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ABSTRACT

This paper investigates the potential alkali silica reactivity of selected Namibian aggregates from certified quarries in the following towns: Opuwo, Omakange, Tsumeb, Otjiwarongo, Walvis Bay and Windhoek. The susceptibility of the selected aggregates to alkali silica reaction (ASR) was investigated using laboratory-made cement-based mortar bar specimens cast according to ASTM C 1260 specifications. Six mortar mixes were used to cast the test specimens. Three replicate specimens were cast for each mortar mix. The concentration of reactive silica in the aggregates was determined using X-Ray Fluorescence (XRF). From the test results, it can be concluded that the susceptibility of the aggregates under investigation to ASR was minimal. All aggregates, except for those sourced from Windhoek, were non-reactive. Aggregates from Windhoek exhibited slow/mild potential to alkali silica reactivity. An increase in SiO2 content in aggregates resulted in a corresponding increase in the susceptibility to ASR and the percentage expansion.

Keywords: Alkali silica reaction, XRF, aggregates, mortar bar

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1. INTRODUCTION

Alkali aggregate reaction (AAR) is a global problem that has been observed in many concrete structures. It was first reported by Stanton in the USA in 1938 and has been researched extensively since then [1–3]. AAR is an adverse chemical reaction between the alkali in concrete pore solution and the reactive compounds in aggregates. It can be classified into three broad categories depending on the nature of the aggregate involved in the process: alkali-silica reaction, alkali-silicate reaction and alkali-carbonate-rock reaction.

Alkali silica reaction (ASR) is the chemical reaction that occurs between the alkaline concrete pore solution and the metastable forms of silica found in aggregates such as volcanic glasses, cristobalite, tridymite and opal. It can also refer to the reaction between the concrete pore solution and aggregates containing or comprising cherts, chalcedony, microcrystalline quartz, cryptocrystalline quartz or strained quartz. It entails the formation of two types of gel products, namely a non-swelling calcium-alkali-silicate hydrate (C-N(K)-S-H) and a swelling gel alkali-silicate-hydrate (N(K)-S-H) [2–4]. ASR is deemed safe if only the non-swelling gel is formed and unsafe if both products are formed. For the swelling gel to form, four conditions ought to be met simultaneously: (i) a sufficient amount of alkali (generally believed to be higher than 0.6% in terms of sodium oxide equivalent) should be present in the concrete; (ii) a reactive form of silica in sufficient quantity (generally in the aggregates) is required; (iii) a source of soluble calcium (such as portlandite) to react with dissolved silica and form the deleterious gel; and (iv) a sufficient source of moisture is required. ASR will not occur if any of the four mentioned conditions fails to exist. ASR results from a series of reaction processes which occur sequentially, namely: the dissolution of metastable silica, the formation of non-colloidal silica sol, the gelation of the latter and the swelling of the gel [2, 3, 5, 6].

ASR is influenced by: aggregate type, content of reactive aggregate, porosity of aggregate, mineralogy of the reactive silica, diffusivity of the relevant ions, source and concentration of ions, the presence of a pozzolan, the quantity of free $Ca(OH)_2$ in the hydration process, aggregate size, the property of the reaction product and exposure conditions [2, 3, 5–9]. A detailed explanation on how each of these parameters influence ASR can be obtained from the cited literature. The expansive gel formed due to ASR induces tensile stresses in the concrete. These stresses result in cracks which would compromise the aesthetics, durability and structural integrity of the affected concrete structures. The negative effects of ASR have been countered in practice through the use of low-alkali cements (sodium oxide equivalent lower than 0.6%), chemical admixtures containing lithium and calcium nitrate, concrete moisture control, use of non-reactive aggregates and the partial replacement of cement with supplementary cementitious materials (SCMs) [1–4, 7, 8, 10–12].

