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Role of test method in detection of alkali–silica reactivity of concrete aggregates

Muhammad Junaid Munir MSc
Junior Lecturer, Department of Civil Engineering, Mirpur University of
Science and Technology (MUST), Mirpur, AJK, Pakistan
(Orcid:0000-0003-4060-5576)

Safeer Abbas PhD
Assistant Professor, Department of Civil Engineering, University of
Engineering and Technology (UET), Lahore, Pakistan

Asad Ullah Qazi PhD
Professor, Department of Civil Engineering, University of Engineering and
Technology (UET), Lahore, Pakistan

Moncef L. Nehdi PhD, PEng
Professor, Department of Civil and Environmental Engineering, Western
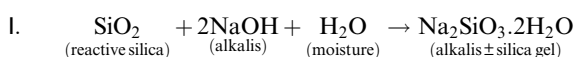University, London, ON, Canada (corresponding author: mnehdi@uwo.ca)

Syed Minhaj Saleem Kazmi MSc
Junior Lecturer, Department of Civil Engineering, Mirpur University of
Science and Technology (MUST), Mirpur, AJK, Pakistan
(Orcid:0000-0002-7913-4065)

The risk of alkali–silica reaction of concrete aggregates in many parts of the world remains largely unexplored. In particular, a suitable approach for testing aggregates with marginal to moderate alkali–silica reactivity has not been clearly identified. In this study, the mineralogical compositions of aggregates from five different quarries were investigated. Mortar bar expansion for these aggregates was tested as per the guidelines of both C 227 and C 1260. Although the tested aggregate sources proved non-reactive under ASTM C 227 test conditions, ASTM C 260 identified one group of aggregates as potentially reactive. Scanning electron microscopy imaging confirmed that two sources of aggregates were reactive. The compressive and flexural strength test results of aged specimens with reactive aggregates indicated that the strength reduction of those subjected to 1 month of ASTM C 260 exposure was similar to those of specimens under 6 months of ASTM C 227 exposure. Based on the experimental results, it appears that aggregates with potential alkali–silica damage may be characterised as non-reactive if the appropriate test method is not adopted. The findings indicate that the ASTM C 1260 procedure is more effective in determining the reactivity potential of marginally to moderately reactive aggregates.

1.   Introduction

Alkali–silica reactivity (ASR) in concrete is one of the primary mechanisms of concrete damage. It essentially consists of a chemical reaction (Equation I) between the hydroxyl ions in the concrete pore solution and the reactive silica in the aggregate. The product of this reaction is an alkali–silica gel that forms within and around the aggregates. This gel can absorb moisture and expand, causing distress and damage to the cementitious matrix (ACI 221 (ACI, 1998); Yildirim and Sumer, 2014). Minerals such as opal, quartzite and chert are sources of reactive silica in aggregates (ASTM C 294 (ASTM, 1998)). Such minerals react with alkalis in the presence of moisture to form alkali silica gel (Dent and Kataoka, 1981) according to the following equation.

I. $$\underset{\text{(reactive silica)}}{SiO_2} + \underset{\text{(alkalis)}}{2NaOH} + \underset{\text{(moisture)}}{H_2O} \rightarrow \underset{\text{(alkalis} \pm \text{silica gel)}}{Na_2SiO_3.2H_2O}$$

ASR is typically a slow process. The associated damage can take several years to be observed. Expansion of 2–3% (by volume) can occur as a result of ASR in concrete (Yildirim and Sumer, 2014) and tends to be larger within the concrete mass than at its surface (Jones and Clark, 1998), eventually leading

to cracking (Stark et al., 1993). ASR has been under study for nearly eight decades (Stanton, 1940), and reported in over 60 countries (Fournier and Berube, 2000). For instance, in Argentina, more than 100 concrete structures have been recognised as affected by ASR since the 1950s (Fava et al., 1991). Moreover, ASR has caused damage in Norway's Elgeseter Bridge (Jensen, 2004) and affected more than 20 bridges in the Netherlands (Siemes et al., 2002). The effects of ASR on the mechanical properties of concrete have been widely explored (Jones and Clark, 1996; Monette et al., 2000; Siemes and Visser, 2000; Takemura et al., 1996). It was found that ASR significantly affects the modulus of elasticity and tensile strength of concrete (Koyanagi et al., 2000; Larive et al., 1996).

Generally, ASR has been detected and monitored primarily using field inspection (ACI 221 (ACI, 1998)). Assessing structures more than 10 years old, made with the aggregate source under consideration and subjected to wetting and drying can usually give an indication of the reactivity of an aggregate source (ACI 221 (ACI, 1998)). The inspection typically involves visual observations with particular focus on indications of distress, such as movements and displacements, map cracking, presence of alkali–silica gel and scaled surfaces having aggregates surrounded by reaction rims (Stark, 1991a,

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1991b) that usually consist of a calcium–alkali–silicate layer (Charlwood and Solymar, 1994). Petrographic examination of concrete cores from such structures should be carried out to confirm the presence of ASR.

Various methods to evaluate ASR potential have been proposed (Berube and Fournier, 1994; Diamond, 1978; Grattan-Bellew, 1981, 1989; Kosmatka and Panarese, 1988; Sims, 1981; Stark, 1991a, 1991b), and detailed methodologies for testing, evaluation and management of ASR have been provided, for instance, by the CSA (2005) and ASTM (Table 1) standards. Different testing methods for assessing the potential of ASR are presented in Table 1, among which ASTM C 227 (ASTM, 2010) and ASTM C 1260 (ASTM, 2014c) are the most commonly used.

ASTM C 227 (ASTM, 2010) has long been a commonly used method for detecting the potential of ASR. However, it requires 6 months to complete (Raja *et al.*, 2014; Stark, 1980). Moreover, the exposure conditions of ASTM C 227 (ASTM, 2010) are not sufficiently severe to generate ASR in a short time. Conversely, while ASTM C 1260 (ASTM, 2014c) is an improved method, it has been perceived as too severe and does not replicate field conditions (Lu *et al.*, 2006; Yildirim and Sumer, 2014). Moreover, there usually are discrepancies between the results of the two test methods. Thus, this study was carried out to evaluate the effectiveness of both the ASTM C 227 (ASTM, 2010) and ASTM C 1260 (ASTM, 2014c) guidelines in detecting the ASR potential of local aggregates.

2. Materials

Aggregates from five different sources were selected because they are widely used in local concrete construction, yet there is ongoing ambiguity regarding their potential ASR. The selected aggregate sources included the Sheikh Hills, Tuguwali Hills and Mach Hills from the Sargodha region, the Jhelum River at the Lehri Mangla and the Kamser Mountains from Muzaffarabad in Kashmir. From the Sargodha and Kashmir sources, large rock fragments were obtained through blasting, whereas, from the Jhelum River source, stones were collected from the riverbed. These rock fragments and stones were then crushed into aggregates at industrial crusher plants. From the Sargodha aggregate source, the dry technique was used for crushing, whereas aggregates from the Jhelum River and Kashmir sources were crushed using the wet technique. Samples of the various aggregates are shown in Figure 1. Locally produced ordinary Portland cement (Bestway Cement) was used throughout this study. Clean tap water was used for mixing the mortar.

3. Experimental procedures

3.1 Materials characterisation

To investigate the mineralogical composition of the aggregates, petrographic examination was performed according to ASTM

C 295 (ASTM, 2012). Moreover, the physical properties of the various aggregates were characterised. The bulk density and voids content were evaluated as per ASTM C 29 (ASTM, 2016a). The specific gravity and water absorption of the aggregates were measured according to ASTM C 127 (ASTM, 2015b). The impact and crushing value tests were performed on the aggregates as per BS 812-112 (BSI, 2014b) and BS 812-110 (BSI, 2014a). The abrasion resistance of the aggregates was examined using ASTM C 535 (ASTM, 2016e).

The chemical properties of the cement used were quantified using X-ray fluorescence. To further characterise the cement, various other tests were carried out, including the standard consistency test described in ASTM C 187 (ASTM, 2011a); setting time according to ASTM C 191 (ASTM, 2013); fineness test as per ASTM C 184 (ASTM, 1994); fineness test outlined in ASTM C 204 (ASTM, 2016d). Moreover, soundness was explored using the EN 196-3 procedure (EN, 2005) and autoclave expansion as per the guidelines of ASTM C 151 (ASTM, 2015c).

3.2 Mortar bar expansion testing

3.2.1 ASTM C 227 test procedure

Mortar bar specimens incorporating aggregates from the various sources were prepared. Aggregates from the selected sources were graded according to ASTM C 227 (ASTM, 2010). Figure 2 shows the gradation curve. The mixture proportions for the mortars involved a cement-to-aggregates mass ratio of 1 to 2·25 and a water-to-cement ratio of 0·47 in accordance with ASTM C 227 (ASTM, 2010). Mixing was conducted using an electric mortar mixer (Figure 3(a)) according to ASTM C 305 (ASTM, 2014a). After 5 min of mixing, the flow diameter of the fresh mortar was determined in accordance with ASTM C 1437 (ASTM, 2015e). The flow diameter for all the tested mixtures was within 105–120 mm (Figure 3(b)). After flow table testing, the mixture was poured into mortar bar moulds in two layers. The mortar bar moulds were two gang prism moulds having dimensions of $25 \times 25 \times 285$ mm with an effective gauge length of 250 mm (Figure 3(c)). Each layer was well compacted using a plastic tamper.

The specimens were covered with a plastic sheet to avoid loss of moisture until demoulding at 24 h. The initial length of each bar specimen was measured using a digital length comparator (Figure 3(d)) as described in ASTM C 490 (ASTM, 2011b). Before measuring the length, a reference bar was used to calibrate the comparator. Specimens were then stored in airtight containers containing water, such that the specimens did not touch the base of the container (Figure 4(a)). The specimen containers were then placed in an oven at 40°C. After 14 d, the containers were stored at 25°C for 16 h, and then length readings were taken. Readings were taken using a

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Table 1. Test methods for evaluating ASR potential of aggregates

Standards/references	Test	Testing material and status	Description
ASTM C 295 (ASTM, 2012)	Petrographic examination	Aggregates (indirect method)	Identify reactive aggregates and the amount of potential reactive materials
ASTM C 227 (ASTM, 2010)	Mortar bar test	Cement aggregate combination (direct method)	6–12 months duration is required. Mortar bars are stored at 38°C under 100% relative humidity (RH)
ASTM C 1260 (ASTM, 2014c)	Accelerated mortar bar test	Cement aggregate combination (direct method)	Modified form of ASTM C 227 (ASTM, 2010), 14–28 d duration is required. Mortar bars are stored at 80°C under 100% RH in 1 N sodium hydroxide solution
ASTM C 289 (ASTM, 2003)	Quick chemical test	Aggregate (indirect method)	Crushed material is sealed at 80°C in 1 N sodium hydroxide solution for 24 h to measure the amount of dissolved reactive silica. Results can be classified as aggregate source is reactive or not
ASTM C 1293 (ASTM, 2015d)	Concrete prism test	Concrete prisms (direct method)	365 d are required. Specimens are placed at 38°C in sodium hydroxide solution having alkali level of 1·25% Na_2Oe
ASTM C 342 (ASTM, 1997)	Potential volume change of cement aggregate	Cement aggregate combination (direct method)	365 d are required. Mortar bars are stored in various temperature and moisture conditions
USACE (1994)	US Army Corps of Engineers modified mortar bar test	Cement aggregate combination (direct method)	Modified form of ASTM C 227 (ASTM, 2010) to detect slow-reacting aggregates. With the help of petrographic examination, siliceous aggregates having strained quartz more than 20% are selected for evaluation through the mortar bar test. Mortar bars are stored at 60°C under 100% RH for 365 d
Bonzel and Dahms (1973), Dahms (1977)	Concrete cube test	Cement aggregate combination (indirect method)	Specimens are stored in a moist cabinet under 40°C. Periodic expansion is done for gel exudations and cracking. However, it is not stated whether aggregate source is deleterious or not
Chatterji (1978)	Nordtest accelerated ASR test	Cement aggregate combination (direct method)	Also a modified form of ASTM C 227 (ASTM, 2010). However, this method is used only for reactive aggregates in Denmark. Mortar prisms having smaller length and greater cross-section than ASTM C 227 (ASTM, 2010) are cured for 4–5 weeks in water and then saturated in sodium chloride solution at 50°C for 8 weeks
Sims (1981), NBS (1958)	Gel pat test	Cement aggregate combination (indirect method)	Mortar bars having smooth sawn surfaces are placed in alkali solution for 3 d. Gel will form in the presence of reactive particles and the percentage of reactive particles can be estimated
Fournier and Berube (1991)	Autoclave mortar bar test	Cement aggregate combination (direct method)	Also a modified form of ASTM C 227 (ASTM, 2010). However, sodium hydroxide is added to water to raise the alkali content. Mortar bars are stored under 100% RH at 23°C for 2 d before autoclave treatment. Autoclave test is performed with steam curing at 130°C
Natesaiyer and Hover (1988, 1989)	Uranyl acetate gel fluorescence test	In situ hardened concrete (indirect method)	This test is used in conjunction with petrographic examination to confirm the presence of ASR products in hardened concrete. Fluorescence will be produced by ASR products in concrete treated with uranyl acetate solution when observed under ultraviolet light. This is a rapid test. However, it should always be performed by trained specialists
Stark (1985, 1991a, 1991b)	ASR in hardened concrete	Hardened concrete (direct method)	To determine the alkalis and reactive silica amounts, cores are extracted and placed in different conditions – that is, in water, in 1 N sodium hydroxide solution and in sealed water at 38°C. The expansion of these cores is measured for 12 months. The results of length change under different conditions indicates possible future ASR expansion in concrete

