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ORIGINAL ARTICLE

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Deterioration of the volcanic kerb and pavement stones in a humid environment in the city centre of Izmir, Turkey

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Abstract İzmir is the third largest city in Turkey and has being the centre of art, culture, tourism and trade activities throughout the 5,000 years of its history. Natural stones brought from different parts of the world have been widely used for construction of the prestigious buildings, monuments and roads etc., in the past in the city. Renovation of the street pavements and public gathering areas in the city centre has been undertaken by the Metropolitan Municipality in 2000 and continued through the year of 2001. These renovation activities have mainly been carried out in the streets running parallel to the sea shore. Volcanic rocks brought from the Central Anatolia Ankara-Gölbası (andesites) and Kayseri-İncesu (tuffs) have been used in the renovation works. These rocks have shown extensive deteriorations within 4 years of their usage between 2001 and 2005 under the influence of different environmental factors. In this study, the deteriorations developed in the recently placed volcanic rocks used as kerb and pavement stones in the city centre of İzmir in the light of their mineralogical, chemical, physical and mechanical properties, used locations and the environmental factors are presented.

Keywords Andesite · Tuff · Ignimbrite · Deterioration · Kerb and pavement stones · Environmental factors

Introduction

İzmir is the third largest metropolitan city located on the western coast of Turkey (Fig. 1) with 3.5 million population and has been well known as a centre for art, culture, tourism and trade activities throughout the 5,000 years of its history (Akurgal 1993). The present most popular entertainment, trade and cultural activity areas are located along the streets running in north south directions parallel to the sea shore between the Alsancak and Konak districts in the city centre (Fig. 1). This part of the city is very heavily used by people every day. The Metropolitan Municipality has renovated the pavements and the public gathering areas by using the Ankara andesites (Gölbası) and Kayseri tuffs (İncesu) from central Turkey in 2000 and 2001 as part of the renovation of the infrastructure in the city (Fig. 1).

The volcanic rocks were used as kerb and pavement stones in the renovation works. While the kerb stones were mainly of 10×20×50 cm sized prism, the pavement stones were of 30×30×7 and 5×10×7 cm sized plates (Table 1, Fig. 2). These stones were mainly placed over 30–50 mm thick sand layer in order to obtain flat surfaces in the streets (Fig. 2).

There has been noticeable degradation in these volcanic rocks with varying degrees, developed within 4 years of their emplacement. The factors causing deterioration of these volcanic rocks within the İzmir city centre is investigated by considering the environmental factors such as temperature, sea water salinity and rain water acidity as well their material properties.

In the first stage of the investigation, detailed field observations are made of the kerb and pavement stones to determine the degradation types and zones occurred

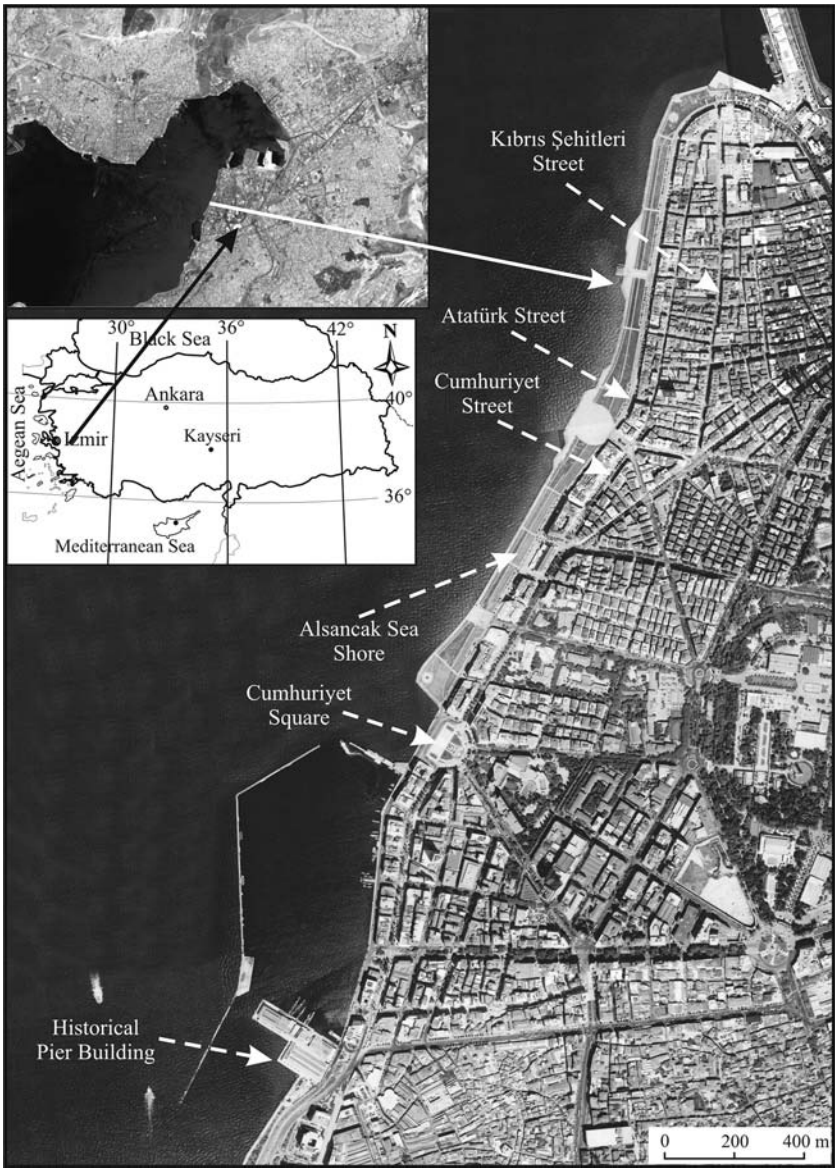

Fig. 1 The areas where volcanic rocks are used as kerb and pavement stones in the city centre of İzmir Turkey

on the volcanic kerb and pavement stones over the last 4 years.

In the second stage of the study, the material properties of the degraded stone samples obtained from the street pavements and the fresh unused stone samples obtained from the warehouses of the Metropolitan Municipality of İzmir were determined for comparison. As part of this study, mineralogy of the rock samples were determined from the petrographic thin sections, XRD diffraction of the samples were obtained at the İzmir High Technology Institute, Material Research Centre, chemical analysis were made at the ACME Analytical Laboratories LTD., in Canada, pore size determination of the rock samples were made by mercury porosimeter (Pore master 6) at the Department of Material Sciences and Engineering University Anadolu, Faculty of Engineering and Architecture and the physico-mechanical tests were made at the Torbalı Vocational School of Higher Education of the Dokuz Eylül University (DEU).

Freezing and thawing tests were carried out using the fresh and sea water on fresh stone samples according to the Turkish Standards (TS 699 1987), the $NaSO_4$ salt crystallization test according to RILEM (1980) and the wetting and drying test according to ASTM (1992a) to assess the weatherability of these volcanic rocks. The material loss ratios of the volcanic rocks were determined after the tests.

Additionally, the meteorological data obtained from the State Meteorological Departments Poligon Branch

Table 1 The locations, sizes and the usage types of volcanic rocks

Rock type	Usage locations[a]	Usage types	Dimensions (cm)
Grey andesite	Atatürk street, Alsancak Sea Shore	Pavement stone	30×30×7
	Cumhuriyet street, Kıbrıs Sehitleri street	Kerb stone	10×50×20
Red andesite	Atatürk street, Alsancak Sea Shore	Pavement stone	30×30×7
	Cumhuriyet street, Kıbrıs Sehitleri street	Kerb stone	10×50×20
Red tuff	Cumhuriyet street (Cumhuriyet Square-Historical Pier Building)	Pavement stone	30×30×7
Dark tuff	Kıbrıs Sehitleri street	Pavement stone	30×30×7–5×10×7

[a]See Fig. 1 for locations

at İzmir for the last 5 years and the sea water salinity data of the İzmir bay obtained from the DEU Marine Science Institute of İzmir for the years 1994–2004 were included in order to assess the influence of environmental factors on the degradation of andesites and tuffs when they were used as the kerb and pavement stones.

Field observations

Volcanic rocks brought from the Central Turkey to İzmir have been used for the renovation of the streets and the public gathering areas in the Metropolitan City of İzmir in 2000–2001. Grey and red andesites from Ankara (Gölpazarı) and red and dark tuffs from Kayseri (İncesu) were used for replacement of the old kerb and pavement stones in the city centre. These rocks were subjected to continental climate having wet and cold weather in winters and hot and dry weather in summers. The decoration of the streets and public gathering areas by these different coloured rocks have given attractive appearance to the streets at first. But, these rocks are noticed to have undergone rapid discolouration and deterioration within a short time of their emplacement.

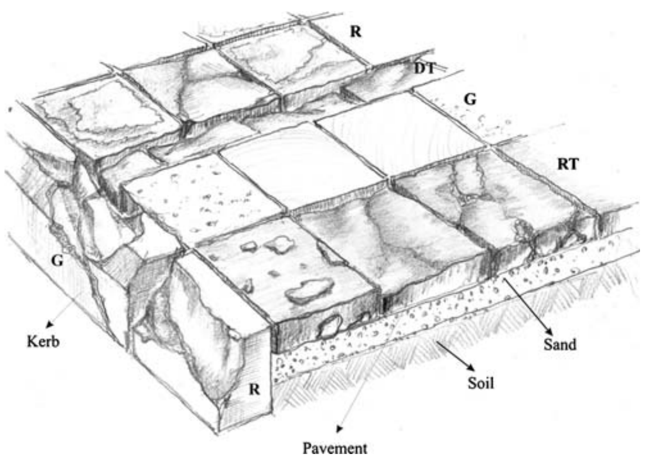

Fig. 2 Schematic presentation of the kerb and pavement stones in use, in the streets of İzmir (*G* grey andesite, *R* red andesite, *RT* red tuff, *DT* dark tuff)

The degradation rate has been noticed to be varying with their place of use and the rock types (Fig. 2).

