THE EFFECT OF ALKALI CONTENT OF CEMENT ON ASR EXPANSION: EVALUATION AND ITS MITIGATION USING FLY ASH

HAMZA TARIQ [*] **, RIZWAN AZAM, ALI AHMED, WASIM ABBASS, SAFEER ABBAS**
Civil Engineering Department, University of Engineering and Technology, Lahore, Pakistan

Alkali silica reaction (ASR) is one of the main deterioration problems faced by reinforced concrete structures. Many structures including dams and bridges are severely affected by this phenomenon. To prevent ASR in new construction, the deterioration mechanism and the factors affecting the ASR phenomenon must be investigated. Many studies have been conducted to understand the deterioration mechanism of the concrete by ASR. However, there are still a few areas which need further research. The current study was designed to investigate the effect of alkali content of cement on expansion by ASR. In addition, effectiveness of fly ash to mitigate ASR expansion was evaluated. Moreover, the effect of ASR on mechanical properties of the mortars was investigated. For this purpose, a total of 27 mortar bar specimens and 54 cubes and prisms were cast, conditioned and tested as per guidelines of ASTM C 227 and ASTM C1260. The test variables included the alkali content of cement (0.58%, 0.53% and 0.43%) and Fly ash proportions (25%, 30% and 35% by cement weight). Test results indicated that ASR expansion is significantly affected by the alkali content of cement to such extend that alkali content of cement should be considered as one of the parameters while evaluating the alkali silica reactivity of the aggregates. It was also observed that minimum 30% fly ash was needed to mitigate the expansion by ASR in highly reactive aggregates. Due to ASR, the compressive and flexural strengths of specimens were reduced by 15% and 31%, respectively.

Keywords: *Alkali-silica reaction, Mortar Bar expansion, Fly ash, Alkali content of cement*

1. Introduction

Alkali-silica reaction (ASR) is a chemical reaction between alkali hydroxides present in the concrete pore solution and reactive silica existing in some aggregates. A gel is formed around the aggregate particles, as result of this reaction which expands when encounters the moisture and results in cracking of the concrete. Various reinforced concrete structures all around the globe including massive structures such as dams, bridges and other water retaining structures have been significantly affected by the damage caused by ASR highlighting the severity of this problem [1, 2].

To mitigate the effects of ASR in concrete, several approaches have been used in literature including the use of non-reactive aggregates, the inclusion of different pozzolans (SCMs) and the use of cements with low alkali contents. Many studies have been reported in literature that investigated the reactivity of aggregates from different regions of the world [3-10]. In addition, several researchers have worked on the use of different pozzolans (SCMs) to mitigate the ASR expansion [11-17]. However, a relatively fewer studies have been reported in literature that investigated the effect of total alkali contents of binding materials on the ASR expansion.

[Tosun, Felekoğlu [18]] (2007) investigated the influence of total alkali content of cement on expansion caused by ASR in mortars containing admixtures using mortar bar tests as per ASTM 1260. The cements having total alkali content (Na_2Oe) of 0.53% and 0.98% were used. The authors observed no expansion in mortars containing non-reactive aggregates. However, the expansion was reported in samples incorporating reactive aggregates and the extent of expansion was directly related to the amount of alkali content of cement. Furthermore, it was observed that ASR expansion is also affected by the amount and the type of admixtures used in mortar.

[Shehata and Thomas [19]] (2010) studied the expansion by ASR of concrete prisms containing cements having different equivalent alkali contents (Na_2Oe of 0.36%, 0.54% and 0.94%) and SCMs. The authors observed that the ASR expansion in prisms with no SCMS was significantly affected by the alkali content present in cements. In addition, the expansion caused by ASR in prisms with SCMs was correlated with both the chemical composition of SCMs and amount of alkalis present in cement.

[Li, Afshinnia [20]] (2016) investigated the effect of alkali content present in cement on ASR expansion of reactive aggregates with varying alkali content of cement. The amount of alkalis present in cement was varied between 0.49% and 0.88%. Authors observed that the amount of alkalis present in cement significantly affects the ASR expansion.

The literature review has revealed that the ASR expansion is significantly affected by amount of alkalis present in cement. However, it is

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[*] Autor corespondent/*Corresponding author*,
E-mail: hamzatariq.ce@gmail.com

important to note that almost all studies reported above have used alkali content (Na_2O eq.) more than 0.60% whereas ASTM committee for Portland cement ASTM [21] recommends an alkali content of 0.60% or lower to effectively control of ASR. Therefore, there is a need to investigate the effect of amount of alkalis present in cements on ASR expansion using cements with Alkali contents of 0.60% or lower. The current study was designed to investigate the correlation between alkali content in cement and expansion by ASR.

