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The impact of cyclic loads on physicommechanical properties of the massive and vesicular basalts

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Abstract. Stone monuments are the most visible and essential structures of our cultural heritage; however, many of the historical structures around the world are now suffering from stone deterioration. Diyarbakır City Walls, which were acknowledged the status of World Heritage Site by UNESCO, are among the most extensive surviving structures from ancient times. The City Walls have also some deterioration related problems. Basalts having such different textural properties as massive and vesicular were employed as the principal material in the construction of the Diyarbakır City Walls. Weathering is strongly related to the climatic and environmental conditions of the site. In order to evaluate the physical deterioration, environmental conditions were artificially simulated in accelerated weathering tests such as wetting-drying, freezing-thawing, and salt crystallization. For this purpose, 180 massive and vesicular basalt samples were prepared. The effects of these tests were evaluated by visual examination, weight loss, effective porosity, dry and saturated unit weights, water absorptions under atmospheric and vacuum pressure, sonic velocity and uniaxial compressive strength. It is found that the salt crystallization is the most effective accelerated weathering test deteriorating the basalt samples most aggressively.

1. Introduction

Stone has been valued as a building material especially, for its long-term performance. Today, for instance, numerous historical structures spread across the world are still standing thanks to the durability of stone. Considering the monuments erected by different civilizations in different regions, one can go so far as to claim that “the history of civilization has been captured in stone” [1].

Contrary to common sense, stone has a limited service life. Like other construction materials, stone is also affected by weathering in the course of time. All naturally occurring materials on the earth's surface are subject to destructive weathering processes, whether in their natural settings or in construction. Weathering is commonly slow, continuous and destructive process that changes the characteristic properties of stone. The weathering of stone may result in the loss of integrity, aesthetic value and structural stability of the historical structures. Even a small amount of surface weathering may deteriorate priceless pieces of monuments [2–4].



From a geological point of view, the nature of stone deterioration is associated with intrinsic factors (mineralogical, chemical or structural characteristic) and extrinsic ones (environmental conditions, weathering agents or interventions). Moreover, rates of deterioration can change in response to changes in environmental conditions or interventions. For instance, extensive exposure of the stone to weathering episodes (e.g., freezing and thawing; wetting and drying) or inappropriate repair techniques can accelerate the process of stone deterioration [5].

The Diyarbakır City Walls (DCW), is a World Heritage Site located in the southeast of Turkey. The City Walls are among the most gigantic and surviving structures from ancient times. The history of the DCW stretches back more than four thousand years, therefore making the extant City Walls a combination and reflection of influences of the various civilizations that settled in the region [6]. The reflections of these civilizations can be identified in the City Walls' architectural elements, construction techniques and material applications (Figure 1).



Figure 1. Aerial view of the DCW (captured from Google Earth)

Basalt is the main construction material of the City Walls. It has been employed in almost all of their architectural elements (Figure 2). Like many other historical structures, the DCW are also suffering from stone deterioration. Different deterioration forms, including, cracks, detachments, erosions, efflorescences, material losses and biological colonization can be seen in different sections of the City Walls (Figure 3). This deterioration of the City Walls damages not only their integrity; but also, aesthetic value and structural stability.



Figure 2. Basalt applications on Diyarbakır City Walls

This study aims to understand how the cyclic loads impact the basalt with which the DCW were constructed. To accomplish this, fresh (massive and vesicular) basalts samples were collected from different sections of the study area. In order to determine their durability, environmental conditions were artificially simulated in accelerated weathering tests.

