

The effect of natural sand composition on concrete strength



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HIGHLIGHTS

- Natural sands vary in composition and may cause different concrete strength.
- We highlight some mechanical aspects regarding the use of sand from different origins.
- Sands containing smectite-type clays cause lower concrete strength.
- Na₂O content of sands is important for predicting the strength of concrete.

ARTICLE INFO

Article history:

Received 15 May 2015

Received in revised form 9 February 2016

Accepted 25 February 2016

Available online 10 March 2016

Keywords:

Aggregate

Alkali-silica reactions

Concrete

Natural sand

ABSTRACT

Natural sands show a variety of mineralogic compositions and chemical characteristics; when sand is used in concrete aggregate, these properties may result in different concrete strengths. However, there is little data about the effects of different sand aggregates on concrete strength. In this work we highlight some mechanical aspects regarding the use of sand from different origins such as concrete aggregate. The sand samples were first tested to determine their mineralogic and chemical characteristics and their aggregate properties. Then, concrete test samples were prepared using these aggregates, and the properties of the fresh and hardened concrete were determined. The results show that although all the samples were found to be suitable for use as fine aggregate in high-strength concrete production, natural sands that contained smectite-type clays have poor aggregate quality compared with other sands. Conversely, the chemical composition of the natural sand samples, especially the Na₂O content, is important for predicting the strength properties of hardened concrete.

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1. Introduction

Aggregates form the major constituent of concrete. They generally account for 75–80% of the volume of the concrete and would therefore be expected to have an important influence on the concrete's properties. Another constituent of concrete is natural sand, which makes up about 25–28% of the volume of aggregate used in the construction industry [1,2].

Good quality aggregate should consist of particles of adequate strength and desirable engineering properties as well as resistance to exposure conditions [3–5]. Aggregates containing materials such as coatings, reactive silica, sulfate, clay, feldspar, and mica can potentially cause damage to the short- and long-term performance of the concrete [6]. Aggregates with varying mineralogical composition produce concrete of diverse characteristics. According to Alexander [7], the aggregate properties affect the strength, stiff-

ness, and long-term deformation of hardened concrete. For example, some aggregates may react negatively with cement or, in contrast, they may interact beneficially with the cement paste, enhancing the concrete's strength or stiffness. As a result, concrete properties such as elastic modulus, creep, or shrinkage can vary as much as 100% depending on the aggregate type. The type of aggregate also affects the interfacial transition zone (ITZ), which has an effect on the strength of the concrete. Finally, the type of aggregate influences the abrasion resistance of the concrete, particularly that of high-strength concrete. The coating, the layer of material covering the surface of the aggregate, can increase the demand for water and can impair the bond between the paste and the particles. Coatings are sometimes formed by materials that can interact chemically with the cement, which negatively affect the concrete [8,9]. In addition, natural sand, which consists primarily of uncrushed rounded particles, is often used in concrete mixes because it is generally less expensive, readily available and can be blended easily with other materials. However, natural sand has a smooth, rounded surface texture that greatly reduces the interlocking properties of the concrete, reducing its strength properties [10–14].

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The aim of this study is to evaluate the effects of the composition of natural sand of different origins on concrete strength. To date, many researchers have studied natural sand used for concrete production but there is little information on assessing natural sand samples of different origin for concrete strength.

2. Materials, methods and results

The samples used in this study were collected from sand quarries in different areas of the Marmara region, Turkey, and selected to represent different natural sands (Fig. 1 and Table 1). Sand from seven different areas was subjected to laboratory experiments. The study was conducted in four stages: (a) mineralogical and chemical analysis, (b) aggregate tests (percentage of fine materials, methylene blue

absorption, sand equivalent, particle density, water absorption, loose bulk density, magnesium sulfate value, and alkali–silica reactivity), (c) scanning electron microscopy (SEM) to observe the effects of the alkali–silica reaction (ASR) and its products, and (d) concrete strength assessment; concrete samples were prepared using various sand samples, and the properties of the hardened concrete were determined.

2.1. Description of the selected natural sands

The studied sand was collected from seven different sand quarries in the Marmara region, Turkey, because there are different originated sands in these quarries. Table 1 displays the general characteristics of the studied sand; five sampling sites provided sand from terrestrial sources or river deposits while two sites provided sea sand.

