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Reduction of alkali–silica reaction expansion of mortars by utilisation of pozzolans

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In this study the effects of natural and artificial pozzolans on alkali–silica reaction expansion of mortars were investigated by using the accelerated mortar bar test method in accordance with the ASTM C 1260. For this purpose, four natural pozzolans – ignimbrite powder (IG), perlite powder (PE), pumice powder (PU) and zeolite powder (ZE) – were used as cement at replacement levels of 0, 5, 10, 15, 20, 25, 30, 35 and 40% by weight of ordinary Portland cement. Four artificial pozzolans – fly ash (FA), brick powder (BP), silica fume (SF) and aerated concrete powder (AP) – were used at replacement levels of 0, 5, 10, 15, 20 and 25% by weight. The expansions of mortar bars were reduced as the replacement ratios of each natural and artificial pozzolans were increased, with the exception of specimens with a replacement level of 15, 20 and 25% AP. It is determined that at comparable replacement ratios SF is the most effective among the pozzolans used and is followed by PU, ZE, IG, PE, FA, BP and AP respectively.

Introduction

Alkali–silica reaction (ASR) is one of the most important concerns in the design of durable concrete (Karakurt and Topcu, 2011). It is a deterioration mechanism that affects concrete durability – a reaction between the thermodynamically unstable silica in some aggregates and the alkali hydroxides in the pore solution (Boddy *et al.*, 2003).

It is known that pozzolans affect the durability, and particularly increase the resistance of sulfate attack and resistance to ASR, of cementitious composites. For this purpose, pozzolanic materials are used mostly as an addition or a replacement material in order to improve the various properties and reduce the costs in the cement and concrete industry.

A number of researchers have shown that the ASR expansions can be controlled by using sufficient natural and artificial pozzolans, such as perlite powder (PE), pumice powder (PU), zeolite powder (ZE), fly ash (FA), brick powder (BP) and silica fume (SF) (Ahmadi and Shekarchi, 2010; Andiç-Çakır *et al.*, 2008; Bektas and Wang, 2012; Bektas *et al.*, 2005; Demir, 2010; García-Lodeiro *et al.*, 2007; Gupta, 1992; Khandaker, 2005; Quanlin and Naiqian, 2005; Ramyar *et al.*, 2004; Thomas *et al.*, 1999, 2006, 2007, 2011; Turanli *et al.*, 2003).

The amount of supplementary cementing materials (SCM) required to control expansion, however, varies widely with the chemical and mineralogical composition of the SCM, the amount of alkalies available in the system and the nature of the reactive aggregate. Because of this, it is difficult to provide comprehensive prescriptive guidelines without being overly conservative. A reliable and rapid performance test is required to determine the minimum safe level of SCM required with a particular aggregate (Lindgård *et al.*, 2012; Thomas *et al.*, 2007).

Except for ignimbrite powder (IG) and aerated concrete powder (AP) the effect of pozzolans (PE, PU, ZE, FA, BP and SF) used in this study on reducing the deleterious ASR expansions have been researched. A number of investigations have been done on the properties (pozzolanic properties in mortar, physical, mechanical, etc., properties) of ignimbrites used mostly as a processed rock at architectural monuments (Alonso and Martinez, 2003; Erdal and Şimşek, 2010; Korkanç, 2007; Şimşek and Erdal, 2004). However, there has been no investigation on the effect of IG on ASR expansions. Mineral admixtures can also improve the resistance of concrete to thermal cracking (Mehta and Monteiro, 2006); however, only the ASR effect was investigated in this study.

In this study, ordinary Portland cement (OPC) was replaced by IG, PE, PU and ZE at ratios of 0, 5, 10, 15, 20, 25, 30, 35 and 40%, and by FA, BP, SF and AP at the ratios of 0, 5, 10, 15, 20 and 25%. Their effect was investigated by the length change of mortar bars according to the ASTM C 1260 (ASTM, 2007). The effectiveness range of the pozzolans used in the study was determined by controlling the ASR. A special emphasis was given to the effect of

ASR expansion of IG as, to the best of our knowledge, there is no reported case involving the pozzolanicity of IG.