The deterioration was extensive especially in the rocks placed by the sea and in the areas where they were subjected constant wetting and drying and where there are heavy pedestrian traffic (Figs. 3, 4). Grey and red andesites and red and dark tuffs are used in the Atatürk street, a large part of the Alsancak sea shore and the Cumhuriyet street, the Kıbrıs Sehitleri street and the roads running vertical to these streets as the kerb and pavement stones (Fig. 1).

Andesites

Grey and red andesites have undergone deterioration such as breaking up of the kerb stones and pavement stones as well as wearing of plate surfaces within 4 years of their emplacement in the streets near to the sea shore (Fig. 3). However there were little deteriorations observed in the grey andesite placed in the areas about 10 m away from the sea shore. Even the saw cut traces are still present in the grey andesite plates in the areas where they were placed 10 m away from the sea shore (Fig. 3a, b).

Initially, the spheroidal weathering is developed in grey and red andesite plates followed by wearing of the plate surfaces in the areas where they are constantly under the influence of the sea water salinity and moisture within 7.0 m of the sea shore (Fig. 3b, c). Away from this zone, the degree of deterioration decreases gradually and the influence of deterioration is minimum about 10 m away from the sea shore (Fig. 3a, b). The spherical type weathering starts from the edges of the andesite plates and advances towards their centres (Fig. 3d). Such weathering occur within the 1–5 cm distance from the plates edges in grey andesites and there has not been any complete degradations of the whole plate surface noticed within 4 years of their use (Fig. 3d). However the spherical weathering is followed by the wearing of the whole plate surface in red andesites within the 7.0 m of the sea shore. The surfaces of the red andesite plates are generally covered with a thin layer of residual soil due to deterioration (Fig. 3c). There are up to 1–15 mm thick material loss is recorded in the red andesite plates placed near the sea shore (Fig. 3e).

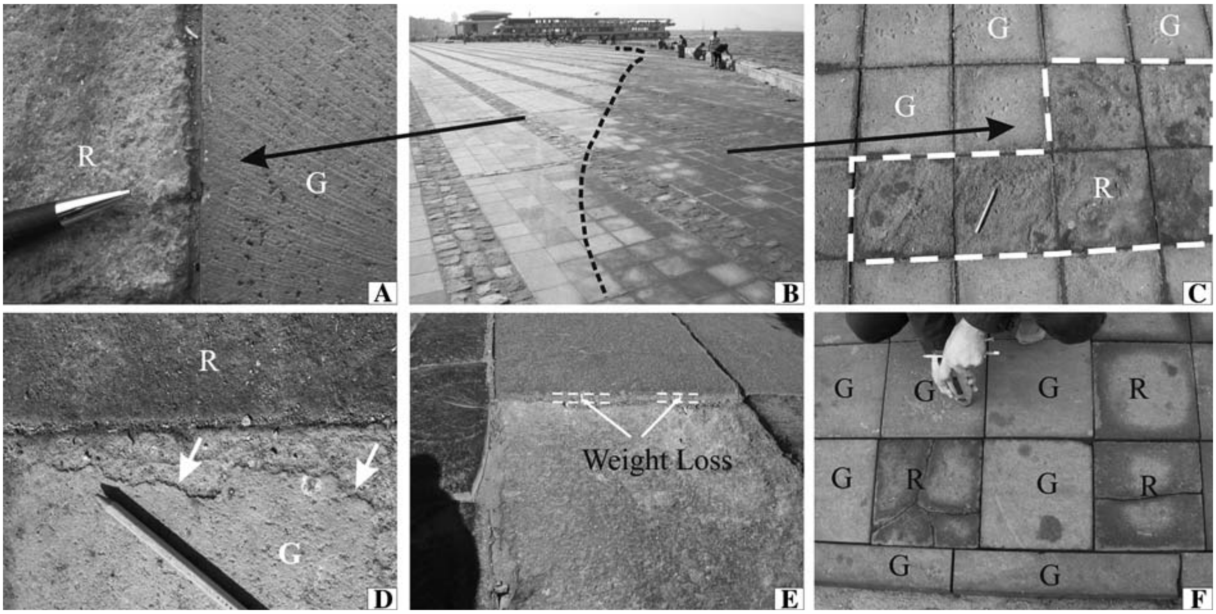

Fig. 3 Deterioration developed in grey and red andesite plates placed near the sea shore (*G* grey andesite, *R* red andesite)

The red andesite plates are noticed remaining moisted longer than the grey andesite plates as shown in Fig. 3f where the surfaces of grey andesites are dry, but the surfaces of the red andesites are still moist in the same area. As a result, fracturing and breaking up of the stones developed in the red andesites but there are not such features observed in the grey andesite used in the same area (Fig. 3f).

Away from the sea shore, the most important factors causing the increased deterioration in the andesites is water. The deterioration of red andesites is highly developed in front of the coffees and restaurants where the pavements are constantly wetted and cleaned with water more often than the other places (Fig. 4). These coffees and restaurants are generally located at the land side of the Atatürk street and the pavements in front of the coffees and restaurants and are wetted two or three times a day for cleaning and for cooling off purposes in the summer months (Fig. 4). The red andesites placed in the pavements in front of these coffees are noticed to be highly deteriorated within the 4 years of their use (Fig. 4). There are up to 1–10 mm thick material loss is recorded in the red andesite plates in these areas (Fig. 4). However there is no noticeable trace of deteriorations in the form of material loss noted in the grey andesite placed in the same area (Fig. 4). Kerb stones are noticed to have been fractured and broken up rather than under going any degradation. The fracturing and breaking up of the kerb stones are mainly developed by the automobile impact to the sides of the streets resulting in opening up of closed cooling joints (Fig. 5)

Tuffs

Red tuffs are placed along the both sides of the Cumhuriyet street from the Cumhuriyet Square to the historical Pier Building (Fig. 1). This area is about 100 m away from the sea shore and there are large number of buildings between this area and the sea shore (Fig. 1).

Red tuffs contain 0.5–5 cm thick volcanic rock particles (Fig. 6a). Deterioration has developed in the red tuffs at noticeable ratio within the 4 years of their use. As the volcanic rock particles are more resistant to deterioration compared to the volcanic tuff matrix, they form small rough hills on the tuff plate surfaces or voids in the areas where these particles are removed (Fig. 6a).

The other physical degradation is the fracturing and breaking up of the red tuff plates (Fig. 6b). The red tuffs are observed to have been very much broken up within the 4 years of their emplacement (Fig. 6b).

$10\times7\times5$ or $30\times30\times7$ cm sized dark tuff plates are placed among the grey and red andesite plates to decorate the pavements (Fig. 6c, d). The deterioration is seen to have developed mainly on the pavement stones in the Kıbrıs Sehitleri street (Fig. 1). This street is closed to automobile traffic and heavily used by the pedestrians every day. The ground floors of the both sides of the street are used as shops. These volcanic rocks are moist in most of the time due to regular washing of the shop fronts besides being heavily used by the pedestrians.

The dark tuff plates placed in the Kıbrıs Sehitleri street have undergone 1–4 cm thick material loss in their surfaces within 4 years of their emplacement (Fig. 6e, f). Thus, the thickness of 7 cm dark tuff plates have been

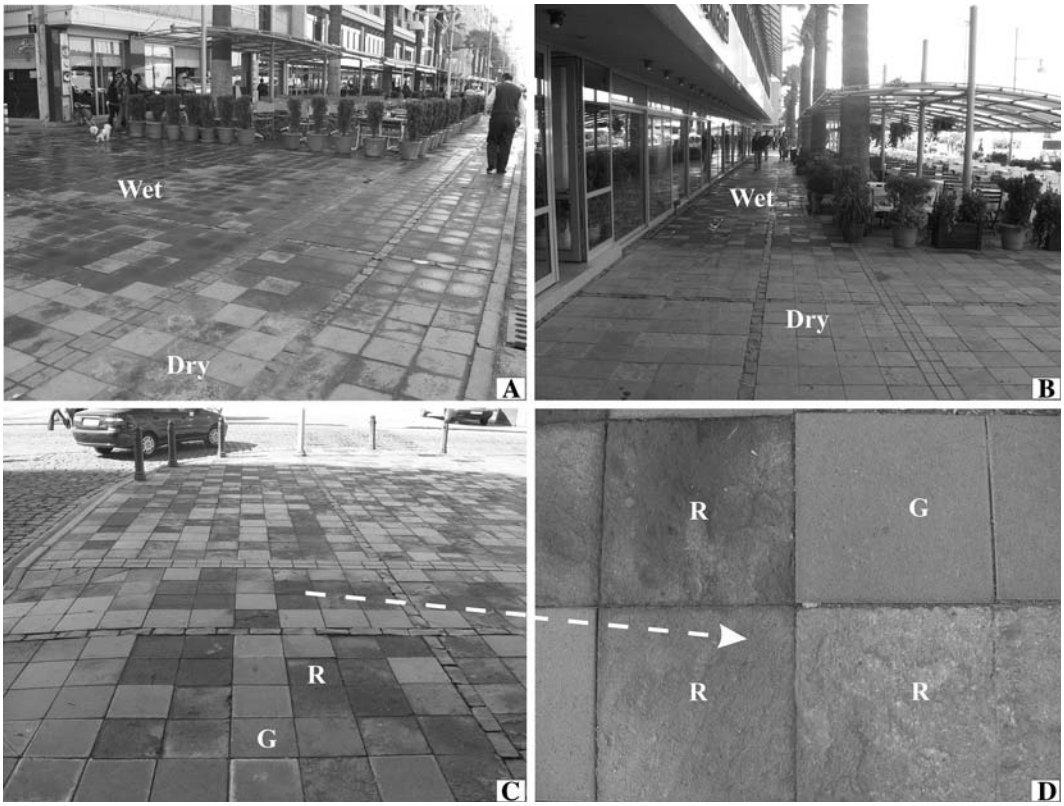

Fig. 4 Deterioration developed in wet red andesite plates in front of the coffees and restaurants away from the sea shore in the Atatürk street (*G* grey andesite, *R* red andesite)

reduced to 3–4 cm within 4 years (Fig. 6e, f). The other physical degradation mechanism is fracturing and breaking up in the dark tuffs. The dark tuffs are highly broken within the 4 years of their emplacement.

