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Quality Assessment of the Armourstones for Some Black Sea Rubble Mound Breakwaters, Turkey

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ABSTRACT

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The Black Sea coastline is a hazardous region in Turkey, 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 of various sizes and types are used in the construction of these structures. The deterioration of these armourstones with time may result in the failure of the breakwater. In this study, the quality and durability of the armourstones (mainly limestone, andesite and sandstone) used or to be used in three rubble mound breakwaters are investigated through field and laboratory studies. Among the studied armourstones, the three limestones are found to be good in long-term quality and durability. However, the sandstone displays poor performance, whereas the andesite is marginal. Both static durability index and CIRIA/CUR evaluation successfully predict the long-term durability of the armourstones.

ADITIONAL INDEX WORDS: *Armourstone,Durability,Rubble mound breakwater, Quality*

INTRODUCTION

For many centuries the coast has been an area of importance for human development. It is attractive in terms of its flat, fertile land, as a base for transport by boat, and as a base for fishing (THOMAS, 1998). However, in order to benefit from the sources of the coast, protective coastal engineering structures such as breakwaters are needed. These structures involve large quantities of naturally quarried rock (armourstone) due to economic reasons and the demand to build environmentally-compatible and suitable structures. 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 applied to it; and the method by which it was extracted from the source and handled prior to its final placement. In time, depending on these properties and the influence of external forces, the armourstone can lose its quality (CLARK, 1988; CLARK and PALMER, 1991; LIENHART, 2003; ERTAS and TOPAL, 2006; LATHAM et al., 2006a, b). This situation directly affects the durability of the coastal structure and, in the long term, the region's economy.

Similarly in Turkey, harbours, breakwaters and ship shelters that are of great importance to navigation and fishing have generally been constructed from armourstone. This is especially so in the Black Sea region, where harsh climatic conditions with dominant wave influence are observed in winter, and these kinds of structures are at great risk. Alapli, Hisaronu and Tarlaagzi rubble mound breakwaters are good examples of such structures used as ship shelters. They are all located on the western Black Sea coast between the Zonguldak and Bartın, where a temperate climate with hot summers, cool winters, and dominant rainfall throughout the year is observed.

The purpose of this study is to investigate the quality and durability of the armourstones (mainly limestone, andesite and sandstone) used or to be used in three rubble mound breakwaters (Figure 1) through field observations and laboratory studies. In order to accomplish this task, physical and mechanical properties of the armourstones were determined. The quality evaluation by Rock Durability Index of FOOKES et al. (1988) and CIRIA/CUR (1991) is compared with the field performance of the armourstones used in the breakwaters.

METHODS

In this study, five armourstones to be used in three breakwaters were investigated. The field studies involved detailed discontinuity survey in the five quarries (namely Kavakdere, Kavukkavlagi, Cömlekcikuyu, Kıran and Tarlaagzi) to assess the volume and size of the stone blocks.

Forty block samples taken from the quarries were subjected to a set of chemical, physical and mechanical tests. In order to carry out the required tests, various cubic and crushed samples with sizes specified in the standards were prepared from the block samples. The tests were performed according to AFNOR (1980); ISRM (1981, 1985); TS699 (1987); CIRIA/CUR (1991); and TS EN1097-1 (2002) standards. The strength-related tests were performed in both dry and wet conditions, in order to consider in-service condition of the armourstones.

The determined properties of the stones included: effective porosity; unit weight; water absorption; uniaxial compressive strength; point load strength index; slake durability; methylene blue adsorption; wet-dry; freeze-thaw; Los Angeles abrasion; micro-deval value; magnesium and sodium soundness; impact resistance; modified impact value; 10% fines and crushing value of the stones. Additionally, mineralogical and petrographical properties of the samples were determined. The data obtained were interpreted in terms of quality and durability of the stones, and compared with their actual field performances.

ANALYSIS AND RESULTS

In the Kavakdere quarry, the rock is grey-pink and beige limestone, 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.