Whereas extensive studies on the susceptibility of aggregates from various localities to ASR have been reported in literature [1–3]; research on the susceptibility of Namibian aggregates to ASR has not been reported. Consequently, many engineers and contractors in Namibia have continued to specify and use concrete without an in-depth knowledge on their susceptibility to ASR. Chatterji [7], Rashidi et al [13] and Mahomed [2] report that a proper understanding of the composition and behaviour of aggregates ought to inform the assessment of the susceptibility of an aggregate to ASR. Considering the lack of local research on the susceptibility of Namibian aggregates to ASR, this study sought to: (i) investigate the elemental composition of selected Namibian aggregates from six towns; and (ii) assess the potential reactivity of the selected aggregates to ASR using the accelerated mortar bar test as described in ASTM C 1260 [14]. The chemical composition of the aggregates was examined using X-Ray Fluorescence (XRF). The results from this study would inform the selection of suitable aggregate sources for use in the construction of concrete buildings and infrastructure in Namibia.

2. EXPERIMENTAL METHODOLOGY

The following materials were used to cast the mortar mixes for this study:

i. Cement: CEM I, 42.5 N (meeting ASTM C 150 requirements); percentage alkalis = 0.9521% Na2Oeq (Sourced from a local cement plant).
ii. Fine aggregates: passing through the 4.75 mm sieve and retained on the 150 μm sieve (sourced from different quarries across Namibia).

Table 1: Mix design proportions per batch (aggregates with relative densities ≥ 2.45)

Material	Quantity	
	Relative density ≥ 2.45	Relative density < 2.45
Cement (g)	440.0	440.0
Water (ml)	206.8	206.8
Graded aggregate (g)	990.0	440.0
Water:cement (w/c) ratio	0.47	0.47

iii. Sodium hydroxide (NaOH): concentration = 1.0 ± 0.01 N (Source: Biodynamics, Windhoek, Namibia).

Coarse aggregates samples were collected randomly from certified quarries that supply aggregates for use in construction in the following towns in Namibia: Opuwo, Omakange, Tsumeb, Otjiwarongo, Walvis Bay and Windhoek. The sampling was done according to Method MB1 of TMH5 [15]. The samples were labelled as S1 (Walvis Bay), S2 (Opuwo), S3 (Tsumeb), S4 (Otjiwarongo), S5 (Omakange) and S6 (Windhoek). The labelled samples were oven-dried, cooled, crushed and sieved according to ASTM C 33 [16], ASTM C 136 [17] and ASTM C 1260 [14] specifications. The portion of the graded fine aggregate that passed through the 4.75 mm sieve and was retained on the 150 µm sieve was separated for use in this study.

A 1 kg aggregate from each quarry was pulverised, packed in a plastic bag and sent to the Ministry of Mines and Energy in Windhoek for X-Ray Fluorescence (XRF) analysis. XRF was used to determine the elemental composition of each aggregate sample. The relative density of the graded aggregates from each source was determined using a pycnometer according to TMH1 Method B15 [18] specifications. The proportioning of the materials for casting the mortar mixes was determined. A mortar mix was cast from each aggregate source. The mass of each mix constituent was determined on the basis of the relative density (r.d) of each aggregate as presented in Table 1 The equations that were used to determine the aggregate proportions are presented in ASTM C 1260 [14] and Strack et al [6].

The constituents of each mortar mix were mass batched and mixed using a mixer, paddle and a mixing bowl. Mixing was done according to ASTM C 305 [19]. Three specimens were cast from each of the six mixes. 18 No. 25 x 25 x 285 mm mortar bar specimens were cast within 2 minutes and 15 seconds after mixing and placed in steel moulds in two approximately equal layers. Each layer was hand compacted with a tamper. The top surface of each specimen was levelled and smoothened with a trowel. The freshly cast specimens were marked then kept in a moist cabinet (temperature = 23 ± 2°C; relative humidity = 100%) for 24 ± 2 hours before demoulding. Figure 1 shows a freshly-cast mortar bar in a moist cabinet.

Specimens were removed from the cabinet and dried using a towel to a saturated surface dry (SSD) condition. A digital Vernier calliper was used to measure the initial length of each specimen immediately after its removal from the cabinet (Figure 2). Measurements were made to the nearest 0.002 mm. Utmost care was taken to prevent the loss of moisture in the specimens.