Mineralogy of the rocks

Thin sections were made from the fresh and weathered andesites and tuffs used in the renovation of the İzmir city centre and studied under the polarized microscope to determine their mineralogical features and that the influence of weathering on them.

Grey andesite

Grey andesites are hypocrystalline microlitic textured with weak lineation in thin sections. The rock is made up of 5% regular shaped plagioclase, 3% amphibole + pyroxene and 92% matrix (Table 2). The pyroxene and amphibole minerals are altered to a large extend. The matrix is made up of microlitic plagioclase and gas voids. The grey andesites are determined as to be vesicular andesitic lavas based on the microscopic studies.

Red andesite

Red andesites are also hypocrystalline microlitic textured with weak lineations in thin sections. The rock contains 12% clinopyroxene, 2% amphibole, 1% biotite, 0.5% plagioclase minerals and 84–85% matrix (Table 2). There are also plenty of gas voids within the rock matrix. The plagioclase and amphibole minerals are highly altered. The red coloured volcanic rocks are defined as crystal fragments rich tracky andesite based on the microscopic investigations.

Red tuff

Red tuffs are made up of 17–18% matrix, 80% rock fragments and 2–3% irregular or partially regular shaped clinoproxene, plagioclase and sanidine crystals (Table 2). The matrix is completely composed of volcanic ash (Table 2). The red volcanic rock is determined as slightly welded ignimbrite based on the thin section studies.

Dark tuff

Dark tuffs are made up of 1% clinopyroxene, 5% plagioclase and 0.5% sanidine crystals, 23–24% rock

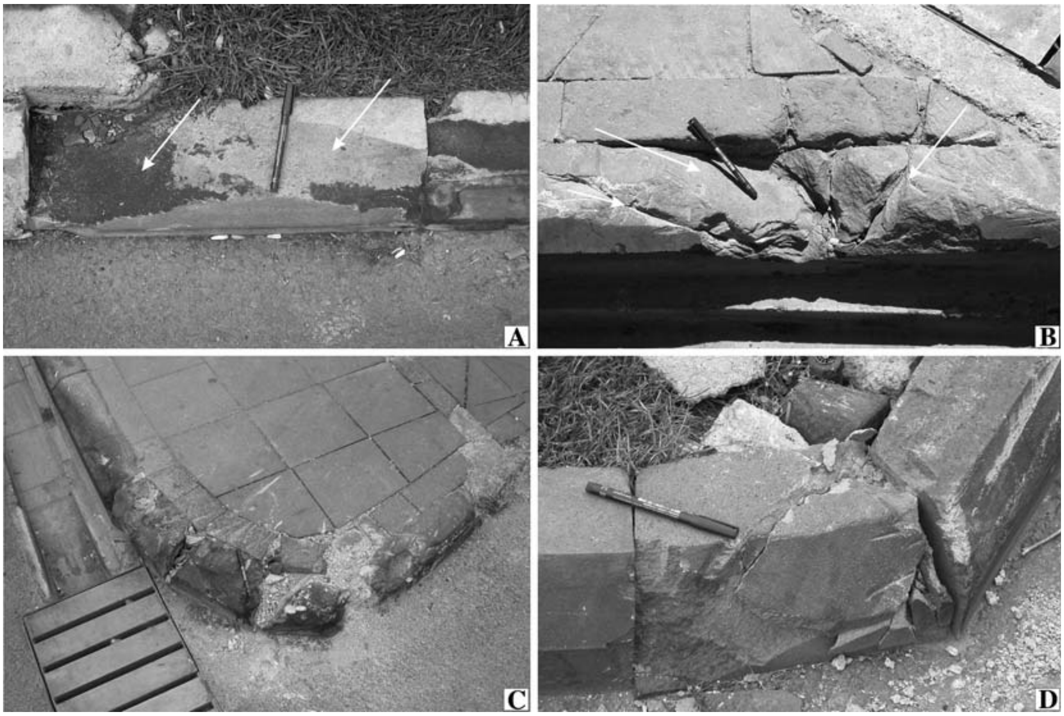

Fig. 5 Fracturing and breaking up of the andesite kerb stones near the roads

fragments and 70% matrix (Table 2). The matrix is made up of microcrystalline plagioclases and pyroxenes and volcanic glasses. The dark coloured tuff is determined to be as slightly welded glassy ignimbrite from microscopic investigations.

Since the matrix forming minerals of the tuffs are fine-grained the individual minerals and the weathering products in the matrix could not be identified under an optical microscope as also noted by the other researchers worked on the similar rock types (Irfan 1994, 1999; Ng et al. 2001; Topal 2002). The deteriorated part of the kerb and pavement stones are confined to the upper 1 cm thick part. In the deterioration part, the feldspar phenocrystals are observed to be disintegrated becoming loose and forming residual soil on the plate surfaces. There in no new mineral formation observed due to chemical alteration of the already existing minerals in the kerb and pavement stones.

The matrix of the fresh and deteriorated andesites and tuffs were investigated under the SEM in order to sea the influence of the deterioration in them. Figure 7a–d show the SEM micrographs of these selected fresh and deteriorated rock samples. While there is very little change in the SEM micrograph of the grey andesite matrix (Fig. 7a), the material loss is clearly obvious in the deteriorated SEM micrographs of the red andesite, and red and dark tuffs (Fig. 7b–d).

Chemical properties

The major and trace elements analysis of the fresh and deteriorated volcanic rocks used as kerb and pavement stones in the city centre of Izmir were made at the geochemistry laboratory of the ACME Analytical Laboratories LTD in Canada and the XRD diffraction of the samples were obtained at the İzmir High Technology Institute, Material Research Centre. The chemical analysis results and XRD micrographs showed that there are no major chemical difference between the fresh and deteriorated volcanic rocks used as kerb and pavement stones (Table 3). While the SiO_2 ratio of fresh volcanic rocks are found to vary between 55 and 63%, it is found to be varying 55 and 64% for the deteriorated rocks (Table 3).

Physical and mechanical properties of the volcanic rocks

The index properties of fresh and deteriorated volcanic rocks are determined in order to establish the influence of the degradation on these rocks (Table 4). For this purpose, the pore sizes were determined using the mercury porosimeter, the physical properties such as dry and saturated unit weight, effective porosity, void ratio, water absorption ratio and the weight loss after the wetting and drying. The freezing and thawing and the salt crystallization tests and the dry sonic velocity of

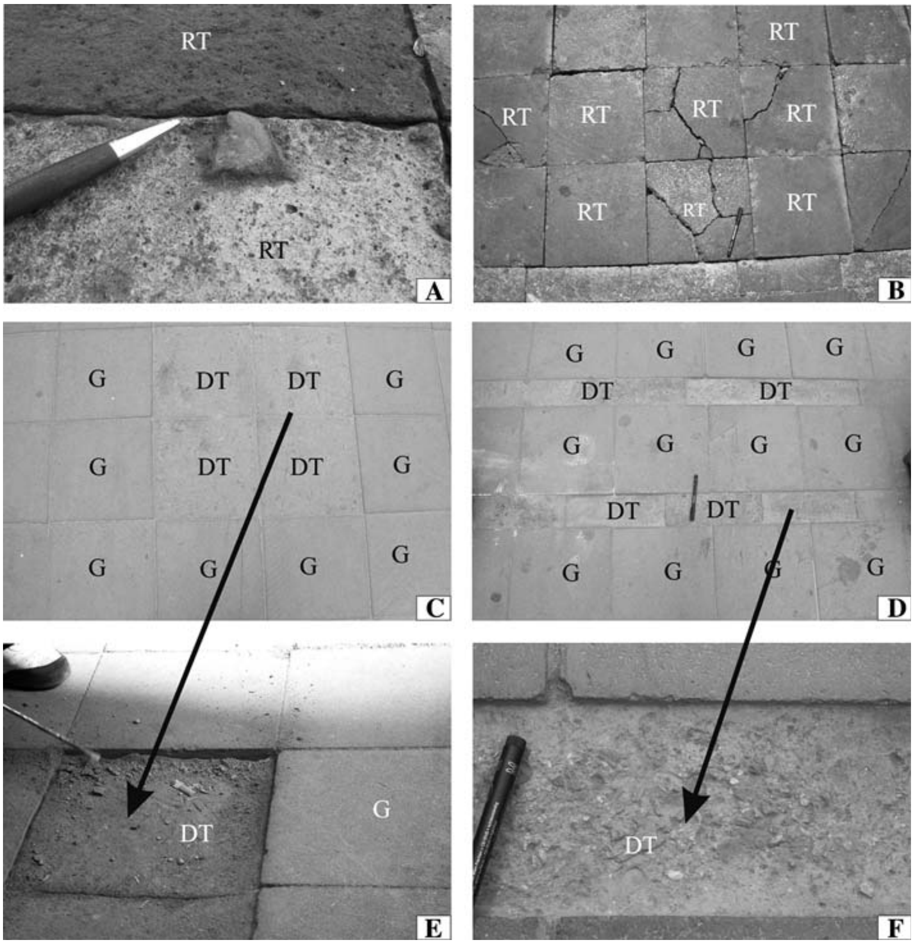

Fig. 6 A general view of the material loss and the fracturing and breaking up of the deteriorated red tuff plates and dark tuff plates (*RT* red tuff, *G* grey andesite, *DT* dark tuff)

the fresh and deteriorated volcanic rocks were determined on 7.0 cm cube samples using the CNS-Farnell make Pundit Plus equipment. Additionally the mechanical properties such as uniaxial compression, Brazilian indirect tensile and bending strengths and Bohme surface abrasion values of the volcanic rock samples were determined (Table 4).

