2	18.38	1.20	2.40
	Sonic velocity				✓	1.00	16.97	1.11	1.11
	Point Load strength				✓				
	Schmidt impact resistance				✓				
	LA abrasion				✓				
	Specific gravity				✓	1.67	15.56	1.02	1.70
	Water absorption				✓				
	Adsorption / absorption		✓						
	Magnesium Sulphate Soundness			✓		1.33	15.56	1.02	1.36
	Freeze-thaw loss				✓				
	Wet-dry loss				✓				
						Mean	15.28	**Overall Rating**	**2.34 (Marginal)**

5.4 Average Pore Diameter

Average pore diameter is another parameter used for the classification of the armourstones. However, different from the previously mentioned methods, it depends solely on the average pore diameter values of the samples. Therefore, the final classifications of the samples were made also by considering the laboratory performances.

Larsen and Cady (1969), considered that the average pore diameter is an important parameter of the rocks reflecting their susceptibility to freeze-thaw effect. The authors suggest that the rocks having pore size diameter less than 5 μm are susceptible to frost damage because of the undrained pore water.

Based on the intrusion data of mercury porosimetry, the average pore diameter of the Kavakdere limestone, Kavukkavlağı limestone, Tarlaağzı limestone, Çömlekçikuyu andesite and Kıran sandstone are 0.16 μm, 0.76 μm, 0.09 μm, 0.77 μm and 0.12 μm, respectively. The above results reflect that all of the samples are susceptible to frost damage according to their average pore diameters. However, the laboratory performances of the samples during the freeze-thaw test reflected that the limestone samples are not affected from the frost damage retaining their original physico-mechanical properties. This is attributed to the low effective porosities of the limestones.

5.5 Saturation Coefficient

Like the average pore diameter, saturation coefficient is another index property of the rocks used as a classification criterion. It is evaluated from the ratio between the water absorption under atmospheric pressure and pressure tests (TS699, 1987).

However, the final classification of the samples were also made by considering the laboratory performances.

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, 1972 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 coefficients of the samples studied in this thesis are given in Table 5.20.

Table 5.20 Saturation coefficients of the samples

Sample	Saturation Coefficient
Kavakdere Limestone	0.64
Kavukkavlağı Limestone	0.66
Tarlaağzı Limestone	0.96
Çömlekçikuyu Andesite	0.87
Kıran Sandstone	0.95

The above results suggest that the Kavakdere and the Kavukkavlağı limestones are not susceptible to frost damage based on their saturation coefficient values. On the other hand the Tarlaağzı limestone, the Çömlekçikuyu andesite and the Kıran sandstone are susceptible to frost damage according to their saturation coefficient values. However, laboratory performances of the samples during the freeze-thaw test indicated that the Tarlaağzı limestone is not affected from the frost damage retaining its original physico-mechanical properties. Therefore the saturation coefficient classification should not be considered as reliable method for the Tarlaağzı limestone.

5.6 Wet –to- Dry Strength Ratio

The final classification method is the wet-dry strength ratio suggested by Winkler (1986 and 1993). According to him, 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. It is 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.

For the evaluation of the wet-dry strength ratio of the samples, the dry and wet UCS data derived from the laboratory tests were used. According to Figure 5.1, the wet-dry strength ratios of the Kavakdere, Kavukkavlağı, Tarlaağzı limestones and the Çömlekçikuyu andesite fall in the excellent range reflecting high durability. On the other hand, the wet-dry strength ratio of the Kıran sandstone falls in the fair range reflecting a less durable rock. These results are in good agreement with the laboratory observations except the Çömlekçikuyu andesite.