2. Materials

The aggregates were provided from Mach Hill area situated in Sargodha region. This source produces one of the most reactive aggregate as investigated by Munir, Abbas [7] (2017). Moreover, aggregates from Mach hill are being widely used in the local construction industry. Petrography analysis was performed to determine aggregates mineralogical composition and textural features in thin slices of aggregates with a microscope. Aggregates mineralogical composition and textural features are shown in Figure 1. It is clear from Figure 1 that aggregates consist of quartz, feldspar, mica and iron oxide. Presence of these minerals specially quartz, feldspar and mica has been linked to ASR susceptibility by different authors (Hagelia and Fernandes [22], Šachlová, Kuchařová [23]). Generally, ASR potential of aggregates is linked to quartz grain size, however in presence of quartz-feldspar-mica interface the role of quartz grain size becomes secondary. Under normal conditions, silica is provided by quartz for ASR reaction but in alkaline solution feldspar also release silica for ASR reaction and porous nature of mica mineral act as catalyst to ASR reaction (Hagelia and Fernandes [22]).

Cement used in this research was provided from six locally available manufacturers. To determine equivalent alkali content (Na_2O_{eq} %), chemical composition of each source of cement was carried out (Table 1). The percentage content of Na_2O and K_2O was used to calculate equivalent alkali content using Eq. 1 below. The equivalent alkali content of all cement sources was found to range between 0.43% and 0.58%. Out of the initially selected six cement sources, three were selected for further investigation. The physical properties of these three cement samples have been given in Table 2.

Na_2O_{eq} (%) = Na_2O (%) + 0.658 x K_2O (%) Eq. 1

Class F Fly Ash was incorporated in mix to study its potential to mitigate ASR expansion. Ordinary tap water was used for mixing purposes.

3.Experimental Program and Methods

To investigate the effect of amount of alkalis present in cement on ASR expansion, 18 mortar bar specimens were cast. Nine specimens were cast and conditioned as per ASTM [24] whereas nine specimens were cast and conditioned as per ASTM [25]. Three cements with varying amounts of alkalis (0.43%, 0.53% and 0.58%) were used and for each alkali content three specimens were cast. Additional nine mortar bar specimens were cast to investigate the efficiency of fly ash to mitigate the damages associated to ASR. Three different fly ash proportions (25%, 30% and 35%) were used and for each fly ash proportion three specimens were cast. The details of all 27 mortar bar specimens are presented in Table 3.