Table 2 Mineralogical composition of the fresh volcanic rocks used in the İzmir city centre as kerb and pavement stones

Rock type	Mineral content
Grey andesite	Plagioclase (5%), amphibole + pyroxene (3%), Matrix (92%)
Red andesite	Clynopyroxene (12%), amphibole (2%), biotite (1%), plagioclas (0.5), matrix (84–85%)
Red tuff	Plagioclase + pyroxene + sanidine (2–3%), rock fragments (80%), matrix (17–18%)
Dark tuff	Plagioclase (5%), pyroxene (1%), sanidine (0.5%) rock fragments and pumice (23–24%), matrix (70%)

The effective porosity and the pore sizes of the selected rock samples were determined using the mercury intrusion technique following the procedures in ASTM D 4404 (1984) (Table 4, Fig. 8). The porosity measurements were made on oven-dried samples using the poremaster-6 type porosimeter. The mercury porosimeter found effective porosity values are found to be in the same order as the porosity values determined by the water absorption technique (Table 4). The average pore diameters are in general found to be varying between 100 and 10 μm (Fig. 8) for the andesites and between 50 and 10 μm for the tuffs (Fig. 8). The red andesites and tuffs have smaller pore diameters. These small pore sizes make these rocks retain water longer than other volcanic rocks (Fig. 8).

In this study, wetting and drying, freezing-thawing and salt crystallization tests are carried out to determine the weatherability of the volcanic rocks. The wetting and drying test was carried out on 7×7×7 cm sized rock samples following the procedure given in ASTM (1992a). The samples were first dried at 65°C for 6 h and then saturated by submerging them into the distilled water for 12 h. The procedure has been repeated for 30

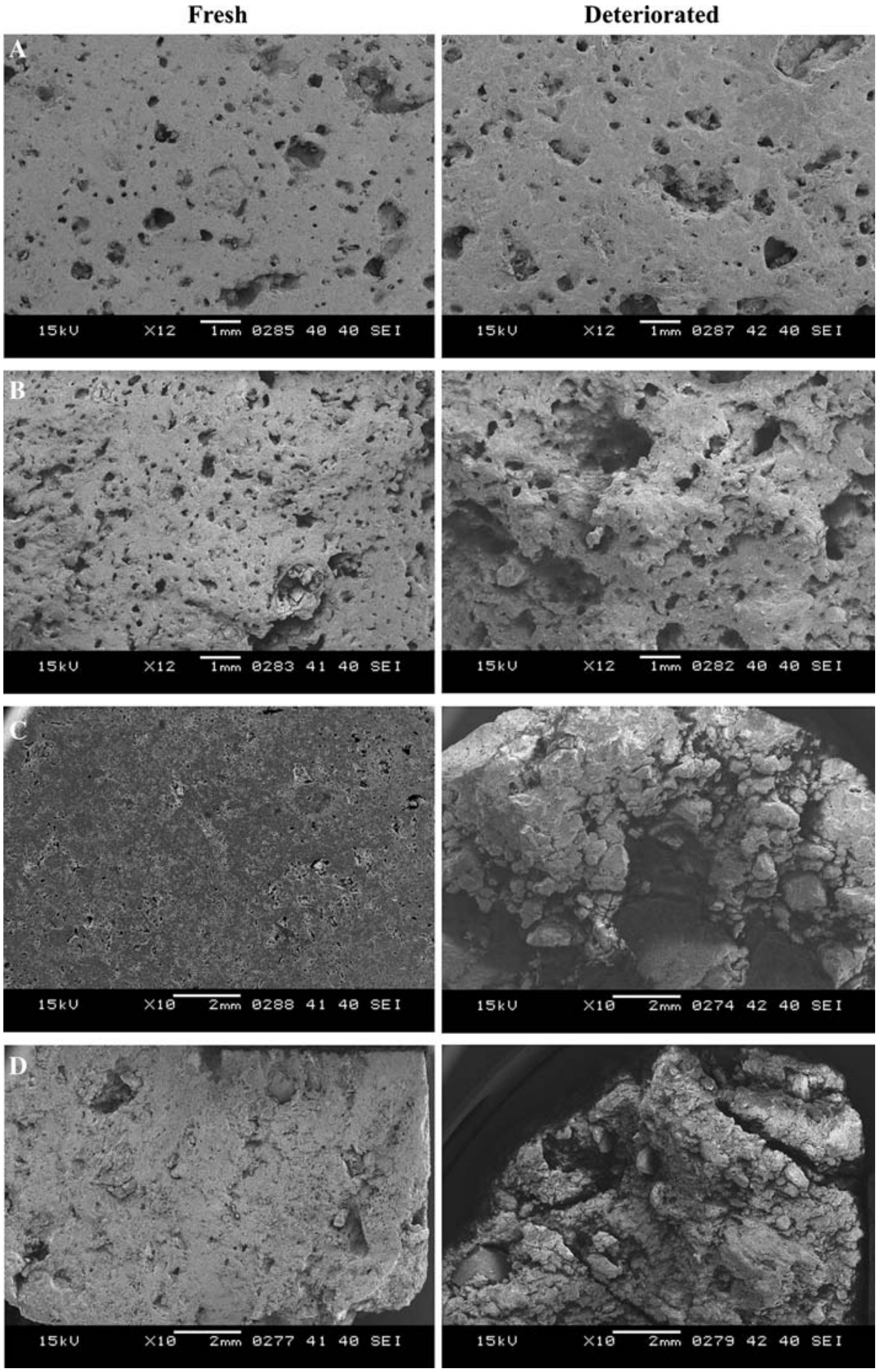

Fig. 7 SEM micrographs of the fresh and deteriorated andesites and tuffs (**a** grey andesite, **b** red andesite, **c** red tuff, **d** dark tuff)

times and the weight loss of the samples was determined after 10, 20 and 30 tests (Fig. 9a). The test results show that while there was no noticeable weight loss in grey andesite, there were noticeable weight loss in red andesite, red and dark tuffs. Additionally, the maximum weight loss has been taken place in the dark tuffs (Fig. 9a).

The freezing and thawing tests were carried out on the 7.0 cm cube samples using the domestic water to assess the weatherability of the volcanic rock samples by determining their weight loss after 25 cycles of freezing (−20°C) and thawing process (TS 699). In order to establish the effect of the salinity of the sea water on the weatherability of these rocks, the freezing and thawing

Table 3 The chemical analysis results of the fresh and deteriorated volcanic rocks used in renovation of the İzmir city centre

