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Cement and Concrete Research 35 (2005) 505–512

CEMENT AND CONCRETE RESEARCH

Evaluation of selected basalts from the point of alkali–silica reactivity

M. Korkanç [a],*, A. Tuğrul [b]

[a]Department of Geological Engineering, Niğde University, TR-51100 Niğde, Turkey
[b]Department of Geological Engineering, İstanbul University, Avcılar, TR-34320 İstanbul, Turkey

Received 29 March 2004; accepted 8 June 2004

Abstract

Basaltic rocks are potential rocks for alkali–silica reaction (ASR). The objective of this study is to determine reactivity of the basalts of different compositions and textures. The study was carried out on basalts that are widespread in the Middle Anatolian Region of Turkey. They form the major source of local crushed rock aggregates. Early Quaternary Melendiz volcanites, Quaternary Karataş volcanites and İğredağ basalts were selected around the Niğde Region, and the experimental studies were conducted on these rocks. The samples were collected as being representative of 11 different basalt types. The basalts were firstly classified according to their petrographical and chemical composition. Petrographic techniques and accelerated mortar bar test were then used to evaluate the potential alkali reactivity of the basalt aggregates. The basalts having acidic-intermediate character and matrix that is mainly composed of volcanic glass are potentially suitable for alkali–aggregate reaction (AAR) according to the standard values.

Keywords: Basalt; Alkali–aggregate reaction; SEM; Volcanic glass

1. Introduction

Alkali–silica reaction (ASR) is the most common form of alkali–aggregate reaction (AAR). ASR is a chemical reaction between the alkalis in Portland cement and certain siliceous aggregates and form a silica gel. It is well known that alkaline components of Portland cement chemically react with silica in certain forms found in certain aggregates [1]. There are many studies concerning the effect of the reactive aggregates on the ASR gel formation and the subsequent expansion of concrete [2–10].

The use of alkali-reactive siliceous aggregates in concrete can cause severe damage to concrete structures due to the development of the expansive ASR [5,6]. In the presence of free moisture, the gel will expand and cause cracking and differential movements in structures, as well as other deleterious effects, such as reductions in freeze–thaw durability and in strength properties of concrete [7]. As the concrete deteriorates, more water enters to fuel the reaction. This cycle continues until the concrete deteriorates past the point of serviceability [8]. The expansion behavior of mortars due to ASR varies significantly depending on a combination of both the mineralogical composition of cement and the reactive component of aggregate because for a given reactive aggregate, the degree of ASR is influenced by hydration characteristics of cement used [9,10].

Fookes [11] gave examples of aggregates that cause AAR. They are cherty limestone and mudstone, and some volcanic rocks having acidic or acidic-intermediate character. Grattan-Bellew et al. [12] studied mortar bars made with basalt, dolostone, granite, limestone, and pure crystalline quartz. They indicated that aggregate composition and particle size affect the expansion of mortar bars. Wakizaka [13] and Marfil and Maiza [14] implied that volcanic rocks, including volcanic glass, are dangerous from the point of alkali–silica reactivity. St. John [15] also indicated that volcanic glass in the groundmass of rhyolite, dacite, and andesite is the principal reactive component of rocks. In addition, Katayama et al. [16] indicated that where the silica content of the bulk composition exceeds 50%, basalt may be potentially reactive and should be treated as if it is an andesite in terms of reactivity.

Basaltic rocks have variable composition and texture depending on character of volcanism. Basalts of different compositions and textures were not correlated before, from the point of ASR. The aim of this study is to evaluate aggregate constituents, especially the presence of deleteri-

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* Corresponding author. Tel.: +90-388-2250115; fax: +90-388-2250112.
E-mail address: mkorkanc@nigde.edu.tr (M. Korkanç).