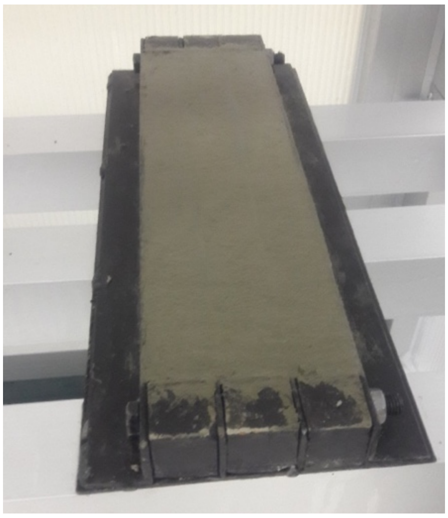

Figure 1: A freshly-cast mortar bar in a moist cabinet.

The accelerated mortar bar test – despite its limitations as presented in Chatterji [7], Kandasamy and Shehata [11], Rashidi et al [13], Mahomed [2] and Strack et al [6] - was used to test for the potential alkali silica reactivity of the aggregates in accordance with ASTM C 1260 [14]. The constraints of limited time for this research and the unavailability of equipment informed the adoption of this test method. The SSD mortar bar specimens were immersed fully in a storage container with potable tap water at a temperature of 23 ± 2°C. The container was then sealed and placed in an oven maintained at 80 ± 2°C for 24 hours. The hot mortar bar specimens were removed from the oven, one at a time, and their surfaces dried using a towel. A zero length reading was taken and recorded. Thereafter, the mortar bar specimens were immersed in a container with 1.0 N sodium hydroxide solution (NaOH) at 80 ± 2°C for 14 days. The change in length in each specimen was monitored throughout the 14 days of immersion in NaOH. Length measurements were taken at 1, 5, 7, 12 and 14 days after immersion in NaOH. The percentage expansion in each specimen was calculated as per the ASTM C 1260 [14] recommendations. The mean percentage expansion of each mortar mix was calculated from three test results.

3. RESULTS AND ANALYSIS

3.1 Elemental composition

The elemental composition of the aggregates under investigation were determined using XRF analysis. The XRF results are presented in Figure 3. From the XRF results it can be observed that silica content in the aggregates decreased in the following order: S6, S2, S1, S5, S3 and S4. Based on the geological map of Namibia [20], it can be inferred that the variations in silica content can be attributed to the mineralogy of the rocks from which the aggregates were sourced. The silica content is generally high in aggregate sources that contain quartzite and granite (e.g., S1 and S6).

3.2 Mortar bar test results

The test results from the mortar bar test are presented in Figure 4. From Figure 4, it can be

Figure 2: length measurements using a digital Vernier calliper

observed that aggregates from Windhoek (S6) exhibited the largest percentage expansion while aggregates from Otjiwarongo (S4) exhibited the least percentage expansion after 14 days of immersion in 1.0 N sodium hydroxide (NaOH) solution. The percentage expansion in the other aggregates varied between these two values.

The relationship between silica content and the percentage expansion after 14 days of immersion in NaOH solution in each aggregate is presented in Figure 5.

The percentage expansion in the aggregates after 14 days of immersion in 1 N NaOH is closely related to their silica content as shown in Figure 5. A juxtaposition of Figure 3 and Figure 5 reveals that very strong positive correlation - with a correlation coefficient of 0.9 - exists between silica content and the percentage expansion in the aggregates after 14 days of immersion in NaOH. Thus, it can be concluded that an increase in silica content will result in an increase in percentage expansion. The expansion in the aggregates was also observed to be closely related to the Ca/Si ratio. The reported observations are consistent with literature [2,3,5–7]. The percentage expansion was larger in aggregates with low Ca/Si ratio than in those with high Ca/Si ratio. Aggregates with a low Ca/Si produces a net negative charge in the C-S-H gel. This negative charge would absorb the cations in the pore solution which would consequently increase the percentage expansion and the susceptibility to ASR. Aggregates from Windhoek (S6) had the most silica content (90.1%) while those from Otjiwarongo (S4) had the least silica content (1.6%). All the aggregates under investigation, except for those from Windhoek, can be classified as 'innocuous' as per the ASTM C 1260 [14] specifications. The aggregates from Windhoek, however, are potentially reactive. Thus, their use in concrete ought to be carefully informed, especially in critical infrastructure such as dams where the susceptibility to ASR would result in disastrous consequences.