Elements	Grey andesite (F)	Grey andesite (D)	Red andesite (F)	Red andesite (D)	Red tuff (F)	Red tuff (D)	Dark tuff (F)	Dark tuff (D)
wt.%								
SiO_2	61.99	62.89	55.35	55.20	61.94	61.70	63.47	64.51
Al_2O_3	17.51	17.11	12.79	12.63	15.90	16.17	15.54	14.89
Fe_2O_3	5.08	4.80	6.43	6.37	6.14	6.12	4.08	3.77
MgO	0.48	0.50	5.25	5.28	2.23	2.27	1.18	1.07
CaO	4.25	4.25	7.01	7.13	4.85	4.99	2.93	2.65
Na_2O	4.69	4.65	2.24	2.24	4.51	4.60	3.73	3.98
K_2O	2.67	2.66	7.27	7.17	1.95	1.99	3.19	3.09
TiO_2	0.81	0.75	1.31	1.30	1.13	1.11	0.77	0.73
P_2O_5	0.50	0.51	1.0	1.05	0.30	0.30	0.21	0.20
MnO	0.03	0.02	0.08	0.08	0.09	0.09	0.08	0.07
Cr_2O_3	0.001	0.002	0.072	0.066	0.002	0.002	0.001	0.001
LOI	1.8	1.7	9	1.2	0.9	0.6	4.8	5
Total	99.82	99.85	99.73	99.74	99.95	99.95	99.98	99.96
ppm								
Sc	7	7	21	20	15	15	9	9
Mo	0.3	0.4	0.1	0.1	0.5	0.4	0.2	0.2
Cu	19.0	19.9	17.8	17.3	24.1	33.1	19.1	26.2
Pb	2.6	1.9	1.1	3.7	2.3	2.2	3.2	2.8
Zn	55.0	62	32	36	40	41	24	26
Ni	27.0	23.1	70.5	57.2	6.7	5.6	2.3	3.8
As	10.2	15	3.4	4.0	0.6	0.6	0.5	0.7
Cd	< 0.1	< 0.1	0.1	< 0.1	< 0.1	< 0.1	0.1	0.1
Sb	0.2	0.2	0.2	0.3	0.2	0.2	0.1	0.1
Bi	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Ag	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Au	1.3	< 0.5	1.4	1.3	0.8	2.2	0.8	2.3
Hg	0.01	0.01	0.01	0.01	0.01	0.01	0.04	0.03
Ti	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	0.1	< 0.1
Se	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5
Ba	1144.2	1031.9	1644.7	1590.4	428.2	429.7	470.0	476.7
Be	2	2	5	5	2	2	2	2
Co	5.4	5.2	23.1	23.0	14.6	16.2	5.6	5.0
Cs	1.5	1.5	6.4	5.9	1.8	2.2	3.8	3.9
Ga	18.2	18.6	18.4	18.9	19.0	19.3	18.1	17.8
Hf	5.2	5.1	18.7	18.2	6.0	5.6	8.3	8.8
Nb	21.2	19.9	39.9	39.8	13.4	13.5	15.6	16.5
Rb	57.0	61.1	228.4	225.5	56.1	58.6	88.9	98.8
Sn	1.0	1	5	5	2	2	2	3
Sr	738.0	677.1	1285.5	1269.1	346.0	343.6	215.2	199.2
Ta	1.4	1.3	2.6	2.6	1.0	1.1	1.4	1.4
Th	11.8	12	38.4	38.0	12.5	12.1	16.8	17.2
U	3.1	3.1	7.5	7.1	3.6	3.5	4.5	4.9
V	64	60	79	81	96	92	38	34
W	1.3	2.4	3.3	3.3	1.7	1.7	2.0	2.0
Zr	212.8	205.1	645.5	635.1	246.6	241.4	336.6	351.4
Y	23.7	23.2	28.1	27.7	29.9	30.6	36.2	37.3
La	56.9	51.5	127.2	124.9	30.8	31.2	35.0	37.0
Ce	95.6	86.7	239.7	239.4	58.9	60.9	68.8	68.7
Pr	10.36	9.26	27.62	27.77	6.92	7.12	7.76	8.0
Nd	37.8	32.8	95.9	96.8	25.1	26.4	28.9	30.1
Sm	5.9	5.2	14.8	15.0	5.2	5.3	6.2	6.2
Eu	1.54	1.34	3.11	3.13	1.45	1.44	1.40	1.37
Gd	4.50	4.37	9.66	9.39	5.29	5.40	5.76	5.88
Tb	0.79	0.70	1.18	1.24	0.86	0.90	1.02	1.05
Dy	3.96	3.73	5.36	5.53	5.02	4.85	5.65	5.93
Ho	0.86	0.80	0.95	0.96	1.08	1.04	1.28	1.27
Er	2.37	2.23	2.37	2.30	2.93	3.01	3.79	3.67
Tm	0.36	0.38	0.35	0.35	0.45	0.45	0.58	0.57
Yb	2.27	2.25	1.94	2.08	2.85	2.69	3.44	3.50
Lu	0.33	0.35	0.30	0.29	0.43	0.43	0.53	0.51

F Fresh, *D* deteriorated

Table 4 Selected index properties of fresh and deteriorated volcanic rocks

Physico-mechanical properties	*n*	Grey andesite (F)	*n*	Grey andesite (D)	*n*	Red andesite (F)	*n*	Red andesite (D)	*n*	Red tuff (F)	*n*	Red tuff (D)	*n*	Dark tuff (F)	*n*	Dark tuff (D)
Dry unit weight (kN/m^3)	10	23.39 ± 0.22	10	23.26 ± 0.25	10	21.75 ± 0.031	9	20.24 ± 2.60	10	19.63 ± 0.19	10	17.46 ± 0.27	10	16.58 ± 0.045	6	11.38 ± 0.39
Water saturated unit Weight (kN/m^3)	10	24.09 ± 0.19	10	24.06 ± 0.22	10	22.98 ± 0.019	9	21.75 ± 2.29	10	21.78 ± 0.18	10	20.18 ± 0.32	10	19.33 ± 0.27	6	15.67 ± 0.18
Effective porosity (%)	10	6.99 ± 0.74	10	7.94 ± 0.39	10	12.23 ± 1.17	9	15.14 ± 0.57	10	21.51 ± 0.36	10	27.29 ± 1.52	10	27.51 ± 1.87	6	42.96 ± 5.09
Mercury porosity (%)	1	7.85			1	11.76			1	22.85			1	27.24		
Void ratio (%)	10	7.53 ± 0.86	10	8.63 ± 0.46	10	13.95 ± 1.5	9	17.85 ± 0.80	10	27.41 ± 0.59	10	37.60 ± 2.95	10	38.03 ± 3.59	6	76.49 ± 15.88
Water absorption by weight (%)	10	2.99 ± 0.33	10	3.41 ± 0.20	10	5.63 ± 0.61	9	7.44 ± 0.35	10	10.95 ± 0.26	10	15.64 ± 0.89	10	16.62 ± 1.59	6	37.91 ± 5.80
Weight Loss after freezing and thawing (%) (in tab water)	5	0.146 ± 0.023			10	0.466 ± 0.130			5	1.07 ± 0.254			5	1.78 ± 0.224		
Weight loss after freezing and thawing (%) (in sea water)	5	0.22 ± 0.026			10	0.701 ± 0.203			5	1.40 ± 0.22			5	2.21 ± 0.575		
Weight loss after salt crystallization (%)	5	0.34 ± 0.070			10	1.592 ± 0.389			5	2.57 ± 0.728			5	4.187 ± 1.33		
Ultrasonic P wave velocity (Dry)(km/sn)	5	3.22 ± 0.20	5	3.17 ± 0.2	5	2.75 ± 0.11	5	2.55 ± 0.10	5	2.41 ± 0.12	5	2.14 ± 0.10	5	2.05 ± 0.29	5	1.43 ± 0.149
Uniaxial compressive strength (Dry) (MPa)	6	119.8 ± 12.3	5	91.13 ± 9.36	10	70.55 ± 3.37	5	44.7 ± 4.32	5	61.13 ± 3.16	6	28.89 ± 8.08	5	40.25 ± 1.63	5	10.37 ± 1.88
Uniaxial compressive strength (WS) (MPa)	5	102.6 ± 9.6			9	61.13 ± 6.28			6	42.57 ± 2.62			5	22.86 ± 2.63		
Bending strength (Dry) (MPa)	5	16.47 ± 4.61	3	13.4 ± 3.18	8	13.64 ± 2.88	5	9.21 ± 0.74	5	6.31 ± 0.84	5	3.30 ± 0.4	5	4.12 ± 1.7	4	1.32 ± 0.19
Bending strength (WS) (MPa)	5	15.97 ± 3.58			9	11.81 ± 1.34			5	4.24 ± 0.9			5	2.23 ± 0.42		
Impact strength (Dry) ($N\ mm/mm^3$)	5	16.8 ± 4.38			15	8.4 ± 3.04			5	6 ± 0			5	2 ± 0		
Impact strength (WS) ($N\ mm/mm^3$)	5	13.6 ± 3.57			10	5.6 ± 1.26			5	4.4 ± 2.19				0		
Indirect tensile strength (Brazilian test) (Dry) (MPa)	5	11.0 ± 1.5			5	6.84 ± 0.43			5	5.91 ± 1.21			5	3.11 ± 0.95		
Indirect tensile strength (Brazilian test) (WS) (MPa)	5	9.46 ± 1.33			5	5.69 ± 0.84			5	4.17 ± 0.60			5	1.43 ± 0.27		
Bohme surface abrasion values (Dry) ($cm^3/50\ cm^2$)	5	11.89 ± 0.76	3	16.56 ± 4.72	5	14.35 ± 2.41	3	22.51 ± 2.51	5	15.36 ± 1.94	3	25.53 ± 3.1	5	19.19 ± 1.94	4	32.93 ± 6.11

F Fresh, *D* deteriorated, *AFT* after freezing and thawing, *WS* water saturated, *n* number of samples