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Table 1. Continued

Standards/references	Test	Testing material and status	Description
Donnell *et al.* (2013)	Microwave method	Cement aggregate combination (direct method)	Mortar bar specimens are prepared according to ASTM C 1260 (ASTM, 2014c) and then sealed in water at 38°C, and microwave measurements are made. Specimens are then placed under ambient conditions for 36 d and final measurements are taken. This test is based on the property that due to the formation of gel and attraction of free water from the environment, readings of microwave methods vary

similar procedure after each month for up to 6 months, and the water in the containers was replaced. The length change was quantified using the following equation

1. $$L = \frac{(L_x - L_i)}{G} \times 100$$

where L is the change in length at age x (%), L_x is the comparator reading at age x (mm), L_i is the initial comparator reading of specimens (mm) and G is the nominal gauge length (250 mm).

3.2.2   ASTM C 1260 test procedure
Aggregates from the selected sources were graded according to ASTM C 1260 (ASTM, 2014c) and used to prepare standard mortar bars. Similar mixture proportions as described above were used. After measuring their initial length, the bar specimens were placed in water in sealed containers. The containers were then placed inside an oven at 80°C. After 24 h, the initial length of each specimen was measured. Specimens were then immersed for 14 d in a 1 N sodium hydroxide (NaOH) solution (Figure 4(b)) at 80°C. Length measurements were conducted after 14 and 28 d.

3.3   Mechanical properties
To explore the effects of ASR on the compressive strength and modulus of rupture of the various mortars, 90 cubes and prisms incorporating aggregates from the various sources investigated were cast. Cube specimens were cast in two layers using three gang $25 \times 25 \times 25$ mm cube moulds. Each layer was compacted by tamping it 32 times using a plastic tamper. Prisms of $40 \times 40 \times 160$ mm size were also cast in layers and compacted in a similar manner. The specimens were covered with a plastic sheet for the first 24 h to avoid loss of moisture. After demoulding, nine control cubes and prisms for each aggregate source were cured in fresh water. Moreover, nine cubes and prisms for each aggregate source were stored in an air-tight container containing water such that the specimens did not touch the base of the container. Six specimens (cubes and prisms) were then kept in an oven at 40°C according to ASTM C 227 (ASTM, 2010). The remaining three cubes and prisms for each aggregate source were kept in water for 1 d at 80°C (Figure 4(c)) and then immersed in

a 1 N sodium hydroxide solution inside air-tight containers placed in an oven at 80°C according to ASTM C 1260 (ASTM, 2014c). After 1 and 6 months, the control specimens and the specimens placed at 40°C were removed and tested. Specimens placed at 80°C were tested after 28 d of exposure.

Compressive testing was conducted at a loading rate of 1000 N/s as per ASTM C 109 (ASTM, 2016c). The modulus of rupture was obtained by applying a rate of 2640 N/s as per ASTM C 348 (ASTM, 2014b). Furthermore, scanning electron microscopy (SEM) imaging of selected mortar bar specimens was carried out to investigate the microstructural features of the tested mortars after various regimes of exposure.

4.   Results and discussion

4.1   Binder characteristics
Table 2 shows the chemical analysis results of the cement, which indicates that all chemical compounds were in accordance with the limits specified in ASTM C 114 (ASTM, 2015a), except for the alkalis (i.e. 0·85%), which was higher than the ASTM C 114 (ASTM, 2015a) recommended maximum of 0·60%. The amount of alkalis mainly depends on the nature of the raw materials of the cement and on the production process. To reduce the alkali content, modifications in the manufacturing process of cement may be required, which is typically uneconomical (Johansen, 1989). Table 3 reports the results of physical tests on the cement. Generally, these physical properties were within ASTM and European (EN) standard limits. For example, the cement fineness (99% and 2996 cm²/g) satisfy the ASTM C 184 (ASTM, 1994) and C 204 (ASTM, 2016d) standard limits (fineness of cement should not be <90% and 2250 cm²/g). The autoclave expansion was 0·075%, which satisfies the ASTM C 151 (ASTM, 2015c) guidelines. The soundness of the cement also met the EN 196-3 (EN, 2005) standard requirements.

4.2   Petrographic examination of aggregates

4.2.1   Sheikh Hills aggregates
Figure 5(a) shows the petrographic examination results for the Sheikh Hills aggregate, which were mainly composed of three

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Figure 1. Illustration of samples from the various aggregate sources: (a) Sheikh Hills aggregate, (b) Tuguwali Hills aggregate, (c) Mach Hills aggregate, (d) Jhelum river stone and (e) Kamser Mountains stone

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rock types: dolerite, quartzite and rhyolite. Dolerite is dominant (56%); with quartzite (27%) and rhyolite (17%) constituting the rest of the aggregates. The composition of the dolerite mineral is presented in Figure 5(b). The dolerite was fine- to
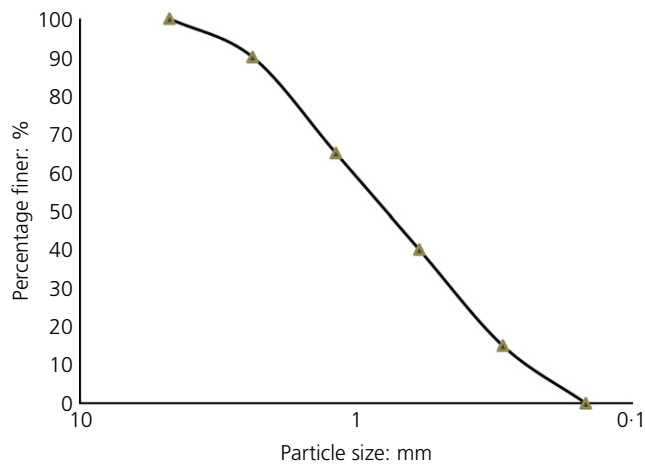
Figure 2. Gradation curve of aggregate sources

medium-grained and micro-porphyritic, having ophitic to sub-ophitic texture. It was moderately chloritised, sericitised and calcitised. Dolerite was found to be a non-alkali reactive rock type (WAPDA, 2004). The mineralogical composition of the quartzite is outlined in Figure 5(c). The quartzite was mainly composed of fine-grained to vitreous quartz (about 87% of the rock) with interstitial muscovite and sericite. Tiny grains of quartz were interlocking and mono-crystalline. Muscovite and sericite occur as small anhedral flakes and represent about 8% of the rock. Some subhedral to anhedral crystals of secondary calcite were also present (about 3% of the rock). Sporadic fine grains of haematite were also observed (about 7% of the rock). According to previous studies (ACI 221 (ACI, 1998); WAPDA, 2004), quartzite is usually slowly alkali reactive. The composition of the rhyolite is shown in Figure 5(d). The rhyolite pieces were light to medium grey on fresh surfaces and rusty brown to yellowish grey on weathered surfaces. The rock was fine grained and microcrystalline to cryptocrystalline having about 36% of quartz. Rhyolite is generally alkali reactive (ACI 221 (ACI, 1998); WAPDA, 2004). The presence of reactive quartzite and rhyolite in the Sheikh Hills aggregates warrants a careful study of their potential ASR.
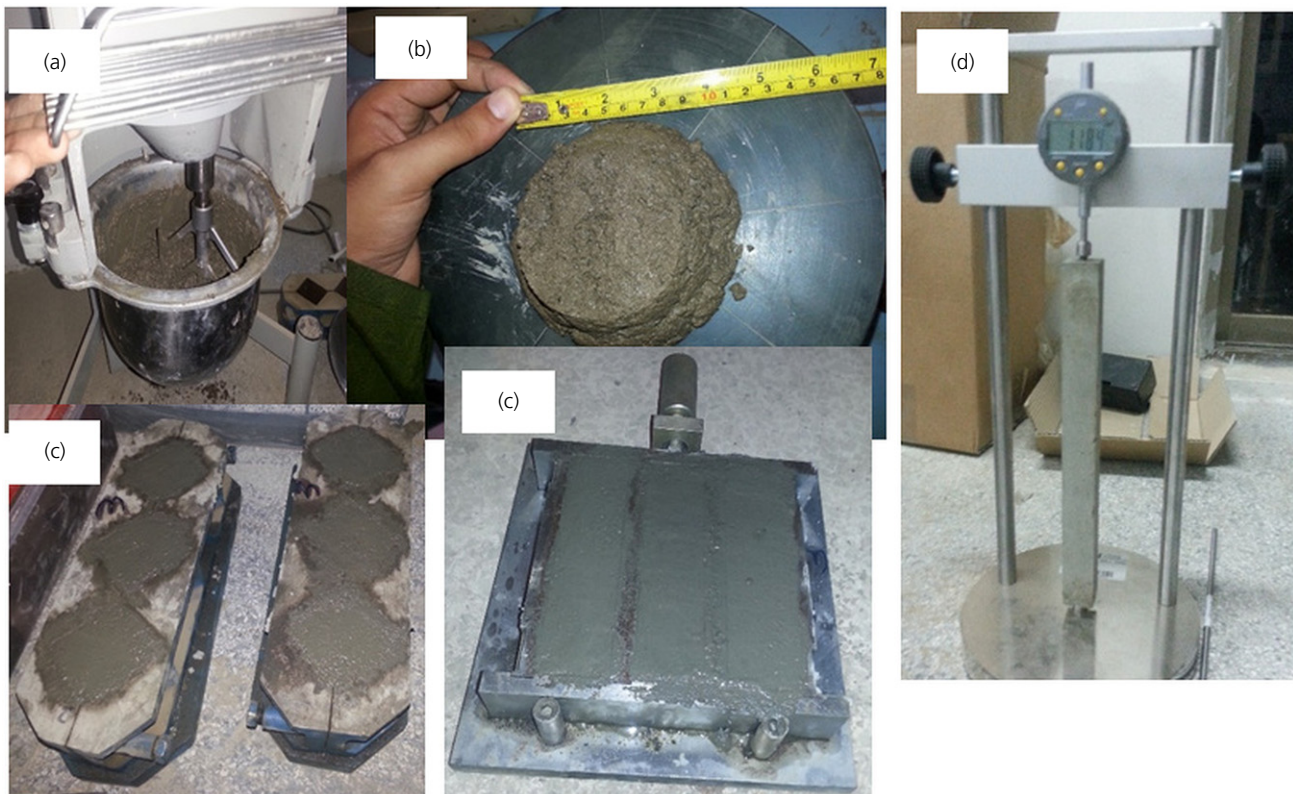

Figure 3. Illustration of (a) mortar mixing procedure, (b) flow table measuring, (c) typical mortar cube and bar casting and (d) digital length comparator