A strong positive correlation – with a correlation coefficient of 0.5 - exists between the silica content and the percentage expansion in the aggregates from 5 to 14 days. Thus, it can be inferred that an increase in silica content will result in an increase in the percentage expansion due to ASR. A negative correlation with a correlation coefficient of 0.6 exists between Ca/Si ratio and the expansion at 14 days. Similarly, a weak negative correlation coefficient exists between the Ca/Si ratio and the percentage expansion in the aggregates from 5 to 14 days. It can thus be inferred that

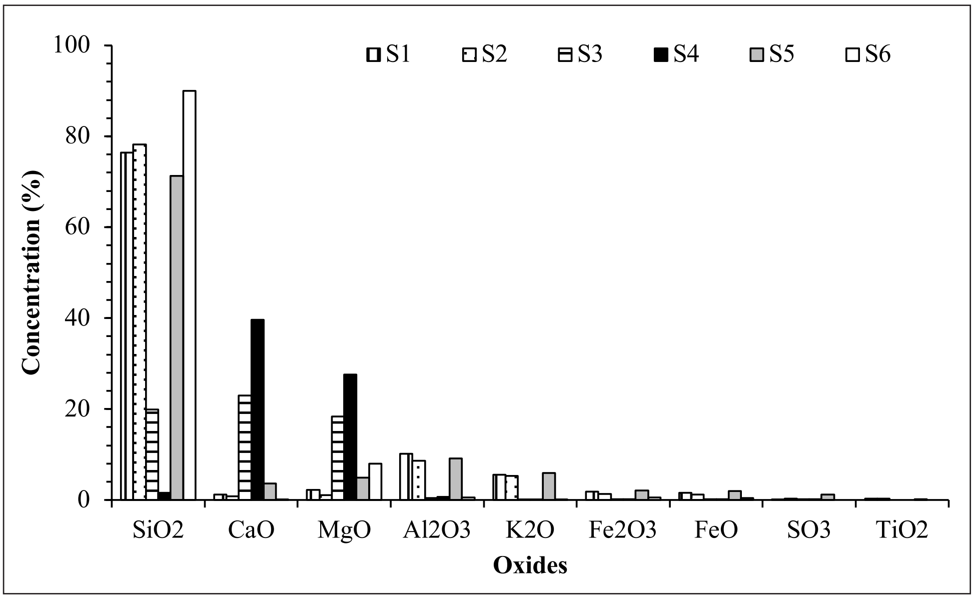

Figure 3: Elemental composition of aggregates.