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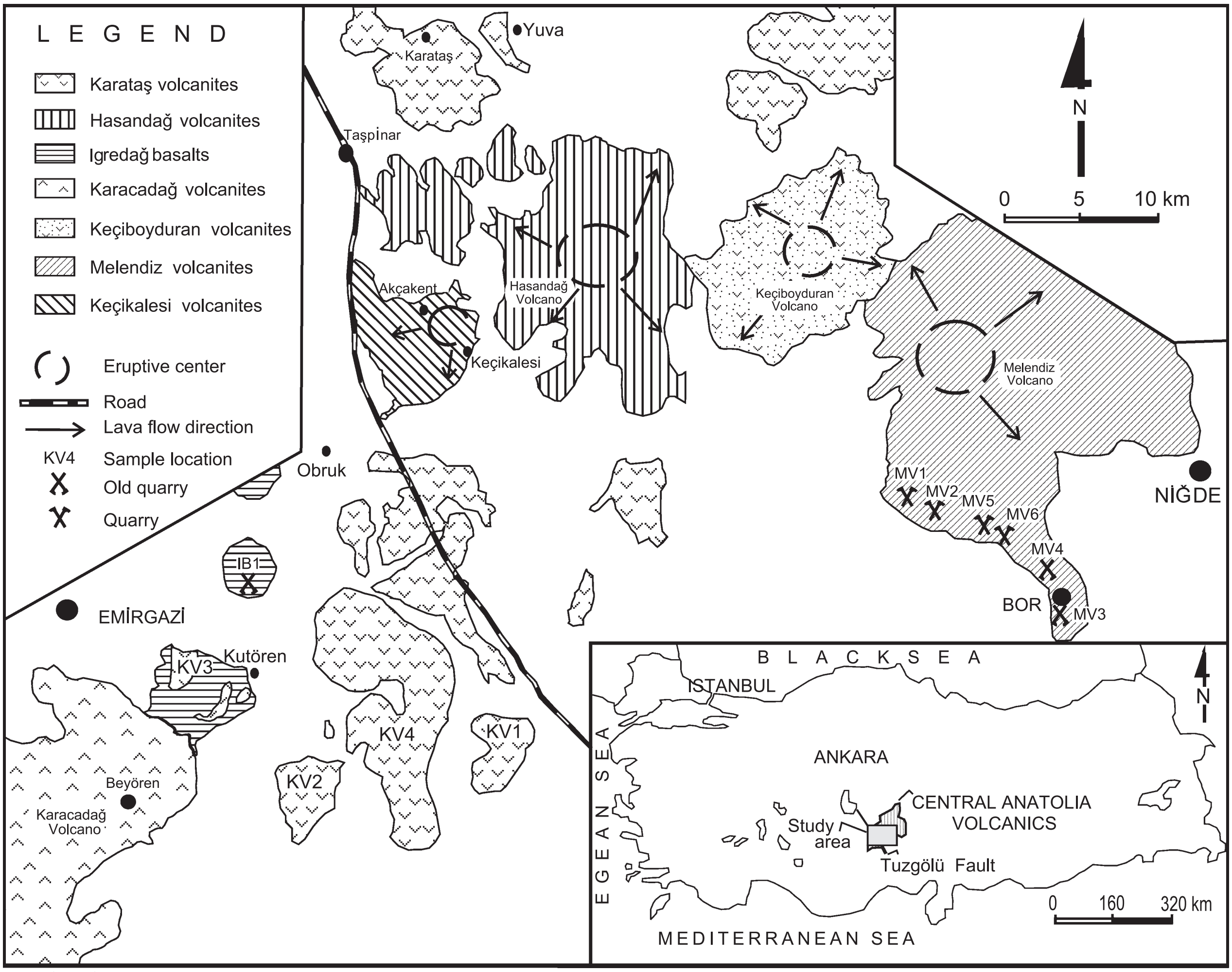
doi:10.1016/j.cemconres.2004.06.013



Modified from [19,20]

Fig. 1. Map showing location of the samples.

ous components and find main causes of the AAR based on the petrographic studies on the basalt aggregates and also to determine the reactivity of the basalts by means of accelerated mortar bar tests. Minerals of the basalt aggregates and their percentages were determined by using point counter under optical microscope. The effect of aggregate composition on the expansion of mortar bars, due to ASR, was evaluated by mortar bars made with basalts having different composition and texture. Scanning electron microscope (SEM) studies were conducted to evaluate microcracking,

