USE OF GROUND GRANULATED SLAG TO OVERCOME THE EFFECTS OF ALKALIS IN CONCRETE AND MORTAR

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1. ABSTRACT

Use of finely ground water granulated blast furnace slag as a partial replacement for high alkali portland cement in mortar and concrete can markedly reduce the expansion from alkali aggregate reaction, while improving the rate of strength gain. Recent commercial production of the material in the U.S. affords an offset against problems associated with high alkali cements. The replacement material can be produced utilizing only about one-fifth the energy required to produce portland cement.

1.1 Key Words

Slag, alkalies.

2. MANUSCRIPT

The Atlantic Cement Company, Inc. has become the first American industry to produce and market finely ground water granulated slag as a cement replacement in the production of concrete. Pioneering efforts in this regard have been fruitful in other parts of the world, namely in South Africa and Japan, and efforts to produce such a product from pelletized blast furnace slag in Canada and in the U.K. predate Atlantic's U.S. entry into the field.

Heretofore in the U.S., 30 to 40 percent water granulated slag has been interground with portland cement clinker to produce portland blast furnace slag cement. Though no longer in production, the high quality of those products is demonstrated by the continued existence of 30-year-old highway systems and structures made from portland blast furnace slag cement in those States in which such products were available at the time of construction. But these interground products had several drawbacks: 1) Because granulated slag is usually much harder to grind than portland cement clinker, the interground product was composed of very finely ground clinker and coarsely ground slag. Thus in the normal course of hydration, the slag fraction could not contribute its full strength-producing potential within the 28-day field testing procedure.

A second objectionable feature of interground portland blast furnace slag cements in the States was the fixed nature of the clinker-to-slag ratio. These products contained only about 35 to 40 percent slag and were intended for general construction concrete. Such products could not be expected to perform up to their potential under sulfate attack or when used with reactive silicious aggregates.

Twenty years ago, with bountiful supplies of cheap fuel at hand, U.S. cement producers were not as energy conscious as their European counterparts, who fostered pre-heater kilns and slag cements to conserve fuel. For the most part, such developments in the States awaited the Energy Crisis of 1974, when U.S. cement manufacturers found themselves well behind Europe and Japan in technological developments to conserve energy.

Along with the revolution in pre-heater installations came increases in alkali-sulfate contents of the resulting clinker. Cement strengths, up to age 7 days increased but then tapered off at 28 days. Likewise, many cements that had previously been classified as "low alkali" because high alkali cements with the attendant concern over potential expansion with reactive aggregates.

The sulfur entrapped with the alkali also contributed its own set of problems. Sulfur in the clinker made it difficult for the plant chemist to add enough gypsum for optimum SO_3 content without exceeding the specification limit for SO_3 in the cement. As a result, setting time behavior became unpredictable, especially when concrete admixtures were involved.

Problems with these alkali-sulfate distressed cements gave impetus to the use of mineral admixtures in concrete. Pozzolans, mostly fly ash, were used to reduce the risk of expansive reactions from the alkali with questionable aggregate. In many cases indiscriminate use of fly ash with high or variable carbon content resulted in wide fluctuations in strength and in air-entrainment of the resulting concrete. Also, it was found that some of the fly ashes available in the U.S. contained as much as 4.23 percent/1/ alkalies as sodium oxide and therefore could be a major potential contributor to the alkali-aggregate reaction.

The energy crisis prompted some U.S. cement producers to look again toward blended cements. Such interest was evidenced by the inordinate attention given to the development of ASTM C595, Specification of Blended Hydraulic Cements. The Federal Government encouraged these developments through the U.S. Department of Energy which published a report on "Potential for Energy Conservation Through the Use of Slag and Fly Ash in Concrete."/2/ The report concluded, in part, that "the use of glassy blast furnace slag and fly ash as partial cement replacements, either in blended cements or as admixtures in concrete, present the potential for sizable energy savings."

With this background, several U.S. cement producers began to investigate the possibility of utilizing granulated blast furnace slag as an ingredient in a blended cement, or as a separately ground product to replace a portion of the portland cement going into the concrete mixer. The latter application had several advantages over a blended product.

1. The concrete producer would have complete flexibility to adjust the ratio of slag to portland cement to the specific job requirements of the concrete. Optimum mixes could be prepared for early strength development and cold weather concrete by using low percentages of slag, or higher percentages of slag could be utilized for concrete to be exposed to sulfate conditions, with reactive silicious aggregates, or to reduce the heat of hydration in mass concrete. High ultimate strength could be achieved in the mid-range additions of slag.

2. This wide range of concrete characteristics could be achieved with an inventory of only two cementitious products: ordinary portland cement and ground granulated slag.

3. The grinding system could be designed specifically for the hard-to-grind granulated slag, thus avoiding the difficulties encountered in intergrinding materials of quite different grindability.

4. The separate slag product could be produced at about one-fifth the total energy required to produce portland cement, and therefore at much lower cost.

5. Pricing of the separate product could be completely independent of the pricing of portland cement.

Granulated blast furnace slag has several advantages over fly ash as a mineral admixture:

1. It could be quality controlled during production.

2. Fineness could be changed to meet market requirements.

3. It could be utilized in concrete at much higher percentages than fly ash, imparting a high degree of durability without loss of strength.

4. Its handling characteristics were similar to those of portland cement as opposed to the difficulty in containing and controlling the flow of fly ash.