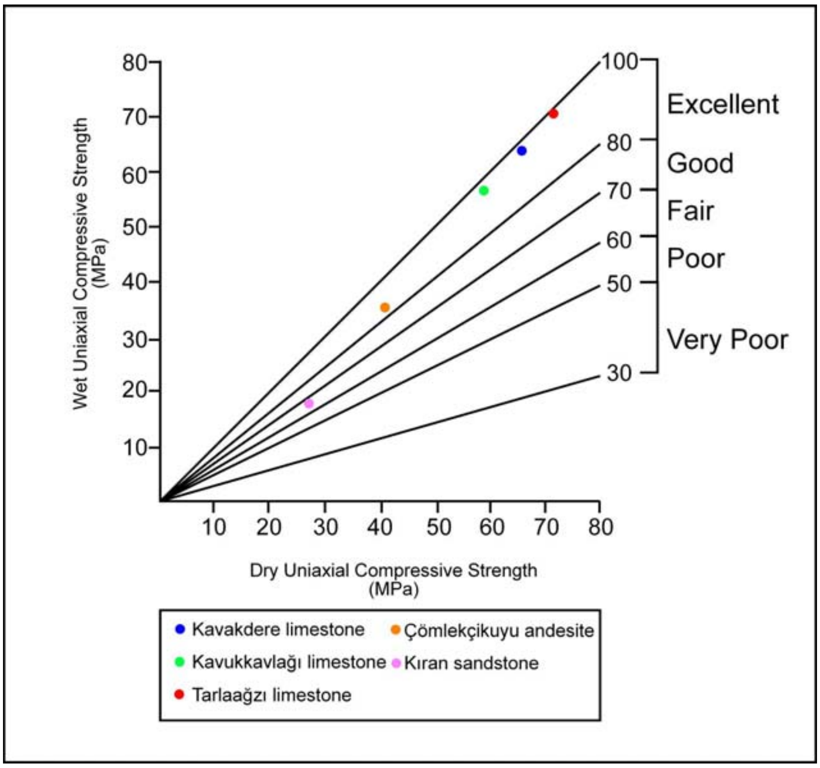


Figure 5.1 Durability evaluations of the samples based on the wet-to-dry strength ratio (after Winkler, 1986).

CHAPTER 6

GENERAL EVALUATION

The classification methods applied in the previous section showed that depending on different formulas and classification methods different results are obtained for the same sample. However, it is also observed that the limestone samples generally fall in the good range where the andesite is generally marginal and the sandstone is poor. The results of these classifications are summarized in Table 6.1.

Table 6.1 Durability assessment of the samples according to various classifications

Classification / Sample	CIRIA/ CUR*	Static Rock Durability index* (RDI_s)	Dynamic Rock Durability index* (RDI_d)	Rock Engineering Rating System* (RERS)	Average Pore Diameter*	Saturation Coefficient*	Wet-Dry Strength Ratio*
Kavakdere Limestone	VG-M	VG	G	G	P	G	VG
Kavukkavlağı Limestone	VG-M	VG	G	G-M	P	G	VG
Tarlaağzı Limestone	VG-M	VG	G	G	P	P	VG
Çömlekçikuyu Andesite	G-P	P	M	M	P	P	M
Kıran Sandstone	M-P	P	P	M	P	P	M

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

The CIRIA/CUR, RDI_d, RERS and Wet-Dry strength ratio classifications are generally in good agreement with the in-situ observations and results of the laboratory tests. However RDI_s, Average Pore Diameter and Saturation Coefficient classifications do not fully reflect the reality. This may be due to the narrow range of variables used in these classifications.

In Alaplı breakwater where the Kavakdere and Kavukkavlağı limestones are used, no deterioration of the samples is observed after two years (Figures 6.1 and 6.2). Although it is a good quality rock compared to the Kavakdere limestone, the Kavukkavlağı limestone is less favorable because it contains too many micro-cracks and frequently cut by secondary calcite veins. Although the infilling material does not create a considerable strength loss, during the laboratory experience some early failures of this sample were observed. Today, the Kavukkavlağı quarry is abandoned due to the completion of the breakwater, but this quarry and the Kavukkavlağı limestone are good sources for the future projects. However, one must be careful to separate highly fissured samples from the others, and more care has to be paid during the use of explosives.

Figure 6.1 A close up view of the Kavakdere limestone used in the Alaplı breakwater

Figure 6.2 A close up view of the Kavukkavlağı limestone used in the Alaplı breakwater

In Hisarönü breakwater where the Çömlekçikuyu andesite is used, some deterioration of the sample is observed after two years (Figures 6.3 and 6.4). Although it is a homogeneous igneous rock, the Çömlekçikuyu andesite has moderate strength and quality in most of the tests and qualifications. However, compared to the other quarries, the Çömlekçikuyu quarry is the most favorable quarry due to the columnar joints. The spacing of the joints at the lower levels is high and decrease towards the up. Thus, it has a wider block size range (at the lower levels) which is a desired property for the breakwater construction. In addition, the natural blocks created from the columnar joints and flow layering really enhance the construction time of the breakwater. As an overall source, the Çömlekçikuyu andesite might not have a long service life compared to the other samples, and may be weak against harsh climatic conditions. Using a source rock in Black Sea coast where dominant rain and storms are observed through out the year, is a question mark. Today, the Çömlekçikuyu quarry is abandoned due to the completion of the breakwater; in the future, this quarry and the Çömlekçikuyu andesite can be used for future projects where good quality armourstone is not required unless one must show great care selecting the least weathered samples from the quarry.