Table 1
Geological and petrographical characteristics of the basalts

Sample code	Formation	Sample location	Rock name[a]	Age	Minerals and relative abundance
MV1	Melendiz volcanites	North of Bor	Basalt	Early Pliocene–Pleistocene	plg>ol>op>sm>px
MV2	Melendiz volcanites	North of Bor	Basalt	Early Pliocene–Pleistocene	plg>px>sm>op
MV3	Melendiz volcanites	Bor (Kayabaşı)	Olivine Basalt	Early Pliocene–Pleistocene	plg>ol>op>sm
MV4	Melendiz volcanites	Bor (Mezarlık)	Olivine Basalt	Early Pliocene–Pleistocene	plg>px>ol>op>sm
MV5	Melendiz volcanites	Northeastern Bor	Basalt	Early Pliocene–Pleistocene	plg>ol>sm>op
MV6	Melendiz volcanites	Northeast of Bor	Basalt	Early Pliocene–Pleistocene	plg>px>sm>op
KV1	Karataş volcanites	East of Kutören	Olivine basalt	Late Quaternary	plg>ol>op>px
KV2	Karataş volcanites	South of Kutören	Olivine basalt	Late Quaternary	plg>ol>op>px>sm
KV3	Karataş volcanites	West of Kutören	Basaltic andesite	Late Quaternary	plg>g>ol>op
KV4	Karataş volcanites	East of Kutören	Olivine basalt	Late Quaternary	plg>ol>op>sm
IB1	İğredağ Basalts	İğredağ quarry	Olivine basalt	Early Quaternary	plg>ol >px>op

plg.: Plagioclase, px: pyroxene, ol: olivine, g: volcanic glass, sm: secondary minerals, op: opaque minerals.

[a] According to Ref. [27] classification.

Table 2
Chemical composition of the cement

Component (%)	LOI	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	Na_2O_{eq}
Cement	3.28	19.75	5.00	4.07	64.07	1.94	0.64	0.57	1.015

characteristics of the aggregate–cement interface, and the development of reaction products.

2. Materials and methods

The locations of the volcanic complexes are shown in Fig. 1. They are Karacadağ, Hasandağ, Keçikalesi, Keçiboyduran, and Melendiz volcanic complex, which activated in different periods of time. Besides these complexes, there are also İğredağı, Karataş, and different monogenic (secondary) eruptions out of the complexes. These complexes generally have a basic character.

İğredağ basalts, Karataş volcanites, and basaltic lavas belonging to the Melendiz volcanic complex were selected for detailed studies (Fig. 1). Lower Pliocene Melendiz volcanic complex is made up of agglomerate, breccia, basalt, andesite, and basaltic andesite [17,18]. Early Quaternary İğredağ basalts contain olivine basalts, and Late Quaternary Karataş basalts contain olivine basalt, basaltic andesite, and basalt [19,20]. Changes in composition and texture of selected basalts are very frequent in the region; for this reason, they were classified into 11 different groups, according to their macroscopic characteristics, such as colour, texture, pores, and fractures (Table 1). These are Melendiz volcanites, (MV1, MV2, MV3, MV4, MV5, and MV6), Karataş volcanites (KV1, KV2, KV3, and KV4), and İğredağ Basalts (IB1).

The petrographic composition and textural characteristics of the basalts collected from the region were determined by thin section studies. The studies were conducted under an optical microscope.

To determine chemical characteristics and type of volcanic sequence of Melendiz and Karataş volcanites and İğredağ basalts, chemical analyses were performed. Using ICP-AES method, chemical analyses were performed and the major element oxides were determined.

A number of tests are available for an evaluation of the potential alkali reactivity of aggregates, and the reactivity of a particular cement–aggregate combination, such as petrographic method ASTM C 295 [21], the quick chemical test (ASTM C289, [22]), the mortar bar test (ASTM C227, [23]), the accelerated mortar bar test (ASTM C1260, [24]), and the rock cylinder test (ASTM C586, [25]). Petrographic analyses and accelerated mortar bar test were performed to determine reactivity of the basalts.