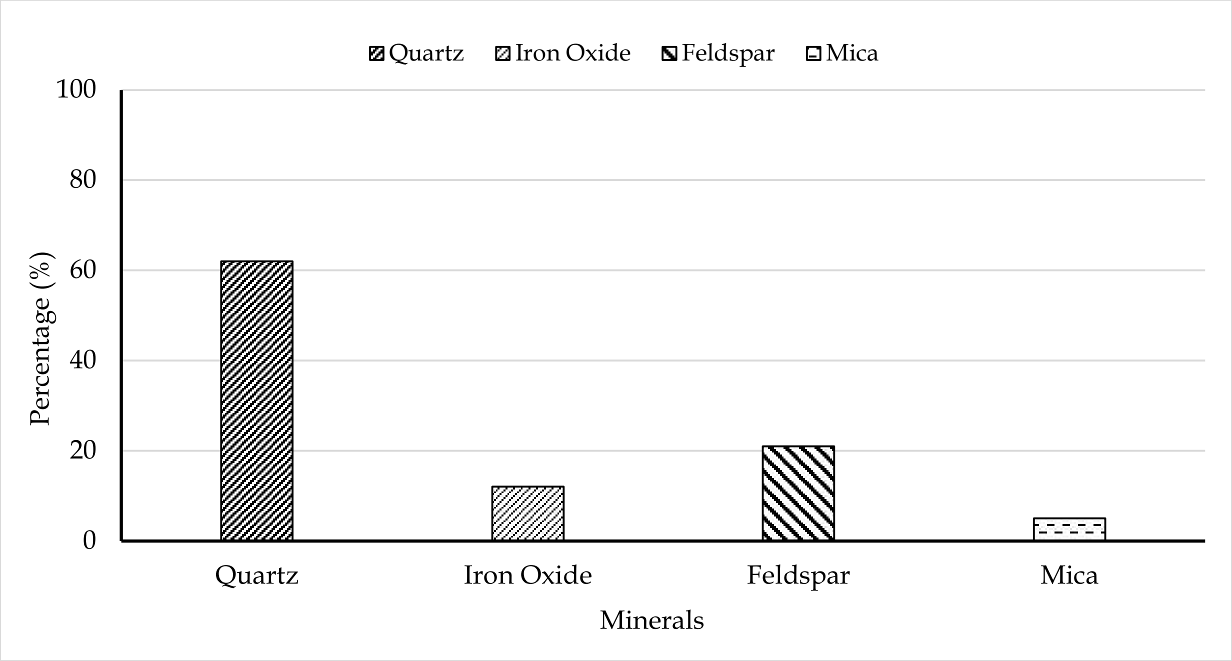

Fig. 1 - Mineralogical nature of Mach Hills aggregates.

Table 1

Chemical analysis results of Ordinary Portland cement (OPC) brands used in local market

Sr. No.	Elements	Cement Type (% age)						ASTM C 114 Limits
		A1	**A2**	**A3**	**A4**	**A5**	**A6**	
1	CaO	62.510	62.860	62.440	59.950	62.650	61.700	-
2	MgO	0.850	1.880	1.790	2.100	1.650	1.850	6 max
3	SiO_2	19.110	20.620	21.300	21.010	21.910	22.120	20 min
4	SO_3	2.340	2.520	2.480	2.440	1.950	1.820	3 max
5	Al_2O_3	5.200	5.360	5.370	6.050	5.880	5.780	6 max
6	Fe_2O_3	3.180	3.120	3.340	4.200	3.060	3.120	6 max
7	*L.O.I	4.000	1.720	1.670	2.150	1.420	1.890	3 max
8	IR	1.040	0.520	0.610	0.520	0.430	0.470	0.75 max
9	K_2O	0.730	0.675	0.531	0.675	0.617	0.580	-
10	Na_2O	0.101	0.090	0.085	0.090	0.072	0.083	-
Total Alkali		0.83	0.77	0.62	0.77	0.69	0.66	-
Alkali Equiv. (Na_2O_{eq})		0.58	0.53	0.43	0.53	0.48	0.46	-

*L.O.I = Loss on ignition

Table 2

Physical Property Tests of selected cement brands

Cement Type	Property	Standards	Values	Limits
C1	Standard Consistency	ASTM C 187	30%	-
	Initial Setting Time	ASTM C 191	145 min	> 45 min
	Final Setting Time	ASTM C 191	220 min	< 375 min
	Fineness of Cement	ASTM C 184	6%	-
	Soundness of Cement	EN 196-3	7 mm	Max. 10 mm
C2	Standard Consistency	ASTM C 187	31%	-
	Initial Setting Time	ASTM C 191	140 min	> 45 min
	Final Setting Time	ASTM C 191	220 min	< 375 min
	Fineness of Cement	ASTM C 184	7%	-
	Soundness of Cement	EN 196-3	8 mm	Max. 10 mm
C3	Standard Consistency	ASTM C 187	29%	-
	Initial Setting Time	ASTM C 191	130 min	> 45 min
	Final Setting Time	ASTM C 191	205 min	< 375 min
	Fineness of Cement	ASTM C 184	7%	-
	Soundness of Cement	EN 196-3	6 mm	Max. 10 mm

Table 3

Details of mortar bar specimens

ASR Conditions	Duration of Test	Amount of Fly ash	Alkali Content of Cement			Total Specimens
			0.43%	0.53%	0.58%	
ASTM C227	Six Months	None	3	3	3	9
ASTM C1260	28 Days	None	3	3	3	9
		25%	-	-	3	9
		30%	-	-	3	
		35%	-	-	3	

Table 4

Details of cubes and prisms

ASR Conditions		Duration of Test	Alkali Content of Cement			Total Specimens
			0.43%	0.53%	0.58%	
ASTM C227	Control	One Month	3	3	3	36
		Six Months	3	3	3	
	ASR Conditioned	One Month	3	3	3	
		Six Months	3	3	3	
ASTM C1260	Control	28 Days	3	3	3	18
	ASR Conditioned	28 Days	3	3	3	

A total of 54 mortar cubes (25 mm) and 54 prisms (40 mmx40 mmx160 mm) were also cast and tested to investigate the influence of ASR on mechanical properties (compressive strength and modulus of rupture) of specimens. The details of all cubes and prims are presented in Table 4. A total of 36 cubes and prisms were cast, conditioned and tested as per ASTM C227 whereas 18 cubes and prims were cast, conditioned and tested as per ASTM C1260.