Materials and methods

Materials

In this study, perlite aggregate, which was collected from a quarry in Çubuk location (Ankara/Turkey), was used as the reactive aggregate in all of the tests applied. Specific gravity (g/cm^3) and water absorption (%) of perlite aggregate were determined as 2·30 and 1·25 respectively. Gökçe and Şimşek have shown in their study (Gökçe and Şimşek, 2010) that the perlite aggregate is highly reactive.

OPC, compatible to ASTM type I, was used in the production of mortar. IG, PE, PU and ZE obtained from their rocks by grinding and passing through a 75-mm sieve were used in the study as natural pozzolans. BP and AP obtained from their waste pieces by grinding and passing through a 75-mm sieve, and FA and SF were used in the study as artificial pozzolans. Chemical and physical properties of the cement and pozzolans are presented in Table 1.

Some information on the natural pozzolans used in the study

Ignimbrite rocks, which were supplied from the Ahlat region in Bitlis (Turkey), include volcanic glass, coloured by iron oxides and hydroxides and granular opaque minerals. In addition to these, plagioclase and pyroxene crystal particles are present (Şimşek and Erdal, 2004). Perlite, which was supplied from the Çubuk region in Ankara (Turkey), is a volcanic glassy rock. Pumice, which was supplied from the Gölcük region in Isparta (Turkey), is basaltic pumice. Pumice is also lighter than the other natural materials because of its high porous structure. Zeolite, which was supplied from Bigadiç region in Balıkesir (Turkey), is a large group of hydrated aluminum silicates of the alkali and alkaline earth elements which are soft and usually white or light colored (ASTM C 294, ASTM, 2012a). In contrast to block sizes of ignimbrite and zeolite, perlite and pumice are supplied in granular sizes.

Some Information on the artificial pozzolans used in the study

FA was obtained from Yatağan Thermic Power Plant in Turkey. In BP, waste brick pieces were supplied from a brick factory in Kırşehir (Turkey). SF was obtained from Antalya-Etibank Ferro-Chrome Factory in Turkey. In preparation of AP, waste aerated concrete pieces which were in our laboratory were used.

Methods

Pozzolanic activity values of the pozzolans were determined according to TS 25 (TS 25, TSI, 2008), a standard method similar to ASTM C 593 (ASTM C 593, ASTM, 2011). The preparation, cure, measurement and calculation of mortar bar expansions were performed for the determination of ASR length changes according to ASTM C 1260 (ASTM C 1260, ASTM, 2007). In the design of specimens, cement was replaced by natural pozzolans (IG, PE, PU and ZE) at the ratios of 0, 5, 10, 15, 20, 25, 30, 35

Composition: %	OPC	IG	PE	PU	ZE	FA	BP	SF	AP
Silicon dioxide (SiO_2)	20·35	64·05	71·36	59·0	64·59	45·38	40·12	82·61[c]	48·94
Aluminium oxide (Al_2O_3)	5·98	15·33	13·72	16·6	11·09	19·74	14·91	0·71	5·34
Iron (III) oxide (Fe_2O_3)	3·06	4·90	3·31	4·8	1·40	7·47	16·05	0·92	1·41
Calcium oxide (CaO)	63·35	2·00	1·58	4·6	3·59	1·22	13·75	1·29	26·97
Magnesium oxide (MgO)	1·89	0·53	0·21	1·8	2·94	2·79	3·19	4·75	1·18
Sulfur trioxide (SO_3)	2·89	0·03[a]	1·24[a]	0·11[a]	0·15[a]	5·63	0·56	0·38	5·00
Sodium oxide (Na_2O)	0·58	5·46	1·14	5·2	0·00	0·57	0·00	0·4	0·33
Potassium oxide (K_2O)	0·88	4·81	8·23	5·4	3·45	2·24	1·84	3·41	1·14
Loss on ignition (LOI)	0·50	7·80	2·50	0·50	5·17	1·87[b]	9·58	2·60[c]	—
Fineness, cm^2/g	3350	3598[a]	3380[a]	6289[a]	6333[a]	3392	5894	200 000	5850
Density, g/cm^3	3·100	2·490	2·252	2·410	2·300	1·940	2·140	2·370	2·13
Comp. Strength (MPa)	51·9 (28-d)	—	—	—	—	—	—	—	—
7-d Pozzolanic activity (min. 4 MPa)		7·9[a]	7·2[a]	8·8[a]	8·5[a]	7·8	14·5	24·1	4·1
70% $\leqslant SiO_2 + Al_2O_3 + Fe_2O_3$		84·28[a]	88·39[a]	80·40[a]	77·08[a]	72·59[b]	71·08	84·24	55·69