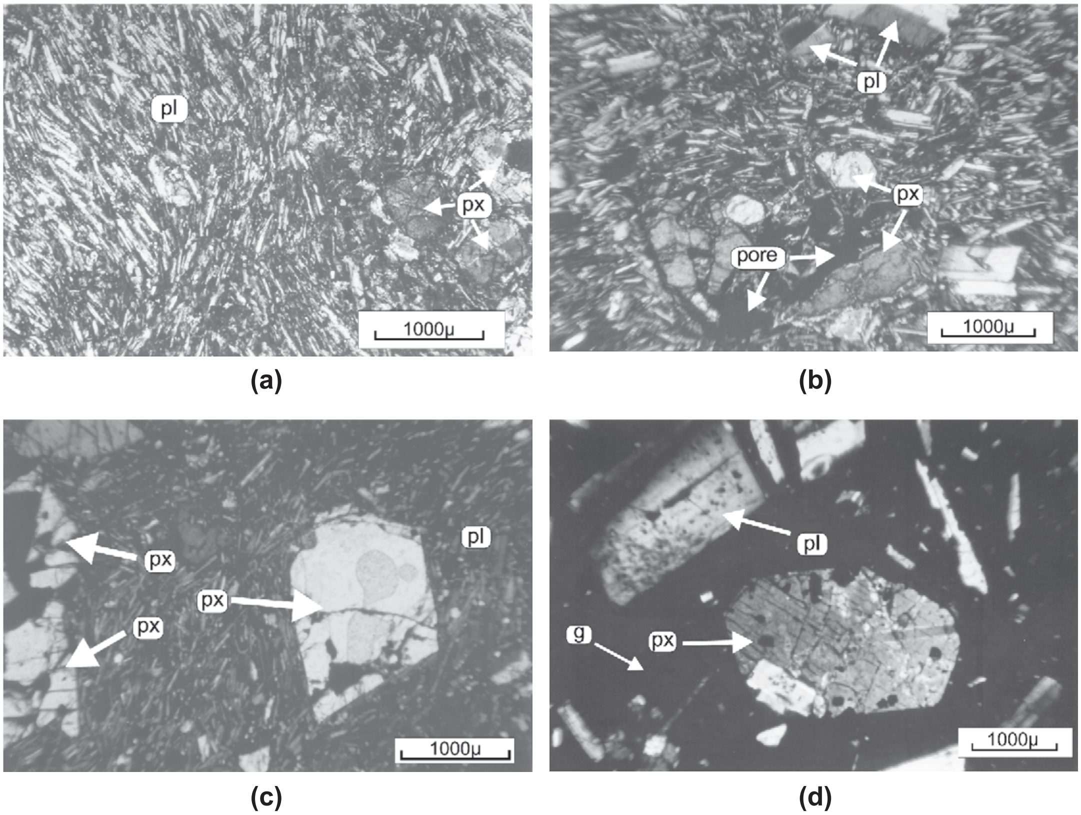


Fig. 2. Photomicrographs of (a) basalt, (b) olivine basalt, (c) olivine basalt, and (d) basaltic andesite. (a) Pyroxene in a matrix formed by plagioclase microcrysts (MV6). (b) Olivine and plagioclase phenocrysts in a matrix formed by an abundance of plagioclase and pores (MV3). (c) Clinopyroxene (augite) phenocrysts in a matrix formed by an abundance of plagioclase (KV2). (d) Plagioclase and clinopyroxene phenocrysts in a matrix mainly composed of volcanic glass (KV3).

Table 3
Chemical composition of the basalts

Major element oxide (%)	MV1	MV2	MV3	MV4	MV5	MV6	KV1	KV2	KV3	KV4	IB1
SiO_2	60.97	60.92	51.19	51.07	60.89	60.97	49.17	48.36	54.36	49.06	49.69
Al_2O_3	17.01	16.99	17.14	17.02	16.9	16.79	15.91	16.05	20.37	16.65	15.48
Fe_2O_3	5.48	5.50	8.13	8.06	5.41	5.40	8.74	8.49	7.04	9.16	8.21
MgO	2.96	2.67	6.50	6.61	3.23	2.98	9.31	9.12	2.67	7.96	9.14
CaO	7.09	7.12	9.12	9.08	7.17	7.29	10.70	10.69	8.96	9.52	11.02
Na_2O	3.27	3.30	3.83	3.83	3.23	3.26	3.33	2.34	2.97	3.41	3.05
K_2O	1.21	1.21	1.61	1.63	1.28	1.18	0.68	0.67	1.81	0.89	1.00
TiO_2	0.70	0.70	1.31	1.30	0.69	0.70	1.12	1.29	0.71	1.54	1.01
P_2O_5	0.14	0.14	0.56	0.56	0.14	0.15	0.36	0.32	0.17	0.36	0.35
MnO	0.09	0.08	0.13	0.13	0.08	0.08	0.15	0.14	0.12	0.15	0.14
Cr_2O_3	0.009	0.007	0.025	0.026	0.008	0.006	0.048	0.049	<0.001	0.031	0.055
LOI	0.6	1.2	0.1	0.2	0.7	0.9	<0.1	1	0.6	0.8	0.4
Sum	99.63	99.94	99.83	99.69	99.83	99.81	99.57	99.67	99.9	99.67	99.72