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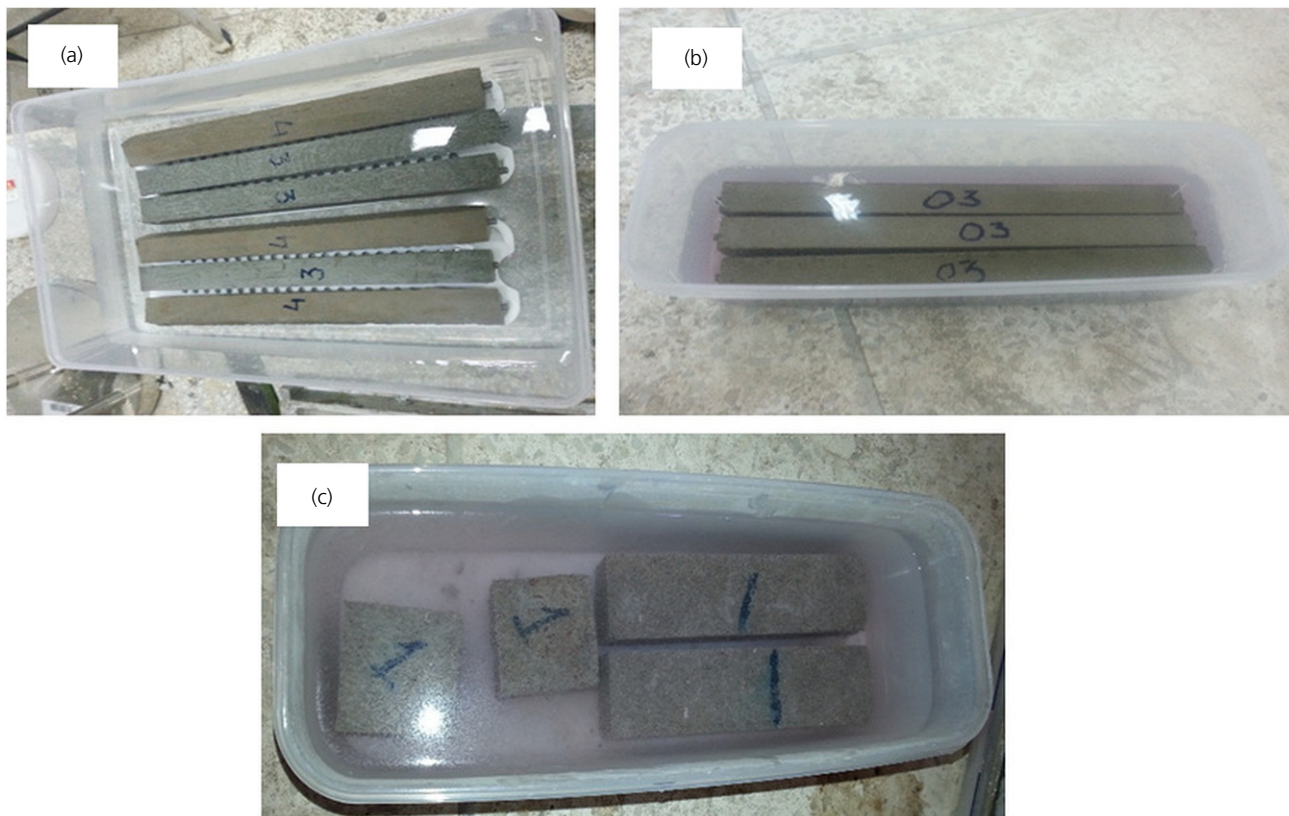Munir, Abbas, Qazi, Nehdi and Kazmi

Figure 4. Illustration of (a) specimen positioning in container, (b) mortar bar specimens in sodium hydroxide solution and (c) cube and prism specimens placed at 80°C in water

Table 2. Chemical analysis of cement

Constituent: %	Ordinary Portland cement	ASTM C 114 limits (ASTM, 2015a)
Silicon dioxide (SiO$_2$)	20·50	20 minimum
Aluminium oxide (Al$_2$O$_3$)	5·08	6 maximum
Ferrous oxide (Fe$_2$O$_3$)	3·18	6 maximum
Calcium oxide (CaO)	62·4	—
Magnesium oxide (MgO)	2·28	6 maximum
Free lime	1·24	2 maximum
Sulfur trioxide (SO$_3$)	1·96	3 maximum
Insoluble residue (IR)	0·60	0·75 maximum
Loss on ignition (LOI)	2·04	3 maximum
Sodium oxide (Na$_2$O)	0·42	—
Potassium oxide (K$_2$O)	0·66	—
Equivalent alkali content (Na$_2$O$_e$)	0·85	0·60 maximum

4.2.2 Tuguwali Hills aggregates

Figure 6(a) displays the petrographic examination results of the aggregates from Tuguwali Hills. These aggregates were mainly composed of rhyolite rock, with the presence of several other minerals. For instance, K-feldspar was around 23% in the rock. Rhyolite pieces were light to medium grey in fresh surfaces and rusty brown to yellowish grey on weathered surfaces. The rock was fine grained and microcrystalline to cryptocrystalline. Quartz occurs as anhedral to idioblastic, whereas K-feldspar was anhedral to sub-idioblastic to blasto-porphyritic. Plagioclase was generally present as micro-blasto-porphyritic and as tiny crystals in the groundmass. Calcite was present as groundmass and ilmenite/leucoxene occurred as fine-grained crystals.

4.2.3 Mach Hills aggregates

Figure 6(b) portrays the results of the petrographic examination for the Mach Hills aggregate, which were mainly composed of a volcanogenic slate rock type, with the presence of a variety of other minerals. For example, muscovite represented 35% of the rock. The aggregates were generally uniform in appearance. Aggregate particles were found to be greyish green on fresh surfaces and rusty brown on weathered surfaces. Some particles were spotted with dark-coloured minerals. The rock pieces exhibited moderate fissility on a macroscopic scale. The rock was fine grained and showed a faint orientation of the

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Table 3. Physical properties of cement

Property	Standard	Value	Limits
Standard consistency	ASTM C 187 (ASTM, 2011)	24%	—
Initial setting time	ASTM C 191 (ASTM, 2013)	91 min	> 45 min
Final setting time	ASTM C 191 (ASTM, 2013)	165 min	< 375 min
Fineness (passing no. 200)	ASTM C 184 (ASTM, 1994)	98·6%	Min. 90%
Fineness (Blaine air permeability)	ASTM C 204 (ASTM, 2016d)	2996 cm^2/g	Min. 2250 cm^2/g
Soundness	EN 196-3 (EN, 2005)	0·60 mm	Max. 10 mm
Autoclave expansion	ASTM C 151 (ASTM, 2015c)	0·075%	Max. 0·8%
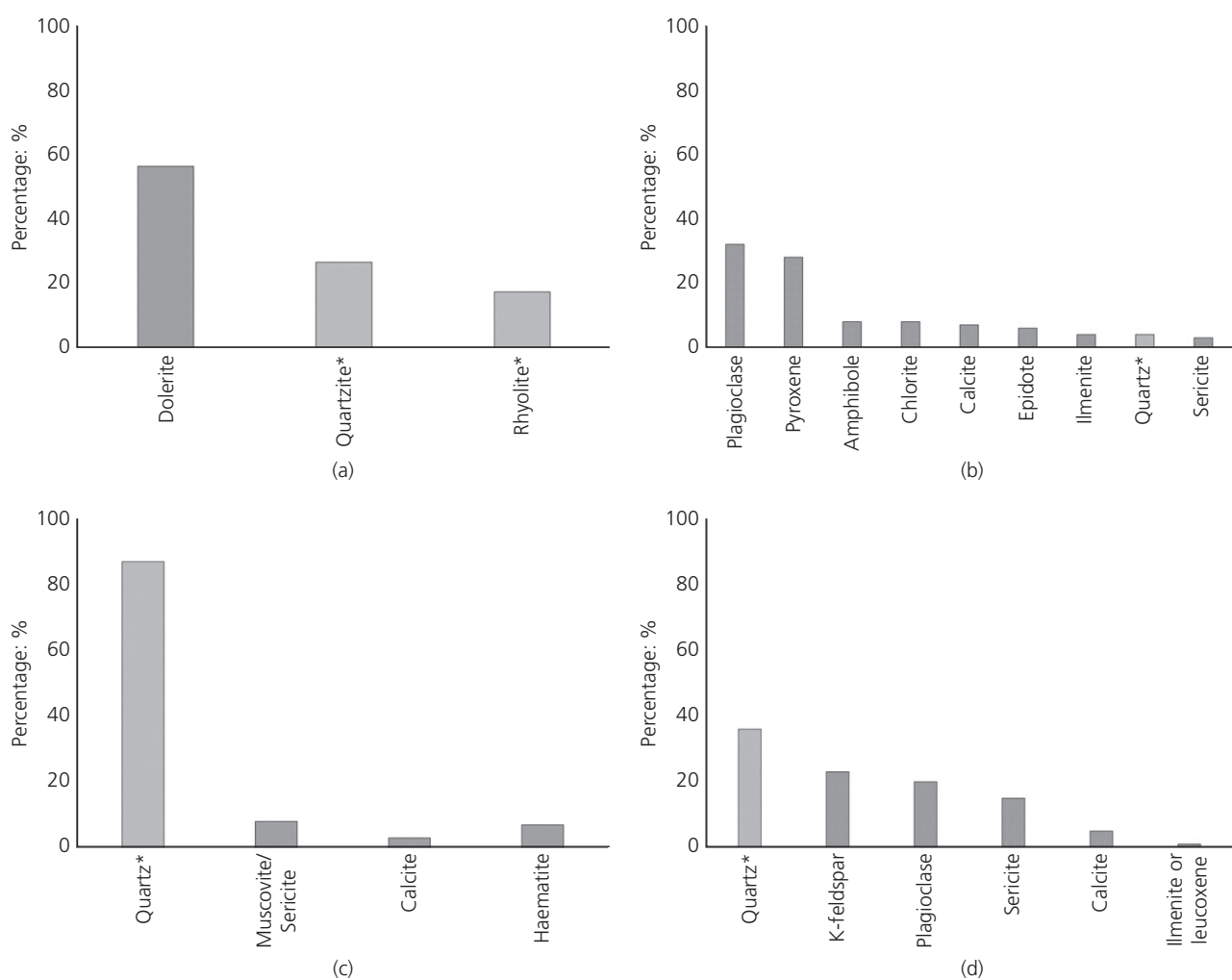
Figure 5. Mineralogical composition of Sheikh Hills aggregate: (a) composition of Sheikh Hills aggregate, (b) mineralogical composition of dolerite, (c) mineralogical composition of quartzite and (d) mineralogical composition of rhyolite. * shows reactive minerals

muscovite flakes. Quartz was present as small, rounded fragments and very fine-grained muscovite formed the matrix of the rock. A significant proportion of the rock was composed of slowly reactive quartz mineral.