In Hisarönü coast where thick successions of the Kıran sandstone are deposited, considerable deterioration of the sample is observed (Figures 6.5 and 6.6). Although Kıran district is a favorable locality due to its closeness to the coast and favorable block size distribution, the Kıran sandstone is an extremely weak rock. Almost in every laboratory test, the least favorable results are obtained for the Kıran sandstone. Therefore, the Kıran sandstone must not be used in any coastal engineering structure. Both as a core material and armourstone, the use of this material may result in tremendous problems. The Kıran sandstone is a good example reflecting that one has to evaluate in-situ observations and laboratory tests together before deciding on a source. Like in the Kıran sandstone, sometimes the in-situ observations might reflect a favorable source where laboratory tests may be the reverse.

Figure 6.3 A close up view of the Çömlekçikuyu andesite in the Hisarönü breakwater

Figure 6.4 Andesite blocks containing cooling joints in Hisarönü breakwater

Figure 6.5 A view of the Kıran sandstone along the Hisarönü coast

Figure 6.6 Result of weathering in the Kıran sandstone

Finally, in the Tarlaağzı breakwater where the Tarlaağzı limestone is used, no deterioration of the sample is observed after two years (Figure 6.7 and 6.8). In general, the Tarlaağzı limestone is a strong and favorable rock suitable for the breakwater structures. However, in the Tarlaağzı quarry, some parts are highly jointed decreasing the overall strength of the rock. Today, the Tarlaağzı quarry is abandoned due to the completion of the breakwater, but this quarry and the Tarlaağzı limestone are good sources for the future projects. However, one must be careful to separate highly weathered samples from the others, and more care has to be paid during the use of explosives.

Figure 6.7 A close up view of the Tarlaağzı limestone used in the Tarlaağzı breakwater

Figure 6.8 Tarlaağzı limestone after two years of service

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

This study focuses on the durability of various rock types (the Kavakdere, the Kavukkavlağı and the Tarlaağzı limestones, the Çömlekçikuyu andesite and the Kıran sandstone) which are used or to be as armourstones in the Alaplı, the Hisarönü and the Tarlaağzı ship shelters.

Based on the observations and analyses, following conclusions are drawn;

1. The Kavakdere limestone is a limestone breccia consisting of angular to sub-angular limestone pebbles embedded in a calcareous matrix. The Kavukkavlağı limestone is pelsparite composed of highly abundant pellets and trace amount micro crystalline quartz with calcite veins. The Tarlaağzı limestone is biosparite composed of dominantly micro-fossil fragments. The Çömlekçikuyu andesite is a volcanic rock consisting mainly of plagioclase, clino-pyroxene and rarely amphibole phenocrysts with hypo-crystalline semi-porphyritic texture and micro-crystalline inter-granular matrix. The Kıran sandtone is a sandstone with coarse- to medium-sized volcanogenic sand grains.

2. Based on the laboratory test results, all limestones are found to be resistant to saturation. However, the andesite and sandstone are adversely affected from the saturation.

3. All of the quarries studied in this thesis yield block sizes suitable as armourstone.

4. The use of various durability classification methods (CIRIA/CUR, RDI_d, RERS, Wet-Dry strength ratio, RDI_s, Average Pore Diameter and Saturation Coefficient) reveal that the limestone samples generally fall in the good range whereas the andesite is generally marginal and the sandstone is in the poor range.

5. Field performances of the limestones showed that they are durable rocks. However, the andesite has marginal durability and the sandstone has poor durability.

6. The CIRIA/CUR, RDI_d, RERS and Wet-Dry strength ratio classifications are in good agreement with the in-situ observations and the results of the laboratory tests. However RDI_s, Average Pore Diameter and Saturation Coefficient classifications yield predictions different than the armourstone performances. Therefore, they need to be reevaluated with new data.

Based on the test results and the experience gained in this study the followings are recommended;

1. Systematic tests and field observations should be conducted on various rock types to outline their field performances. By this way with the known performances of other rock types all around the world, these tests and observations help engineers to suggest new durability evaluation methods which may better predict the long term stone durability.

2. The selection of armourstone in Turkey is based on only one criterion which the bulk density of the rock (2.2 gr/cm^3). This thesis study clearly showed that this kind of approach for selecting armourstone is not enough. Apart from density many other parameters such as resistance to abrasion, strength, durability, etc. should be considered. If not, one can come up with

a poor rock type for armourstone; therefore the armourstone selection criterion in Turkey should be revised and systematic testing and evaluation should be considered.

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