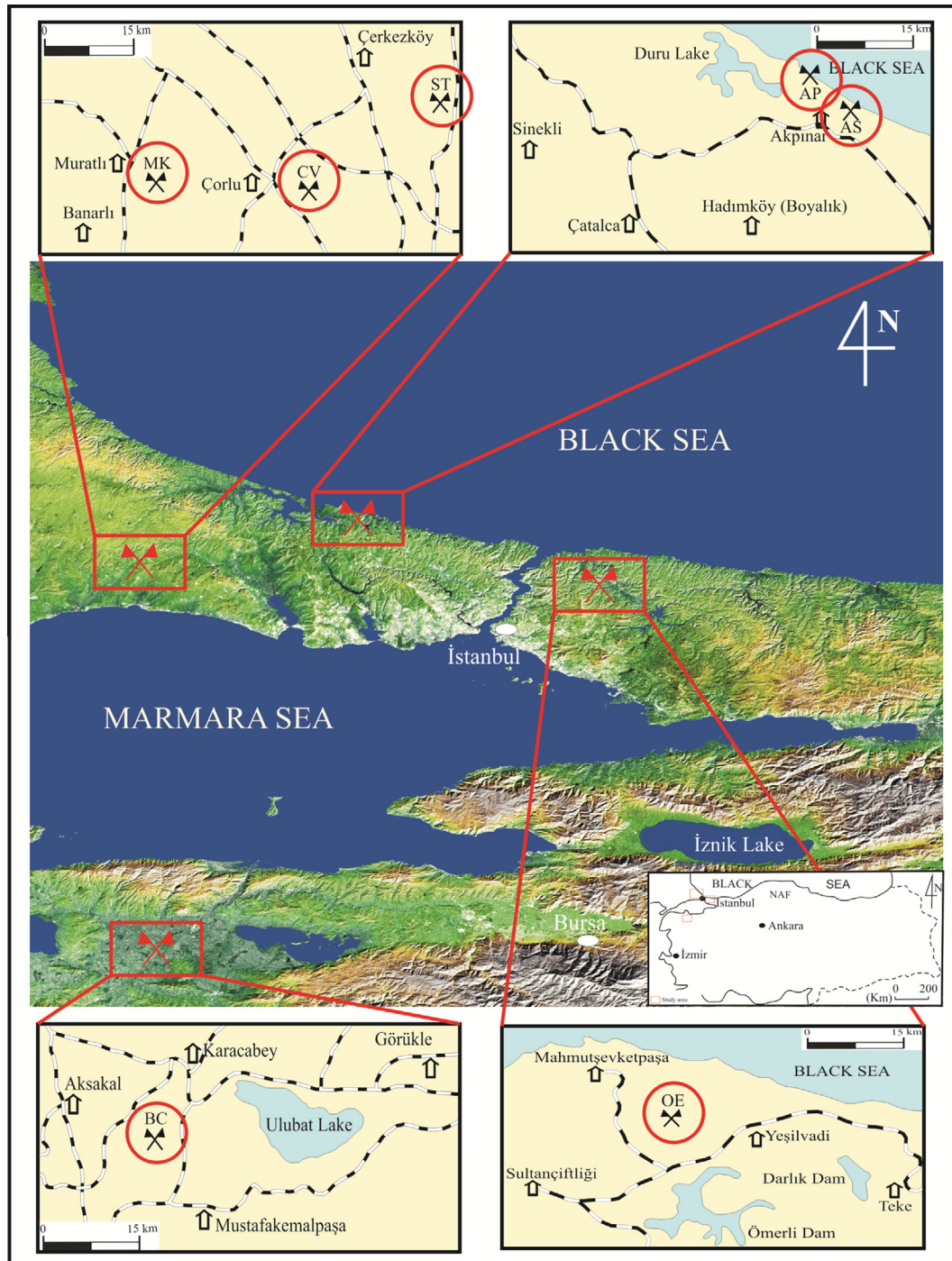


Fig. 1. Location map of the natural sands tested.

Table 1

Locations and geological characteristics of studied sands.

Sample code	Sample location	Color	Depositional settings	Age
AP	Black Sea shore (taken from sea)	Grayish white, yellowish	Marine	Holocene
AS	Black Sea shore	Grayish white, yellowish	Dune	Holocene
MK	Thrace-Muratlı	Whitish yellow	Terrestrial-river (alluvial-fluvial)	Middle-Upper Miocene
CV	Thrace-Çorlu	Brownish yellow-white	Terrestrial-river (alluvial-fluvial)	Middle-Upper Miocene
ST	Thrace-Sinekli	Brownish yellow-white	Terrestrial-river (alluvial-fluvial)	Middle-Upper Miocene
OE	İstanbul-Ömerli	Whitish yellow	Terrestrial (alluvial)	Upper Oligocene- Miocene
BC	Bursa-Mustafa Kemalpaşa	Yellowish white, Brownish grey	Terrestrial - river (alluvial-fluvial)	Quaternary