4.2.4 Jhelum riverbed aggregates
Figure 6(c) illustrates the petrographic examination results of the Jhelum riverbed aggregates, which were mainly composed of quartzite (54%) and sandstone (36%). The mineralogical
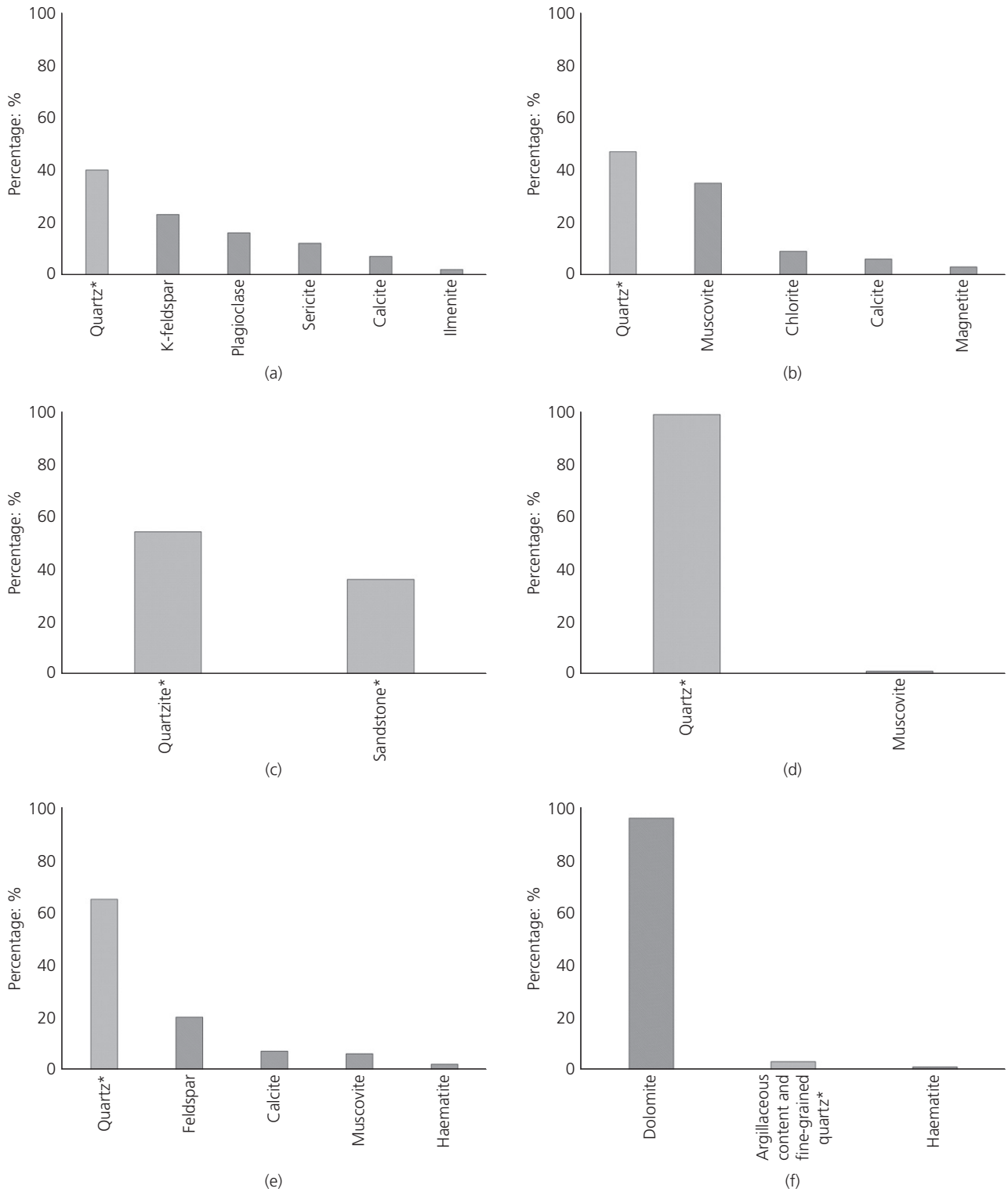
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Figure 6. Mineralogical nature of the various aggregates and their compositions: (a) composition of Tuguwali Hills aggregate, (b) composition of Mach Hills aggregate, (c) Jhelum River aggregate, (d) quartzite in Jhelum River aggregate, (e) sandstone in Jhelum River aggregate and (f) composition of Kamser Mountain aggregate. * shows reactive minerals

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composition of the quartzite mineral is shown in Figure 6(d). The rock pieces were creamy to light grey in colour and showed no signs of weathering. The grain boundaries of the quartz were irregular and wavy. Most of the grains were polycrystalline and strained. Rare flakes of muscovite were also present. A small volume of pore spaces was lined with microquartz. Overall, quartz constituted about 99% of the rock. The composition of the sandstone is outlined in Figure 6(e). Rock pieces were medium grey, purple grey and greenish grey in colour. Some pieces were faintly weathered while most were fresh. Thin sectioning showed that the sandstones possess comparable mineralogy to quartzite. Such sandstone-containing quartz is known to be slowly alkali reactive (Munir et al., 2016; Rivard et al., 2002; WAPDA, 2004).

4.2.5 Kamser Mountain aggregates

Figure 6(f) portrays the petrographic examination results of aggregates from Kamser Mountain, which were primarily composed of dolomite (about 96%), with the presence of several other minerals. For instance, argillaceous and fine-grained quartz represented about 3% of the rock. Aggregates appeared medium to dark grey in colour and were found to be non-reactive using cold diluted hydrochloric acid (HCl). Results showed that the rock was mainly composed of fine-grained anhedral to subhedral dolomite crystals. The fabric of the rock may be described as fine-grained equi-granular to sub-equi-granular, having intergranular pore spaces between crystals. This may have resulted from the bulk volume shrinkage that accompanies calcite replacement by dolomite (ACI 221 (ACI, 1998)). Haematite (about 1% of the rock) was present as fine grains, distributed in the rock and as coating on the grain boundaries. This rock may cause alkali carbonate reaction, and is generally considered ASR non-reactive. Yet, a previous study (Abbas et al., 2017; NESPAK, 2011) concluded that such rock can be ASR reactive.

4.2.6 Overall reactivity of various aggregate sources

Figure 7 exhibits the amount of reactive constituents in each aggregate source based on petrographic examination. It can be observed that some of the aggregate sources present real alkali–aggregate reactivity potential. For example, the amount of reactive constituents in the Jhelum River source is 77%. With respect to ASR, the reactive constituents were more significant in the Jhelum River source and the least in the Kamser source. However, the Mach, Tuguwali and Sheikh Hills aggregate sources were also considered as slow reactive. Various researchers proposed different classifications for slow reactive aggregates. For instance, Magni et al. (1986) suggested 15% as an acceptable limit for the amount of reactive minerals, whereas, in Norway, if the quantity of reactive constituents is >20%, further testing is recommended (Borge, 1995). ASTM C 33 (ASTM, 2016b) recommends testing including the

chemical test and the mortar bar test to qualify ASR when reactive materials are present even at <1%. Therefore, it can be argued that all the tested sources of aggregates may possibly cause ASR, and thus should be further investigated, for instance under ASTM C 227 (ASTM, 2010) and ASTM C 1260 (ASTM, 2014c), before using such aggregates in full-scale construction works to ensure adequate service life performance of structures.

4.3 Physical properties of tested aggregates

Table 4 shows the physical properties of the aggregate sources. The highest bulk density was measured for the Kamser aggregates and the lowest was for the Mach Hills source. The bulk density generally ranged from 1200 to 1760 kg/m^3. The Mach Hills aggregate had the highest voids content, whereas the Kamser source had the least. The volume of voids is typically governed by the grading and shape of the particles. It normally ranged from 33 to 42% (ACI 221 (ACI, 2001)), which is within typical values.

Specific gravity was higher for the Kamser aggregate source and the least for the Jhelum River source. However, there was an opposite trend for water absorption. The Kamser aggregates showed less water absorption compared with the Jhelum River aggregates (primarily sandstone). According to a previous study (Carlson, 1938), aggregates composed of sandstones usually have higher water absorption and relatively lower specific gravity.

Table 4 reports the impact, crushing and abrasion test results of aggregates from the various sources explored in this study. The Kamser source aggregate exhibited highest resistance against impact and abrasion, while the Jhelum River aggregate had the least. The aggregates from the Tuguwali Hills showed
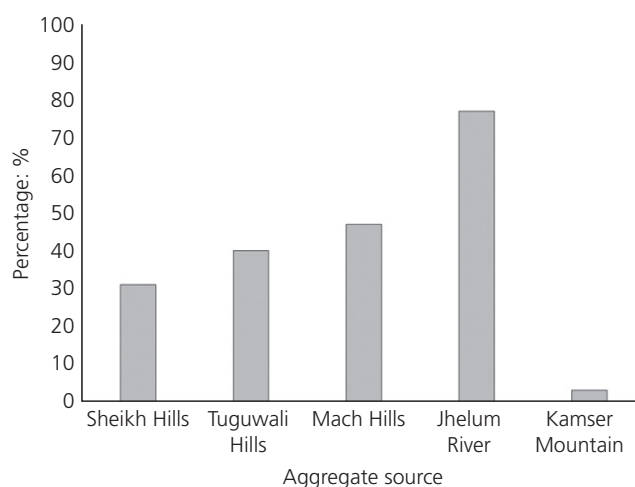

Figure 7. Reactive constituents in the various aggregate sources

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Table 4. Physical properties of aggregates

	Aggregate sources				
Property	Sheikh Hills	Tuguwali Hills	Mach Hills	Jhelum Riverbed	Kamser Mountain
Bulk density: kg/m^3 (ASTM C 29) (2016a)	1551	1548	1535	1596	1699
Voids content: % (ASTM C 29) (2016a)	39·99	41·24	41·66	38·54	37·53
Specific gravity (ASTM C 127) (2015b)	2·73	2·64	2·59	2·56	2·77
Water absorption: % (ASTM C 127) (2015b)	1·03	0·98	1·12	1·47	0·76
Impact value (BS 812-112) (2014b)	11·90	13·10	13·30	14·50	10·10
Crushing value (BS 812-110) (2014a)	18·90	14·80	25·20	21·30	17·10
Abrasion test (ASTM C 535) (2016e)	19·20	21·80	24·20	26·90	17·90
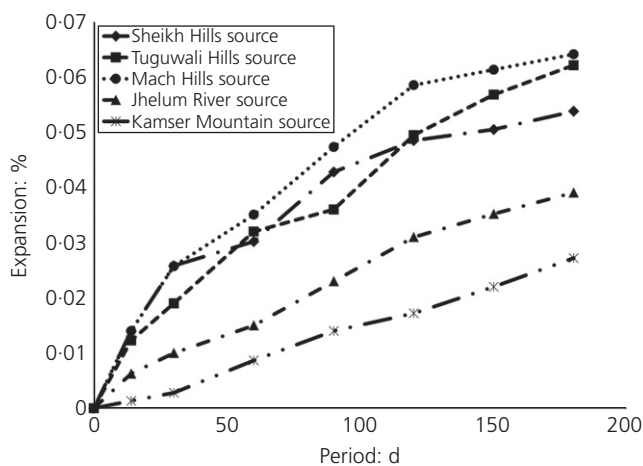
Figure 8. Mortar bar expansion results according to ASTM C 227 (ASTM, 2010)

the highest resistance against crushing, while the Mach Hills source showed the least resistance. The impact and abrasion resistance is usually higher for crushed aggregates than for round aggregates (Alexander and Mindess, 2005), which explains the results of the Jhelum River aggregates. Generally, the abrasion of aggregates ranges from 15 to 50% (Neville, 2000). Abrasion values of all the tested aggregate sources, which ranged between 17·9 and 26·9%, are within specifications. The impact value of aggregates is usually <25% and the crushing value generally ranges from 14 to 30% (Alexander and Mindess, 2005). Experimental results for the tested aggregates show that the impact and crushing values were <15 and 26%, respectively, indicating suitability of the aggregates for use in concrete construction works.

4.4 Results of ASTM C 227 and ASTM C 1260 tests

4.4.1 Mortar bar expansion
Figure 8 illustrates the average ASTM C 227 (ASTM, 2010) mortar bar expansion for specimens incorporating the various aggregates. After 3 months, mortar bars made with the

Tuguwali aggregate showed less expansion than those made with the Sheikh Hills aggregate. However, at the end of the 6-month exposure, the results were reversed. The Tuguwali aggregate had more reactive minerals than the Sheikh Hills source. Yet, due to its slower reactivity, more expansion was observed at later ages. Similar behaviour was reported for other aggregates in previous studies (Ahmed et al., 2013; Carlson, 1938; Islam and Ghafoori, 2013; Thibodeaux et al., 2003). The average expansion of mortar bars incorporating the Mach Hills aggregate was the highest. Specimens incorporating the Mach, Tuguwali and Sheikh Hills aggregates exhibited expansion in the range of 0·05–0·07% at the end of 6 months. Results were consistent with findings of the petrographic examination. According to ASTM C 33 (ASTM, 2016b), aggregates are considered alkali–silica reactive if the mortar bar expansion is more than 0·10% after 6 months under the ASTM C 227 (ASTM, 2010) test conditions. None of the aggregates tested herein has shown expansion >0·07%. No distress was observed on mortar bar surfaces after the 6-month exposure period. However, the ASTM C 227 (ASTM, 2010) is not used for acceptance and rejection of aggregate sources. The longer term ASTM C 1293 (ASTM, 2015d) is usually adopted for this purpose.

