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Long term investigation and inhibition on alkali-aggregates reaction of Three Gorges Dam concrete

Huaquan Yang [a], Pengxiang Li [a], Meijuan Rao [b,*]

[a] Changjiang River Scientific Research Institute, Wuhan, Hubei 430010, China
[b] State Key Laboratory of Silicate Materials for Architectures, Wuhan University of Technology, Wuhan 430070, China

HIGHLIGHTS

- Investigate the effect of AAR on the Three Gorges Dam Concrete for over 30 years.
- Use the "Five Finger Peak" shape to take a comparison of variety rocks.
- Make a comparison of six kinds of alkali contents(Na2Oeq) for a very long period.

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ABSTRACT

The Three Gorges Dam is famous for being the largest dam throughout the world. Research studies were first conducted in 1984 to investigate the effect of alkali-aggregate reaction (AAR) on the concrete used to construct this dam. The expansion rate of AAR is closely related to the time changes (the time-cumulating effect). The results of AAR were obtained from the observations recorded for a time period of about 20–30 years. In this study, we discovered that the expansion rate cumulates as the age extends, and the maximum value of expansion rate can be observed only in certain periods. In particular, the "peak" in the curve of expansion rate appears circa in ages 13–16 years. Thereafter, the expansion rate of mortar witnessed a declining trend; perhaps, some parts of the long-term mortar containing non-reactive aggregates will undergo a harmful expansion if the alkali content exceeds over 1.20%. Thus, the expansion in this circumstance would be more than 0.1%. However, micro analysis indicates that although the expansion rate of mortar is over 0.1%, no apparent characteristics of AAR are apparent. We could effectively inhibit AAR by adding fly ash and slag. Alumina-oxygen tetrahedron$(AlO_4)^{5-}$ was formed, and it rapidly hydrated and intensively absorbed the ions into the gel structure. Once the hydration products attain a high specific surface area in an alkaline medium, the products participating in the reaction involving reactive aggregates of alkali undergo reduction consequently.

1. Introduction

Alkali-aggregate reaction (AAR) is a chemical reaction that occurs between the alkali metals present in cement and an active aggregate. The reaction leads to an uneven expansion of concrete, resulting in cracking. Although research studies have been conducted on AAR test methods and the results have been publicized since 1940, it was T.E. Stanton who first expressed concerns about the undesirable results of AAR [1]. To determine whether the suitability of aggregates obtained from both new and existing sources would be suitable enough for use in concrete, we determine the potential reactivity of aggregates in an alkaline environment of the concrete. For the purpose of analysis, ASTM test methods are widely accepted since decades, especially C227, C289, and C295 [2–4]. Although these methods have been extensively used in different geological and geographical regions, we discovered a major drawback of these methods of analysis: the results obtained are not always in accordance with field experience. These limitations have been presented within the latest guidelines published by ASTM International. Presently, ASTM International has published newer methods, which are based on the testing of concrete specimens in hot alkali solutions. All the latest methods have been standardized. However, even these novel methods have been modified extensively in various settings, leading to some novel developments worldwide. The modified versions of these methods have been recently accepted as standard test procedures in certain countries (CSA 1994, ASTM 1994). By evaluating the test, scientists

* Corresponding author.
E-mail address: raomeijuanding@163.com (M. Rao).

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have confirmed the reliability and reproducibility of these methods. Moreover, they have also determined whether these modified versions are suitable for both rapid and slow/late alkali-reactive aggregates. The International Union of Laboratories and Experts in Construction Materials, Systems, and Structures (RILEM, the name is derived in French) has been working diligently in establishing universally accepted test methods and assessing the suitability of potential alkali-reactive aggregates. The methods TC 106 and TC 191-ARP have been finalized and published by RILEM members present in different parts of the world [5–6]. In standard test procedures, we used ASTM methods to conduct AAR of granite but the test results did not comply with engineering practices in some cases. To construct Moxot'o dam in Brazil, engineers used biotite granite as concrete aggregates. After eight years, its strength and durability were severely impacted by the harmful cracking effect of AAR [7]. To construct the Shambon dam in France, engineers used gneiss and isinglass granite as aggregate; the height expansion of this dam was over 10 cm, while the top of the dam inclined upstream at about 15 cm [8–11]. In 1973, Gogte et al. suggested that AAR should be viewed from a different angle [12]. They claimed that crystalline quartz-bearing rocks could also act as potential alkali-reactive aggregates provided a slow/late mechanism was employed instead of the well-known rapid alkali-aggregate reactions. It was commonly used as a tool to quantify the alkali reactivity of quartz-bearing rocks that contained strained quartz [13–16]. However, many scientists have expressed ambiguity in the results obtained by examining the undulatory angle of strained quartz, thus raising questions on the validity of the method [17–19]. In the AAR of granite, the rate and progression is influenced by many interacting and interdependent parameters, such as deformed quartz. Standard tests are performed on aggregates to determine alkali activity in them during a geological exploration; these tests serve as control measures that may help in the selection of quarries and to avoid the use of alkali-reactive aggregate. Presently, the control measures used in alkali-aggregate reactions mainly include the use of non-active aggregates, control over the total alkali content in concrete, humidity control, and the suppression of material and chemical admixtures in a regulated manner [20–22].