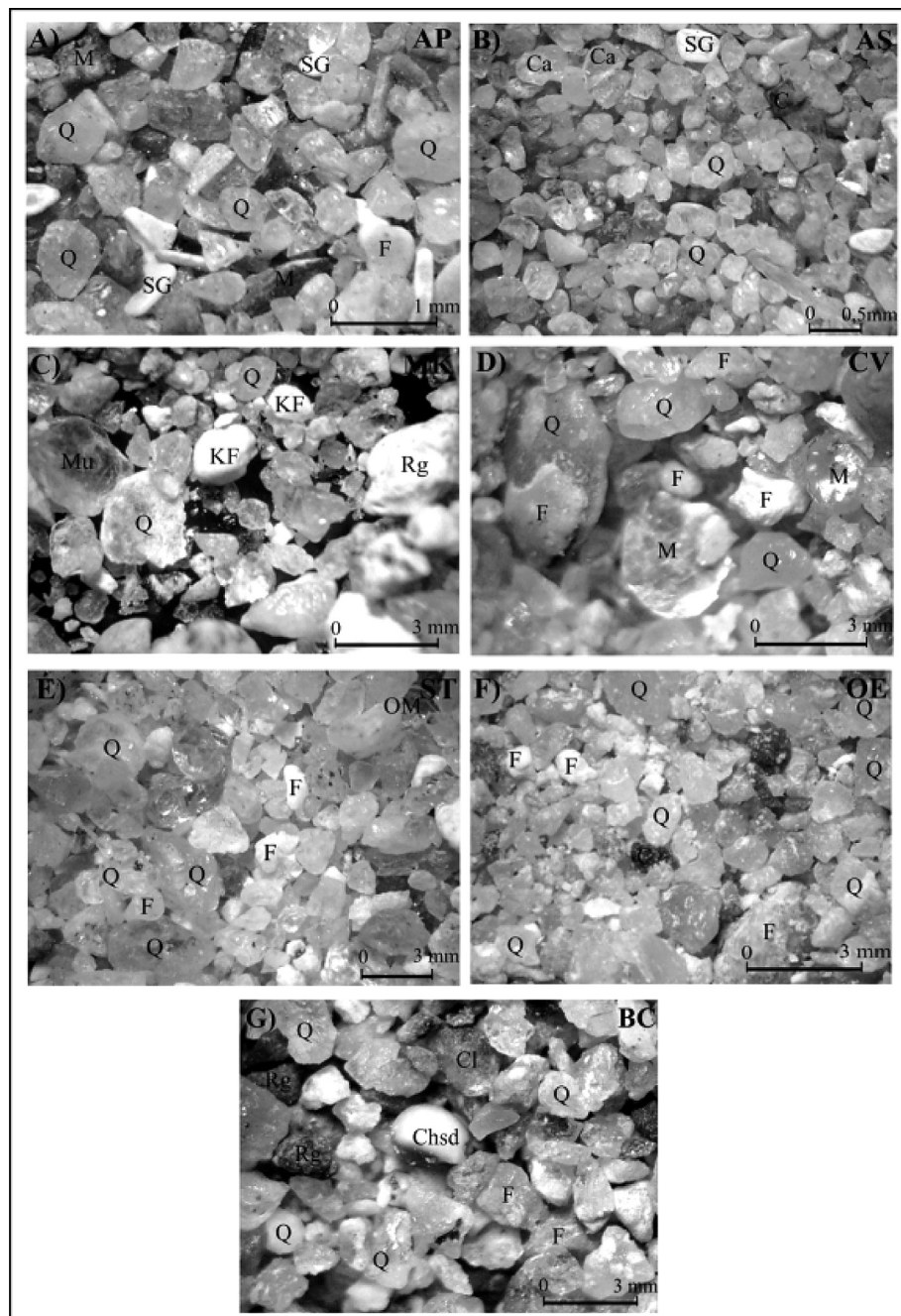


Fig. 2. Binocular microscope photographs of the studied sands collected from plant in quarries A) AP, B) AS, C) MK, D) CV, E) ST, F) OE, G) BC (Q: Quartz, F: Feldspar, C: Clay (smectite), SG: Shell Grain, Ca: Calcite, M: Mica, OM: Oxidized Mineral, Mu: Muscovite, KF: Kaolinized Feldspar, Cl: Chlorite, Chsd: Chalcedony, Rg: Rock grain such as granite, volcanic rock particle and their alteration products).

Table 2
Mineralogical composition of the sands and mortars.

Sample code	Mineralogical composition			Mineralogical composition of mortar
	Binocular microscopic observations	Quartz Content (%)	XRD analysis (relative abundance)	
AP	Quartz, calcite, feldspar, muscovite, amethyst, chert/chalcedony, chlorite, epidote, sea shell (30%) (Fig. 2a)	50–60	Quartz > calcite > feldspar (K, Plj) > muscovite	Quartz, quartzite grains, calcite
AS	Quartz, calcite, chert/chalcedony (1–2%), feldspar, sea shell (3–5%) (Fig. 2b)	95–97	Quartz > calcite > feldspar (K, Plj) > muscovite	Quartz, calcite, plagioclase, oxidized minerals, metamorphic rock (schist, phyllite) and quartzite grains
MK	Quartz, muscovite, chert/chalcedony, feldspar, granite grains, smectite clay (Fig. 2c)	95–98	Quartz > feldspar (K, Plj) > muscovite/illite > dolomite	Quartz, plagioclase, K-feldspar, quartzite grains
CV	Quartz, feldspar, muscovite (5–6%), biotite, chlorite (2–3%), clay, chalcedony (3%), rock grains (phyllite, schist), epidote, zircon, garnet (Fig. 2d)	80–90	Quartz > feldspar (K, Plj) > muscovite > smectite > dolomite	Quartz, plagioclase, schist grains
ST	Quartz, muscovite, biotite (2–3%), smectite clay (10%) granite grains, chalcedony, kaolinized feldspar grains, garnet (Fig. 2e)	95–98	Quartz > feldspar (K, Plj) > muscovite > dolomite > smectite	Quartz, rock grains, plagioclase, chalcedony, quartzite grains
OE	Quartz, rock fragments, smectite clay (20%) (Fig. 2f)	80–85	Quartz > feldspar (K, Na) > illite > kaolinite	Quartz, quartzite grains, K-feldspar
BC	Quartz, mica, granite grains, chert/chalcedony, epidote, biotite, muscovite, smectite clay, rock grains (mica schist, volcanic rock, phyllite) (Fig. 2g)	65–70	Quartz > feldspar (K, Plj) > muscovite > kaolinite > calcite > dolomite	Quartz, quartzite grains, chalcedony, rock grains (granite, volcanic rock particle and their alteration products)

K: Potassium feldspar (orthoclase); Plj: Plagioclase; Na: Sodium feldspar (albite).

Table 3
Percentages of major element oxide of the sands.

Sample code	Major element oxide content (%)							
	SiO ₂	Na ₂ O	MgO	Al ₂ O ₃	SO ₃	K ₂ O	CaO	Fe ₂ O ₃
AP	68.15	0.89	0.62	7.36	0.37	2.39	17.19	1.47
AS	77.32	0.62	0.79	4.01	0.52	2.04	13.35	1.15
MK	85.67	1.27	0.50	8.19	0.04	3.50	0.76	–
CV	79.41	1.64	0.56	10.05	0.29	4.20	1.17	2.02
ST	79.59	1.70	0.76	10.53	0.09	3.36	1.22	1.93
OE	83.93	0.30	0.36	12.77	0.11	1.60	0.42	1.01
BC	66.74	1.44	5.17	13.23	0.05	3.30	5.32	3.98

2.2. Laboratory analysis

2.2.1. Petrographic, mineralogical and chemical properties

The samples were firstly examined with a binocular microscope. Then, X-ray diffraction (XRD) analysis was performed on an XRD-6000 diffractometer (Shimadzu, Japan) with a Cu X-ray tube ($\lambda = 1.5405$ Å). The XRD analysis results were consistent with those of the binocular microscope (Fig. 2 and Table 2).