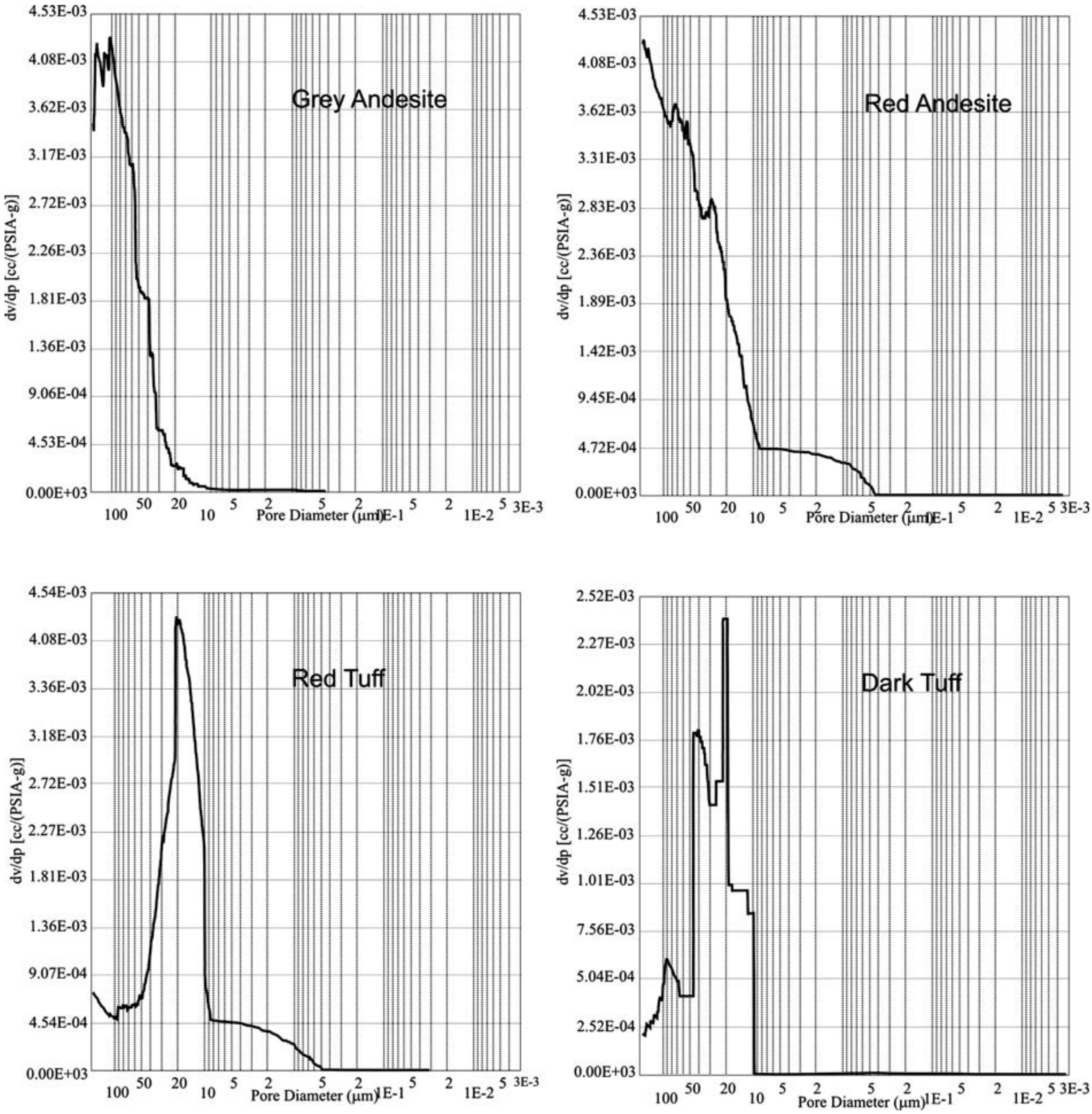

Fig. 8 Mercury penetration volume pressure (*dv*/*dp*) versus pore diameter for the volcanic rocks

test was repeated on fresh rock samples using the sea water taken from the İzmir Bay (Table 4, Fig. 9b). The chemical composition of the tab and sea waters used in the freezing and thawing tests are given the Table 6.

The salt crystallization test attempts to reproduce the effects on salt crystallization occurring under harsh environmental conditions (RILEM 1980; Rossi-Dora 1985; Topal 1997; Topal and Doyuran 1997a, b). Salt crystallization tests by total immersion are carried out by using a 14% solution of sodium sulphate decahydrate ($Na_2S0_4{\cdot}10H_2O$) solution on the fresh rock samples as well. After immersion of the samples into the solution for 2 h, they are removed from the solution and dried in an oven at 105°C for 24 h. For every test cycle, a new solution is prepared. The test results are given in Table 4. The weight loss values are found after the freezing and thawing test using the sea water, the tab water and the $NaSO_4$ immersion tests (Table 4). While the grey andesites are least effected, the dark tuffs are found to be highly affected from the freezing and thawing test. Additionally, $NaSO_4$ immersion tests have given the maximum weight loss among the three tests (Table 4, Fig. 9b).

Wet to dry strength ratio is a good and rapid method of testing the durability of stones (Winkler 1986, 1993;

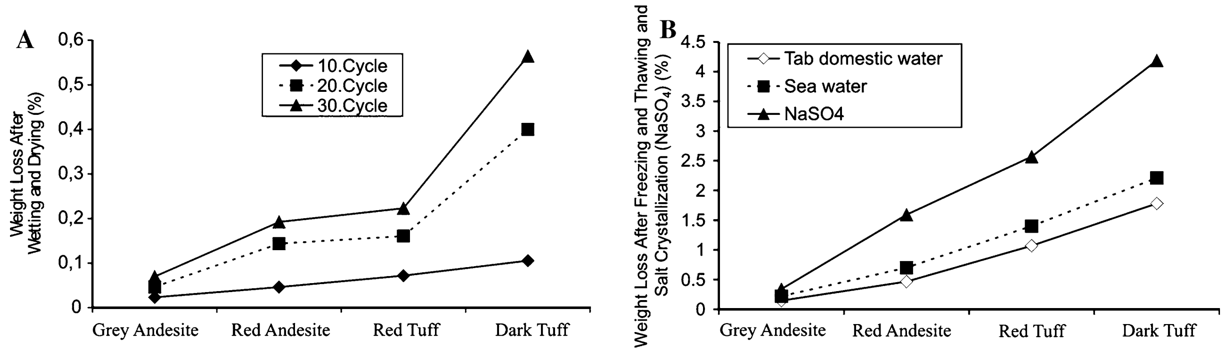

Fig. 9 Variation of weight loss of the volcanic rocks after wetting and drying (**a**) and variations of weight loss of the volcanic rocks after freezing and thawing and salt crystallization test ($NaSO_4$) (**b**)

Topal and Doyuran 1997a, b). In this study, the mechanical tests such as uniaxial compressive, bending, impact and indirect tensile (Brazilian) tests have been done on dry and wet volcanic rock samples (Table 4, Fig. 10). There are noticeable differences in the strength values of the dry and saturated volcanic rock samples (Table 4, Fig. 10). The strength of especially, the red andesite, red tuff and dark tuffs had noticeable decrease on saturation (Table 4, Fig. 10c, d). Additionally the experimental results show that there has been decrease in the unit weight, ultrasonic Primary wave velocity, uniaxial compressive, bending and impact strengths and increase in the effective porosity, void ratio and water absorption of the volcanic rocks due to the deterioration (Table 4, Fig. 10a–g). While the differences between the properties of fresh and deteriorated samples are less in the grey andesites, they are very high in the red andesites and red and dark tuffs (Table 4).

Environmental factors

Meteorological properties of the city of İzmir

The city centre of İzmir is located over a plain formed by the Melez stream and surrounded by high mountains having very little trees. Mediterranean type climate prevails in İzmir. The monthly rainfall for the years 2001–2004 are given in Fig. 11, for İzmir. Figure 11 shows that there is very little rainfall in the summer in İzmir. The maximum rainfall has occurred in 2002 among the years 2001–2004 (Fig. 11). The seasonal mean temperatures are given in Table 5 for İzmir for the years 2001–2004 measured at 07, 14 and 21 h during the day at the Poligon meteorological station in İzmir (Table 5, Fig. 12a–c).

Figure 12a–c shows that there are very little temperature variations from the year to year for the recorded times and seasons between 2001 and 2004. Additionally, the mean monthly humidity values are given in Fig. 12d for the year 2001–2004. The relative humidity is an important factor in the abrasion of moisted semiporous and porous stones (Winkler 1997). Figure 12d shows that the humidity value varies between 50 and 80% through the years. While the humidity is least in June and July, it is high in most of the other months. Figure 13 gives the times when the temperature had fallen below zero in İzmir. This data also show that the temperature had fallen below the zero 19 times between 2001 and 2004.

Sea water salinity

The salinity measurements of the İzmir Bay water made by the DEU Marine Science Institute of İzmir between 1994 and 2004 is given in Figure 14. This figure shows that the salinity of the İzmir Bay water varied between 37 and 41 psu over the past 10 years (Fig. 14). These salinity values are slightly higher than the salinity of the oceans and open seas which have mean salinity variation between 32 and 35 psu (Senjyu 1999). This slight increase in the salinity of İzmir Bay water is due to its being a heavily polluted interior sea and İzmir having a highly hot climate (Fig. 12a–c). The salinity is lower in the winter months compared to the summer month as expected (Fig. 14). Additionally, the chemical composition of the sea water is given in Table 6.

Acid rain

The pH values of the rain water has been determined to be varying between pH 5.6–6.1 in and around İzmir (Naik et al. 2002; Tuncel 2003). Such pH value indicates that there is no acidity in the rain water of İzmir. Thus, the acidity of rain water does not have contributing factor to the deterioration of the kerb and pavement stones used in the city centre of İzmir.