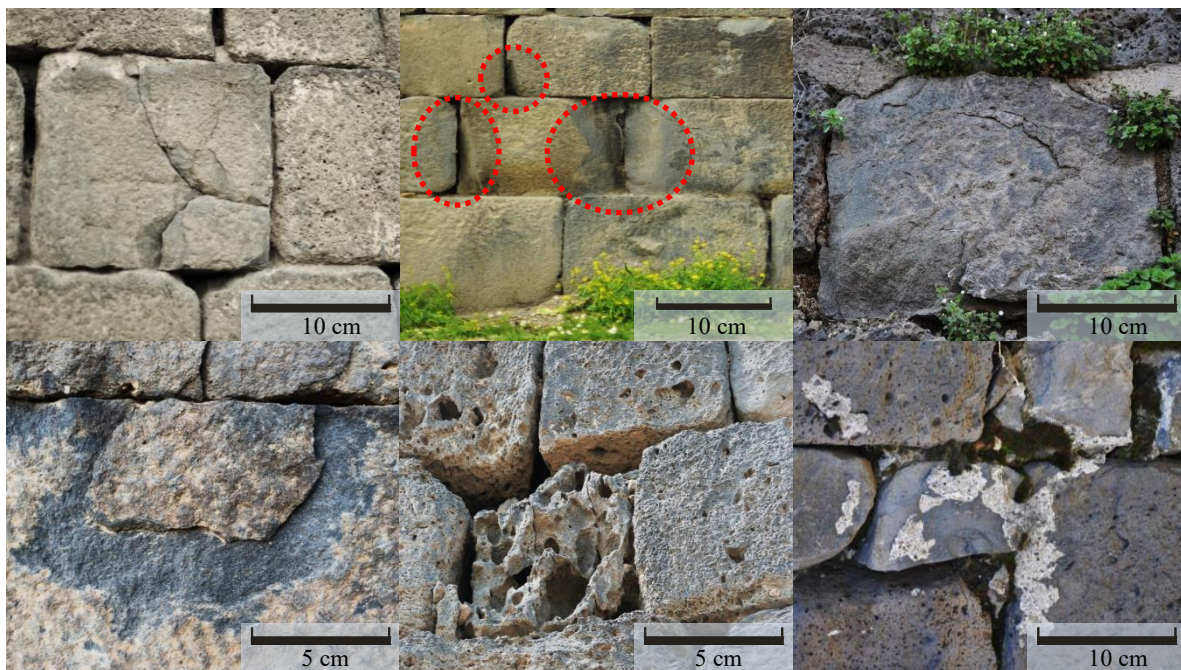


Figure 3. Some of the deterioration forms observed on the DCW (clockwise: crack networks, chipping, flaking, lichens, erosion, scaling)

2. Material and Methods

Based on the field and previous studies, it can be understood that the basalts beneath the DCW are derived from the lava eruptions of Karacadağ Volcano and are classified as Karacadağ volcanics. Basalts with different types of textures were commonly used in the construction of the DCW. In order to evaluate the impact of the cyclic loads, basalt blocks were collected from several locations, mostly from the outcrops along the DCW and from the quarries in their vicinity. The samples were then prepared for the laboratory studies in different sizes specified by the international suggestions and standards [7,8].

Selecting the most suitable accelerated weathering tests is based on the climatic and environmental conditions of the study area. The severe continental climate conditions of Southeast Anatolia dominate the province of Diyarbakır. Based on the environmental characteristics of the site where the stone is exposed and field observation, wetting-drying, freezing-thawing and salt crystallization tests were performed in this study to assess the durability of the massive and vesicular basalts. The wetting-drying test was conducted on two sets of 30 massive and 30 vesicular basalt samples by following the procedure described in ASTM standard [12]. The material properties of the massive and vesicular basalt samples were evaluated after 10, 30, 50, 60, 70 and 80 test cycles. The freezing-thawing test was conducted on two sets of 30 massive and 30 vesicular basalt samples by following the procedure described in ASTM standard [11]. The material properties of these samples were evaluated after 10, 20, 70, 80, 90 and 100 test cycles. The salt crystallization test was conducted using magnesium sulfate (epsomite: $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$) by following the procedure described in related standard [9]. The salt crystallization test was performed using two sets of 30 massive and 30 vesicular basalt samples. The material properties of these samples were evaluated after 10, 20, 30, 40 and 50 test cycles. A total of 180 (90 massive and 90 vesicular) cubic basalt samples with 7 centimeter edge lengths were used to evaluate the impact of accelerated weathering tests on massive and vesicular basalts. The samples were examined visually, then such properties of the samples as the weight loss, effective porosity, dry and saturated unit weights, water absorption, the sonic velocity and the uniaxial compressive strength of the samples were measured at different test cycles and compared with those of the fresh samples. The durability tests and physico-mechanical properties of the samples were performed and determined by following the recommendations and standards [9–12].

3. Results and Discussion

3.1. Wetting-Drying Cycles

The average values of the material properties of the massive and vesicular basalt samples are shown in Table 1. At the end of 80 wetting-drying tests, no specific change in weight is observed for the questioned samples (Table 1). The measured total weight losses of the massive and vesicular basalt samples are 0.7% and 0.9%, respectively. The effective porosity of the massive and vesicular basalt samples, on the other hand, increases by 30.2% and 37.7%, respectively. There are slight changes in the dry unit weight of the samples. The reduction in the dry unit weight of the massive and vesicular basalt samples is almost equal at 2.7% and 2.9%, respectively, at the end of 80 wetting-drying cycles. The water absorption under the atmospheric pressure of the massive and vesicular basalt samples is increased by 37.7% and 44.9%, respectively. The sonic velocity of the dry massive and vesicular samples decreases by 6.3% and 16.7%, respectively, at the end of 80 wetting-drying cycles; and finally, the uniaxial compressive strengths (UCS) of the massive and vesicular basalt samples are reduced by 24.9% and 31.3%, respectively.