Additionally, to observe the petrographic characteristics of the sand grains, a thin section was prepared from mortar composed of cement and sand for each of the sand samples and polarizing microscopic studies were conducted on the thin sections (Table 2 and Fig. 3).

Table 4
Results of aggregate tests.

Aggregate tests and standard no.	AP	AS	MK	CV	ST	OE	BC
Fine materials (%)	2	2.4	2.8	4.4	5.3	1.2	2.5
TS EN 933-1 (1999)							
Methylene blue absorption (g/kg)	1.3	1	1.6	2.3	1.9	1	1.5
TS EN 933-9 (2010)							
Sand equivalent (%)	86	96	95	78	83	93	86
TS EN 933-8 (1999)							
Saturated surface dried particle density (Mg/m ³)	2.61	2.62	2.62	2.58	2.56	2.61	2.56
TS EN 1097-6 (2002)							
Water absorption (%)	1.33	1.02	1.27	2.32	2.54	1.22	1.94
TS EN 1097-6 (2002)							
Loose bulk density (Mg/m ³)	1398	1408	1436	1324	1374	1454	1420
TS EN 1097-3 (1999)							
Magnesium sulfate (MgSO ₄) value (%)	8.5	12.8	4.2	9.8	14.5	5.5	10.7
TS EN 1367-2 (2011)							

To determine the chemical characteristics of the natural sand, chemical analyses were performed by semi-quantitative elementary analysis using an X-ray fluorescence spectrometer (Philips PW-2404), and the major element oxides were determined. The chemical compositions of the sand samples are given in Table 3.

2.2.2. Aggregate properties

The aggregate tests undertaken include the percentage of fine materials, methylene blue test, sand equivalent test, relative density, water absorption, loose bulk density test, and magnesium sulfate value. The results are presented in Table 4. The tests were performed in accordance with the TS EN Standards.

2.2.3. Cement properties

The cement type used in this study was CEM I 42.5 R, which was verified as conforming to TS EN 197-1 (2000). The chemical, physical, and mechanical features of this cement are given in Table 5.

2.2.4. Preparation of concrete specimens

To investigate the effects of the different samples of natural sand on the strength of the concrete, seven concrete mixes were designed. Tests were performed in accordance with the TS 802 (1985) standard. In all the mixes, the water/cement ratio was kept constant and a lignosulfonate-based plasticizers admixture was used. The mix proportions of the tested concrete samples are given in Table 6. Limestone aggregates were used as coarse aggregate in the concrete mixtures. The properties of the limestone aggregates are given in Table 7. The tests were performed in accordance with the TS EN Standards (EN), (Table 7).

Table 5
Properties of cement (CEM I 42.5 R) used in experiments.

Chemical composition (%)	Test results
Loss of ignition	2.19
Insoluble residue	0.25
MgO	1.02
SO ₃	2.95
SiO ₂	19.74
Al ₂ O ₃	5.13
Fe ₂ O ₃	3.01
CaO	62.08
K ₂ O	0.36
Na ₂ O	0.30
Na ₂ O _{eq}	0.54

2.2.5. Alkali–silica reactivity

The ASR is an internal chemical reaction between the alkaline components in the cementitious system and certain silica-based mineral constituents in some of the aggregates. The reaction results in the formation of a gel that absorbs water, expands, and produces internal stresses sufficient to cause the concrete to crack [15–17] resulting in loss of concrete strength [18–20]. To evaluate the aggregate constituents, especially in the presence of deleterious components, and identify the potential for ASR, petrographic and mineralogical analyses of the natural sands were carried out according to [21] (Table 3). The reactivity of the natural sands was also determined by an accelerated mortar bar test (AMBT), which is a fast and reliable test for the potential alkali–aggregate reactivity of an aggregate source. This test was performed on at least three samples in accordance with ASTM C [22], which is similar to CSA [23].

For the AMBT, mortar mixes were prepared using each of the seven sand samples and tested in a standard gradation with high-alkali Portland cement (CEM I 42.5 R) and distilled water. The chemical characteristics of the Portland cement are shown in Table 5. The prepared mortar bars were removed from the molds after 1 day of storage in air at 20 °C and a relative humidity of more than 50%, and cured in alkaline solutions at 80 °C. Their lengths were measured after 24 h and successive measurements were taken after 7, 14, 16, 21, and 28 days. The percent linear expansion of the mortar prisms for a given curing time was determined as the average of the expansion of three specimens. The results of the AMBTs are shown in Fig. 4.

Table 6
Concrete mix design including equal water/cement ratio.

Sample code	Cement (kg/m ³)	Water (kg/m ³)	Natural sand (kg/m ³)	Crushed stone 4–11.2 mm (kg/m ³)	Crushed stone 11.2–22.4 mm (kg/m ³)	Chemical additive (kg/m ³)	Water/cement ratio
AP	300	170	648	594	654	3.6	0.56
AS	300	170	648	594	654	3.6	0.56
MK	300	170	818	517	558	4.5	0.56
CV	300	170	696	575	616	5.1	0.56
ST	300	170	652	594	635	4.8	0.56
OE	300	170	704	575	616	3.6	0.56
BC	300	170	690	575	616	3.6	0.56

Table 7
Aggregate test results of limestone.