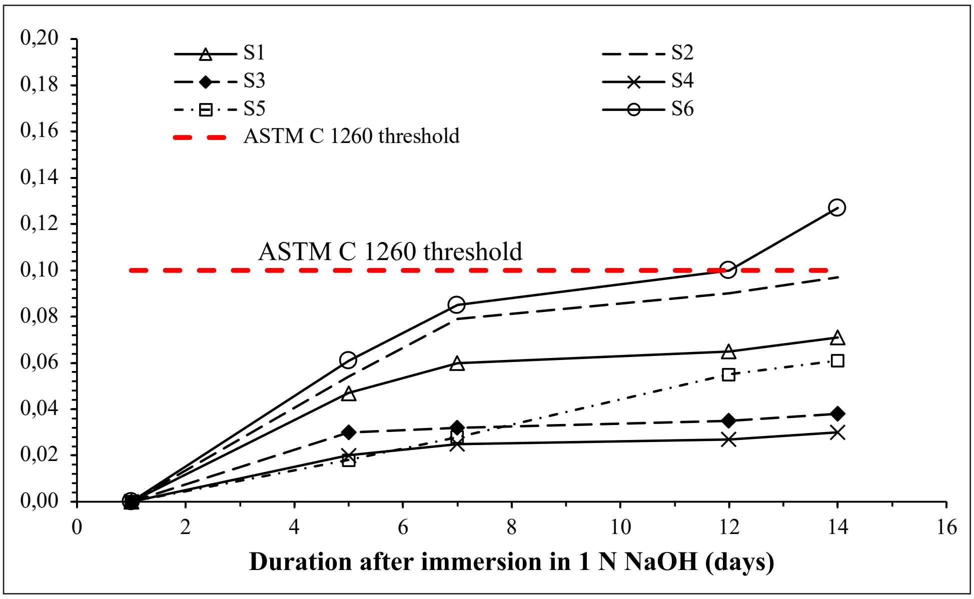

Figure 4: Mortar bar results.

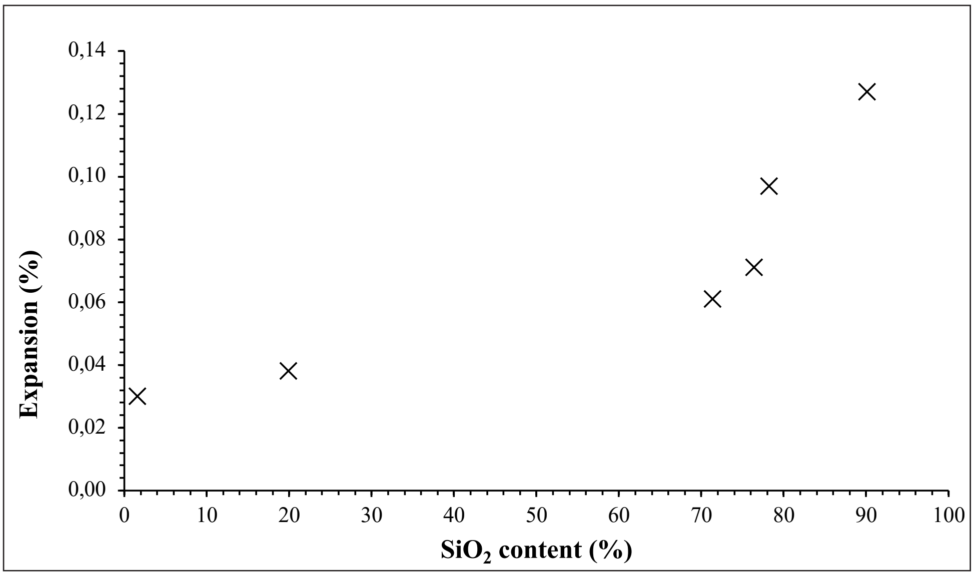

Figure 5: Silica content versus percentage expansion after 14 days of immersion in NaOH

a reduction in the Ca/Si ratio will increase the percentage expansion in the aggregates at 14 days and the percentage change in length from 5 to 14 days. Further studies, however, ought to be done to investigate this relationship in detail. Also, it can be observed that the high alkali content of the cement used in this study (i.e., 0.9521 Na2O eq) could contribute to the susceptibility to ASR; especially in instances where reactive or mildly reactive aggregates are used. Utmost caution ought to be observed while using this cement – especially in the construction of critical infrastructure such as dams which would be adversely affected by ASR.

4. CONCLUSIONS

The susceptibility of selected Namibian aggregates to ASR attack has been discussed. From the test results, the following conclusions can be made:

i. The silica content of Namibian aggregates varies widely depending on their geology.
ii. The susceptibility to ASR increases with an increase in silica content.
iii. The percentage expansion due to ASR increases with an increase in silica content.
iv. The susceptibility of the selected Namibian aggregates to ASR is generally low. All the aggregates under investigation, except for those from Windhoek, are non-reactive. Aggregates from Windhoek exhibited slow/mild potential of alkali silica reactivity.

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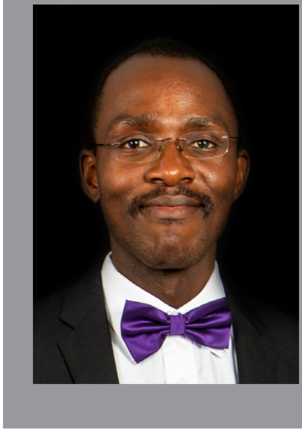

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