Minerals of the basalt aggregates, which cause AAR, and their percentages, were determined by using point counter under optical microscope, according to ASTM C 295 [21].

A quick and reliable test for the assessment of the potential alkali–aggregate reactivity is the accelerated mortar bar test. This test was performed on at least three samples in accordance with CSA A23.2-25A [26] that is similar to ASTM C1260 [24]. Concrete mixes were prepared using each of the basalts and tested in a standard gradation, a high-alkali Portland cement (PC 42.5), and distilled water. Table 2 gives the chemical and physical characteristics of the Portland cement used along with its phase composition calculated by the Bogue method. Industrial cement containing 1.015% Na_2O_{eq} and broken basalts were used to prepare bars (25 × 25 × 285 mm). The cement met all the requirements for use in the mortar bar. The bars were demoulded after 1-day storage in air at 20 °C and relative humidity more than 50%, and subsequently cured in alkaline solutions at 80 °C. Their elongation was first measured after 24 h. Successive measurements were taken after 7, 14 and 21 days. The percent linear expansion of the prisms at a given curing time was determined as the average expansion of three specimens. Mortar bars with surface cracks attributed to the AAR were observed using SEM equipment.

3. Results and discussion

3.1. Petrographical characteristics of the basalts

According to the petrographical studies, mineralogical composition, texture, and fabric characteristics of different

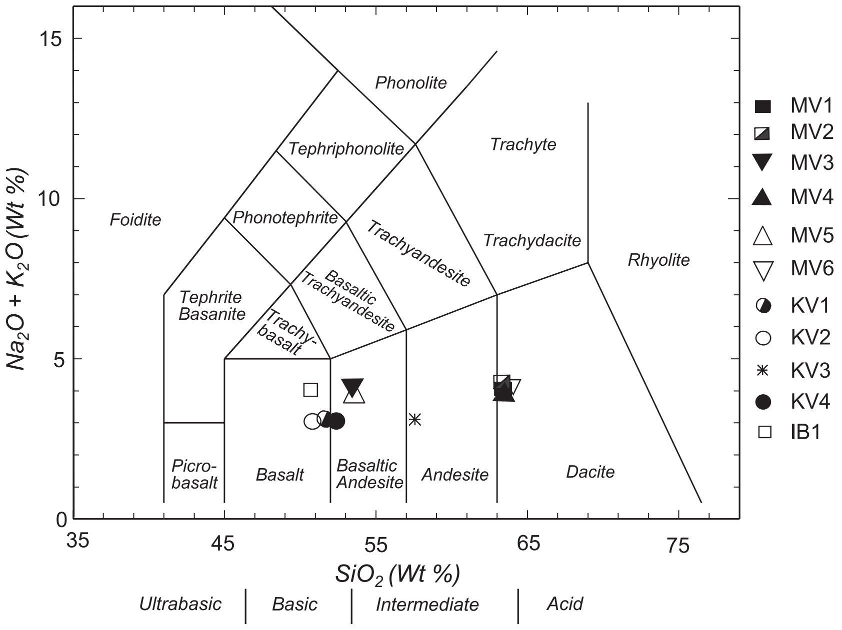


Fig. 3. Classification of the basalts according to Ref. [28].