Figure 9 portrays the average ASTM C 1260 (ASTM, 2014c) accelerated mortar bar expansion values. It can be observed that the specimens incorporating the Mach Hills aggregate incurred the highest expansion, whereas those made with the Kamser aggregate had the least expansion. This is ascribed to the greater reactive minerals content in Mach Hills aggregates as observed in the petrographic examination. The specimens made with the Mach, Tuguwali and Sheikh Hills aggregate sources, which all come from the Sargodha region, exhibited expansion values >0·10 and 0·20% after 14 and 28 d, respectively. Hence, based on ASTM C 1260 (ASTM, 2014c), such aggregates can be considered alkali–silica reactive. These aggregates were not considered reactive under ASTM C 227 (ASTM, 2010) testing. Generally, ASTM C 1260 (ASTM, 2014c) has been considered as more effective for testing slow reactive minerals in previous studies (Davies and Oberholster, 1987; Hooton, 1990; Stark et al., 1993).
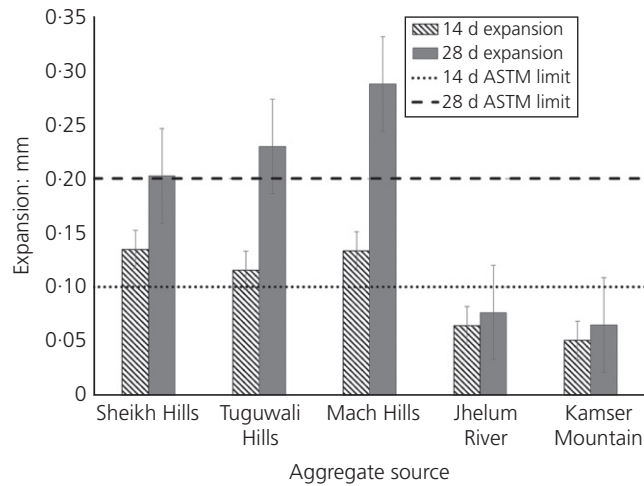
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Figure 9. Accelerated mortar bar expansion results according to
ASTM C 1260 (ASTM, 2014c)

Figure 10. Compressive strength of specimens under ASTM
C 227 (ASTM, 2010) exposure conditions

Mortar bar expansion results showed that the aggregates from
the Jhelum River and Kamser are not reactive under both
ASTM C 227 (ASTM, 2010) and C 1260 (ASTM, 2014c) stan-
dard test methods. The results for the Kamser source were
consistent with both the petrographic examination and past find-
ings (Islam and Akhtar, 2013). However, despite petrographic
examination indicating the highest content of reactive minerals
(i.e. 77%) in the Jhelum River aggregate, mortar expansion
results for this aggregate source were <0·04 and 0·085%,
in accordance with ASTM C 227 (ASTM, 2010) and ASTM
C 1260 (ASTM, 2014c), respectively. This can be explained by
the so-called pessimum effect (Ichikawa, 2009; Johansen, 1989).
The pessimum effect is defined as the largest expansion of con-
crete due to a definite proportion of reactive siliceous aggregates.
However, if the reactive aggregates content decreases or increases
from the pessimum level, a decrease in expansion can be
observed (Ichikawa, 2009; Stanton, 1940). It is believed that the
77% reactive mineral content in the Jhelum River aggregate
largely exceeded the pessimum value, thus leading to low expan-
sion. However, this needs to be investigated further using the
ASTM C 1293 (ASTM, 2015d) concrete prism test.

4.4.2 Effect of ASR on compressive strength

Figure 10 displays the compressive strength results of mortar
specimens tested under ASTM C 227 (ASTM, 2010). As
expected, the control specimens reached a higher compressive
strength at 6 months than that at 1 month due to the progress
of hydration reactions. Conversely, the specimens tested under
1 month of ASTM C 227 (ASTM, 2010) ASR exposure con-
ditions had compressive strength values at 6 months comparable
to, and in some cases lower than, that reached at 1 month. For
instance, after 6 months of ASTM C 227 (ASTM, 2010)
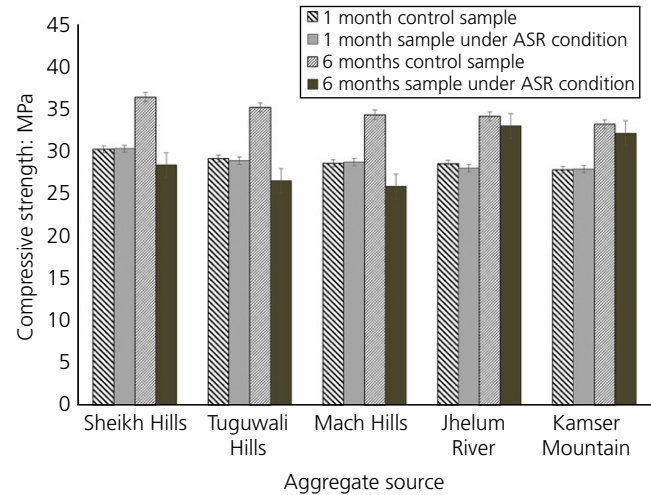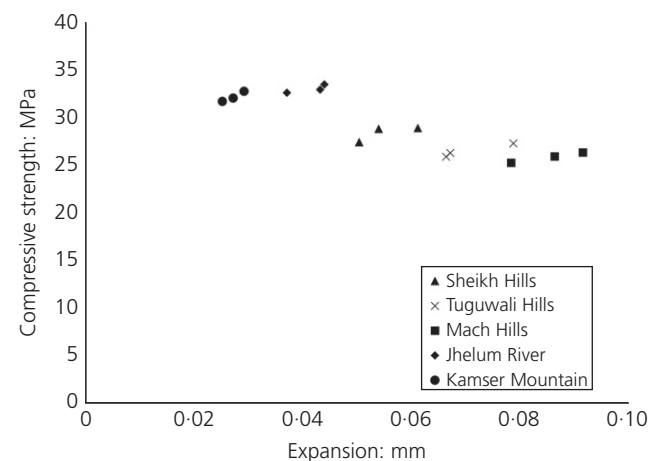exposure, a 25% decrease in compressive strength was recorded

Figure 11. Relationship between compressive strength and
expansion of specimens under ASTM C 227 (ASTM, 2010)
exposure conditions

for specimens incorporating the Mach Hills aggregate compared
with that of the control specimens. This decrease in compressive
strength was more prominent for the Sargodha aggregate
sources due to its alkali–silica reaction as discussed earlier and
reported by others (Ahmed *et al.*, 2013; Bignozzi and Saccani,
2012). However, the specimens incorporating the Kamser and
Jhelum aggregates also incurred a slight decrease in compressive
strength (about 3%), likely due to the limited ASR expansion
associated with these aggregates as discussed above. Figure 11
shows the relation between compressive strength and 6-month
mortar bar expansion under ASTM C 227 (ASTM, 2010) test
conditions. A decreasing trend can be observed between

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compressive strength and expansion values, as reported by others (Giaccio *et al.*, 2008).

Figure 12 portrays the compressive strength of specimens incorporating the various sources of aggregates under ASTM C 1260 (ASTM, 2014c) exposure conditions. Results show that specimens tested under ASTM C 1260 (ASTM, 2014c) demonstrated a decrease in compressive strength. For instance, specimens incorporating the Mach Hills aggregate incurred a 22% decrease in compressive strength. Similar to the case of ASTM C 227 (ASTM, 2010) exposure, specimens incorporating aggregates from the Sargodha region exhibited a significant decrease
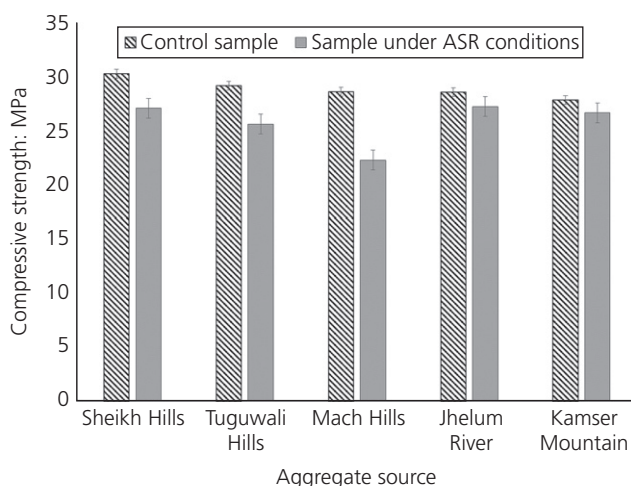
in compressive strength under ASTM C 1260 (ASTM, 2014c) exposure conditions compared with that of the control specimens. Specimens made with aggregates from the Jhelum and Kamser sources incurred a comparatively lower decrease in compressive strength. This is ascribed to lower ASR expansion as discussed above. The relationship between compressive strength and ASTM C 1260 (ASTM, 2014c) expansion also showed a decreasing trend (Figure 13). Increased expansion due to ASR resulted in reduced compressive strength (Giaccio *et al.*, 2008).

It can be concluded that the compressive strength of specimens incorporating aggregates from the Sargodha region was more affected by ASR, especially at later ages. The more reactive aggregates yielded a more significant decrease in compressive strength. The overall reduction in compressive strength for specimens tested under ASTM C 227 (ASTM, 2010) ranged from 22 to 25%, while it ranged from 10 to 22% for identical specimens tested under ASTM C 1260 (ASTM, 2014c) conditions. This is ascribed to the difference in exposure conditions between the two test methods and to the fact that ASTM C 227 (ASTM, 2010) results represent later age (6 months) behaviour, whereas those for ASTM C 1260 (ASTM, 2014c) are obtained after 1 month of exposure, in accordance with previous research (Ahmed *et al.*, 2013; Islam, 2010).

4.4.3 Effect of ASR on modulus of rupture
Figure 14 shows the flexural strength results of control specimens and specimens tested under ASTM C 227 (ASTM, 2010) conditions. For specimens tested under 1-month ASR conditions of ASTM C 227 (ASTM, 2010), an increase in flexural strength was observed as compared with 1-month control samples. This may be due to the presence of slow reactive

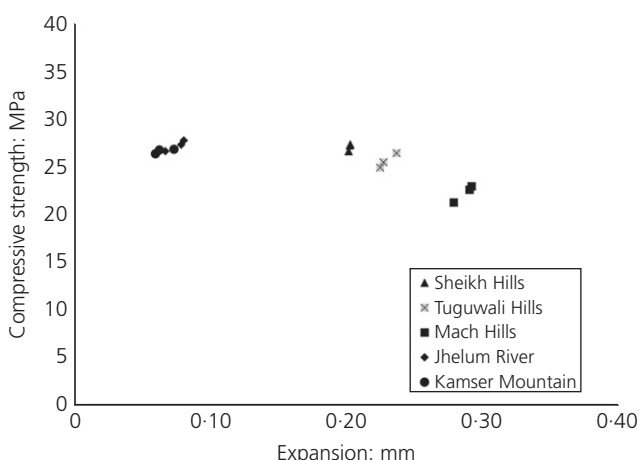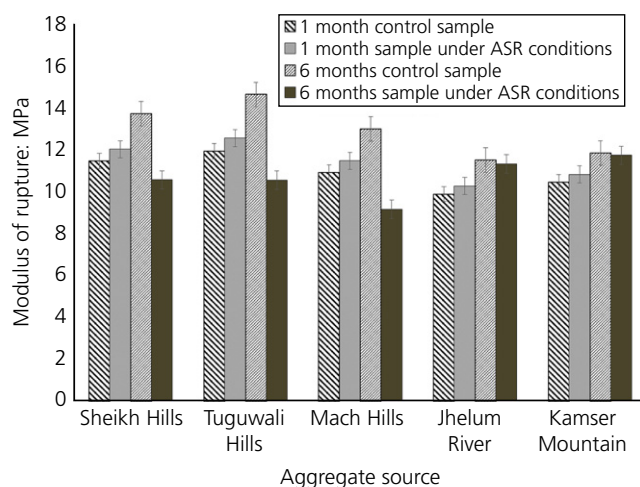**Figure 12.** Compressive strength of specimens under ASTM C 1260 (ASTM, 2014c) exposure conditions

Figure 13. Relationship between compressive strength and expansion of specimens under ASTM C 1260 (ASTM, 2014c) exposure conditions

