EFFECT OF REACTIVE AGGREGATE POWDER ON SUPPRESSING EXPANSION DUE TO ALKALI-SILICA REACTION

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ABSTRACT

A condition under which alkali — silica reaction (ASR) damages occur is put forward and based on this a powder of an identified reactive aggregate was used to inhibit the deleterious expansion of mortars due to ASR containing the same aggregate sand with five fractional particle sizes. The results show that the powder could reduce the expansion and the further reduction of expansion could be accomplished with increased amount of the powder. For example, when alkali level remains 3.5% $Na_2O_{equi.}$ in mortars, the expansion after autoclaving was reduced by 43.6%, 59.5%, 77.1%, 89.5% and 95.4% from the control value of 0.46% as 30, 40, 50, 60 and 70% of powder was used to replace the same amount of cement, respectively. This implies a very promising approach to economically and effectively preventing mortars or concrete from the serious occurrence of ASR. The effect of the powder on setting times of cement and on strengths as well as on the flowability of mortars were also studied.

Keywords: ASR, reactive aggregate powder, suppression of expansion, preventing ASR

INTRODUCTION

The number of reports on the occurrence of ASR in concrete constructions all over the world is growing, and the losses due to this harmful reaction in rebuilding or rehabilitating these damaged constructions are also accordingly on the increase. Therefore, an inhibition of the reaction is calling so much attention that extensive studies on this subject have been undertaken from phenomena to mechanisms.

The following conditions under that ASR damages occur are put forward by the present authors: ① the presence of reactive aggregate particles with detrimental radii, generally considered within the range of 0.15-0.60 ㎜ (Ono et al. 1986); ② the presence of high level alkalies and therefore their concentration around these aggregate particles and thus ③ in-situ alkali-aggregate reaction occurring in certain restrained interfacial space and consequently the increased volumes or the swelling of the reaction products. Among the above three ② and ③ play a very important part in the expansion process. So excluding the reactive aggregate from use is the safest way but this is not always feasible, however, controlling the other conditions might more economically and feasibly reach the destination for preventing the damage.

To control the in-situ reaction or the swelling of reaction products, a variety of chemical and mineral admixtures have been selectedly studied.

Since Li^+ ions can penetrate into the structures and substitute some parts of Na^+, K^+ ions in N(K)-C-S-H gels produced from the ASR and consequently anti-swell, the use of Li-containing chemicals as inhibitors for ASR has resulted in a large volume of findings since the constructive work of McCoy et al (McCoy et al. 1951). Their research, using pyrex glass and a high-alkali cement (1.15% Na_20 equivalent), revealed that different Li-containing chemicals have significant reductions in expansions, for instance, 88% by adding 1.0% LiCl of cement, 91% by 1.0% Li_2CO_3, 98% by 1.0% LiF etc., respectively, after curing for 8 weeks. Sakaguchi et al (Sakaguchi et al. 1989) studied the effects of lithium carbonate, nitrite and hydroxide on expansions of mortars, and verified their effectiveness too. In our previous work, we also confirmed that $LiNO_2$ reduced ASR expansion most effectively at a Li/Na ratio of 0.8 when alkali content is greater than 2.0%, while smaller ratios would be desired for lower alkali levels (Bian et al. 1995).

In view of the conditions used by different authors, we conclude that the effectiveness of lithium compounds on suppressing expansion depends in a complicated way on the variety of chemicals used, alkali levels in cement and concrete, Li/Na molar ratios (thereby the amount of compounds used) and probably the ratio of alkali to available silica in reaction.