[a] Suitable according to TS 25 (TSI, 2008). [b]Suitable according to ASTM C 618 (ASTM, 2012b) [c]Suitable according to ASTM C 1240 (ASTM, 2011)
AP, aerated concrete powder; BP, brick powder; OPC, ordinary Portland cement; PE, perlite powder; PU, pumice powder; SF, silica fume; ZE, zeolite powder

Table 1. Chemical, physical and mechanical properties of cement and pozzolans

and 40%, and by artificial pozzolans (FA, BP, SF and AP) at the ratios of 0, 5, 10, 15, 20 and 25%. For each mixture three mortar bars (25 × 25 × 285 mm) were produced; in total 108 mortar bars were created.

Mortars were moulded in two equal layers, and each layer was compacted by means of jolting table for a minute (60 jolts). Moulds were cured for 24 h at 23 ± 1·7ºC in curing room at 90% relative humidity. Afterwards, the specimens were demoulded and kept in 80 ± 2·0ºC pure water for 24 h.

The first length values of mortar bars were measured and then the mortar bars were kept in the curing tank at 80ºC and 1 N sodium hydroxide solution until the end of test period. Eventually, 3, 7, 10, 14, 21 and 28-day length change of the mortar bars were measured at 0·002 mm sensitivity and length change values (%) of the mortar bars were calculated according to ASTM C 1260 (ASTM, 2007).

Results and discussion

In this study, average % length change values of mortar bars are presented in Table 2 for a 28-day period. Except for a few measurements the specimens have shown positive length change (expansion).

In Figure 1, 14-day expansion values (*y*-axis) are plotted against pozzolan replacement level (*x*-axis). The 14-day expansion value of no pozzolan-containing specimen (0·806) is chosen as the reference reading value.

Except for the 5% BP containing specimens, all of the 14-day expansion values are lower than that of the reference reading.

Pozzolan	Level of pozzolan replacement: %	Number of specimens	Average % length change of mortars depend on time: day					
			3	7	10	14	21	28
Reference	0	3	0·138	0·411	0·585	0·806	1·075	1·309
IG	5	3	0·080	0·324	0·499	0·698	0·984	1·198
	10	3	0·079	0·292	0·435	0·601	0·850	1·020
	15	3	0·052	0·204	0·310	0·431	0·629	0·786
	20	3	0·022	0·104	0·170	0·249	0·395	0·511
	25	3	0·008	0·046	0·087	0·140	0·245	0·335
	30	3	0·005	0·025	0·050	0·087	0·169	0·241
	35	3	0·001	0·012	0·027	0·050	0·115	0·179
	40	3	0·000	0·008	0·017	0·028	0·074	0·119
PE	5	3	0·141	0·385	0·544	0·736	0·972	1·175
	10	3	0·113	0·310	0·445	0·611	0·804	0·984
	15	3	0·084	0·240	0·351	0·493	0·678	0·848
	20	3	0·039	0·139	0·219	0·359	0·492	0·658
	25	3	0·015	0·064	0·118	0·201	0·333	0·465
	30	3	0·011	0·024	0·050	0·103	0·194	0·291
	35	3	0·013	0·018	0·028	0·058	0·124	0·193
	40	3	0·008	0·009	0·011	0·019	0·062	0·114
PU	5	3	0·063	0·272	0·408	0·576	0·839	1·038
	10	3	0·022	0·119	0·200	0·301	0·478	0·628
	15	3	0·008	0·033	0·078	0·141	0·260	0·368
	20	3	0·003	0·011	0·025	0·053	0·118	0·188
	25	3	0·000	0·006	0·013	0·026	0·061	0·112
	30	3	−0·001	0·000	0·006	0·014	0·027	0·054
	35	3	−0·002	0·000	0·005	0·013	0·023	0·044
	40	3	−0·002	−0·002	0·000	0·008	0·014	0·026