Figure 14. Modulus of rupture tested under ASTM C 227 (ASTM, 2010) exposure conditions

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aggregates. As expected, the control specimens gained higher modulus of rupture after 6 months compared with that at 1 month. However, the 6-month flexural strength of specimens exposed to ASTM C 227 (ASTM, 2010) conditions was comparatively lower than that of the control specimens at the same age. For instance, there was a 22% decrease in flexural strength of specimens incorporating the Tuguwali Hills aggregate compared with that of the control. This decrease in flexural strength can be attributed to ASR, which can create micro-cracks that decrease flexural strength (Thibodeaux *et al.*, 2003). Specimens incorporating aggregates from the Kamser and Jhelum sources showed no significant decrease in flexural strength (< 2%) compared with the control specimens, which is
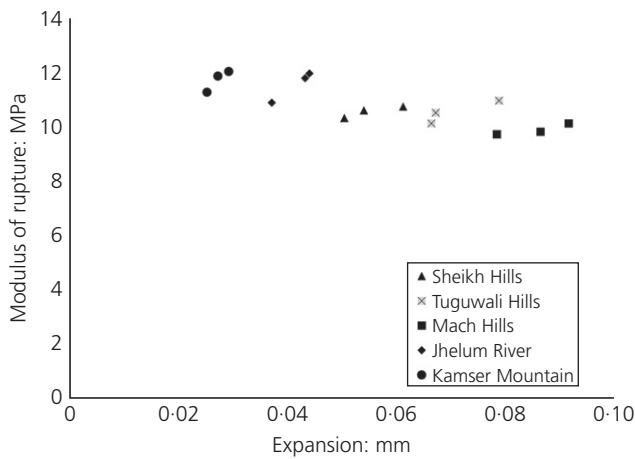
consistent with the mortar bar expansion results. Figure 15 shows the relation between flexural strength and ASTM C 227 (ASTM, 2010) expansion, indicating decreased flexural strength with increased expansion.

Figure 16 shows the flexural strength results for specimens tested under ASTM C 1260 (ASTM, 2014c) exposure. A decrease in flexural strength for specimens tested under ASTM C 1260 (ASTM, 2014c) compared with the control specimens can be observed. For example, specimens incorporating aggregates from the Sheikh Hills source suffered a 22% decrease in flexural strength compared with the control specimens. All tested aggregates from the Sargodha sources have shown a distinct decrease in flexural strength under ASTM C 1260 (ASTM, 2014c). This decrease was more prominent for specimens incorporating the Mach Hills aggregates, likely due to its higher ASR expansion and the associated micro-cracking as discussed above. Specimens made with aggregates from the Jhelum and Kamser sources had comparatively smaller decrease in flexural strength (up to 8%) under ASTM C 1260 (ASTM, 2014c) exposure compared with the control specimens. Furthermore, a decreasing trend was also observed for flexural strength plotted against ASTM C 1260 (ASTM, 2014c) expansion values (Figure 17).

Similarly to compressive strength, it was observed that the flexural strength of specimens from the Sargodha aggregate sources was more significantly affected by ASR. The more reactive the aggregate, the greater the decrease in flexural strength. The overall reduction in the flexural strength of the specimens tested under ASTM C 227 (ASTM, 2010) ranged from 23 to 29%, while it ranged between 22 to 34% for those tested under ASTM C 1260 (ASTM, 2014c). Marzouk and Langdon (2003) also reported a reduction in flexural strength of up to 24%

Figure 15. Relationship between modulus of rupture and expansion of specimens under ASTM C 227 (ASTM, 2010) exposure conditions
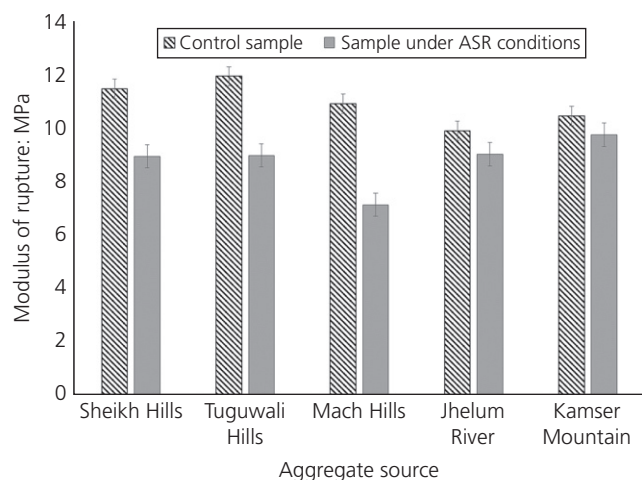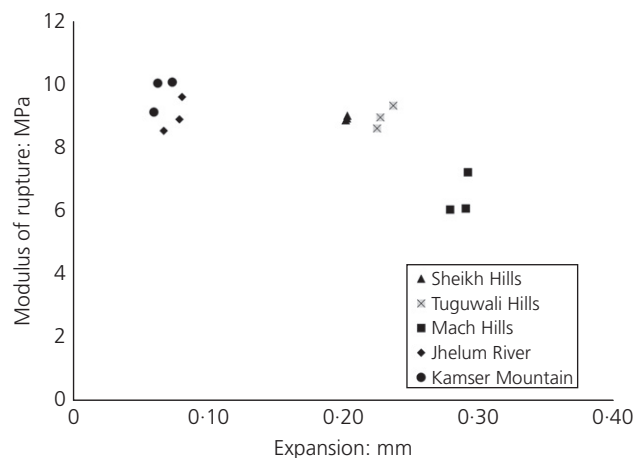

Figure 16. Modulus of rupture of specimens under ASTM C 1260 (ASTM, 2014c) exposure conditions

Figure 17. Relationship between modulus of rupture and expansion of specimens under ASTM C 1260 (ASTM, 2014c) exposure conditions

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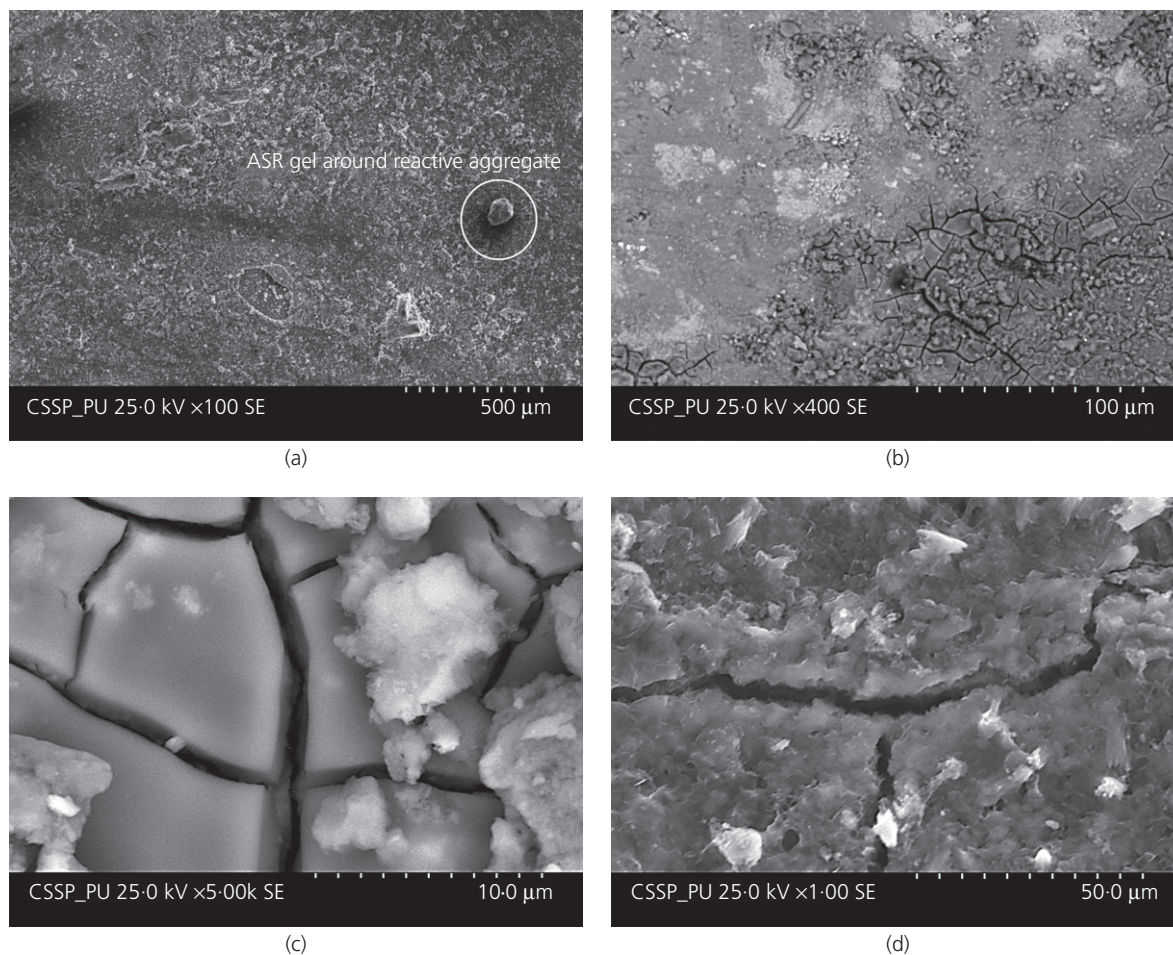aggregates
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Figure 18. SEM images of mortar bar incorporating Mach Hills aggregates under ASTM C 1260 (ASTM, 2014c) exposure conditions: (a) presence of ASR gel around reactive aggregate particle, (b) cracking observed in mortar specimens around reactive aggregates and (c), (d) cracks due to ASR

associated with moderately reactive aggregates. Highly reactive aggregates can drastically decrease flexural strength (up to 84%), as reported elsewhere (Ahmed *et al.*, 2013).
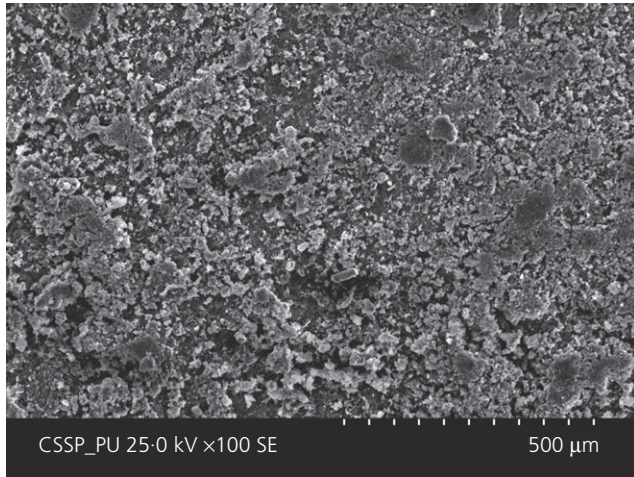
4.5 Microscopic examination

SEM was performed to examine the microstructure of mortar bar specimens under different ASR exposure conditions. Figure 18 shows SEM images of specimens incorporating the Mach Hills aggregate tested under ASTM C 1260 (ASTM, 2014c) conditions. SEM images (Figures 18(a) and 18(b)) indicate the presence of ASR gel around the reactive aggregate particle. It was also observed that more abundant cracking developed in those mortar bar specimens. Such cracks had a size of 4 µm or less (Figure 18(c)), and were not observed in the control specimens. This indicates that cracks are not related to specimen preparation. However, no cracks or ASR
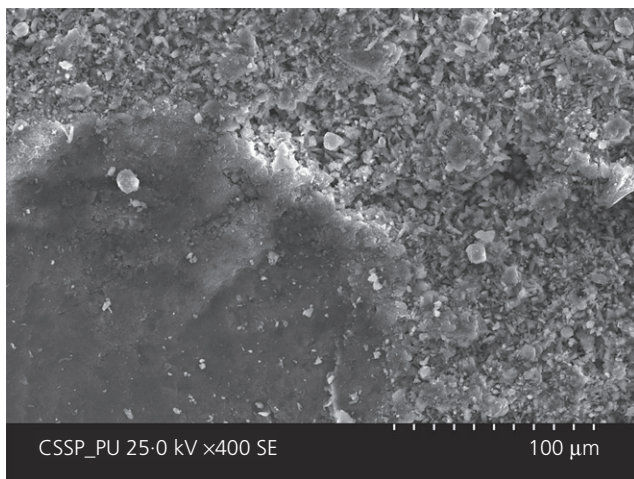
gel formation were observed in specimens incorporating the Sheikh Hills aggregate source tested under both ASTM C 227 (ASTM, 2010) and C 1260 (ASTM, 2014c) conditions (Figure 19). Likewise, SEM images of specimens incorporating the Tuguwali and Mach Hills aggregate sources and tested under ASTM C 227 (ASTM, 2010) showed no presence of cracks or ASR gel (Figure 20). Generally, SEM findings identified ASR gel in those specimens incurring higher expansion and exhibiting an associated decay in mechanical properties.