Aggregate tests and standard No.	Crushed stone 4–11.2 mm	Crushed stone 11.2–22.4 mm
Flakiness indices (%)	13	11
TS EN 933-3 (1997)		
Saturated surface dried particle density (Mg/m ³)	2.70	2.71
TS EN 1097-6 (2002)		
Water absorption (%)	0.63	0.50
TS EN 1097-6 (2002)		
Micro-Deval coefficient (%)	16	
TS EN 1097-1 (2011)		
Los Angeles coefficient (%)	15	
TS EN 1097-2 (2010)		
Loose bulk density (Mg/m ³)	1435	1338
TS EN 1097-3 (1999)		
Magnesium sulfate (MgSO ₄) value (%)	3.3	
TS EN 1367-2 (2011)		

2.2.6. Scanning electron microscope (SEM) observations

SEM analysis was carried out to examine the effects of the ASR and its products following the AMBTs. The samples for the SEM analysis were dried at 105 °C for 24 h. Then the dried concrete samples were carefully broken. Freshly fractured surfaces were coated with gold in a vacuum evaporator and then examined by SEM to determine their morphologic features.

2.2.7. Fresh and hardened concrete properties

To evaluate the fresh concrete properties, we performed slump, air void, and density tests on the fresh concrete (Table 8). The tests were performed in accordance with TS EN Standards. The initial slump was determined according to the procedures recommended by TS EN 12350-2 (2009). In this study, to compare the fresh and hardened concrete properties, the initial slump values were kept constant in all the mixes. The air content and density of the fresh concrete were also determined according to TS EN 12350-7 (2009) and TS EN 12350-6 (2009), respectively.

The hardened concrete properties were determined from six 150 × 150 × 150-mm cubes. After 24 h, the concrete samples were removed from the mold and cured in lime-saturated water until testing. Compressive strength tests were performed to determine the hardened concrete properties. The results of these tests are given in Table 9.

3. Discussion

Fine materials in aggregates cause a decrease in the workability of concrete. When some coatings are not removed during processing, fine material can impair the aggregate–cement bond [3,6,24]. To determine the quality of the very fine particles in fine aggregates, methylene blue and sand equivalent tests can indicate the amount of potentially harmful fine material [25]. Low absorption values may indicate a small amount of clay [26]. There is no absolute value given in published standards that limits these values. However, results based on past research indicate that if the methylene blue value is below 1 g/kg, there is no negative effect on concrete strength; a high sand equivalent value for fine aggregate indicates a positive effect on concrete properties [27,28]. According to our test results (Table 4), except for the AS and OE samples, the methylene blue values of the other sand samples are above 1 g/kg. The CV and ST samples in particular show higher methylene blue