AP, aerated concrete powder; BP, brick powder; FA, fly ash; IG, ignimbrite powder; PE, perlite powder; PU, pumice powder; SF, silica fume; ZE, zeolite powder

Table 2. Average length change of mortar bars: % (continued on next page)

Pozzolan	Level of pozzolan replacement: %	Number of specimens	Average% length change of mortars depend on time: day					
			3	7	10	14	21	28
ZE	5	3	0·016	0·176	0·341	0·545	0·848	1·087
	10	3	0·009	0·148	0·310	0·501	0·766	0·971
	15	3	0·002	0·077	0·211	0·369	0·594	0·773
	20	3	−0·004	0·002	0·044	0·134	0·295	0·440
	25	3	−0·004	−0·004	0·002	0·004	0·023	0·074
	30	3	−0·006	−0·010	−0·005	−0·007	0·002	0·009
	35	3	−0·006	−0·009	−0·006	−0·009	−0·004	0·000
	40	3	−0·008	−0·013	−0·010	−0·013	−0·010	−0·008
FA	5	3	0·076	0·362	0·550	0·769	1·071	1·260
	10	3	0·068	0·331	0·501	0·699	0·972	1·142
	15	3	0·049	0·268	0·404	0·569	0·810	0·962
	20	3	0·021	0·163	0·264	0·394	0·600	0·742
	25	3	0·010	0·094	0·168	0·267	0·433	0·554
BP	5	3	0·083	0·384	0·583	0·812	1·094	1·335
	10	3	0·078	0·347	0·518	0·711	0·972	1·132
	15	3	0·066	0·310	0·464	0·639	0·879	1·025
	20	3	0·052	0·245	0·365	0·501	0·689	0·802
	25	3	0·033	0·197	0·297	0·419	0·613	0·720
SF	5	3	0·061	0·237	0·360	0·520	0·791	0·997
	10	3	0·009	0·022	0·068	0·138	0·284	0·407
	15	3	0·007	0·010	0·020	0·049	0·152	0·239
	20	3	0·004	0·009	0·014	0·022	0·070	0·124
	25	3	−0·002	0·000	0·001	0·006	0·015	0·032
AP	5	3	0·025	0·213	0·406	0·645	0·968	1·233
	10	3	0·021	0·192	0·389	0·632	0·991	1·253
	15	3	0·020	0·206	0·426	0·698	1·081	1·366
	20	3	0·015	0·206	0·441	0·725	1·117	1·394
	25	3	0·014	0·214	0·452	0·732	1·098	1·345

Table 2. (continued)

Similarly, the more expansion effect of 5% BP than those of reference, Khandaker (2005), Duchesne and Berube (2001) and Hasparyk *et al.* (2000) reported that the ASR expansions of specimens with pozzolan replacements were observed more than those of reference specimens in their study.

It was also observed that the expansions decrease by increasing pozzolan replacement level. However, 15, 20 and 25% AP-containing specimens have shown an increasing expansion trend by increasing pozzolan replacement level. Karakurt *et al.* (2010), Grutzeck *et al.* (2004), and Kuş and Carlsson (2003) remarked that autoclaved aerated concrete is normally manufactured from a mixture of finely ground silica sand or FA, Portland cement, lime, gypsium, water and pore-generating aluminium powder. Thus, it is considered in the study that the expansions of AP at the replacement level of 15, 20 and 25% originated from the composition of the AP pozzolan which has these components of autoclaved aerated concrete.

The 14-day expansions of mortar bars were lower than 0·1% ASTM limit when the replacement level of ⩾ 15% SF, ⩾ 20% PU, ⩾ 25% ZE, ⩾ 30% IG and ⩾ 35% PE were used. The pozzolans FA, BP and AP were not effective in controlling the 14-day ASR expansion of specimens at all replacement levels used in this study.