Table 4
Results of the accelerated AAR test

Sample code	Expansion at 7 days, E_7 (%)			Expansion at 14 days, E_{14} (%)			Expansion at 21 days, E_{21} (%)		
	Minimum	Maximum	Mean	Minimum	Maximum	Mean	Minimum	Maximum	Mean
MV1	0.005	0.123	0.072	0.062	0.128	0.093	0.068	0.159	0.119
MV2	0.008	0.025	0.018	0.040	0.057	0.049	0.076	0.093	0.083
MV3	0.006	0.017	0.012	0.010	0.038	0.021	0.015	0.042	0.025
MV4	0.009	0.030	0.018	0.009	0.031	0.019	0.010	0.039	0.027
MV5	0.053	0.088	0.073	0.157	0.170	0.163	0.181	0.205	0.191
MV6	0.027	0.010	0.072	0.030	0.010	0.074	0.027	0.116	0.085
KV1	0.002	0.010	0.006	0.005	0.112	0.009	0.006	0.016	0.011
KV2	0.005	0.029	0.017	0.006	0.029	0.017	0.074	0.035	0.021
KV3	0.030	0.047	0.039	0.076	0.087	0.081	0.124	0.134	0.130
KV4	0.017	0.039	0.028	0.045	0.068	0.056	0.054	0.077	0.065
IB1	0.007	0.019	0.011	0.009	0.021	0.013	0.011	0.021	0.016

basalts were determined. A summary of the geological and petrographical characteristics of different basalts is given in Table 1.

The samples MV1, MV2, MV5, and MV6 that were collected from Melendiz volcanites were differentiated according to their phenocrysts, pores, and opaque mineral contents. They have a composition between basalt and andesite. They are composed of clinopyroxene (augite) with a lesser amount of opaque minerals, in a matrix formed by an abundance of plagioclase microcrysts (Fig. 2a). Clinopyroxenes are slightly weathered. The MV5 and MV6 samples contain a higher percentage of secondary epidote (approximately 4.5%) as hydrothermal alteration product. Plagioclase microcrysts have fluvial texture. The matrix content is higher than crystal content within these samples. The MV3 and MV4 samples belonging to Melendiz volcanites were classified according to their crystal and matrix content and the size of plagioclase microcrysts (Fig. 2b). They are olivine basalts and have porous structure. Their epidote content as hydrothermal alteration product is 3.5%. Opaque mineral content is higher than the other facies. Olivine and plagioclase phenocrysts are in a matrix formed by an abundance of plagioclase.

The Karataş volcanites KV1, KV2, and KV4 were classified, according to their olivine and clinopyroxene and opaque mineral content, as olivine basalts. They are composed of olivine and clinopyroxene (augite) phenocrysts and a lesser amount of opaque minerals. The opaque mineral content is approximately 3–5% and this value is highest in KV4. They have porphyritic and pilotaxitic texture (Fig. 2c). The matrix content is higher than crystal content within these samples. Slightly weathered matrix contains microcrystalline plagioclase microlites. KV3 sample that belong to Karataş volcanites is basaltic andesite, and consists of plagioclase phenocrysts and a lesser amount of clinopyroxene (augite), opaque mineral, and pores (Fig. 2d). Opaque mineral content is generally 1%. Its matrix mainly composed of unweathered volcanic glass (43.6%) and texture is hyaloporphyric and porphyritic.

İğredağ basalts (IB1) are composed of coarse olivine phenocrysts with a lesser amount of opaque minerals, in a matrix formed by an abundance of plagioclase microcrysts and a lesser amount of volcanic glass. Percentage of opaque minerals is between 2 and 3. Opaque minerals are generally magnetite. Epidote, calcite, and chlorite are secondary minerals. They have poikilitic and intersertal texture. Matrix content is higher than crystal content within these samples. The olivine crystals are slightly weathered.

3.2. Chemical composition of the basalts

The chemical compositions of the basalts are given in Table 3. As seen in this table, the basalts contain 49.06–60.97% SiO_2, 15.48–20.37% Al_2O_3, 2.67–9.31% MgO, 7.09–11.02% CaO, 2.97–3.83% Na_2O, 0.67–1.81% K_2O, 0.69–1.54% TiO_2, and 0.14–0.56% P_2O_5. Total Fe_2O_3 content is low and between 5.40% and 9.16%, except MV3 and MV4 samples. MnO and Cr_2O_3 contents are also low, between 0.08% and 0.15% and between $<0.001\%$ and 0.049%, respectively. Loss on ignition changes between $<0.1\%$ and 1.2%.