Another common method for preventing mortar or concrete damage due to ASR is the utilization of blending materials, though there are some debates on their effectiveness (Duchesene et al. 1994a &b). Duchesene et al (Duchesene. 1994a) conducted investigations into the effect of blending materials (silica fume, fly ash, slag etc.) against ASR. They observed a pessimum effect for concrete containing about 5% of silica fume or about 20% of very high alkali fly ash, and found that even as much as 10% of silica fume of high alkali content may not limit the concrete expansion to a satisfactory level (e.g.<0.04% after 2 years). On the other hand, 35 to 40% of slags as well as about 20% of low alkali fly ashes (<3.5% $Na_2O_{equi.}$) may result in good results. Based on this, they further concluded that at higher alkali contents both in blending materials and in concretes a much greater amount of substitution for cement is needed, which might be accomplished with lower quality of concrete. Qian et al (Qian et al. 1994a) concluded that the main reason for mineral admixtures alleviating ASR is the relieving of corrosion of reactive aggregate from alkali owing to the adsorption of OH^- ions on the surfaces of admixture particles, resulting in a reduced amount of alkali attacking the surfaces of aggregates, and that the higher the acidity of the admixtures, the lower the expansion.

Based on the foregoing observations, there seems to be a need for an auxiliary admixture in order to effectively suppress the unexpected expansion through transforming an in-situ reaction to an innocuous one or through anti-swelling. The ground reactive aggregate powder might be selected as such a kind of admixture as it usually contains reactive silica with higher acidity. Furthermore, in view of the compatibility between aggregate and admixture, it can reasonably be deduced that the utilization of such a powder could expectantly prevent mortars or concretes from suffering ASR.

STARTING MATERIALS AND PROCEDURES

Starting materials

Cement: An ordinary portland cement (OPC) with low alkali level (0.46% Na_2O equi.) was used as a cementitious material (Blaine's value 3360 cm^2/g).

Aggregate: An andesite composed mainly of bronzite andesite was crushed into five fractions and used to fabricate mortars (Bian et al. 1995). It was previously identified as a potentially reactive aggregate by ASTM C289 with its Sc of 732 and Rc 177 mmol/l. It was also demonstrated that α-cristobalite is the primary reactive component of the andesite by XRD.

The chemical analyses of the materials are shown in Table 1.

Table 1 Chemical compositions of starting materials (%)

	LOI	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	TiO_2	P_2O_5	MnO
OPC	2.1	20.9	5.1	3.1	64.2	1.5	1.9	0.20	0.42	0.26	0.10	0.11
Andesite	1.9	66.2	16.1	3.4	3.3	2.0	0.0	3.50	2.60	0.23	0.10	0.06

Admixture: Powders of the same aggregate with different Blaine values of 2900, 5640, 7800, 8045 and 11330 cm^2/g were used as admixtures to replace part of the cement. The replacements accounted for 30, 40, 50, 60 and 70%.

Solid NaOH was used as an additional reagent to adjust the Na_2O content in mortars to desired levels of 0.5, 1.0, 1.5, 2.0, 2.5, 3.0 and 3.5% wt. against cement mass.

Procedures

Mortar specimens with the dimensions of 4 × 4 × 16 cm, equipped with pins at two ends, were cast with a cement/aggregate ratio of 1: 2.25 and a ratio of water to cement of 0.50. Immediately following their establishments of initial lengths (L_0, μ) after curing for 24 hours in a fog room, the mortars were demoulded, and were autoclaved for 4 hours at a gauge pressure of 0.28 MPa with 1-hour interval of temperature-rising. They were then moved into the same fog room for another 24-hour-curing and their augmented lengths (L, μ) established. Thereafter, they were put into a container at 45 ℃ for long-term measurements.

The effects of aggregate powder on setting times of cement and on flowability as well as on the strength of mortars made of Japanese standard sand (Toyoura sand) were also studied.

RESULTS AND DISCUSSIONS

Expansion characteristics

The effect of amount of powder on expansion

The effect of reactive aggregate powder (Blaine's value 7800 cm^2/g) on the expansion of mortars are substantiated. Fig.1 gives the relation between expansion and aggregate powder amount incorporated in mortars.

It could be seen that for any alkali level, the expansion of mortars decreased remarkably with an increasing amount of powder, especially at high alkali levels. For example, at the highest alkali content of 3.5% Na_2O in this study, the expansion decreased by 43.6%, 59.5, 77.1, 89.5 and 95.4%, from 0.46% of the control specimen for 30, 40, 50, 60 and 70% of powder replacement, respectively. It is obvious that the effectiveness of reactive aggregate powder on suppressing the excessive expansion depends strongly on the alkali contents available. Generally about 50% of the powder could depress the expansion below 0.1% with alkali greater than 3.0% Na_2O equivalent, and 35% of the powder could reach the same level when 2.5% of alkali was available and less amount for lower alkali levels. Therefore, the lower the alkali level, the lower the replacement.