The 14-day average expansion of reference specimens was quite high (0·1% < 0·8% about 8 times higher than ASTM C 1260 limit value), thus the pozzolans were effective at relatively high levels of replacement. Similarly, Bektas *et al.* (2005), Hasparyk *et al.* (2000) and Gökçe *et al.* (2010) presented in their studies

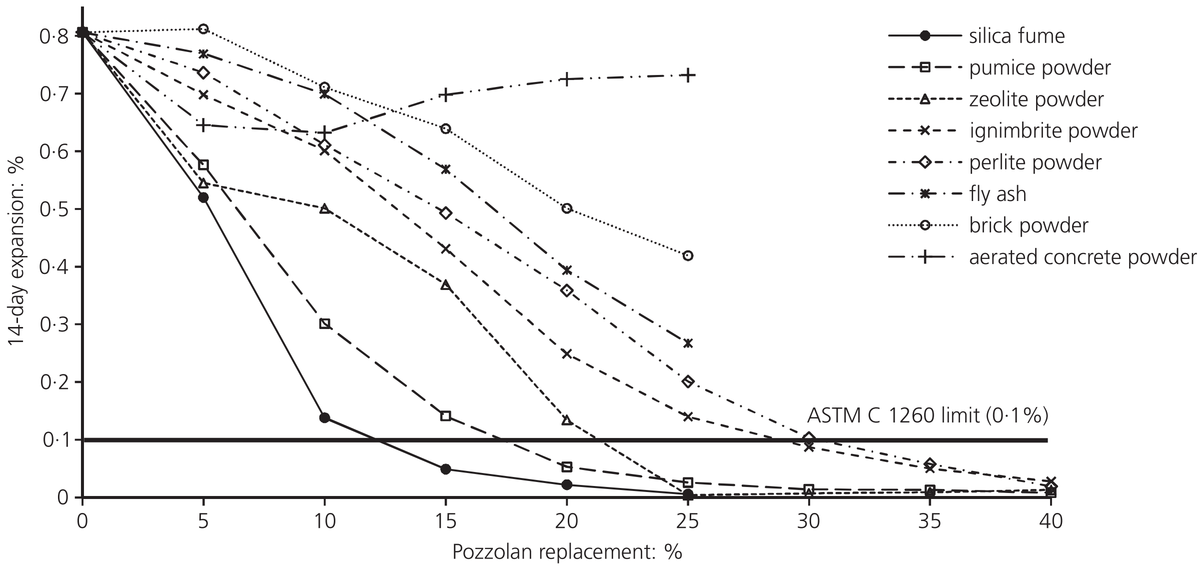

Figure 1. 14-day expansions of mortar bars depending on pozzolan replacement

with different reactive aggregates that the higher replacement levels of pozzolans were needed to control ASR expansion of relatively more reactive aggregate.

In Figure 2, 28-day expansion values (*y*-axis) are plotted against pozzolan replacement level (*x*-axis). The 28-day expansion value of no pozzolan-containing specimen (1·309) is chosen as the reference reading value.

Table 3 indicates whether the replacement levels of the pozzolans can control (✓) or cannot control (×) the ASR expansion according to 14-day ASTM C 1260 limit value (0·1%). Moreover, pozzolans, which are presented by 7-day pozzolanic activity value (MPa), are ranged from 1 (the most effective) to 8 (the least effective) according to their effectiveness on controlling the 14-day ASR expansions, and similar effectiveness of the pozzolans is seen in 28-day ASR expansion results.

In the study, it is determined that SF (1) is the most effective pozzolan in controlling the ASR expansions, which is followed by PU (2), ZE (3), IG (4), PE (5), FA (6), BP (7) and AP (8), the least effective pozzolan, respectively.