Katayama et al. [16] implied that, where the silica content of the bulk composition exceeds 50%, basalt may be potentially reactive and should be treated as if it is an andesite in terms of reactivity. According to the chemical analyses, most of the basalts have more than 50% SiO_2, and therefore, should be studied from the point of alkali reactivity. The results of the chemical analysis were also evaluated according to Ref. [28]. The samples MV3, MV4,

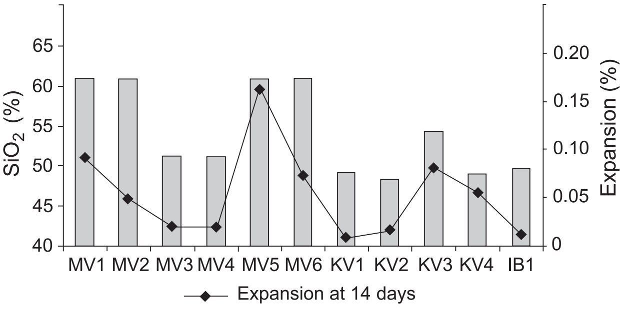


Fig. 4. Bar chart showing the SiO_2 content of the basalt and changes in expansion values at 14 days.

KV1, KV2, KV4, and IB1 have a basic character while others have an acidic-intermediate character (Fig. 3).

3.3. Alkali–aggregate reactivity

According to petrographic observations, the matrix of KV3 sample is mainly composed of volcanic glass. Unaltered volcanic glass is important as deleterious material from the point of alkali–aggregate reactivity. The reactivity of volcanic glass was indicated firstly by Stanton et al. [29] and Rhoades [30]. The solubility of volcanic glass in alkali solution is very high. If a rock has a small glass content, it almost completely dissolves in solution, and so the dissolved concentration becomes large [31]. Quartz polymorphs that cause ASR were not observed in the studied basalts.

The results of the accelerated mortar bar test are given in Table 4. According to the results obtained, maximum dilatation in length at 14 days is 0.161%. Fig. 4 shows the changes in dilatation in length against time. The dilatation in length after 14 days is maximum in MV5 and minimum in KV1. The samples having a higher percentage of SiO_2 (Fig. 4; MV1, MV2, MV5, MV6, and KV3) show more expansion than olivine basalts. The samples MV1, MV2, MV5, and MV6 have an acid-intermediate character; KV3 has a matrix that is composed of volcanic glass.

According to ASTM C1260 [24], the percentage of dilatation in length for 14 days should be under 0.10%. Expansions of less than 0.10% at 14 days are indicative of innocuous behavior in most cases. Expansions between 0.10% and 0.20% at 14 days include both aggregates that are known to be innocuous and deleterious. In such a situation, it may also be useful to take comparator readings until 28 days. According to CSA A23.2-94 [26], percent expansion at 21 days for coarse and fine aggregates should be under 0.10% and 0.15%, respectively. Expansion less than 0.10% (0.15% for fine aggregates) related with nonreactive aggregates, and expansion between 0.10% and 0.40% (0.15–0.45% for fine aggregates) related with aggregates having potential for significant slow ASR. Davies and Oberholster [32], and Hooton and Rogers [33] also indicated that expansions of less than 0.10% at 14 days after casting are indicative of satisfactory behavior in most cases.

Although most of the results of the AAR test are under the standard limits, the MV1, MV5, MV6, and KV3 showed expansion more than 0.10%. For this reason, comparator readings were taken until 28 days. The results were under 0.20%. The basalts having acidic-intermediate character and matrix that is composed of volcanic glass cause expansion. However, the obtained results are applicable only to the studied samples, as there are records of basaltic rocks that are highly reactive with respect to the ASR, where mortar bar expansions greatly exceed the threshold values set by the standards.

As indicated by Mather [34], excessive expansion of concrete due to ASR will not occur if any one of the following circumstances exists: (1) the aggregate is insufficiently reactive; (2) the pH of the pore fluid is not too high; (3) the amount of reaction product formed is not sufficiently large or not sufficiently expansive so that its expansion can cause damage; or (4) there is not enough available water to cause the reaction to progress so as to develop the expansive product and to be available for imbibitions by the product so as to cause it to swell and disrupt the concrete.