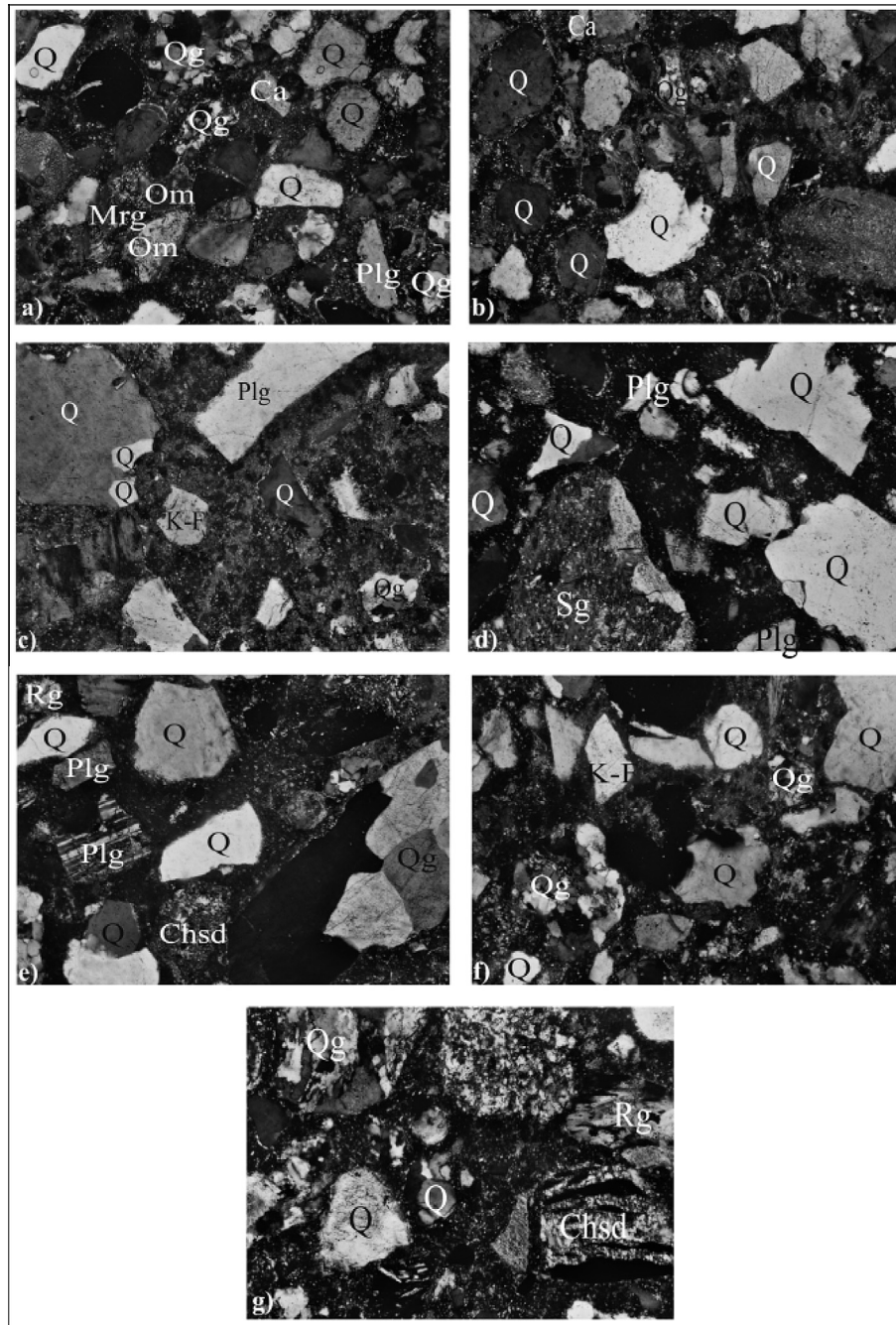


Fig. 3. Polarized microscope photographs of the mortar produced with sand samples a) AP, b) AS, c) MK, d) CV, e) ST, f) OE, g) BC (Q: Quartz, Qg: Quartzite grains, Ca: Calcite, Om: Oxidized mineral, Mrg: Metamorphic rock grains, Plg: Plagioclase, Sg: Schist grain, Rg: Rock grain, Chsd: Chalcedony, K-F: K-Feldspar).

Table 8

The properties of fresh concrete.

Fresh concrete tests	AP	AS	MK	CV	ST	OE	BC
Slump (mm) (initial)	180	180	180	180	180	180	180
Air content (%)	2.7	3.4	3.5	3.6	3.0	3.0	2.8
Density (kg/m ³)	2365	2349	2345	2323	2330	2354	2340

Table 9

The properties of hardened concrete.

Hardened concrete tests	AP	AS	MK	CV	ST	OE	BC
Compressive strength tests	2 days	25.0	23.0	20.5	18.5	19.5	23.5
	7 days	39.5	36.5	36.5	33.0	36.5	41.5
	28 days	48.0	46.0	46.0	42.0	43.5	50.0

values and lower sand equivalent values than the others, which could be due to the presence of clay (smectite) (Table 2). In addition, Al_2O_3 , K_2O , Na_2O and Fe_2O_3 contents of these samples (Table 3), are related to the existence of feldspar, clay and mica minerals (Table 2).

Fig. 5 shows the water absorption and magnesium sulfate values and the percentage of calcium oxide (CaO) of the seven sand samples. The results for all the samples apart from the AS and AP show that higher water absorption causes an increase in the magnesium sulfate value. Although the AS and AP samples have similar

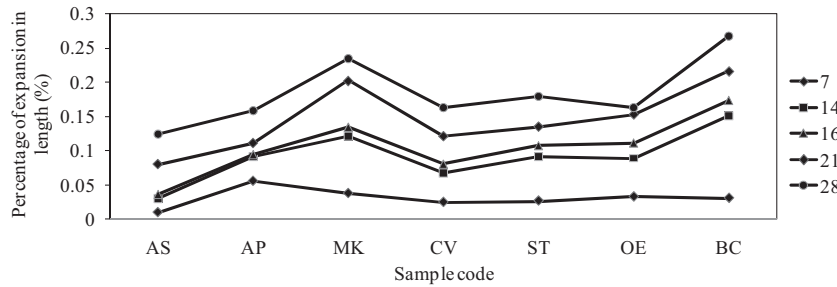


Fig. 4. Changes in expansion values at 7, 14, 16, 21 and 28 days.

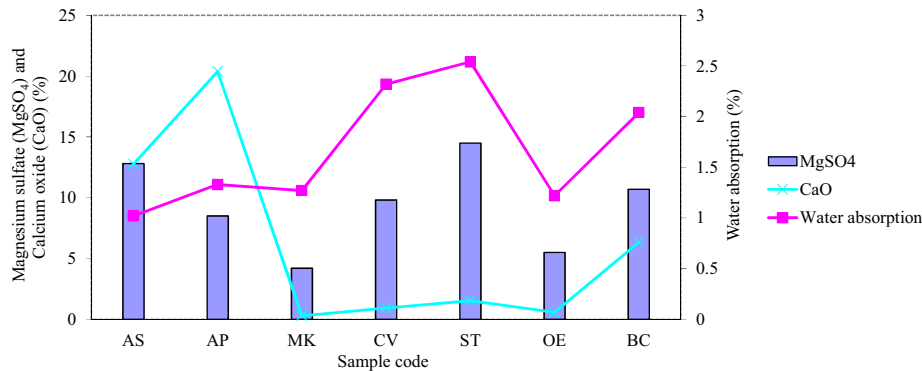


Fig. 5. Relationship between water absorption and magnesium sulfate values and percentage of calcium oxide.