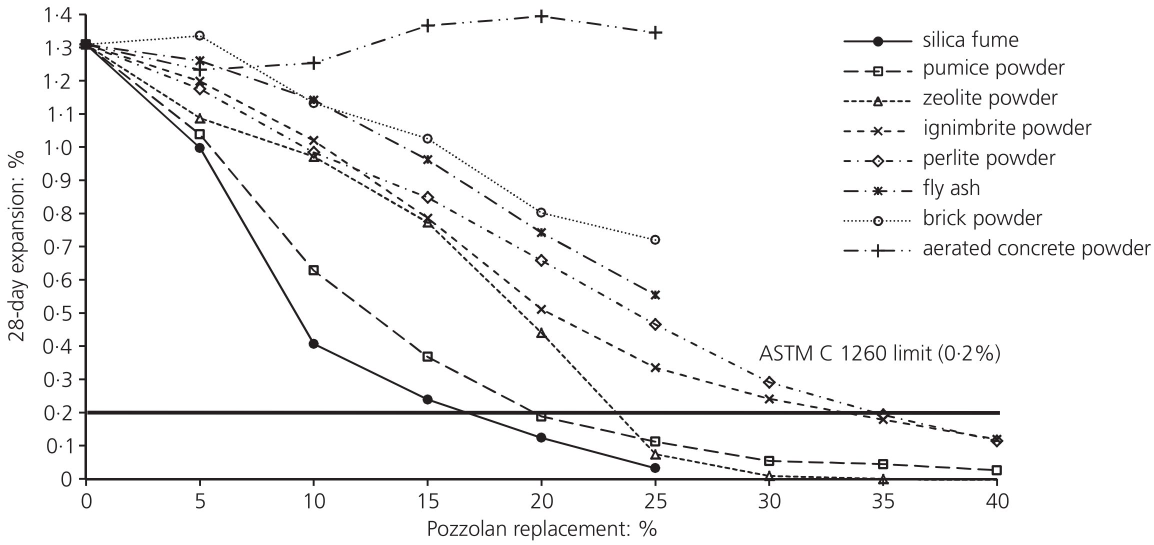

Figure 2. 28-day expansions of mortar bars depending on pozzolan replacement

Effectiveness degree	7-d pozzolanic activity: MPa	Replacement: %	0	5	10	15	20	25	30	35	40
1	24·1	SF	×	×	×	✓	✓	✓	*	*	*
2	8·8	PU	×	×	×	×	✓	✓	✓	✓	✓
3	8·5	ZE	×	×	×	×	×	✓	✓	✓	✓
4	7·9	IG	×	×	×	×	×	×	✓	✓	✓
5	7·2	PE	×	×	×	×	×	×	×	✓	✓
6	7·8	FA	×	×	×	×	×	×	*	*	*
7	14·5	BP	×	×	×	×	×	×	*	*	*
8	4·1	AP	×	×	×	×	×	×	*	*	*

***** Evaluated according to increasing expansion trend by compare with same replacement levels
AP, aerated concrete powder; BP, brick powder; FA, fly ash; IG, ignimbrite powder; PE, perlite powder; PU, pumice powder; SF, silica fume; ZE, zeolite powder

Table 3. Effectiveness degrees and pozzolan levels controlling the alkali–silica reaction expansion according to the 14-day ASTM C 1260 limit value (0·1%)

Conclusions

For the materials tested and methods applied in this study the following conclusions were drawn.

- In this study, the effect of ignimbrite powder on ASR expansions was studied. The results indicated that ignimbrite powder is an effective pozzolanic material in controlling the ASR expansions of mortar specimens when replaced more than 30% by weight of cement.
- The expansions were decreased with respect to reference specimen without pozzolan and the effect become more pronounced as each pozzolan replacement level was increased in the study. However, the expansions of specimens were higher than that of reference specimen at the levels of 5% BP and ⩾ 15% AP.
- The deleterious ASR expansions were controlled (lower than 0·1% ASTM C 1260 limit value) at the replacement levels of ⩾ 15% SF, ⩾ 20% PU, ⩾ 25% ZE, ⩾ 30% IG and ⩾ 35% PE in this study.
- It is seen that SF is the most effective one for controlling ASR expansions among the the pozzolans evaluated in the study.
- It is concluded from the study that the all pozzolans are effective in reducing ASR expansion except for the specimens with 5% BP and ⩾ 15% AP replacements.

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