4.Results and Discussion

4.1.Mortar Bar Results

4.1.1.Effect of Alkali Content of Cement

Figure 2 shows the effect of amount of alkalis present in cement on ASR expansion of mortar bars prepared as per ASTM C 227. At the end of 6-month exposure, the maximum expansion of 0.08%, 0.07% and 0.065% were observed in specimens having cements containing alkali content of 0.58%, 0.53% and 0.43%, respectively. None of samples exceeded the mortar bar expansion limit of 0.1% after 6 months under ASTM C227 conditions. This indicates that aggregates used in this study are non-reactive. However, it is important to note that generally this method (ASTM C 227) is not used to test the reactivity of aggregates instead a more time taking test as per ASTM [26] C1293 is adopted for this purpose Munir, Abbas [7].

Figure 3 shows the effect of amount of alkalis present in cement on expansion caused by ASR in mortar bars prepared as per ASTM C 1260. It is evident in the Figure 3 that the specimens containing cement with high alkali content showed highest expansion and the specimens with cement with low alkali content exhibited small expansion. After 14 days, the expansion of 0.39%, 0.24% and 0.24% were observed in specimens having cements containing alkali content of 0.58%, 0.53% and 0.43%, respectively. Similar results were observed after 28 days exposure. After 28 days, the mortar bar expansion of 0.49%, 0.31% and 0.29% were observed in specimens having cements containing alkali content of 0.58%, 0.53% and 0.43%, respectively. The observed expansion in all the specimens exceeded the 14 day and 28-day mortar bar expansion limits of 0.1% and 0.2%, respectively. This indicates that as per ASTM 1260, the aggregates used in current study are reactive. In past, several studies have used procedures given in ASTM C 1260 to check the reactivity index of aggregates [7, 27, 28].

In general, the effect of amount of alkalis present in cement is not considered while assessing the reactivity of aggregates if the amount of alkalis present in cement is less than 0.6%. In current study, all the specimens were prepared using same aggregates; however, the amount of alkalis present in cement was varied

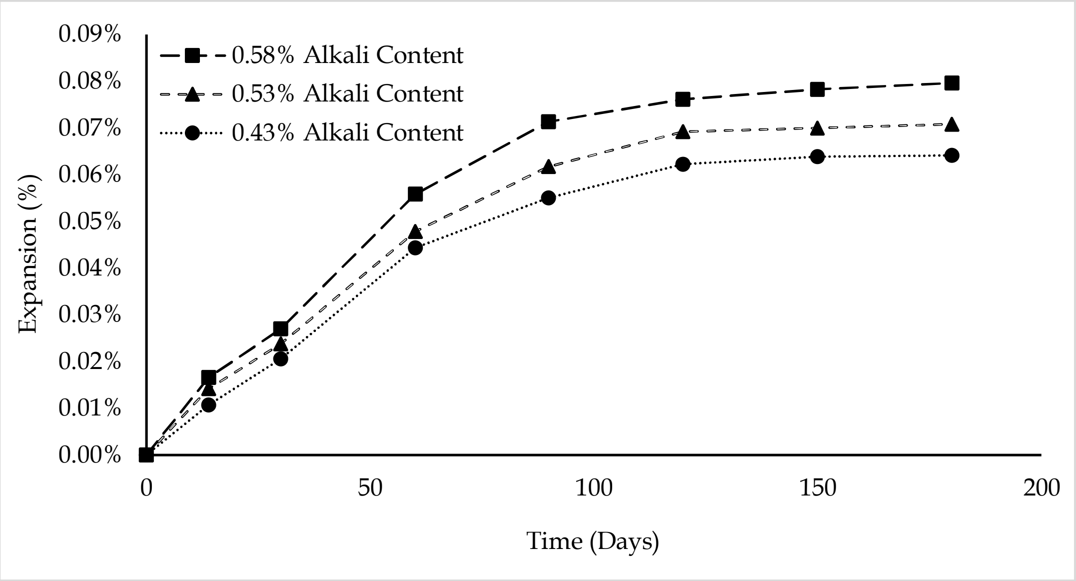

Fig. 2 - Mortar bar expansion results as per ASTM C227 (ASTM, 2010).