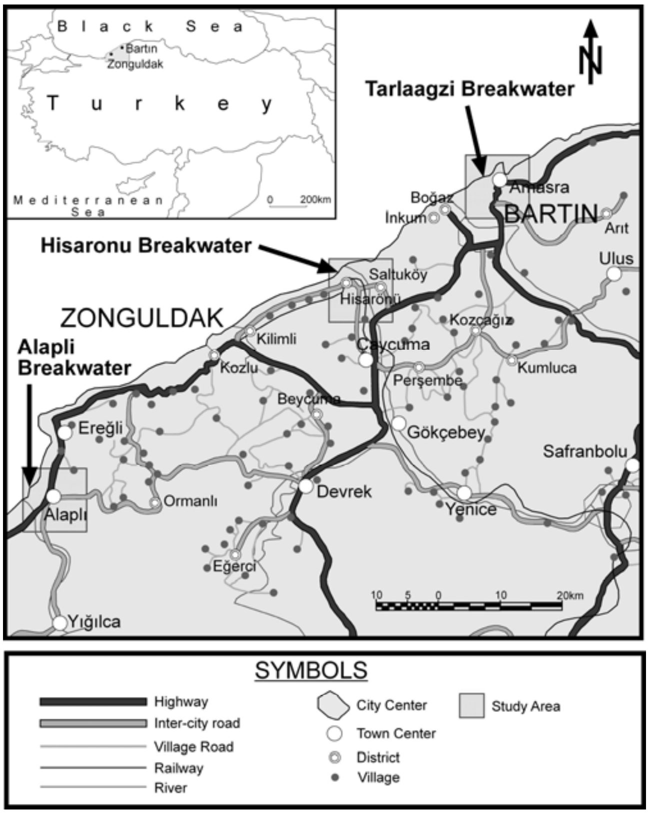

Figure 1. Location map of the study area

The rock is slightly weathered with discoloration along the discontinuities. In the Kavukkavlagi quarry, the rock is dark grey-black limestone, composed of fine clastics. 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. In the Cömlekcikuyu quarry, the rock is grey coloured andesite with white coloured well-grown feldspar minerals (as phenocrysts) distributed randomly inside the rock. 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. In the Kıran quarry, the rock is light brown to grey sandstone composed of coarse to medium-sized sand grains, with no micro-cracks are observed inside the fresh samples. The rock is slightly weathered. Finally, in the Tarlaagzi quarry, the rock is grey-beige homogenous limestone. Secondary micro-cracks filled with calcite minerals are also observed inside the fresh samples. The rock is slightly weathered.

The quality evaluation of the armourstones is firstly done with the Rock Durability Index suggested by FOOKES et al. (1988). The method can be applied to 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 the armour layer. Unlike the CIRIA/CUR (1991) classification, in rock durability index various laboratory test results are used in empirical formulas for a generalised qualitative classification. The static rock durability indicator RDI_s is expressed by the following formula (FOOKES et al., 1988):

$$RDI_s = Is_{(50)} - 0.1(SST + 5\,W_{ab})\rho_{ssd} \qquad (1)$$

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 rock is classified as excellent, good, marginal or poor on the basis of RDI_s. A tentative estimation of the potential durability of rocks based on the static rock quality index is given in Table 1.

Based on the static rock durability classification (Table 1) and the calculated RDI_s values, Kavakdere, Kavukkavlagi and Tarlaagzi limestone are classified as excellent. However, Cömlekcikuyu andesite is marginal, while Kıran sandstone is classified as poor. The corresponding RDI_S results of the samples are given in Table 2.

Table 1: 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

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

$$RDI_d = 0.1\,(MAIV + 5W_{ab}) / (\rho_{ssd}) \qquad (2)$$

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 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 3.

Table 2: Quality evaluation of the samples according to RDI_s values

Sample Name	$Is_{(50)}$-MPa	SST(%)	W_{ab} (%)	ρ_{ssd} (t/m^3)	RDI_s value	Durability Class
Kavakdere	5.65	0.08	0.10	2.75	5.49	Excellent
Kavukkavlağı	4.38	0.11	0.20	2.70	4.08	Excellent
Tarlaağzı	6.07	0.33	0.82	2.67	4.89	Excellent
Çömlekçikuyu	4.05	11.64	2.70	2.42	-2.03	Marginal
Kıran	1.02	25.12	7.54	2.36	-13,81	Poor

Table 3: Tentative estimation of dynamic rock durability (FOOKES et al., 1998)

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

Table 4: Quality evaluation of the samples according to RDI_d values

Sample Name	MAIV(%)	W_{ab} (%)	ρ_{ssd} (t/m^3)	RDI_d value	Durability Class
Kavakdere limestone	14.78	0.10	2.75	0.56	Good
Kavukkavlağı limestone	14.72	0.20	2.70	0.58	Good
Tarlaağzı limestone	12.61	0.82	2.67	0.63	Good
Çömlekçikuyu andesite	18.52	2.70	2.42	1.32	Good
Kıran sandstone	66.42	7.54	2.36	4.41	Poor

Based on the dynamic rock durability classification (Table 3) and the calculated RDI_s values Kavakdere, Kavukkavlagi and Tarlaagzi limestone are classified as good, but are almost at the excellent range; on the other hand, Cömlekcikuyu andesite is classified as good, and Kıran sandstone is classified as poor. The corresponding RDI_S results of the samples are also given in Table 4.