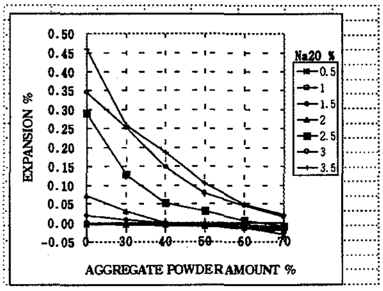


Fig.1 Relation between expansion and aggregate powder amount

The reason for such a powder suppressing expansion can be attributed to the disruption of the in-situ reaction and can be interpreted as follows: First, the powder substitutes some parts of cement, resulting in the reduction of available alkali levels coming from the cement, and also diluted the total alkali concentration in mortars. Moreover, the replacement would increase the acidity of the whole binder, being able to "neutralize" part of the alkalies. Qian et al (Qian et al. 1994b) have confirmed that there is a good relationship between mortar expansion and the acidity of the binder. Increasing acidity of binders could decrease the expansion rate of mortar. On the other hand, the incorporation of powder changes the distribution of alkalies in the binder matrix and mortar, and also between the aggregate and their powder particles. The macro-homogeneously dispersed fine powder particles closely around the aggregate sand absorb more alkalies on their greater specific surface area. Meanwhile, the crushing and milling of aggregate could produce some broken bonds at the particle surfaces. Some defects in crystal lattices such as ≡ Si· (E' center) and ≡ Si-O· (unbridged oxygen hole center, NBOHC) could also exist in siliceous reactive components of aggregate according to recent studies of geochemistry (Ikeya. 1993). These highly reactive free radical groups of unpaired electrons (the so-called dangling bonds) or the broken bonds should be responsible predominantly for their alkali-silica reactivity. Thus for these reasons, the fine particles retain alkalies and react with them through solutions in capillary pores instead of at the interface between cement paste and aggregate, forming complicated products and retarding the alkali migration toward aggregates consecutively. Furthermore, the powders along with their reaction products in the bulk matrix could fill up pores and voids, again densifying the matrix and causing more difficult migration of alkali species. However, such a reaction in the pores could cause practically no expansion, though a very limited expansion is even observed which would also benefit the densification of the matrix. As a result, all of the above mentioned factors would contribute to the prevention of a detrimental reaction or to the suppression of excessive expansion.

Effect of fineness on expansion

The effect of fineness of powder on the expansion of mortar is schematically shown in Fig.2. Evidently there is a sensitive fineness range of 5640 ~ 8045 cm^2/g to the expansion within it the variation of fineness will lead to an evident change of expansion, and below or beyond this range the expansion becomes less sensitively in dependence of fineness, So in this sense that the fineness of aggregate powder should be of about 8000 cm^2/g is technically and economically meaningful.

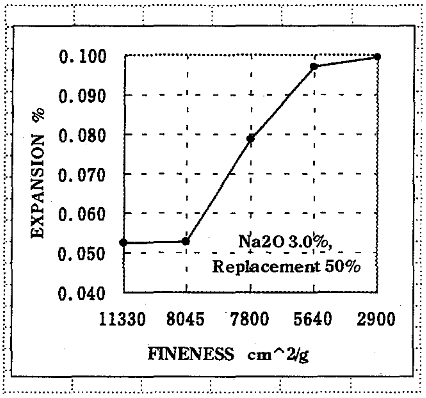


Fig.2 The relation between expansion and fineness of aggregate powder

Powder effect on other properties

Setting times and flowability

The effect of reactive aggregate powder (Blaine's value 7800 cm^2/g) on setting times of cement and on flowability of mortars were also studied at different replacements of OPC by 20, 30, 40 and 50% of powder. For the setting time test, the pastes were made with a constant ratio of water/binder (cement+powder) of 0.26, and for the flowability test the mortars were made with a ratio of binder/aggregate of 0.5, and water/binder ratio of 0.65. The results are shown in Table 2.