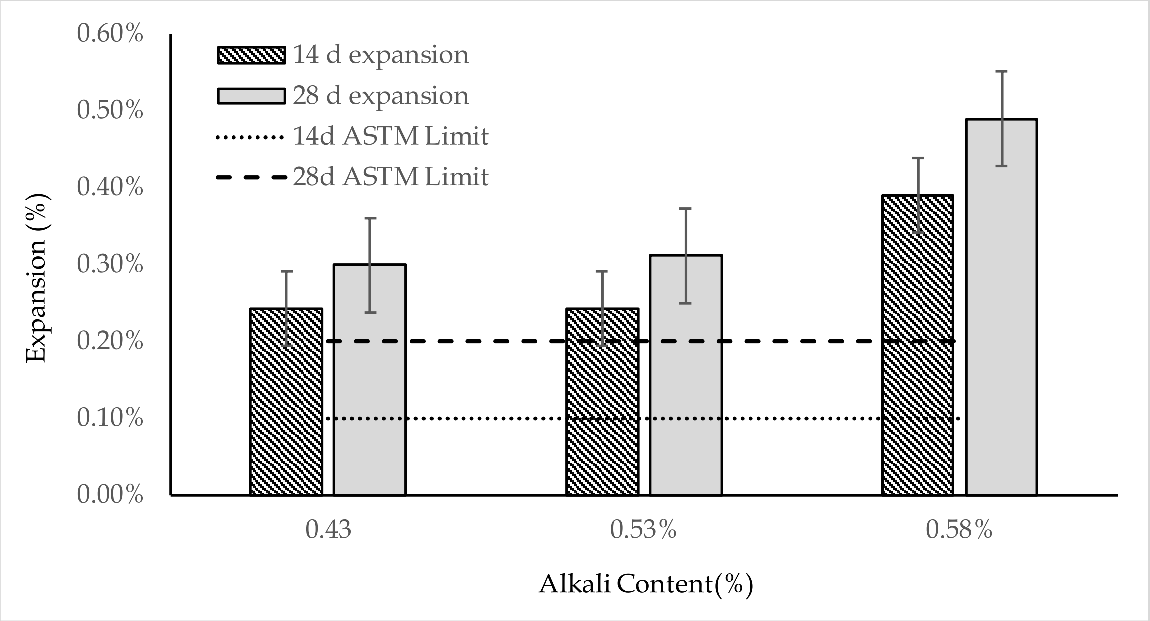

Fig. 3 - Mortar bar expansion results as per ASTM C 1260 (ASTM, 2014c).

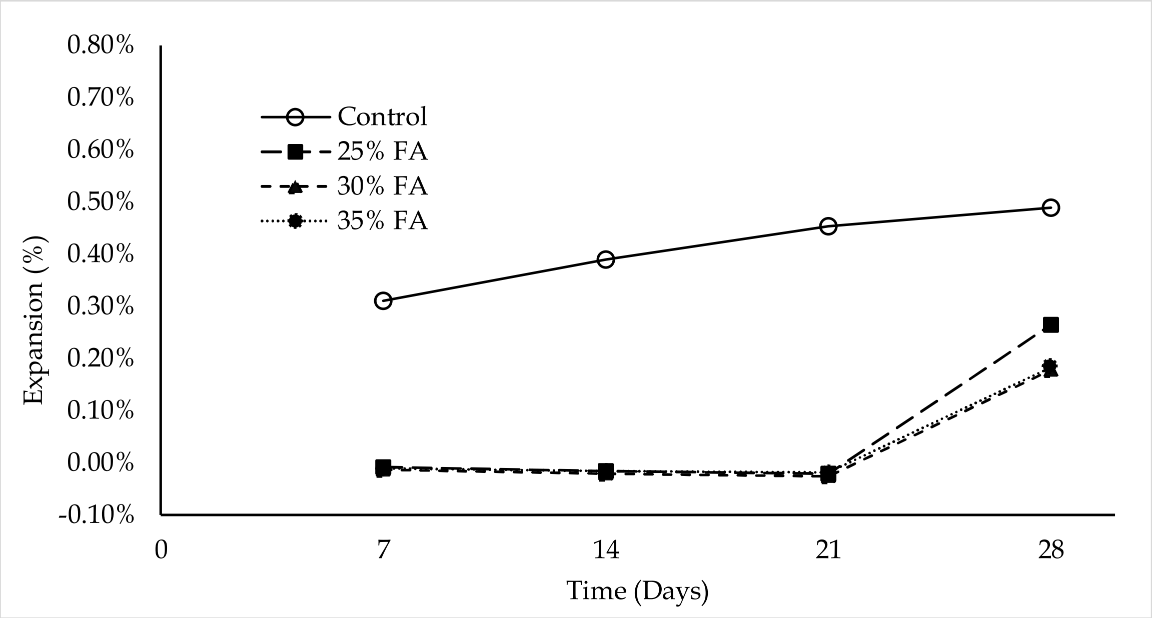

Fig. 4 - Expansion of mortar bar specimens incorporating FA under ASR conditions as per ASTM C1260 (ASTM, 2014c).