Table 1 Average material properties of the massive and vesicular basalts after the wetting-drying cycles (M: Massive; V: Vesicular Basalt samples)

Cycles	Weight		Effective Porosity		Dry Unit Weight		Water Abs. by Weight (atm. press.)		Dry Sonic Velocity		UCS	
	(g)		(%)		(kN/m ³)		(%)		(m/s)		(MPa)	
	M	V	M	V	M	V	M	V	M	V	M	V
0	860.9	847.6	4.1	9.9	27.5	24.5	1.0	2.1	4911.1	3931.1	145.4	63.3
10	860.1	846.8	4.1	10.1	27.5	24.3	1.0	2.1	4904.5	3893.5	139.	58.9
30	858.4	845.6	4.2	10.8	27.4	24.2	1.1	2.2	4882.8	3642.4	135.6	55.6
50	857.4	843.7	4.5	11.8	27.4	24.2	1.2	2.4	4778.1	3440.3	129.5	52.8
60	856.7	841.9	5.0	12.2	27.1	23.8	1.2	2.6	4697.2	3352.2	121.9	49.7
70	855.5	840.3	5.2	12.9	26.9	23.8	1.3	2.8	4603.3	3332.0	115.7	45.9
80	854.7	839.2	5.3	13.6	26.8	23.7	1.4	3.1	4597.4	3274.0	109.1	43.4

3.2. Freezing-Thawing Cycles

The average values of the material properties of the massive and vesicular basalt samples are shown in Table 2. At the end of 100 freezing-thawing cycles, no remarkable change in weight is observed (0.7%) for the questioned massive basalt samples (Table 2). However, the loss in weight for the vesicular samples is relatively higher (3.0%). The effective porosity of the massive and vesicular basalt samples is considerably increased at the end of the freezing-thawing cycles (38.5% for the massive and 49.5% for the vesicular samples). The variations in the dry unit weight are minor for all samples (2.2% for the massive and 3.0% for the vesicular samples). The increases in water absorption under the atmospheric pressure for massive and vesicular basalt samples are measured as 40.4% and 48.4%, respectively at the end of the 100 freezing-thawing cycles. The sonic velocity of the dry sample decreases as the number of test cycles increases. The reduction of the sonic velocity for vesicular basalt samples is higher than the massive basalt samples (7.5% for the massive and % 16.8% for the vesicular samples). The UCS of the samples is also significantly reduced at the end of 100 freezing-thawing cycles. The reduction of the compressive strength is measured for the massive and the vesicular basalt samples as 36.0% and 37.4%, respectively (Table 2).

Table 2 Average material properties of the massive and vesicular basalts after the freezing-thawing cycles (M: Massive; V: Vesicular Basalt samples)

Cycles	Weight		Effective Porosity		Dry Unit Weight		Water Abs. by Weight (atm. press.)		Dry Sonic Velocity		UCS	
	(g)		(%)		(kN/m ³)		(%)		(m/s)		(MPa)	
	M	V	M	V	M	V	M	V	M	V	M	V
0	860.9	847.1	5.3	9.8	27.0	24.7	1.0	2.1	4446.9	4095.5	145.4	63.3
10	860.1	845.1	5.7	10.2	26.9	24.6	1.0	2.4	4438.4	3979.4	128.7	59.1
20	858.4	842.9	6.2	11.4	26.7	24.3	1.1	2.6	4338.2	3886.5	124.7	56.0
70	857.4	838.4	6.3	12.3	26.6	24.2	1.2	2.7	4317.2	3632.7	110.4	46.1
80	856.7	828.7	6.4	12.3	26.6	24.1	1.3	2.8	4285.3	3580.5	103.8	43.6
90	855.5	823.9	6.7	13.8	26.4	24.0	1.3	3.0	4184.9	3473.7	98.3	41.0
100	854.7	821.2	7.3	14.6	26.4	23.9	1.4	3.1	4113.5	3406.0	93.0	39.6

3.3. Salt Crystallization Test

The average values of the material properties of the massive and vesicular basalt samples are shown in Table 3. At the end of 50 salt crystallization cycles, total weight losses for the massive and vesicular basalt samples are measured as 2.2% and 1.1%, respectively (Table 3). The effective porosity of the massive and vesicular basalt samples is considerably increased by the salt crystallization cycles. The effective porosity of the massive and vesicular basalt samples increases by 39.8% and 61.2%, respectively, at the end of 50 salt crystallization cycles. The reduction in the dry unit weight of the massive and vesicular basalt samples is measured as 2.9% and 1.7%, respectively. The water absorption capacity of the samples under the atmospheric pressure increases progressively throughout the salt crystallization cycles (49.3% for the massive and 64.3% for the vesicular samples). At the end of the 50 cycles, the sonic velocities of the dry massive samples decrease by 4.9%. On the other hand, the sonic velocities of the dry vesicular samples increased by 13.0%. Finally, the UCS of the samples are significantly reduced at the end of salt crystallization cycles (40.9% for the massive and 41.8% for the vesicular samples)