Another most commonly-used classification is CIRIA/CUR (1991). The CIRIA/CUR (1991) classification is a simple classification system for the general evaluation of laboratory and field data. It considers rock density (p_r), water absorption (W_{ab}); magnesium sulphate soundness (MSS); freeze/thaw (FT); methylene blue absorption (MBA); fracture toughness (K_{IC}); point load 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 armourstones is given in Table 5. According to the classification, the Kavakdere limestone is excellent-marginal in quality. Similarly, values of Kavukkavlagi limestone and Tarlaagzi limestone fall into the range of excellent-marginal. On the other hand, values for Cömlekcikuyu andesite ranges between good and poor, and for Kıran sandstone, they vary between marginal and poor.

DISCUSSION

The two rock durability and quality evaluation techniques used in this study yield generally consistent results, although some differences exist. The field (in-service) performances of the stones are shown in Figure 2. The three limestones are good in quality, with no deterioration in terms of their integrity and shape of the blocks being observed after two years of service in the breakwaters. The andesite is good to marginal. Local spalling (1-2 mm thick) of the andesite blocks at the outer surface of the stones is observed after two years of service. However, the sandstone is poor. The natural exposure of the sandstone at the coast is severely deteriorated in the form of material loss, with cavity formation due to the coastal processes.

In general, both the static rock durability index of FOOKES et al. (1988) and CIRIA/CUR (1991) methods successfully predict

the long-term durability of the armourstones. On the other hand, the andesite has marginal durability in the field, although it is estimated to be good by the dynamic durability index. The other predictions of the RDI_d are found to be appropriate. Using recent data regarding field and laboratory performances of the armourstones, the authors of this paper suggest that the RDI_d needs improvement.

Based on the laboratory and field performances of the five rock types, the sandstone should not be used in the breakwater as armourstone, and the andesite is expected to have some material losses. However, the limestones will perform well.

CONCLUSION

In this study, the quality and durability of the armourstones (mainly limestone, andesite and sandstone) to be used in three rubble mound breakwaters were investigated through field and laboratory studies. The outcomes of the study reveal that the prediction of the armourstone durabilities by the static durability index and CIRIA/CUR is in good agreement with their in-service performance, whereas a discrepancy exists between the armourstone durabilities predicted by the dynamic durability index and the in-service performance of the stones. The limestones yield good performance, but the andesite is marginal. However, the sandstone displays poor quality and durability, and therefore should not be used in breakwaters as armourstone.

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Figure 2. Field performances of (a) Kavakdere and Kavukkavlagi limestones in Alapli rubble mound breakwater; (b) the Cömlekcikuyu andesite in Hisaronu rubble mound breakwater; (c) the limestone in Tarlaagzi rubble mound breakwater; (d) the Kıran sandstone at the coast to be used as potential armourstone

Table 5: Quality evaluation of the armourstones by CIRIA/CUR (1991)

Properties	CIRIA/CUR CRITERIA				Kavakdere limestone	Kavukkavlagi limestone	Tarlaagzi limestone	Cömlekcikuyu andesite	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	2.74	2.69	2.65	2.35	2.20
Water absorption – W_{ab} (%)	≤0.5	0.5-2.0	2.0-6.0	≥6.0	0.10	0.20	0.82	2.70	7.54
Magnesium sulphate soundness – MSS (%)	≤2	2-12	12-30	≥30	0.08	0.11	0.33	11.64	25.12
Freeze-Thaw – FT (%)	≤0.1	0.1-0.5	0.5-2.0	≥2.0	0.11	0.04	0.23	8.65	15.74
Methylene blue absorption – MBA (g/100g)	≤0.4	0.4-0.7	0.7-1.0	≥1.0	0.53	0.27	0.27	2.93	2.80
Fracture toughness – K_{IC}^* ($MPa.m^{1/2}$)	≥2.2	1.4-2.2	0.8-1.4	≤0.8	1.23	1.02	1.32	0.99	0.46
Point load strength index –** $I_{S(50)}$ (MPa)	≥8.0	4.0-8.0	1.5-4.0	≤1.5	5.45	4.15	6.00	3.96	0.74
Wet dynamic crushing value – WDCV (%)	≤12.0	12-20	20-30	≥30	23.98	22.72	20.19	25.26	32.28
Mill abrasion resistance – k_s (%)***	≤0.002	0.002-0.004	0.004-0.015	≥0.015	0.0065	0.0055	0.0043	0.013	0.262
Block integrity drop test – I_d (%)	≤2	2-5	5-15	≥15	2-5	2-5	2-5	2-5	5-15

*estimated from the point load strength index
**saturated value
***estimated from micro-deval abrasion test performed in accordance with TS EN1097-1 (2002)