between 0.43% and 0.58%. The mortar bar results presented above showed that there is a significant effect of amount of alkalis present in cement on mortar bar expansion. For example, under ASTM C1260 exposure conditions, the expansion of mortar was decreased from 0.49% to 0.29% when alkali content of cement was decreased from 0.58% to 0.43%. There is a probability that if less reactive aggregates would have been used then the mortar bar expansion would have been less than 0.2% (mortar bar expansion limit as per ASTM C1260) for specimen having low alkali content. It is important to mention that all the cements used in current study were being used in field and these are not modified for this study. Therefore, it is recommended to put a lower limit of 0.5% on amount of alkalis present in cement to be used in ASTM C1260 to check reactivity of aggregates. However, more studies may be conducted to access this effect before implementing this recommendation in ASTM.

4.1.2.Effectiveness of SCMs to Control ASR

Figure 4 shows the results of mortar bar specimens having different percentages of fly ash (25%, 30% and 35%) prepared as per ASTM C1260. It can be observed in this Figure that the expansion in mortar bar specimens was significantly reduced with the addition of fly ash. For first 21 days, no expansion was observed in all the specimens rather shrinkage was observed. However, after 28 days, mortar bar expansion of 0.265%, 0.184% and 0.179% was observed in specimens containing 25%, 30% and 35% fly ash, respectively. As expected, the maximum reduction in expansion was for specimens containing high amount of fly ash (35%) whereas minimum reduction in expansion was observed for specimens containing less amount of fly ash (25%). It is possibly due to dilution of cement content in mortar due to fly ash. The expansion of specimens containing 25% fly ash exceeded the 28 day expansion limit of 0.2% specified in ASTM C-1260. However, the expansion in mortar bar specimens containing 30% and 35% fly ash was less than the 28 day mortar bar expansion limit. Other researchers have reported similar results.

The observed shrinkage and reduced expansion of specimens containing fly ash was possibly due to the increase in water demand of the mix. It has been reported in the literature that if cement is replaced with finer particles of fly ash, the water demand of the mix will increase due to high surface area. In addition, The diminish of cement content can be a determining factor for reduced expansions.

5.Mechanical Properties

5.1.Effect of ASR on Compressive Strength of Cubes

Figures 5 and 6 show the effect of ASR on compressive strength of cubes subjected to exposure conditions as per ASTM C-227 and ASTM C-1260, respectively. As expected, the compressive strength of cubes was reduced in ASR conditions. The reduction of compressive strength due to ASR ranged between 9-15%. Similar results have been observed for both exposure conditions. On average 10% reduction in compressive strength of cubes is observed.

5.2.Effect of ASR on Modulus of Rupture

Figure 7 illustrates the effect of ASR on modulus of rupture (MOR) specimens as per ASTM C-227. The flexural strength (MOR) of all specimens was reduced due to ASR.

