

Effect of Ground Granulated Blast Furnace Slag Admixture, and Granulated or Air-Cooled Blast Furnace Slag Aggregate on Alkali-Aggregate Reactions and Their Mechanisms

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ABSTRACT

Reactions of alkalis and several types of blast furnace slags are studied using the chemical method and the mortar bar method. The beneficial effect of reducing expansion caused by alkali-reactivity is shown by the use of granulated slag either as an aggregate or as a cementitious admixture in concrete. The paper also describes the results of an experiment conducted to study the mechanism of interaction of slag in suppressing AAR.

INTRODUCTION

The effectiveness of slag in preventing expansion due to alkali-aggregate reaction (AAR) was first reported by Cox in 1950, and since then a number of papers have been published in many countries. Various theories have been presented regarding the mechanism of the action of slags in reducing AAR expansion (Smolczyk 1974, Bakker 1981, Diamond 1983, Chatterji 1984, Uchikawa 1985, and Hobbs 1982 & 1985).

This paper deals with the usefulness of slag as aggregate or finely pulverized admixture in suppressing AAR.

METHODS USED AND TEST PROCEDURES

To study the stability of blast furnace slag against AAR, samples varying from glassy to crystalline were prepared by changing slag cooling and solidifying conditions and by grinding them to the size of aggregates or admixtures (cementitious material). The quality of ground granulated blast furnace slag (ggbfs) used as cementitious admixture was also investigated using samples from 12 Japanese steelworks and one Canadian steelworks. The alkali content varied from 0.39 to 0.68% Na₂O eqv. In addition to slag, three types of natural reactive aggregates (two andesites and one chert), one non-reactive Palaeozoic sandstone and pyrex (ASTM C441) were tested by the mortar bar method.

The Ordinary Portland Cement used contained an acid soluble alkali content in the range of 0.51% to 1.02%; this alkali content was increased, when necessary, by the use of sodium hydroxide or sodium chloride. Besides ggbfs, a type of flyash also was used as a mineral admixture.

Three series of expansion tests on mortars were carried out. Firstly, the prevention of AAR by slag aggregates from various blast furnaces processed under different cooling conditions was investigated. As air-cooled varieties, two samples of furnace-pit slag, one sample of modified or ladle-pit slag and one sample of slag, which solidified and clung to the shell of ladle and therefore seemed to have been cooled slightly faster were used. As a quenched variety, ordinary water-granulated slag was utilized. For controls, two types of reactive andesite were employed as they were known to be involved in AAR distress in some structures. In preparing the mortar bars for Series 1, the alkali content of the OPC was increased from 0.79 to 1.6% by the addition of sodium hydroxide. The alkali content of these materials is similar to that of ggbfs.

Secondly, slags processed under different cooling conditions were ground and samples were tested for usefulness as a cementitious admixture. Included in these samples were air-granulated slag samples in addition to air-cooled slag samples and water-granulated slag samples. Mortar bars were prepared in accordance with ASTM C 441 using Pyrex aggregate, OPC of 1.12% eq. Na_2O , and ggbfs with varying slag replacement ratios up to 70% (Series 2).

Thirdly, 13 types of Japanese and Canadian ggbfs were tested for their expansion properties. Mixtures of Pyrex aggregate, OPC of 1.02% eq. Na_2O , and the ggbfs were made with slag replacement ratios between 0% and 65% and were tested according to ASTM C 441. Then, three types of ggbfs were selected, i.e., the least effective, medium and the most effective ones in suppressing AAR. These types were combined with the three representative reactive and one non-reactive aggregate to prepare several types of mortar bars. Because the alkali content of the OPC used was 0.51% eq. Na_2O , it was increased to a maximum of 1.96% eq. Na_2O using sodium hydroxide solution. In this case we conducted preliminary leaching tests for OPC, flyash and slag using lime solution at 80°C. The alkali in the slag showed only one sixth or less of the solubility of that in OPC however, it was 2.2 times more soluble in $\text{Ca}(\text{OH})_2$ than in water at 80°C. Pyrex and andesite were selected as reactive aggregates for series 3.

Lastly, the reaction behaviors of slags and flyash in a sodium hydroxide solution were investigated. The tests are conducted in accordance with ASTM C 289 and when it was impossible to obtain these materials in sizes from 150 μm to 300 μm , they were used in the form of fine material. The ratio of 1 N sodium hydroxide solution to slag or flyash was varied between 1:1 and 1:4. The evaluation was based on the volume of residual solution, which was uncombined with the solid, and the change in alkalinity of the solution after reaction. The water soluble alkali content of air-cooled slags is 0.010-0.0004%. Although the air-cooled slag has a water soluble alkali content 2.5 - 10 times greater than that of the flyash, it was also found that the solubility of its alkali is not as large as that of OPC.

EXPANSION, TEST SERIES 1 -SLAG AS AGGREGATE-

Sodium hydroxide was used to adjust the alkali content of the OPC. Expansion of mortar containing andesite was 0.46-0.48% at 6 months, but mortar made with slag aggregates expanded by only 0.017-0.029% in 6 months and less than 0.06% in 12 months showing that the slag was a stable aggregate.