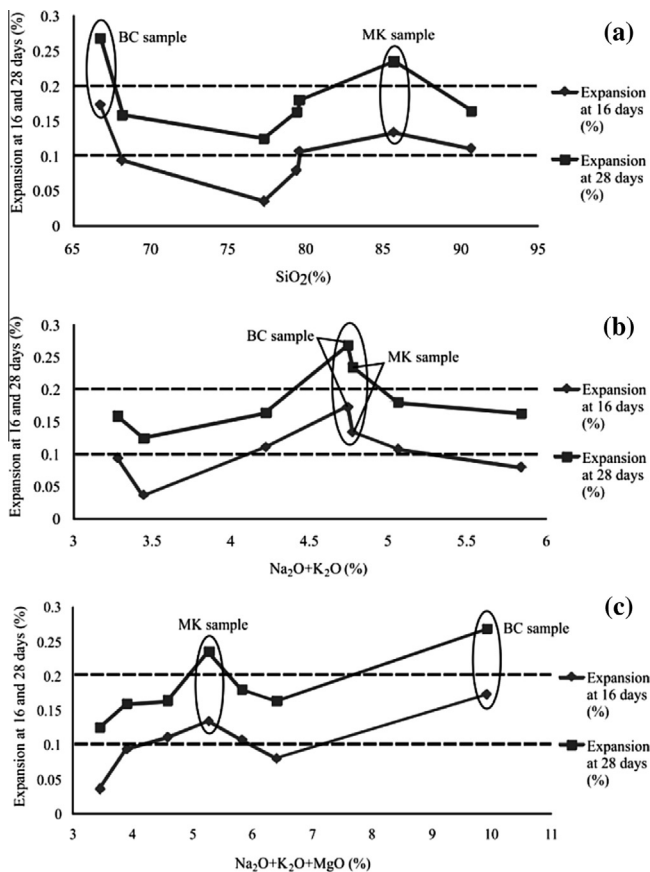


Fig. 6. Relationships between expansion and a) SiO_2 , b) $\text{Na}_2\text{O} + \text{K}_2\text{O}$, c) $\text{Na}_2\text{O} + \text{K}_2\text{O} + \text{MgO}$ content [29].

water absorption values to the MK and OE (Table 4), they have higher magnesium sulfate values and calcium oxide (CaO) percentages than the MK and OE. The higher magnesium sulfate content of the AS and AP are related to the origin of these samples; being marine sands, they contain significant amounts of calcium oxides (CaO), which suggests the presence of shell grains (Tables 1 and 2 and Fig. 2).

As shown in [22], the percentage of expansion in length for 16 days should be under 0.10%. Expansion of less than 0.10% at 16 days is indicative of innocuous behavior in most cases. Expansions between 0.10% and 0.20% at 16 days include aggregates that are known to be innocuous and deleterious. In such cases, it may also be useful to continue taking comparator readings until 28 days. According to our test results, the MK, ST, OE, and BC samples showed expansion of more than 0.10%. Therefore, comparator readings were taken for 28 days. The results were under 0.20% except for the MK and BC (Fig. 4). As shown in [23], the percentage expansion at 14 days should be under 0.10%. Expansion of less than 0.10% related to nonreactive aggregates and expansion of between 0.10% and 0.40% related to aggregates indicate the potential for notable slowing of the ASR. The MK and BC samples showed expansion of more than 0.10% (Fig. 4). The ASR test results show that the MK and BC samples are much weaker than the other sand samples from the alkali-silica reactivity perspective (Fig. 4). This is due to the petrographic, mineralogical, and therefore chemical composition of the sands [29]. The MK sample, with a high percentage of SiO_2 , underwent more expansion after 16 and 28 days than the other sand samples (Fig. 6a) because, as well as non-reactive quartz, this sample contained considerable amounts of active silica such as quartz polymorphs (chert, chalcedony) and a smaller amount of silicate-based minerals. The BC sample contained the least amount of SiO_2 but showed the highest expansion rates after 16 and 28 days (Fig. 6a). This is probably because it contained high percentages of silicate minerals and rock particles and therefore high amounts of MgO, K_2O , and Na_2O (Fig. 6b and c) [29].

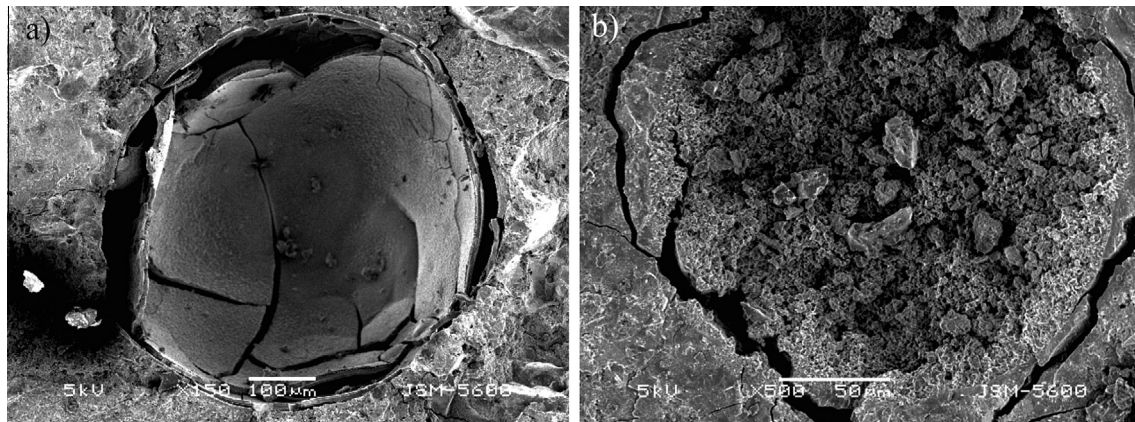


Fig. 7. SEM images of mortar used in accelerated mortar bar test. a) gel product of MK sample, b) gel product formed BC sample and close-range view of circular cracks occurred by alkali-silica reaction.