It is evident that the setting times decrease slowly when less than 30% of the powder is incorporated, and rapidly (especially for the initial setting) when 50% of the replacement is taken. All of these demonstrate that the powder could take part in the hydration reaction and improve the reaction rate. This phenomenon is somehow different from that when normal blending materials are used. On the other hand, once additional alkali are added to the binders, both setting times and flowability are reduced by a much bigger factor due to the hydration of cement which is usually accelerated by alkalies. In the case of higher alkali levels, the shortened setting time of NC40 by the powder compared to NC37 can also be ascribed to both the action between powder and alkali and the effect of powder retaining alkali.

Table 2 Effect of powder on setting times and flowability

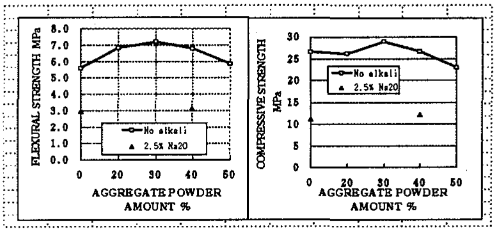
No.	cement %	powder %	Na_2O %	setting time (min.) initial	final	flowability mm
C37	100	—	—	147	269	219
C38	80	20	—	133	243	219
C39	70	30	—	120	226	214
C40	60	40	—	77	216	210
C41	50	50	—	59	167	202
NC37	100	—	2.5	11.5	50	167
NC40	60	40	2.5	8	38	172

However, the flowability of mortar is relatively less influenced by the powder while a relationship between the setting time of cement paste and the flowability of mortar also exists (the shorter the setting time, the lower the flowability) due to the rate of hydration.

Effect on strength

The same mortars as used in the flowability test were cast into 4 × 4 × 16 cm prisms and autoclaved under the same conditions as for expansion test and thereafter cured for 24 hours followed by strength determinations . The results are shown in Fig. 3.

It can be seen that the strengths are similar to or higher than that of pure cement mortar (no replacement) when replacement within 40% and that both flexural and compressive strength acquired the highest values when 30% of powder substituted the same amount of cement. This also verified that the



(a) (b)

Fig.3 Relation between mortar strength and aggregate powder amounts (a) flexural strength; (b) compressive strength reactive powder could take part in the hydration process and modify the strength development. However, elevating the alkali level in mortars decreased the strength markedly due to the decomposition of C-S-H by Na^+ ions, and even in this case (NC40) the incorporation of powder (40%) could also develop the strength by a factor of 5.4% and 9.9% for flexural and compressive strength, respectively, compared with NC37. This is because the reduction of Na_2O based on its reaction with silica resulted in the formation of gels and the newly formed gels, containing more Na^+ ions, could further react with Ca^{2+} ions which could benefit strength too.

CONCLUSIONS

1. The incorporation of reactive aggregate powder seems able to prevent mortars made of the same reactive aggregate sand from severe expansion, implying a promising approach to suppressing ASR.

2. Compared with existing approach, such as incorporating Li-containing chemicals and blending materials (silica fume, ground granulated blast furnace slag and pulverized fly ash), the local use of reactive aggregate powder to suppress ASR is more economical and effective.

3. The amount of powder used to replace part of cement depends mainly on the alkali levels in the mortar and also on the reactivity or the acidity of the powder. The higher the alkali level, the more powder is required and a greater effect can be observed.

4. The reason for aggregate powder inhibiting ASR is explained as follows: the alkalies are retained by and react with aggregate particles (in unconfined spaces) causing a reduction of alkali concentration near to the aggregate surface. Meanwhile, the powder along with its products fill up pores, resulting in a densification of the matrix and difficult migration of alkali species.

5. The fineness of powder affect its effectiveness in preventing ASR and an reasonably appreciable value of about 8000 cm^2/g is recommended.

6. The incorporation of such a powder could consistently shorten the setting times and modify the strength development within an adequate replacement range. Less effect on flowability of mortars could be observed, however.

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