In the Three Gorges Project, the granitic aggregates have many different types of quartz, having different types of dislocation density and distortionof crystal. Because AAR of granitic aggregates is slow/late, AAR lasts for many years. The damage inflicted by AAR is often evident decades after the formation of concrete. The long-term expansion rate cumulates as the age progresses, but it cannot be detected by the AAR accelerated test, which has very high research significance, irrespective of whether it is carried out indoors or outdoors. In this experiment, we determined the alkali reactivity of granitic aggregates by performing the following tests: petrographic examination, long-term examine method, EDS (Energy Dispersive Spectrometer), WDS (Wave Dispersive Spectrometer), and SEM (Scanning Electron Microscope).

2. Experimental

2.1. Raw materials

Gezhouba 525 Portland cement was used in the test. The chemical constituents of cement are listed in Table.1. Their total alkali content of the cement is less than 0.6% (Na_2Oeq). Chemical compositions of raw materials and petrochemical analysis are shown in Table 1.

2.2. Petrographic examination

The petrographic examination results indicate that the aggregates in the borrow sites are granite and granite-porphyry, composed mainly of feldspar, quartz and mica. The feldspar content is 60–70%, the quartz content is 20–40%. Due to the influence of the tectonic movement and stress, the undulance extinction prevail in the aggregate, which the undulance extinction angle is not big but 4.4° at average, the maximum not exceeding 10°. Meanwhile different kind of dislocation forms in the stress concentration area, including bow crook, dislocation net and dislocation tangle. There is not micro particle quartz in the aggregates.

AAR is mainly related with the structure of the quartz in the rock. The more stable the crystal structure is, the lower the alkali activity will be. However, it is not proportionate to the integrity of the quartz crystalloid which can be determined by testing the XRD peak shape of the quartz crystalloid. The ''Five Finger Peak'' shape of quartz crystal can determine the crystallization degree of it. The Full Width at Half Maximum (FWHM) represents the width of the XRD apex at half height of the XRD apex of the mineral, which can quantitatively express the integrity of the crystalloid. The bigger the FWHM is, the lower the integrity of crystallization will be. XRD scanning speed is 0.02°/20 s, XRD scanning range is 66°–70°. The XRD spectrum are listed in Figs. 1–4. It can be seen from Fig. 3 that the''Five Finger Peak''of quartz crystal in flint is obviously widening which indicated low crystallization degree of quartz crystal in flint. The granites are similar to standard non-active quartz sand. The results of Pectra-Decomposition by software ''PRO—FIT AND WPPF'' were shown in Table 2.

The FWHM of flint is obviously bigger than that of the standard non-active quartz sand. The FWHM of the granites are similar to the FWHM of of the standard non-active quartz sand. The FWHM analysis results indicate that the quartz crystalloid in the two kinds of granite is similar to that of the standard non-active quartz sand.

2.3. Test methods and AAR activity of granite

Over long period of time, ASTM C227 tests were carried out in order to evaluate the long-term performance of AAR. The plagioclase granite mortar specimens formed in 1984 were with an alkali content of 0.78%, 0.80%, 1.00%, 1.20%, 1.50%, and 2.00% (Na_2Oeq). Concrete prism test (according to DL/T5150-2001) [23] was used to calculate the changes in length of the samples. A strain meter was buried in the samples beforehand. Then, molding of the test samples was implemented in a mixing room with a temperature of 20 ± 2 °C. Aftermolding, the samples were sent into the reservation room (with a temperature of 20 ± 3 °C and a relative humidity (RH) of above 95%) together with the test molds. Subsequently, the samples were wrapped with wet cloth, put into the sealed plastic bags and placed into the reservation room for reservation under a temperature of 38 ± 2 °C.

Tests were performed on the porphyritic monzonitic granite and the plagioclase granite with the CECS48:93 [24] methods by extending the autoclavable time, the test results are listed in Table 3. The results show that the expansion rate of various mortars was still small, all less than 0.1%. The test result of intensifying rapid method indicates that the quartz would finally react with the alkali leading to expansion with the extension of autoclavable time, even though the quartz crystalloid was still non-active. When the rapid test method of AAR is made, the reaction ages must to be considered. If the reaction ages will be too long, some aggregates proved to be non-active will be considered as active and thus result in misestimations.

3. Results and discussion

3.1. Long term observation (mortar length method)

Figs. 5–7 show the long-term results obtained by mortar length method. In 1986, we analyzed the feeble weathering specimens of granite mortar formed in the process; the alkali content of these individual specimens were as follows: 0.54%, 0.80%, 1.00%, 1.20%, 1.50%, and 2.00% (Na_2Oeq). Fig. 6 illustrates the long-age results.

By observing the results of the reaction occurring in alkali-granite aggregates for 20–30 years, we discovered that the expansion rate cumulates as the age extends, but a maximum rate will be observed only at certain periods. The ''peak'' appears in the expansion rate curve during circa ages 13–16 years; thereafter, the expansion rate of mortar shows a declining trend. This indicates that the cumulating expansion rates vary depending on the extending ages of the medium. Moreover, the accumulated reaction energy was released, leading to an expansion following accumulation. In practical engineering practices, we need to focus on investigating AAR in concrete of ages 13–16 years.

As shown in Fig. 5, expansion increased within 20 years owing increase in the alkali content in the aging mortar, and the maximum expansion is more obvious in this setting. When the alkali content was less than 1.0% in the mortar obtained from plagioclase granite aged for 20 years, the expansion maxima did not exceed 0.10%. The expansion exceeded 0.10% in the granite that was aged