Assessment

İzmir has moderate climate with occasionally occurring low temperatures below the zero. There are no acid rain

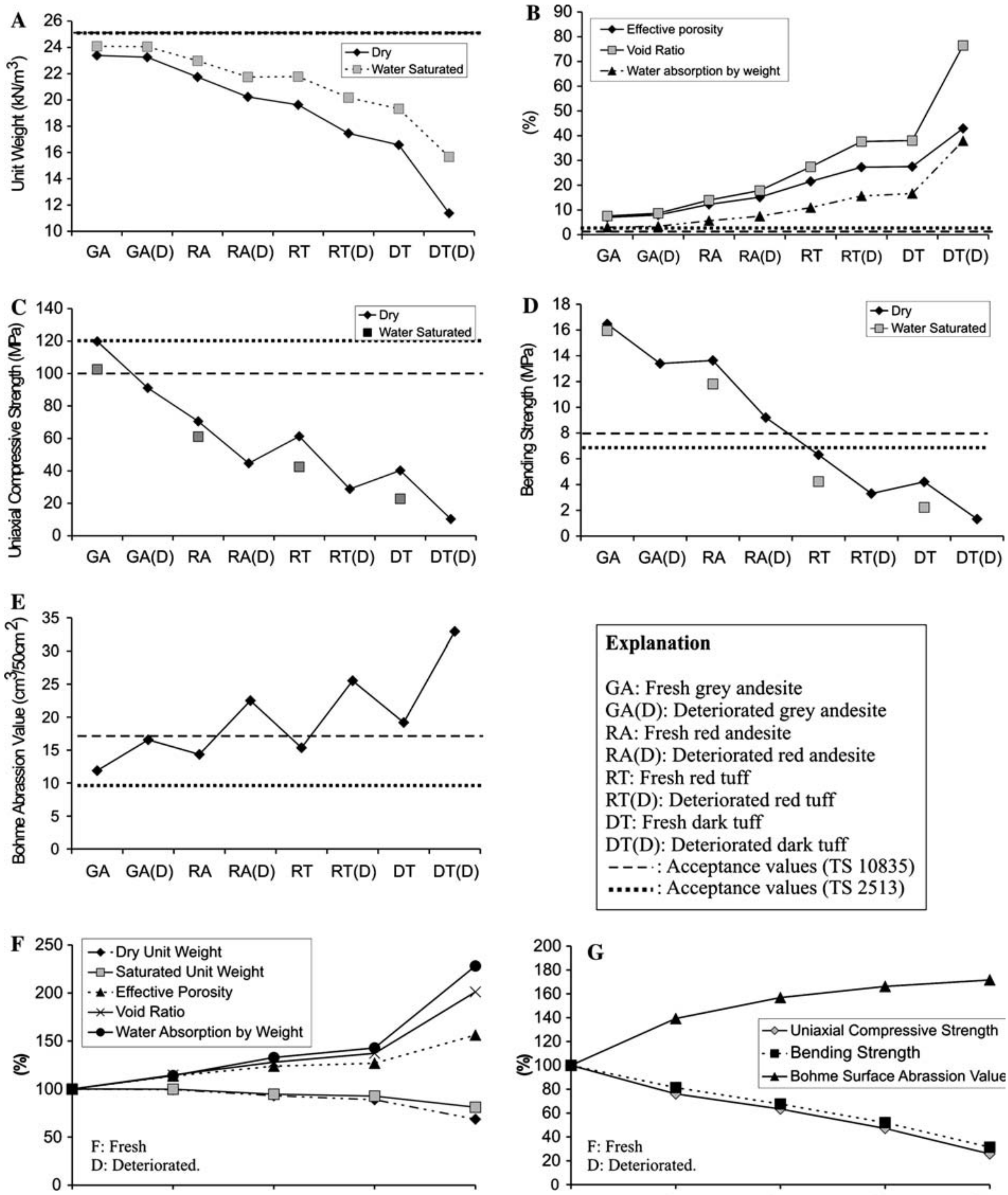

Fig. 10 Variations of selected physical and mechanical properties of the fresh and deteriorated volcanic rocks. **a**–**e** Laboratory found values. **f**, **g** As percentages of the fresh sample properties

problem in İzmir as well. Under such environmental conditions it is expected that the natural stones are expected be able to stand deteriorations over a long time.

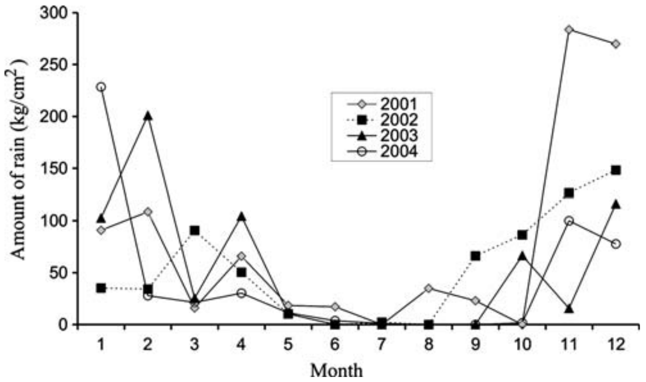

Fig. 11 The average monthly rainfall for the years 2001–2004 in the city centre of İzmir (Meteorological records of the İzmir, Poligon station for the period 2001–2004)

However high rate of deteriorations are observed in the volcanic rocks when used by the sea and in the areas where they are subjected to constant wetting and drying. These field observations are in good agreement with the wetting and drying and freezing and thawing tests results carried out the representative samples (Fig. 9a, b). But, there is no noticeable difference found between mineralogy and chemical compositions of the fresh and deteriorated volcanic rocks. However, there have been weight losses occurred in the wetting and drying tests and the freezing and thawing tests using different test fluids (tab water, sea water and $NaSO_4$). The test results clearly show that the main deterioration mechanism affecting these volcanic kerb and pavement stones in the city centre of İzmir is predominantly physical.

The main deterioration develops on the plate surfaces in the form of spalling of materials and breaking up of the volcanic kerb and pavement stones in the volcanic rocks used in the city of İzmir. The causes of the rapid deterioration of the volcanic rocks used in the renovation works in the city of İzmir can be attributed to strength and weight loss due to constant wetting and drying (Fig. 9a, b) and sea water crystallization and heavy abrasion by the pedestrians. These findings are in agreement with Winkler's (1997) observations that moisture and salts are the most demanding factors in stone decay.

Tuğrul (2004) investigated the pore diameters and effective porosity of the different weathering graded sandstone, limestone, basalt and granodiorite samples using the mercury porosimeter. She noted that, while the effective porosity ratio has increased with increasing weathering grades, the average pore diameters are found to have decreased especially for basalts samples. This is attributed to mineral neoformation in the pore spaces during weathering process as also found for andesites by Mulyanto and Stoops (2003). As the chemical analysis of the fresh and deteriorated volcanic rocks show that there are no new minerals formed in the deteriorated rocks (Table 3). Thus, the pore diameter and the porosity of the volcanic kerb and pavement stones are expected to increase with increasing deterioration (Table 4).

The freezing and thawing tests carried out on fresh volcanic rocks using $NaSO_4$ solution, sea water and domestic tab water have given a good indication of the weatherability of the different rock types. While the material loss is found to be less for the grey andesites it is found to be very high for the dark tuffs (Fig. 9b). The material loss has been almost twice as much in the $NaSO_4$ salt crystallization tests as compared to the sea water used freezing and thawing tests (Fig. 9b). The tab water test has given the least material loses (Fig. 9b). The chemical compositions of the tab and sea waters are given in Table 6. These test results clearly show the

Table 5 Mean temperature values recorded at the Meteorological İzmir-Poligon station for the winter and summer months for the years 2001–2004

Measurement time	2001		2002		2003		2004	
	Winter (°C)	Summer (°C)	Winter (°C)	Summer (°C)	Winter (°C)	Summer (°C)	Winter (°C)	Summer (°C)
07:00	9.07	25.13	8.13	25.14	10.6	24.94	9.49	24.23
14:00	13.33	32.22	13.50	32.12	14.8	32.12	14.13	31.53
21:00	10.6	27.9	9.86	27.43	11.6	27.92	10.60	26.82

Table 6 The chemical composition of the tab and sea waters

	pH	EC (μs/cm)	Na (mg/L)	Ca (mg/L)	Mg (mg/L)	K (mg/L)	CL (mg/L)	HCO_3 (mg/L)	CO_3 (mg/L)	SO_4 (mg/L)
Tab domestic ffwater (1)	8.14	607	19	85.4	27.6	3.7	43.5	290	24	61
Sea water (2)	8.05	56,200	11,472	170	2,740	1,040	23,000	180	–	2,650

1 Simsek et al. (2005), *2* Aksoy (2001)

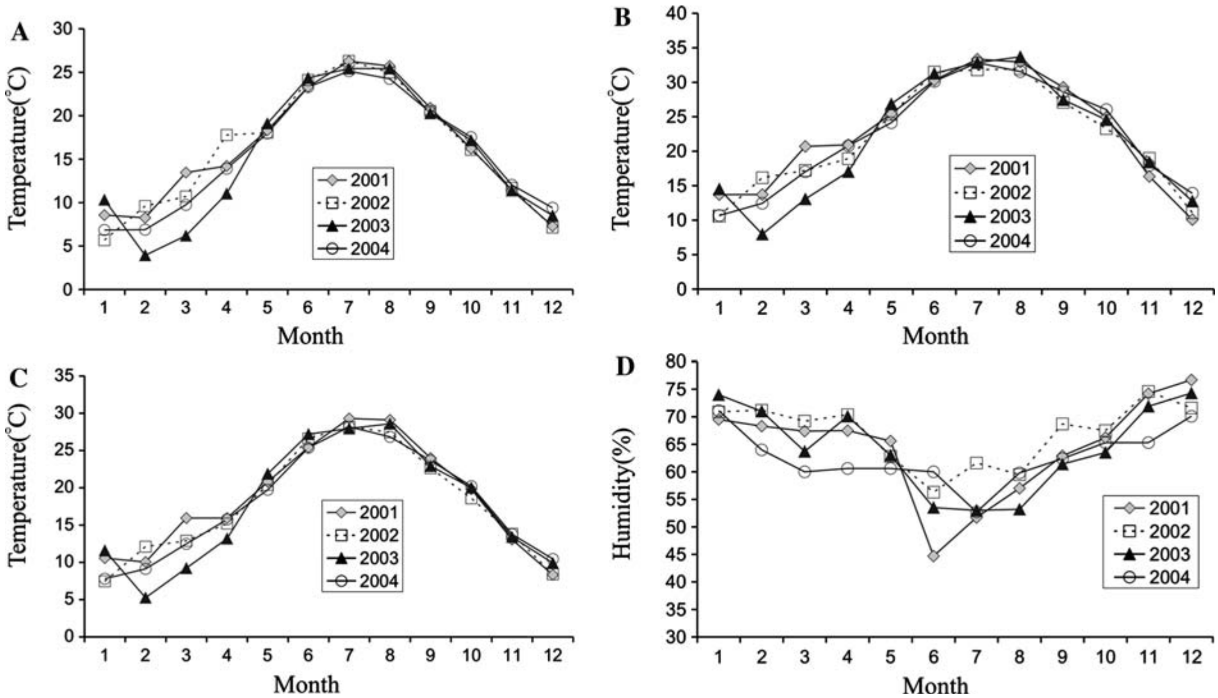

Fig. 12 The average monthly temperature (**a** 07:00AM, **b** 14:00PM, **c** 21:00PM) and humidity (**d**) for the years 2001–2004 in the city centre of İzmir (Meteorological records of the İzmir, Poligon station for the period 2001–2004)

influence of the salt crystallization in deterioration of the volcanic rocks used in the street İzmir city centre.