5. Conclusions

This study explored the characterisation of ASR risk in aggregates with slow reactivity with an attempt to define a suitable test method to quantify such a risk. The mineralogy and physical properties of various aggregate sources were characterised. The ASR-related expansion of mortar bars incorporating
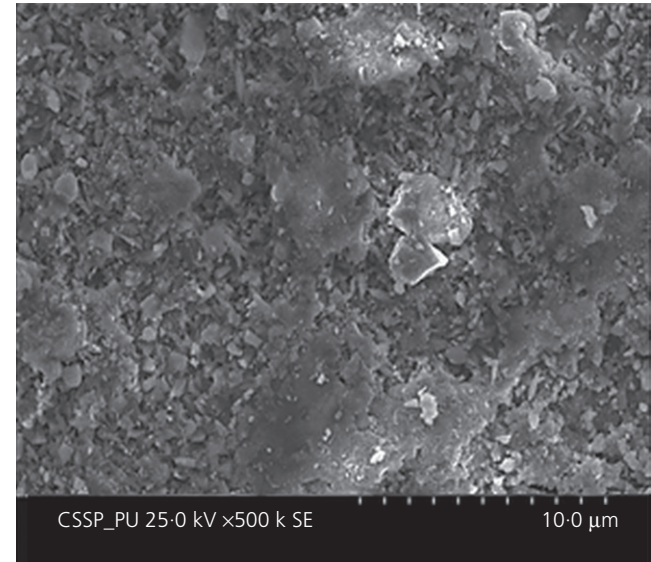
15

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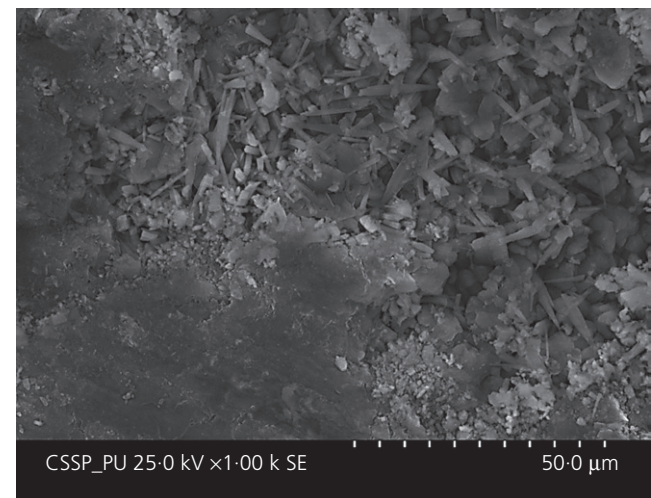Munir, Abbas, Qazi, Nehdi and Kazmi

Figure 19. SEM images of mortar bar incorporating Sheikh Hills aggregate source: (a) mortar bar under ASTM C 1260 (ASTM, 2014c) condition and (b) mortar bar under ASTM C 227 (ASTM, 2010) condition

Figure 20. SEM images of mortar bars incorporating (a) Tuguwali and (b) Mach Hills aggregate sources tested under ASTM C 227 (ASTM, 2010) exposure conditions

such aggregates was explored, along with the associated decay in compressive and flexural strength. SEM imaging was used to capture the microstructural features related to the measured expansion and decay in mechanical properties. The following conclusions can be drawn from the experimental results.

(a) A petrographic examination of the aggregates explored in the study confirms the presence of reactive minerals (3–77%). However, the reactive minerals were considered to be only slowly reactive.

(b) The ASTM C 227 (ASTM, 2010) mortar bar expansion for specimens incorporating aggregates from the Sargodha region ranged from 0·05 to 0·07%. However,

specimens made with the Jhelum and Kamser aggregate sources exhibited lower expansion of <0·04%, either due to the pessimum effect or due to their non-reactive nature.

(c) Using the ASTM C 1260 (ASTM, 2014c) test method provided different results, showing all tested sources of aggregates from the Sargodha region to be reactive with an expansion >0·20%.

(d) The compressive strength of specimens incorporating aggregates from the Sargodha region was more affected

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by ASR, especially at later ages. The more reactive
aggregates yielded a more significant decrease in
compressive strength, as expected.

(e) The overall reduction in compressive strength for
specimens tested under ASTM C 227 (ASTM, 2010)
ranged from 22 to 25%, while it ranged from 10 to 22%
for identical specimens tested under ASTM C 1260
(ASTM, 2014c) conditions.

(f) A decrease in flexural strength was observed for
Sargodha aggregate sources tested under ASTM C 227
(ASTM, 2010) and ranging from 23 to 29%. Similar
specimens incurred flexural strength reduction under
ASTM C 1260 (ASTM, 2014c) ranging from 22 to 34%.
Specimens incorporating aggregates from the Kamser
and Jhelum sources exhibited a smaller decrease in
flexural strength (i.e. 8%).

(g) Specimens included from the Kamser and Jhelum
aggregate sources did not incur significant reduction
either in compressive strength, or in flexural strength
under conditions of exposure conducive to ASR.

(h) SEM imaging confirmed that the Mach Hills aggregate
source has potential ASR. SEM results obtained on the
Mach Hills aggregates also confirmed the effectiveness of
the ASTM C 1260 (ASTM, 2014c) in better identifying
potential ASR in slow reactive aggregates as opposed to
ASTM C 227 (ASTM, 2010). In addition, ASTM
C 1260 (ASTM, 2014c), which requires less time to
conduct, better agreed with the petrographic analysis
results.

(i) The findings of this study should be substantiated with
additional testing using the ASTM C 1293 (ASTM,
2015d) concrete prism test. In addition, the effectiveness
of using locally available supplementary cementitious
materials in mitigating the reactivity of some of the
tested aggregates needs dedicated future research.

REFERENCES

Abbas S, Kazmi SMS and Munir MJ (2017) Potential of rice husk ash for
mitigating the alkali–silica reaction in mortar bars incorporating
reactive aggregates. *Construction and Building Materials* **132**: 61–70.

ACI (American Concrete Institute) (1998) *State of the Art Report on
Alkali Aggregate Reactivity.* American Concrete Institute,
Farmington Hills, MI, USA, ACI 221.1R-98.

ACI (2001) *Guide for Use of Normal Weight Aggregate in Concrete.*
American Concrete Institute, Farmington Hills, MI, USA,
ACI 221.

Ahmed T, Burley E, Rigden S and Abu-Tair AI (2013) The effect of alkali
reactivity on the mechanical properties of concrete. *Construction
and Building Materials* **17(2)**: 123–144.

Alexander M and Mindess S (2005) *Aggregates in Concrete*, 13th edn.
Modern Concrete Technology, New York, NY, USA.

ASTM (1994) C 184: Standard test method for fineness of hydraulic
cement by the 150-μm (no. 100) and 75-μm (no. 200) sieves.
ASTM International, West Conshohocken, PA, USA.

ASTM (1997) C 342: Standard test method for potential volume change
of cement-aggregate combinations. ASTM International,
West Conshohocken, PA, USA.

ASTM (1998) C 294: Standard descriptive nomenclature for
constituents of natural mineral aggregates. ASTM International,
West Conshohocken, PA, USA.

ASTM (2003) C 289: Standard test method for potential alkali-silica
reactivity of aggregates (chemical method). ASTM International,
West Conshohocken, PA, USA.

ASTM (2010) C 227: Standard test method for potential alkali
reactivity of cement-aggregate combinations (mortar-bar method).
ASTM International, West Conshohocken, PA, USA.

ASTM (2011a) C 187: Standard test method for amount of water
required for normal consistency of hydraulic cement paste.
ASTM International, West Conshohocken, PA, USA.

ASTM (2011b) C 490: Standard practice for use of apparatus for
the determination of length change of hardened cement paste,
mortar, and concrete. ASTM International, West Conshohocken,
PA, USA.

ASTM (2012) C 295: Standard guide for petrographic examination of
aggregates for concrete. ASTM International, West Conshohocken,
PA, USA.

ASTM (2013) C 191: Standard test methods for time of setting of
hydraulic cement by vicat needle. ASTM International,
West Conshohocken, PA, USA.

ASTM (2014a) C 305: Standard practice for mechanical mixing of
hydraulic cement pastes and mortars of plastic consistency.
ASTM International, West Conshohocken, PA, USA.

ASTM (2014b) C 348: Standard test method for flexural strength
of hydraulic-cement mortar. ASTM International,
West Conshohocken, PA, USA.

ASTM (2014c) C 1260: Standard test method for potential alkali
reactivity of aggregates (mortar-bar method). ASTM
International, West Conshohocken, PA, USA.

ASTM (2015a) C 114: Standard test methods for chemical analysis of
hydraulic cement. ASTM International, West Conshohocken,
PA, USA.

ASTM (2015b) C 127: Standard test method for relative density
(specific gravity) and absorption of coarse aggregate.
ASTM International, West Conshohocken, PA, USA.

ASTM (2015c) C 151: Standard test method for autoclave expansion of
hydraulic cement. ASTM International, West Conshohocken, PA,
USA.

ASTM (2015d) C 1293: Standard test method for concrete aggregates
by determination of length change of concrete due to alkali-silica
reaction. ASTM International, West Conshohocken, PA, USA.

ASTM (2015e) C 1437: Standard test method for flow of hydraulic
cement mortar. ASTM International, West Conshohocken, PA,
USA.

ASTM (2016a) C 29: Standard test method for bulk density
("unit weight") and voids in aggregate. ASTM International,
West Conshohocken, PA, USA.

ASTM (2016b) C 33: Standard specification for concrete aggregates.
ASTM International, West Conshohocken, PA, USA.

ASTM (2016c) C 109: Standard test method for compressive
strength of hydraulic cement mortars (using 2-in. or [50-mm]
cube specimens). ASTM International, West Conshohocken,
PA, USA.

ASTM (2016d) C 204: Standard test methods for fineness of hydraulic
cement by air-permeability apparatus. ASTM International, West
Conshohocken, PA, USA.

ASTM (2016e) C 535: Standard test method for resistance to
degradation of large-size coarse aggregate by abrasion and

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impact in the Los Angeles machine. ASTM International,
West Conshohocken, PA, USA.

Berube MA and Fournier B (1994) Accelerated test methods for
alkali–aggregate reactivity. In *Advances in Concrete Technology*
(Malhotra VM (ed.)). Natural Resources Canada, Ottawa, ON,
Canada, CANMET publication MSL 94-1(IR), pp. 991–1044.

Bignozzi M and Saccani A (2012) Ceramic waste as aggregate and
supplementary cementing material: a combined action to contrast
alkali silica reaction (ASR). *Cement and Concrete Composites*
34(10): 1141–1148.

Bonzel VJ and Dahms J (1973) *Alkali–Aggregate Reaction in Concrete.*
Beton Herstellung Verwendung, Berlin, Germany.

Borge JW (1995) *Alkali–Aggregate Reactions in Concrete: Properties,
Classification and Testing of Norwegian Cataclastic Rocks.*
PhD thesis, Department of Geology and Mineral Resources
Engineering, Norwegian Institute of Technology, University of
Trondheim, Trondheim, Norway.

BSI (2014a) 812–110: Testing aggregates. Methods for determination of
aggregate crushing value (ACV). BSI, London, UK.

BSI (2014b) 812–112: Testing aggregates. Method for determination of
aggregate impact value (AIV). BSI, London, UK.

Carlson RW (1938) Drying shrinkage of concrete as affected by many
factors. *Proceedings of ASTM* **38(Part II)**: 419–437.