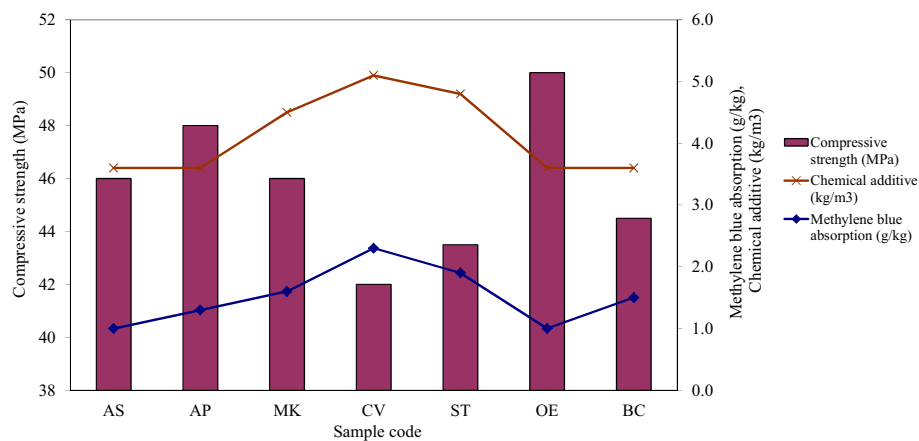


Fig. 8. Relationship between methylene blue absorption of sand samples, the amount of chemical additives and compressive strength of testing concretes.

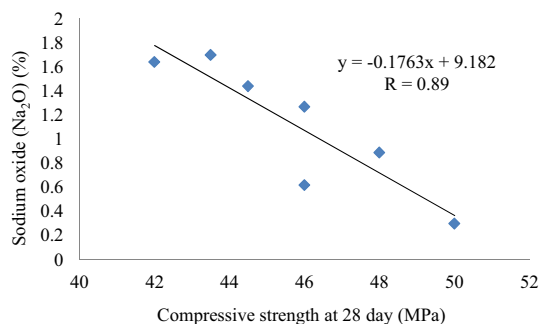


Fig. 9. Relationship between the amount of sodium oxide and compressive strength of testing concrete samples.

The results of the petrographic and mineralogical analyses are consistent with the results of the chemical analysis and the AMBT results (Fig. 6).

To observe the effects of the ASR and its products following the accelerated mortar bar tests, the MK and BC samples were examined using SEM analysis. The morphologic and microstructural features of the mortar used in the accelerated mortar bar tests are shown in Fig. 7. The figure also displays the reaction features of the ASR products, including the ASR gel and the shape of the microcracks formed during the ASR. The SEM results show that the circular cracks that formed on the surface of the MK and BC samples contain the gel product (Fig. 7).

It is known that changing the water/cement ratio and cement content will affect concrete strength. In this study, to investigate the effects of different natural sands on the strength of concrete, the same cement type and water/cement ratios were used to prepare the tested concrete mixes (Table 6). The results of the compressive strengths of the tested concrete samples are shown in Table 9. The compressive strength of the CV and ST samples was lower and that of the OE sample and higher than in the other tested samples. This is because the presence of clay (smectite) in these samples (Table 2) results in a higher chemical additive demand in the concrete mix (Table 6), leading to a decrease in the compressive strength of the CV and ST samples. However [5], indicates that, the 28-day compressive strengths of concrete samples should be more than 40 MPa for high-strength concrete. According to our results, all the concrete samples showed strength values of more than 40 MPa (Table 9).

Fig. 8 shows the methylene blue absorption of the sand samples and the amount of chemical additives in the concrete mixes used in this study, as well as the compressive strength of the tested concretes. The results show that the amount of chemical additives increased when the methylene blue absorption of the sand samples increased. In the sand samples with high methylene blue absorption (indicating clay minerals), the chemical additives are absorbed by the clay minerals, increasing the chemical additive demand. Moreover, the type of clay minerals can also affect the amount of chemical additives. Samples CV and ST containing a smectite-type of clay (Table 2) and having the highest methylene

blue absorption showed a higher demand for chemical additives in the concrete mixes (Fig. 8). Conversely, increasing the methylene blue absorption in the natural sand causes a higher chemical additive demand during concrete mixing (Table 6), leading to a decrease in the compressive strength of the hardened concrete (Fig. 8).

This study showed a linear relationship between the amount of sodium oxide content in the sand samples and the compressive strength of the concrete samples. Fig. 9 indicates that the compressive strength of the concrete samples increased as the amount of sodium oxide in the sand samples decreased.

4. Conclusions

The conclusions drawn from the current research may be summarized as follows.

The strength of the concrete is related to the composition of sands used in concrete mix. Hence, the content and type of clay, and the percentage of feldspar and mica in the aggregates should always be determined before they are used in the concrete mix. The presence of clay in the natural sand reduces the concrete strength by nearly 10 MPa.

Studied sands generally have a high percentage of SiO_2 , which causes greater expansion only if ASR happens. This is because they contain considerable amounts of active silica such as quartz polymorphs (chert, chalcedony) and smaller amounts of silicate-based minerals as well as non-reactive quartz. In contrast, river sand containing a small amount of SiO_2 will also have high expansion characteristics. This is because it contains high percentages of silicate minerals and rock particles and therefore a high amount of MgO , K_2O , and Na_2O .

The chemical composition of the sand, especially its Na_2O contents, is a good indicator of the quality of fine aggregate and can be used to predict the strength and alkali-silica reactivity properties of hardened concrete. Although, a good correlation was identified between the Na_2O contents and the concrete strength, additional testing and comparison is necessary to substantiate this. In addition, alternative resources such as quarry waste, construction and demolition waste, rock and soil from excavations should be evaluated as a crushed sand for concrete production.

Acknowledgment

This study was supported by the Research Fund of the Istanbul University. Project number: T-782/27122005.

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