It is understood from the results of cyclic tests that the wetting-drying cycles result in no significant changes in the weight loss and dry unit weight of the massive and vesicular basalt samples. However, the cycles affect parameters such as porosity, water absorption, sonic velocity and uniaxial compressive strength. The porosity and water absorption of the samples increase greatly, whereas the sonic velocity and uniaxial compressive strength decrease throughout the cycles. In general, wetting-drying has an impact on both the massive and vesicular samples. Nevertheless, the massive basalt samples are more resistant to this test than the vesicular basalt samples.

Table 3 Average material properties of the massive and vesicular basalts after the salt crystallization cycles (M: Massive; V: Vesicular)

Cycles	Weight		Effective Porosity		Dry Unit Weight		Water Abs. by Weight (atm. press.)		Dry Sonic Velocity		UCS	
	(g)	(g)	(%)	(%)	(kN/m ³)	(kN/m ³)	(%)	(%)	(m/s)	(m/s)	(MPa)	(MPa)
	M	V	M	V	M	V	M	V	M	V	M	V
0	969.1	861.1	4.4	7.5	27.3	25.0	0.8	1.3	4767.0	4393.4	145.4	63.3
10	961.6	858.5	5.1	10.0	26.8	24.8	0.9	1.5	4690.6	4580.6	127.0	54.0
20	958.9	855.5	5.3	10.8	26.7	24.7	1.0	1.7	4624.3	4650.6	116.2	47.8
30	957.5	854.0	5.9	11.2	26.6	24.6	1.1	1.8	4587.0	4731.9	101.0	42.5
40	953.5	852.7	6.1	11.4	26.5	24.6	1.1	2.0	4564.7	4869.3	95.0	39.0
50	947.3	851.4	6.2	12.1	26.5	24.6	1.2	2.2	4530.6	4966.0	85.9	36.8

The results show that as the freezing-thawing test cycles increase the effective porosity and water absorption of the samples increase, and their sonic velocity and uniaxial compressive strength decrease. The change in the physico-mechanical properties of the vesicular basalt samples is greater than that of the massive basalt samples. In general, freezing-thawing has a more pronounced effect on the vesicular basalt samples, and the massive basalt samples have relatively better resistance to freezing and thawing.

Finally, the salt crystallization test has a more pronounced effect on the physical appearance of the massive and vesicular basalt samples. As the salt crystallization cycles increase so does their effective porosity and water absorption capacity. The sonic velocity of the massive samples decreases, but it increases in the vesicular samples. This increase may be attributed to incomplete removal of salt from the micropores of the vesicular samples. At the end of the test, it is observed that the uniaxial compressive strengths of both massive and vesicular samples are significantly reduced.

4. Conclusions

In this study, it is aimed to evaluate the impact of cyclic loads on index properties of building material. For that purpose, the principal construction material of a UNESCO World Heritage Site was selected. Basalts having different textural properties (massive and vesicular) were employed as the main material in the construction of the Diyarbakir City Walls. In order to evaluate the physical deterioration and durability of the fresh massive and vesicular basalts, environmental conditions were artificially simulated in accelerated weathering tests such as wetting-drying, freezing-thawing and salt crystallization. The effects of these tests were evaluated by visual examination, weight loss, effective porosity, dry and saturated unit weights, water absorptions under pressure, sonic velocity and uniaxial compressive strength. The durability tests have more or less effect on the physico-mechanical properties of the basalts. Of these parameters, unit weight is the least affected by the durability tests. The porosity, water absorption and UCS are the parameters most affected by the durability tests. Although sonic velocity shows some different trends, it tends to fall throughout the durability tests. Since the samples tested after the durability tests reveal different sonic velocities, such variations in the sonic velocity can be attributed to the basalts' heterogeneity due to different formation mechanisms.

These findings indicate that, except unit weight, all the other physico-mechanical properties are useful for assessing the deterioration of the massive and vesicular basalts. Nevertheless, since UCS and

sonic velocity are better indicators of internal damage to rock material, future studies of basalt should use these parameters. It can be concluded from the results that salt crystallization is the accelerated weathering test that most aggressively affected both the massive and vesicular basalt samples. It is observed that freezing- thawing has also a potential to deteriorate the basalts. Wetting-drying, on the other hand, has minor effect on the deterioration of the massive and vesicular basalts.

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