Mortar bars were also observed by SEM. These observations confirm that the concretes made from MV1, MV5, MV6, and KV3 are affected by ASR, and show the occurrence of alkali–silica gel. Fig. 5a shows a coating of crust on the surface of aggregate exhibiting the characteristic expansion cracks. Similar cracks were observed in KV3 (Fig. 5b). Reaction products were observed to have developed at the aggregate surface and aggregate–paste interface.

According to ASR tests and SEM observations, for the use of ASR-susceptible basalts having acidic-intermediate character or volcanic glass in their matrix as concrete aggregate, some preventive measures should be taken into account as recommended by Fookes [11] and Berra et al. [5]. They are as follows: (1) limiting the alkali content of the

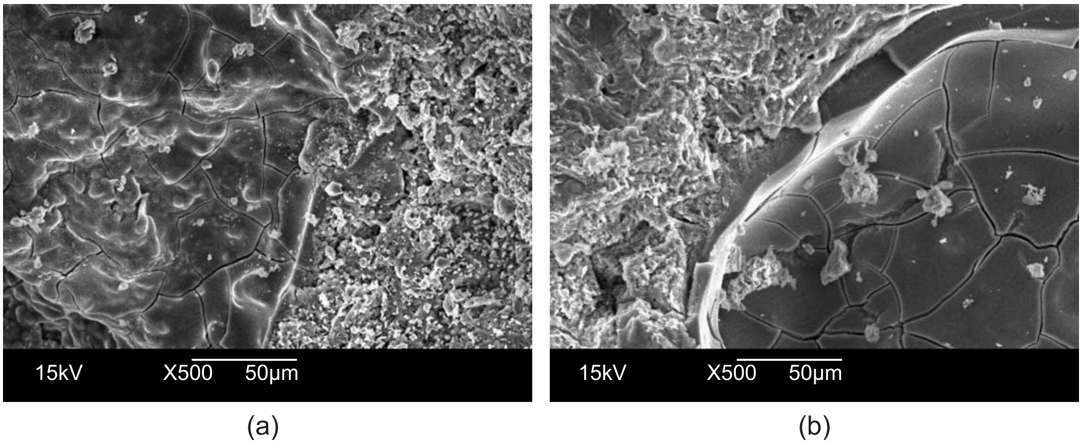


Fig. 5. SEM photomicrographs showing expansion cracks in alkali silica gel. (a) MV6; (b) KV3.

concrete by reducing the cement content and/or by using a low-alkali Portland cement, and (2) adding supplementary cementing materials, such as pozzolan, fly ash, etc.

4. Conclusions

To identify the reactivity of basalt aggregates, the study was carried out in the Niğde Region of Turkey. The detailed studies were carried out on Melendiz volcanites, Karataş volcanites, and İğradağ basalts. Petrographical studies indicate that most of the basalts are basalt, olivine basalts, and basaltic andesite.

The petrographical and accelerated mortar bar methods were carried out on the basalt aggregates from quarries and outcrops. The reactivity of basalts is controlled by the presence of volcanic glass, alteration minerals, and the SiO_2 content more than 50%. Quartz polymorphs that cause ASR were not observed in the studied basalts. AAR gel was identified by SEM observations as the major reaction product. The gel occurred at the aggregate surface and aggregate–cement interface.

According to the results obtained from the AAR test, the expansion rates were not too high. The basalts having acidic-intermediate character or volcanic glass in their matrix show expansion generally more than 0.10% after the test, and they are potentially alkali–aggregate reactive according to the standard values. The others show a little expansion after the test. This may be due to the fact that basalt aggregates are insufficiently reactive, the amount of reaction products are not enough to cause expansion or not sufficiently expansive. However, a larger range of basalts needs to be tested to confirm this correspondence.

Acknowledgements

This study was supported by the Research Fund of the İstanbul University. Project number: 27/08092002. The authors would like to express their thanks to Assist. Prof. Hasan Emre for petrographic descriptions, and to the reviewers for their comments and suggestions.

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