EXPANSION, TEST SERIES 2 -SLAG AS ADMIXTURES-

Differences in expansion between mortars blended with ground slag and ground quartz sand admixtures indicate that the effect of the slag is more than that of simple dilution of alkali in the mix.

The slag activity index values of both ground air-cooled slag and silica sand, measured using an admixture-OPC (50:50) blended mortar, were equally low (about 45% in 28 days), while that of ground water-granulated slag was 94% at the same age. The total pore volumes of the blends by mercury porosimetry was 0.199 cm³/g for water-granulated slag, 0.315 cm³/g for air-granulated slag, 0.301 cm³/g for air-cooled slag, and 0.224 cm³/g for OPC alone. The average pore diameters of the pastes at 29-day were 33 nm, 38 nm, and 34 nm, respectively. The AAR suppressing effect of slag mortar, therefore, cannot be wholly explained from the permeability of slag mortar alone as suggested by the theory of permeability as the governing factor (Bakker 1981). Neither the glassy content nor the degree quenching seems to be the governing factor in the suppressing effect of the slag.

EXPANSION, TEST SERIES 3-SLAG AS ADMIXTURE-

The results of the mortar bar expansion test using Pyrex glass on 13 types of ggbfs are shown in Fig. 2. The suppressive effects of ggbfs on expansion, though increasing with the increase of slag replacement ratios, differ with the origin of the material. As for the ASTM C 595 requirements mentioned earlier, all the Japanese ggbfs are effective for suppressing AAR either at 14 days or 8 weeks, if the slag replacement ratio is more than 61%. The slag replacement ratio which corresponds to RE 75% calculated on the basis of the assumption made previously for the control mixture is 55% to meet the ASTM C 441 requirement for the reduction of mortar expansion. In averages, however, the above values are 54% (for 14d. and 8w.) and 44% (for 75% RE).

The mortar bar test was made with three types of ggbfs, including the one which showed the least suppressive effect on AAR, which were selected from the above 13 types. The ggbfs was mixed, at varying replacement levels, with OPC having soluble alkali levels of 0.51-0.96% and three types of natural reactive aggregates. The results of this test are shown in Fig. 3. Figure 4 shows that the same ggbfs was effective in reducing expansion of mortar bars containing different reactive aggregates. Therefore, the expansion test was carried out using two sets of mortar bars. One set was prepared by replacing various proportions of the OPC by ggbfs without adjustment for dilution of alkali content. The other set was made the same way, but the alkali content was adjusted to correspond to 0% replacement of OPC. Results obtained from the two sets of mortar bar are compared in Fig. 5.

If the alkali dilution of slag is the only factor, the curves with cross marks would be drawn horizontally irrespective of slag replacement ratios (Fig. 5). However, even in this test, the amount of expansion decreased depending on the slag replacement level. It can be deduced from this, therefore, that slag has another function in suppressing AAR apart from its alkali dilution effect.

The threshold value of the alkali content in mortar for harmful expansion increases with the increase in the slag replacement level, although that value in the OPC alone is roughly 5 kg/m³ (Fig. 6).

REACTION BEHAVIOR BETWEEN SODIUM HYDROXIDE SOLUTION AND SLAG

The reaction of slag with NaOH solution was investigated in accordance with ASTM C 289. The quantity of residual solution after reaction with slag or flyash for 24 hours is shown in Fig. 7. From this graph, it is clear that solution is held as hydrated water and/or pore water in hydrated pastes. This residual solution was then analyzed for dissolved silica and hydroxide ion concentration to obtain the reduction in alkalinity (Fig. 8). While flyash releases silica into solution consuming alkali thereby reducing alkalinity, slag hardly releases any silica. Even if slag

released silica, this released silica would precipitate in the neighborhood of slag particles, thus the reduction in alkalinity would be small. From this, it is clear that the original NaOH from the solution tends to be incorporated in hydrated slag paste. In addition, as has been stated, the alkali in slag is hardly dissolved even in lime solution. Thus, the reaction behavior between sodium hydroxide solution and slag seems to differ from that between sodium hydroxide solution and flyash.

CONCLUSIONS

Blast furnace slags, either air-cooled or granulated, can be used as stable aggregates free from harmful alkali-aggregate reactions.

When used as a ground admixture, both the air-cooled slag and the granulated slag are effective for preventing the excessive expansion due to the alkali-silica reaction.

It has been proved that the AAR inhibiting effect of slag derives from not only the dilution of alkali from OPC but also due to a fundamental inherent function of slag. In addition, data indicative of the difference in reaction behavior in the alkali solution between flyash and slag have also been obtained.