Charlwood RG and Solymar ZV (1994) A review of alkali–aggregate
reactions in dams. *Dam Engineering* **5(2)**: 31–62.

Chatterji S (1978) An accelerated method for detection of
alkali–aggregate reactivities of aggregates. *Cement and Concrete
Research* **8(5)**: 647–650.

CSA (Canadian Standards Association) (2005) CSA A864-00: Guide to
the evaluation and management of concrete structures affected by
ASR. CSA, Toronto, Canada.

Dahms J (1977) Influences on the alkali–aggregate reaction under
field conditions. In *Proceedings of 1976 Alkali Symposium,
London, UK* (Poole AB (ed.)). Cement and Concrete Association,
Wexham, UK, pp. 277–290.

Davies G and Oberholster RE (1987) *An Interlaboratory Test
Programme on the NBRI Accelerated Test to Determine the
Alkali-Reactivity of Aggregates.* National Building Research
Institute, CSIRO, Pretoria, South Africa, Special Report
BOU 92-1987.

Dent LS and Kataoka N (1981) The chemistry of alkali–aggregate
reaction. *Cement and Concrete Research* **11(1)**: 1–9.

Diamond S (1978) Chemical reactions other than carbonate reactions.
In *Significance of Tests and Properties of Concrete and
Concrete-Making Materials.* ASTM, West Conshohocken, PA,
USA, Special Technical Publication STP169B, Ch. 40.

Donnell KM, Zoughi R and Kurtis KE (2013) Demonstration of
microwave method for detection of alkali–silica reaction (ASR)
gel in cement-based materials. *Cement and Concrete* **44**: 1–7.

EN (2005) 196-3: Methods of testing cement – Part 3: Determination
of setting time and soundness. European Committee for
Standardization, Brussels, Belgium.

Fava ASC, Manuele RJ, Colina JF and Cortelezzi CR (1991) *Estudios y
Experiencias Realizadas en LEMIT Sobre Reacción que se Produce
Entre el Cemento y los Agregados en el Hormigón de Cemento
Portland.* LEMIT, La Plata, Argentina, Serie Técnica N 85,
(in Spanish).

Fournier B and Berube MA (1991) Application of NBRI quick mortar
bar test to determine alkali reactivity of carbonate aggregate
aggregates produced in St. Lawrence Lowlands (Quebec, Canada).
Part II: proposed limits, rates of expansion and microstructures
of reaction products. *Cement and Concrete Research* **21(6)**:
1069–1082.

Fournier B and Berube M (2000) Alkali–aggregate reaction in concrete:
a review of basic concepts and engineering implications. *Canadian
Journal of Civil Engineering* **27(2)**: 167–191.

Giaccio G, Zerbino R, Ponce JM and Batic OR (2008) Mechanical
behavior of concretes damaged by alkali–silica reaction.
Cement and Concrete Research **38(7)**: 993–1004.

Grattan-Bellew PE (1981) A review of test methods for
alkali-expansivity of concrete aggregates. *Proceedings of 5th
International Conference on Alkali Aggregate Reaction in Concrete*
(Oberholster RE (ed.)). National Building Research Institute
Pretoria, Cape Town, South Africa, Paper S252/9, pp. 1–13.

Grattan-Bellew PE (1989) Test methods and criteria for evaluating the
potential reactivity of aggregates. *Proceedings of 8th International
Conference on Alkali–Aggregate Reaction* (Okada K,
Nishibayashi S and Kawamura M (eds)). National the Society of
Materials Science, Kyoto, Japan, pp. 279–294.

Hooton D (1990) *Inter-Laboratory Study of the NBRI Rapid Test
Method and CSA Standardization Status.* Ontario Ministry of
Transportation, Toronto, ON, Canada, Report EM-92.

Ichikawa T (2009) Alkali silica reaction, pessimum effects and
pozzolanic. *Cement and Concrete Research* **39(8)**: 716–726.

Islam MS (2010) *Performance of Nevada's Aggregate on
Alkali–Aggregate Reactivity of Portland Cement Concrete.*
Doctoral dissertation, University of Nevada, Las Vegas, NV, USA.

Islam MS and Akhtar S (2013) A critical assessment to the performance
of alkali–silica reaction (ASR) in concrete. *Canadian Chemical
Transactions* **1(4)**: 253–266.

Islam MS and Ghafoori N (2013) Evaluation of alkali–silica reactivity
using aggregate geology, expansion limits of mortar bars and
concrete prisms, and kinetic model. *Journal of Materials Science
Research* **2(2)**: 103–117.

Jensen V (2004) Alkali–silica reaction damage to Elgeseter Bridge,
Trondheim, Norway: a review of construction, research and repair.
Materials Characterization **53(2–4)**: 155–170.

Johansen V (1989) Cement production and cement quality.
In *Material Science of Concrete* (Skalny J (ed.)). The American
Ceramic Society, Westerville, OH, USA, pp. 27–72.

Jones AE and Clark LA (1996) A review of the Institution of
Structural Engineers report: structural effects of alkali–silica
reaction (1992). *Proceedings of 10th International Conference on
Alkali–Aggregate Reaction* (Shayan A (ed.)). Commonwealth
Scientific and Industrial Research Organization, Melbourne,
Australia, pp. 394–401.

Jones AEK and Clark LA (1998) The effects of ASR on properties of
concrete and the implications for assessment. *Engineering
Structures* **2(9)**: 785–791.

Kosmatka SH and Panarese WC (1988) *Design and Control of Concrete
Mixtures*, 13th edn. Portland Cement Association, Skokie, IL, USA.

Koyanagi W, Rokugo K, Uchida Y and Iwase H (2000) Deformation
behavior of reinforced concrete beams deteriorated by ASR.
*Proceedings of 11th International Conference on Alkali–Aggregate
Reaction* (Berube MA, Fournier B and Durand B (eds)).
Center for Research on Concrete Infrastructure, Quebec, QC,
Canada, pp. 458–465.

Larive C, Laplaud A and Joly M (1996) Behaviour of AAR-affected
concrete, experimental data. *Proceedings of 10th International
Conference on Alkali–Aggregate Reaction* (Shayan A (ed.)).
Commonwealth Scientific and Industrial Research Organization,
Melbourne, Australia, pp. 670–677.

Lu D, Fournier B. and Grattan-Bellew PE (2006) Evaluation of
accelerated test methods for determining alkali–silica reactivity of
concrete aggregates. *Cement and Concrete Composites* **28(6)**:
546–554.

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Role of test method in detection of
alkali–silica reactivity of concrete
aggregates
Munir, Abbas, Qazi, Nehdi and Kazmi

Magni ER, Rogers CA and Grattan-Bellew PE (1986) The influence of
the alkali–silica reaction on structures in the vicinity of Sudbury,
Ontario. *Proceedings of 7th International Conference on
Alkali–Aggregate Reaction* (Grattan-Bellew PE (ed.)).
Noyes Publications, Park Ridge, NJ, USA, pp. 17–21.

Marzouk H and Langdon S (2003) The effect of alkali–aggregate
reactivity on the mechanical properties of high and normal strength
concrete. *Cement and Concrete Composites* **25(4–5)**: 549–556.

Monette L, Gardner J and Grattan-Bellew P (2000) Structural effects of
the alkali–silica reaction on non-loaded and laded reinforced
concrete beams. *Proceedings of 11th International Conference
on Alkali–Aggregate Reaction* (Berube MA, Fournier B and
Durand B (eds)). Center for Research on Concrete Infrastructure,
Quebec, QC, Canada, pp. 999–1008.

Munir MJ, Qazi AU, Kazmi SMS *et al.* (2016) A literature review on
alkali silica reactivity of concrete in Pakistan. *Pakistan Journal of
Science* **68(1)**: 53–62.

Natesaiyer K and Hover KC (1988) In situ identification of ASR products
in concrete. *Cement and Concrete Research* **18(3)**: 455–463.

Natesaiyer K and Hover KC (1989) Further study of an in situ method
for identification of alkali silica reaction products in concrete.
Cement and Concrete Research **19(5)**: 770–778.

NBS (National Building Studies) (1958) *Reactions between Aggregates
and Cement. Part VI: Alkali–Aggregate Interaction: Experience
with Some Forms of Rapid and Accelerated Test Procedures.*
Her Majesty's Stationery Office, London, UK, NBS Research
Paper No. 25.

NESPAK (National Engineering Services Pakistan) (2011) *Study Report –
Study of Construction Material Sources in AJK.* The State of Azad
Jammu and Kashmir, Planning and Development Department,
Muzaffarabad, Pakistan.

Neville AM (2000) *Properties of Concrete.* Pearson Education Asia
Private Limited, Edinburgh, UK.

Raja M, Jain SK, Vijh GK, Gupta SL and Ratnam M (2014) Test methods
for identifying the susceptibility of aggregate to alkali silica
reaction (ASR) – an overview. *Journal of Emerging Technology
and Advanced Engineering* **4(8)**: 328–334.

Rivard P, Jean-Pierre O and Ballivy G (2002) Characterization of the ASR
rim: application to the Potsdam sandstone. *Cement and Concrete
Research* **32(8)**: 1259–1267.

Siemes T and Visser J (2000) Low tensile strength older concrete
structures with alkali–silica reaction. *Proceedings of 11th
International Conference on Alkali Aggregate Reaction*
(Berube MA, Fournier B and Durand B (eds)). Center for
Research on Concrete Infrastructure, Quebec, QC, Canada,
pp. 1029–1038.

Siemes T, Han N and Visser J (2002) Unexpectedly low tensile strength in
concrete structures. *TNO Building and Construction Research*
47(02): 111–124.

Sims I (1981) The application and reliability of standard testing
procedures for potential alkali–aggregate reactivity. *Proceedings of
5th International Conference on Alkali Aggregate Reaction in
Concrete* (Oberholster RE (ed.)). National Building Research
Institute Pretoria, Cape Town, South Africa, Paper S252/13,
pp. 1–11.

Stanton TE (1940) Expansion of concrete through reaction between
cement and aggregates. *Proceedings of American Society of Civil
Engineers* **66(10)**: 1781–1811.

Stark DC (1980) Alkali–silica reactivity: some reconsiderations. *Cement
Concrete and Aggregates* **2(2)**: 92–94.

Stark DC (1985) *Alkali–Silica Reactivity in Five Dams in SouthWestern
United States.* US Bureau of Reclamation, Denver, CO, USA,
Report REC-ERC-85-10.

Stark DC (1991a) *Handbook for Identification of Alkali–Silica
Reactivity in Highway Structures.* Strategic Highway Research
Program, National Research Council, Washington, DC, USA,
SHRP-C/FR-91-101.

Stark DC (1991b) How to evaluate the state of alkali–silica reactivity
(ASR) in concrete. *Concrete Repair Digest*, August–September:
pp. 104–107.

Stark D, Morgan B and Okamoto P (1993) *Eliminating or Minimizing
Alkali–Silica Reactivity.* Strategic Highway Research Program,
National Research Council, Washington, DC, USA.

Takemura K, Ichitsubo M, Tazawa E and Yonekura A (1996) Mechanical
performance of ASR affected nearly full-scale reinforced concrete
columns. *Proceedings of 10th International Conference on
Alkali–Aggregate Reaction* (Shayan A (ed.)). Commonwealth
Scientific and Industrial Research Organization, Melbourne,
Australia, pp. 410–417.

Thibodeaux K, Kennison L and Kurtis K (2003) *Potential for Alkali–Silica
Reaction in Hollow Glass Spheres to be Used in Oil Well
Cementing Applications.* School of Civil & Environmental
Engineering, Georgia Institute of Technology, Atlanta, GA, USA,
Report.

USACE (US Army Corps of Engineers) (1994) *Alkali–Silica Aggregate
Reactions, Standard Practice for Concrete for Civil Works.*
US Army Corps of Engineers Headquarters, Washington, DC,
USA, EM 1110-2-2000.

WAPDA (Water and Power Development Authority) (2004) *Study
Report – Concrete Materials Studies.* Mangla Dam Raising
Project, Lahore, Pakistan.

Yildirim K and Sumer M (2014) Comparative analysis of fly ash effect
with three different methods in mortars that are exposed to alkali
silica reaction. *Composites: Part B* **61**: 110–115.

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