The prime drawback to the commercial development of granulated slag was the lack of granulating facilities at U.S. blast furnaces. Too, existing furnaces were often quite confined with little space available to granulating facilities.

Two basic types of granulation were available, the air-trajectory pelletizer, and full water granulation, with quite different requirements for space and capital investment.

In late 1978, Bethlehem Steel Corporation completed construction on its huge and modern "L" furnace at Sparrows Point, Maryland. Its output of slag was estimated to be about 750,000 metric tons per year and its coastal location would facilitate water-borne distribution of the product. Its design was such that there was ample room for adjacent granulating facilities of either type. Its large size would require a burden of uniform chemistry, which in turn should produce slag of consistent uniformity. Its high degree of efficiency should insure its continuity of operation even in slack steel market conditions.

In 1979, Atlantic Cement Company negotiated a long-term agreement with Bethlehem Steel to take possession of the entire slag output of "L" furnace and produce from it a cementitious product. The capital investment required for the entire process was to be provided by Atlantic. Drawing heavily from experiences in Europe, Japan and South Africa, Atlantic chose to use full water granulation, a closed circuit dewatering system, drying and separate grinding into a product to be called "NewCem." Atlantic was uniquely equipped to distribute and market the 750,000 tons of slag because of its existing East Coast barge and terminal system through which it continued to handle some 1.5 million tons of portland cement from its Ravena, New York, plant. The details of the Sparrows Point plant are described elsewhere./3/

Design of NewCem was carried out under contract with the Portland Cement Association/4/ and in Atlantic's own research laboratory./5/ Of prime importance to market acceptance was the need for NewCem concrete to reach par strengths with portland cement concrete at curing times between three and seven days. This was achieved at a Blaine fineness of 550 M^2/Kg. The tests confirmed the ability of NewCem blends in concrete to resist chemical attack as reported by other investigators for similar products./6//7//8/ They also confirmed that replacements of high alkali cement with NewCem would dramatically reduce alkali-aggregate reactivity expansion. Suppression of the alkali-aggregate reaction by the addition of slag was cited by Mather,/9//10/ who suggests an alkali limit for portland blast furnace slag cements yielding performance equal to that of 0.60 percent sodium oxide equivalent for portland cements alone could be as high as 1.20 percent sodium oxide equivalent.

Using a cement representing the highest alkali content likely to be encountered on the East Coast of the U.S., about 1.15 percent sodium oxide equivalent, tests were conducted at Atlantic's Research Laboratory by ASTM C227 Test for Potential Alkali Reactivity of Cement-Aggregate Combinations (Mortar-Bar, Pyrex Glass Method) using 40, 50 and 65 percent NewCem (Figure 1), with an alkali content of 0.45 percent. These mixtures represent alkali contents from 0.68 to 0.85 percent sodium oxide equivalent and demonstrate the beneficial effect of slag on the expansion over a 21-month period.

Bakker /11/ described the prevention effects against alkali-silica reactions of slag cement concrete as entirely due to their much lower diffusivity and water-permeability compared with portland cement concrete. He believed the migration of alkalies to reactive particles is an integrated function of diffusivity and permeability and found a reduction of 50 to 65 percent initially, which increased with time. Other investigators/12//13/ believe alkalies are chemically bound in the CSH. It seems reasonable that there is a synergistic effect of the low permeability/diffusivity characteristics and of a particular affinity for alkalies by the slag particle fraction of the concrete. The migration distance for alkali hydroxide to reach the slag particle is microscopic as compared with the distances between reactive aggregate particles. The combination of absorption of alkalies in the CSH structure, and the resulting reduced permeability and diffusivity are the reasons why concrete with slag is superior to portland cement concrete with regard to resistance to alkali-silica reactions. Provided water is available, the slag hydration will continue and thereby retain more and more alkalies and calcium hydroxide, and continue to contribute to increase strength, density, and resistance of concrete.

It is not surprising then, that the slag component, activated by alkalies from a high-alkali cement component will have a beneficial effect on the strength development of the blend. Investigators /14/ attribute the low strength gain of high alkali cements to reactions in the kiln when alkalies that have not been removed by volatilization combine preferentially with sulfates, and the excess alkalies combine with the silicate and aluminate phases, thus reducing both potential C_2S and C_3A. On the other hand, if slag is present in the cementitious component, the alkalies are readily used by the slag particles as an activator, opening up the glass to initiate the hydration process. The new CSH can retain, or recycle, alkalies for the creation of more CSH gel structure. In this way, slag paste will continue to gain strength in contrast to pure portland cement paste.

Using two portland cement samples from U.S. East Coast sources, NewCem was substituted for 50 percent of each in the preparation of mortars for testing by ASTM C109, Compressive Strength of Hydraulic Cement Mortars. Strength development up to 28 days is shown in Figure 2, where it can be seen that the high alkali cement exhibited a poor strength gain from 7 to 28 days as compared to the lower alkali cements. However, when each of the portland cements was replaced by 50 percent NewCem, the strength gains of each blend was improved but that of the high alkali cement received the most benefit from slag substitution.

Thus, it can be seen that alkali-distressed cements can be made to behave in a more normal fashion by substituting finely ground granulated slag at substantial percentages of the total cementitious component. Likewise, the potential for alkali-aggregate reaction can be reduced markedly by such substitutions.

It is likely that other U.S. cement producers will follow Atlantic's example by producing materials similar to NewCem, utilizing domestic or imported granulated slag.

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