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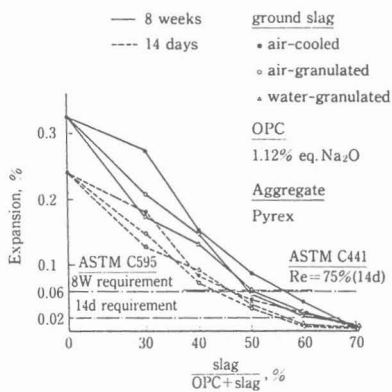


Fig. 1 Effectiveness of slags in preventing AAR

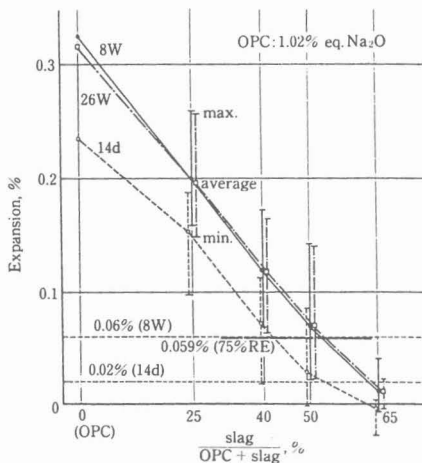


Fig. 2 Relationship between expansion & slag replacement on 13 slags

Andesite ZD2
Alkali: 1.16% eq. Na₂O OPC

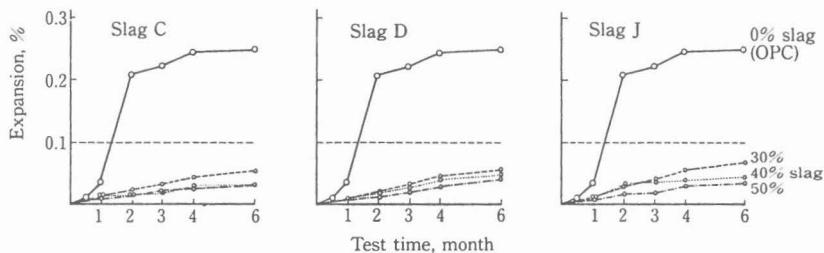


Fig. 3 Influence of the difference in the origin of slag upon the expansion reducing effect

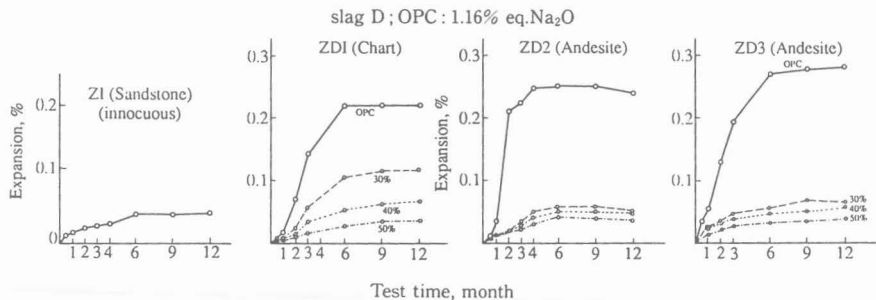


Fig. 4 40 x 40 x 160mm mortar bar expansion

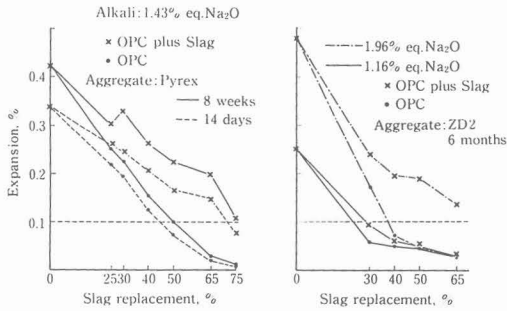


Fig. 5 Expansions of mortar bars made with OPC and with OPC+slag at constant and varied alkali levels.

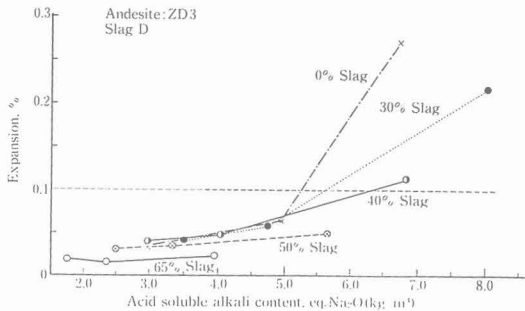


Fig. 6 Variation of expansion at 6 months with alkali content contributed by OPC and OPC/slag blends mortars, assuming that slag has no alkali.

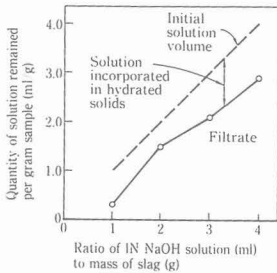


Fig. 7 Change in solution volume

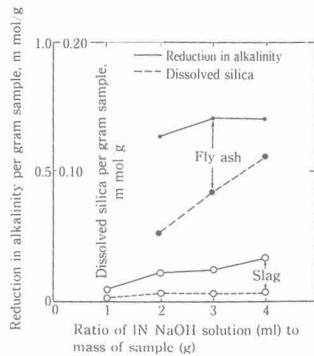


Fig. 8 Change in reduction alkalinity and dissolved silica