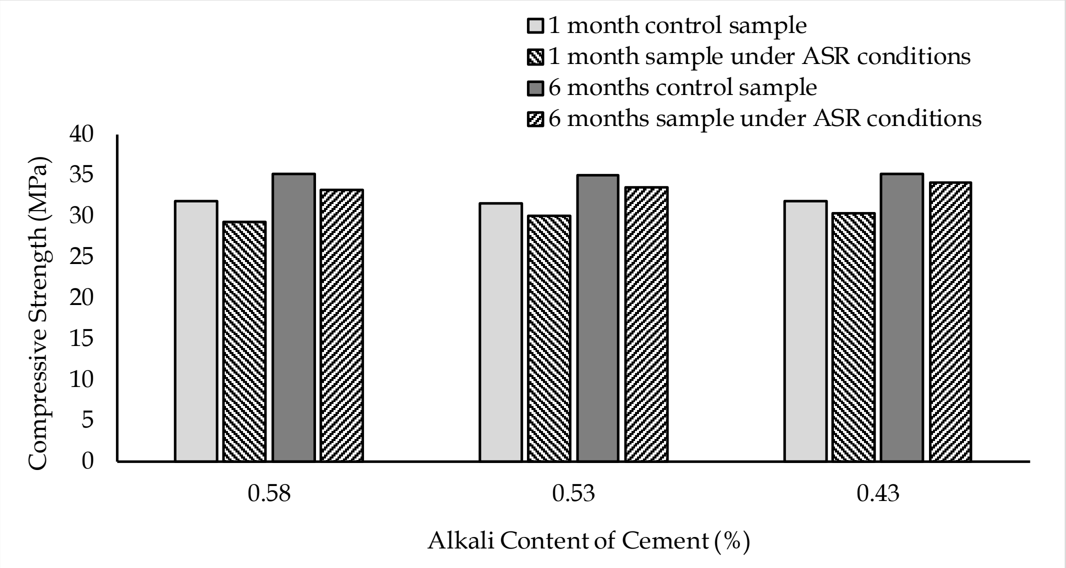

Fig. 5 - Compressive strength of cubes under ASR conditions as per ASTM C 227 (ASTM, 2010).

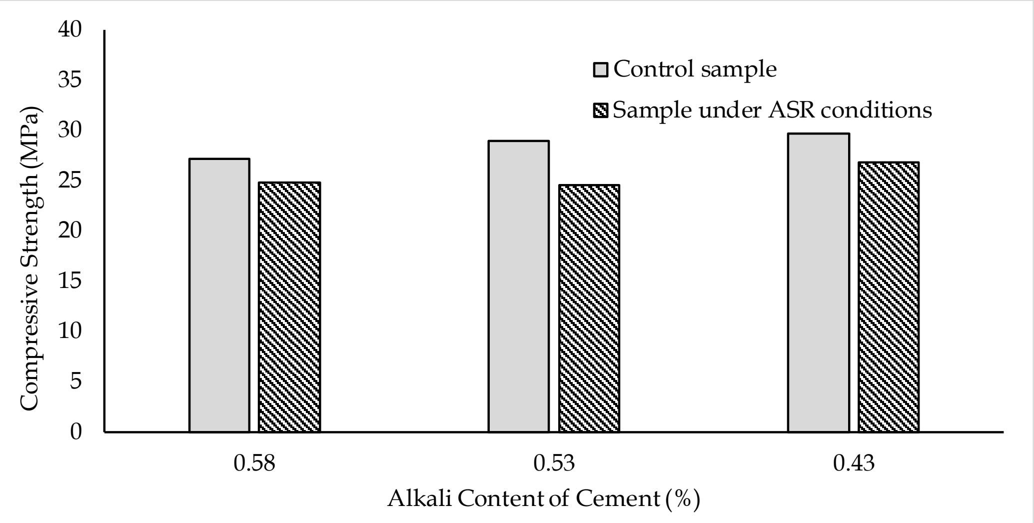

Fig. 6 - Compressive strength of cubes under ASR conditions as per ASTM C 1260 (ASTM, 2014c).

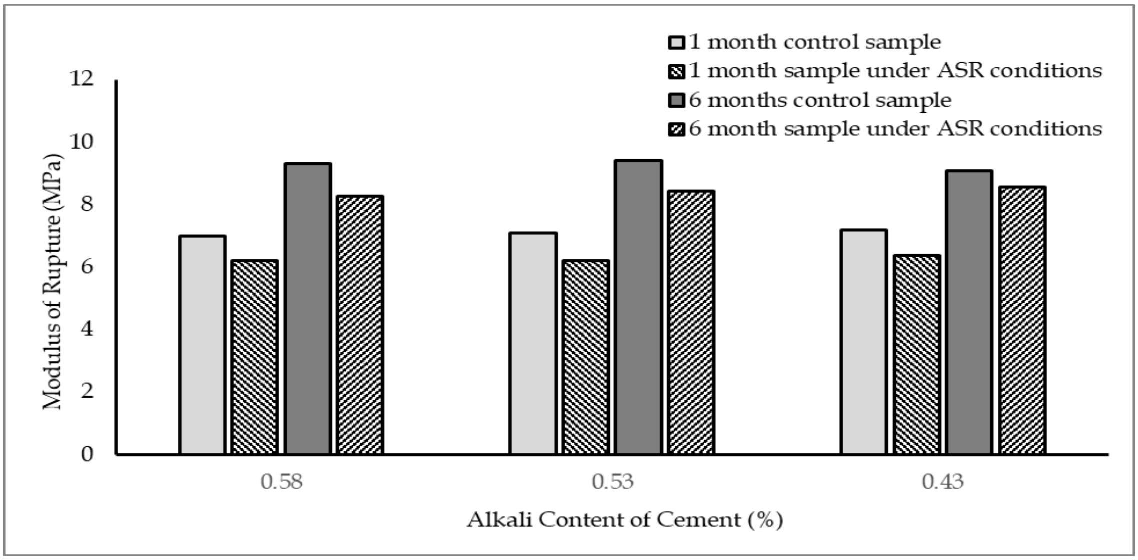

Fig. 7 - Flexural strength (MOR) of prisms under ASR conditions as per ASTM C 227 (ASTM, 2010).