The mechanical properties of the fresh volcanic rocks used as kerb and pavement stones in renovation of the streets and public gathering squares of the İzmir city centre in 2000–2001 have been found to have low strength values than the Turkish Standard Institute (TSE) required threshold values for use of such rocks as

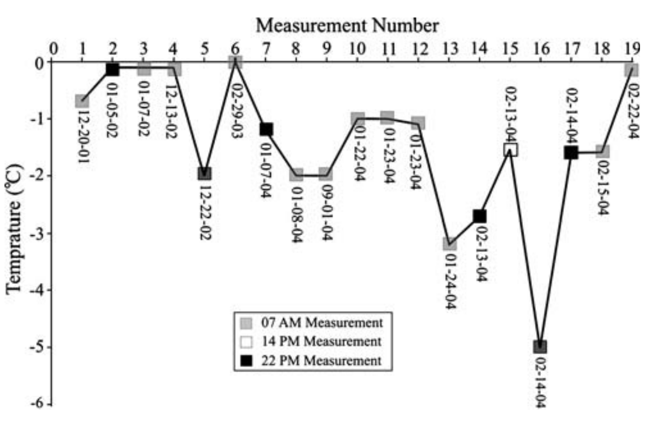

Fig. 13 The times and degrees when the temperature had fallen below the zero in the Izmir city centre of Izmir, between 2001 and 2004 (Meteorological records of the İzmir, Poligon station for the period 2001–2004)

building stone (Tables 4, 7, Fig. 10). Grey andesites are found to have the highest strength among the volcanic rocks used as kerb and pavement stones in the streets of İzmir city centre (Table 4, Fig. 10).

The degree of variations in the selected physical and mechanical properties of the volcanic rocks by comparing their values with the fresh ones as percentage are given in Fig. 10f, g. A fresh sample result is represented by 100% for all the variables. While the effective porosity, void ratio, water absorption by weight, and Bohme abrasion values are found increased significantly, the uniaxial compressive and bending strengths have decreased significantly with deterioration of the volcanic rocks except for the grey andesites (Fig. 10f, g). In general it is found that higher the differences between the fresh and deteriorated volcanic rock sample properties higher the rate of deterioration in them (Table 4, Fig. 10a–g).

The relative degradation ratio of the different volcanic rocks in the light of their place of use is given in Table 8. While the grey andesites have undergone slight rate of degradation in the areas within 6–7 m of the sea shore, but there are very little deterioration observed when they are used in other places. The red andesite have undergone high rate of deterioration in the areas near the shore and in the front of coffees and shops where they are constantly subjected to wetting several times every day. The red tuffs have undergone low rate of deterioration compared to the dark tuffs in the streets used by the pedestrian (Fig. 2). The different deterioration types observed in the different volcanic rocks when they are used as the kerb and pavement stones in the city

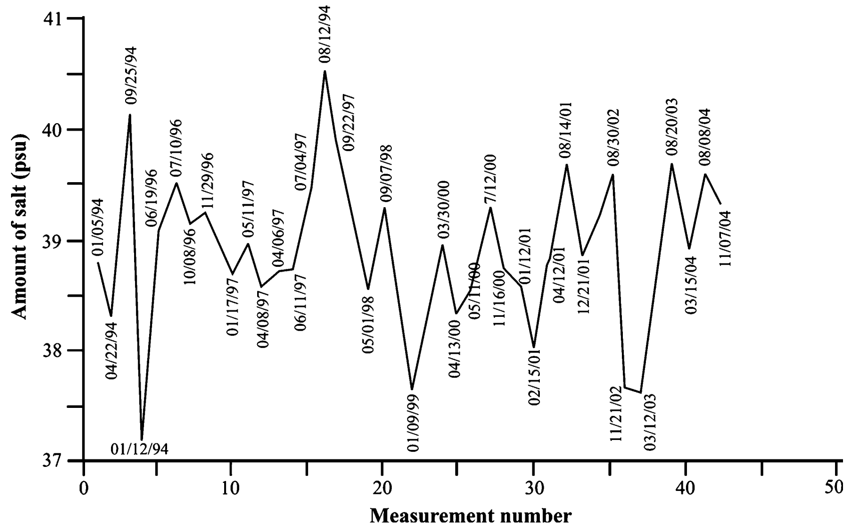

Fig. 14 Variations in the salinity of the İzmir Bay sea water between 1994 and 2004 (DEU Marine Science Institute of İzmir 2005)

Table 7 The physical and mechanical properties acceptance values for the andesite (TS 10835 1993) and building stones (TS 2513 1977), by the Turkish Standards

Rock type	Turkish standard number	Unit weight (kN/m^3)	Effective porosity (%)	Water absorption by weight (%)	Weight loss after freezing and thawing (%)	Uniaxial compressive strength (MPa)	Bending strength (MPa)	Impact strength ($N\ mm/mm^3$)	Bohme surface abrasion value ($cm^3/50\ cm^2$)
Andesite	TS 10835	25.50	–	0.70	1	F 101.9 W 61.1	F 8.1 W 6.1	F 10 W 6	F 17 W 28
Building stone	TS 2513	25.50	–	1.8	5	120	7.5	F 12 W 6	F 10 W 15

F Floor, *W* Wall

centre are depicted all together in Fig. 2 for their relative comparison.

Conclusions

The following conclusions are reached from the observations and findings of the mineralogical, chemical, physical and mechanical properties of the volcanic rocks used as kerb and pavement stones in the city centre of İzmir, and the environment factors prevailing in and around İzmir.

The degradations are observed to be in the form of material loss from the rock plate surfaces and the breaking up and fracturing of the volcanic kerb and pavement stones.

The constant wetting of the volcanic rocks by the sea water and cleaning water together with pedestrian abrasion are found to be the main contributing factor in the rapid degradation of the volcanic kerb and pavement stones, in the city centre of İzmir.

The mercury porosimeter graphs given in Fig. 8 shows that although all the volcanic rocks have mainly similar pore diameter-volume/pressure chance relation, the red andesites and tuffs have smaller pore diameters than the grey andesite and dark tuffs which make them retain water longer, in their structure. Thus, resulting in high rate of abrasion and material loss in them.

The deterioration developed in the volcanic kerb and pavement stones are found to be mainly physical from the mineralogical studies and chemical analysis, wetting and drying and freezing and thawing of the fresh and the deteriorated volcanic rocks.

Table 8 The relative degradation ratio of the different volcanic rocks in the light of their place of use

Rock type	Stone usage locations		
	Sea shore (within 10 m distance of sea)	Heavy pedestrian traffic (constant wetted coffee and shops front)	Heavy pedestrian traffic (rain water)
Grey andesite	1	0	0
Red andesite	3	2	1
Red tuff	–	3	1
Dark tuff	–	3	2

0 Fresh (not obvious weight loss), *1* slightly deteriorated (weight loss < 5 mm thick), *2* moderately deteriorated (weight loss 5–10 mm thick), *3* highly deteriorated (weight loss > 10 mm thick)

The salt crystallization tests made using $NaSO_4$ solution and the freezing and thawing tests made using sea water have given good indications of the weathering order of the volcanic rocks used as the kerb and pavement stones in the city centre of Izmir.

Additionally the difference between the physical and mechanical properties of the dry and wet volcanic rocks gives a good indication of their weatherability. It is generally found that higher the differences between the dry and wet properties, higher the rate of deterioration.

Selection of rock types based on only colour is not a sufficient criterion, their physical and mechanical properties and usage locations and the environmental factors which they will be subjected to in their place of use have to be taken into consideration for their long term durability.

There are no dominant environmental factors such as hostile climate, acid rain and air pollution etc., to cause rapid deterioration in the city of İzmir. The rapid deterioration of these volcanic kerb and pavement stones are mainly due to their use in a wet and abrasive environment than their formation conditions. The change in the environmental conditions is a major feature need to be taken into consideration in assessing the long-term behaviour of rocks in engineering practice.

The physical and mechanical properties of volcanic rocks are very important from deterioration point of view. Only the grey andesites which are the least deteriorated rocks among the volcanic rocks used in the city of İzmir, are found to have mechanical and technical properties close and or above the threshold values given by the Turkish standards (Table 7). In this respect, the threshold values given by the Turkish standards can be regarded as reliable standard values.

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