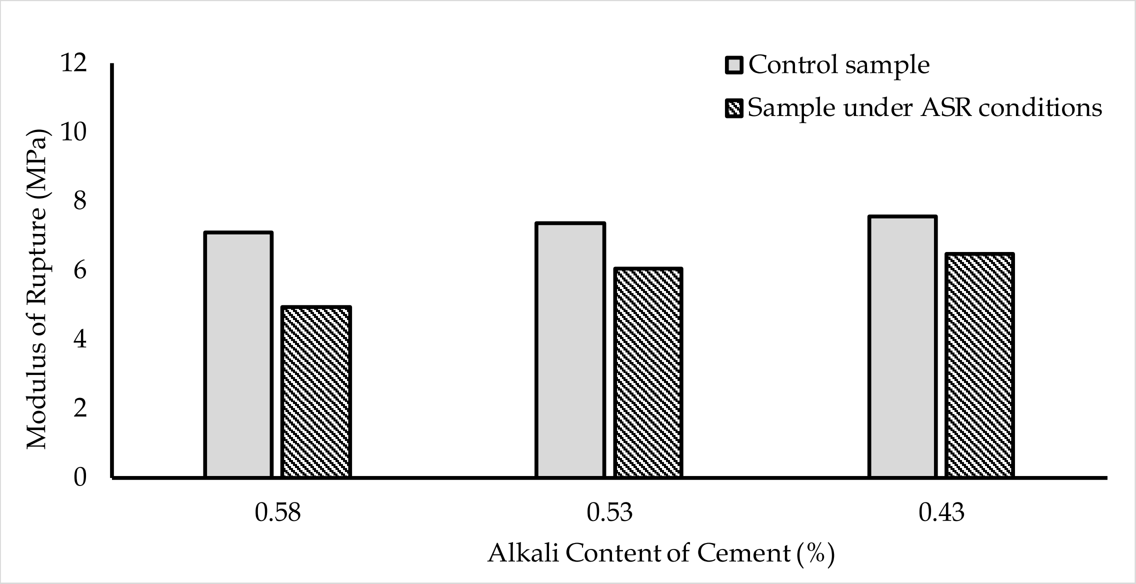

Fig. 8 - Flexural strength (MOR) of prisms under ASR conditions as per ASTM C 1260 (ASTM, 2014c).

The reduction in flexural strength ranged between 6-11%. Highest reduction in flexural strength was observed for specimens with high alkali content.

Figure 8 shows the effect of ASR on MOR of specimens in which ASR phenomenon presents (ASTM C 1260). The flexural strength (MOR) was significantly reduced due to ASR phenomenon. The reduction in flexural strength ranged between 15-31%. The MOR reduction is maximum related to control sample and ASR expanded mortar bars having 0.58% alkali content and it is gradually decreased with the decreased in alkali content of cement to 0.43%.

The higher reduction in flexural strength for specimens with high alkali content is possibly due to higher degree of ASR damage observed in these specimens. In literature, the reduction in flexural strength have been reported between 20 to 84% depending on reactivity of aggregates [6, 7, 29].

6.Conclusions

The effect of amount of alkalis present in cement on expansion caused by ASR and its mitigation using fly ash was investigated using mortar bar specimens conditioned as per ASTM C227 and ASTM C1260. In addition, the effect of ASR on mechanical properties of the mortars was also evaluated. Based on findings of this study, the following conclusions can be drawn:

- The amount of alkalis present in cement significantly affects the ASR expansion. ASR expansion increased as the alkali content of cement increased. At 0.43% alkali content, the 28 days ASR expansion was 0.30%whereas at 0.58% alkali content, the ASR expansion was 0.50% under ASR conditions as per ASTM C1260.
- ASR expansion decreased for mortar bars when cement was partially replaced with Fly ash. The maximum reduction of expansion was

observed when 35% of cement was replaced with Fly ash.

- ASR phenomenon significantly affected the mechanical properties of specimens: the reduction in compressive strength of specimens ranged between 9-15% while the reduction in the flexural strength of specimens ranged between 15-31%.

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