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The effect of elevated conditioning temperature on the ASR expansion, cracking and properties of reactive Spratt aggregate concrete

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HIGHLIGHTS

- 12 °C rise in temperature accelerated the expansion by 3.22 times.
- Similar trend of loss in mechanical properties at both temperatures.
- Slightly larger extent of loss and microstructural cracking at 50 °C than at 38 °C.

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ABSTRACT

In the laboratory study of alkali-silica reaction (ASR), attempts have been made to reduce the test duration by accelerating the rate of reaction, which is usually accomplished by increasing the conditioning temperature. However, the consequences of elevating temperature are not so encouraging. This study evaluated the effects of elevated temperature by comparing expansion, damage rating index and mechanical properties of concrete made with Spratt aggregate conditioned at 38 °C and 50 °C. Increasing the temperature to 50 °C from 38 °C can shorten the test duration by more than three times with little effect on the response of concrete.

1. Introduction

Alkali-silica reaction (ASR) is an undesirable chemical reaction in concrete that causes expansion, cracking and degradation of mechanical properties. Even though ASR has now been adequately understood to ensure that new concrete structures are safe against it, ASR is still a major deterioration problem in many existing structures. The rate of reaction is generally slow and usually takes 10 years or more to show its effects in field concrete structures [1]. In an experimental study that involved large concrete specimens subjected to an outdoor condition, ASR expansion was monitored and it continued for 20 years [2]. However, the urgent need for diagnosis, prognosis and necessary repair measures of existing structures cannot afford such a long duration for an experimental study. Therefore, experimental studies on concrete specimens are typically performed under an accelerated condition. While most of the accelerated studies involve small specimens such as concrete prisms (75 × 75 × 285 mm) and cylinders (Ø100 × height 200 mm), the study of larger specimens (1 m or longer) such as beams and walls are preferred to understand the performance of concrete structures affected by ASR [3–5].

The relatively slow rate of ASR is a challenge for evaluating its implications on structural performance. While small specimens can be accommodated in existing laboratory facilities, maintaining the conditions necessary for accelerating the rate of reaction in large structural specimens and conditioning them for an extended duration can be logistically challenging. These are some reasons why large specimens are rarely examined in ASR studies. One such study [3] involved 3 m long concrete beams (cross-section of 0.25 × 0.5 m) that were subjected to an elevated temperature of 38 °C. The measurements in the beams were reported for 14 months. Yet, the increasing expansion and beam deflection indicated that the reaction was not exhausted by the end of the study duration. Relatively larger thickness of the beams, when compared

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to the small specimens such as prisms, might have partly contributed to the lengthened duration of the reaction. A laboratory study of large structural specimens necessitates an accelerating condition that fosters a faster rate of reaction.

Accelerating the rate of reaction can be achieved by increasing the exposure temperature, relative humidity, or alkalinity, or combinations thereof. Most laboratory studies employ the combination of all three accelerating measures. Nevertheless, increasing the temperature appears to be the most common accelerating variable to increase the rate of reaction.

The most common temperature for accelerating ASR on concrete specimens is 38 °C based on the concrete prism test (CPT), which is regarded as a reliable reference test method for assessing the potential alkali-silica reactivity of aggregates as per ASTM [6], CSA [7] and RILEM [8] standards. However, the duration of the CPT is 1–2 years and the test is regarded as slow for many purposes. Practical requirements have encouraged to shorten the test duration by further increasing the temperature [9–11]. For instance, the accelerated concrete prism test (ACPT), usually performed at 60 °C [12], has emerged as a faster alternative to CPT. Nevertheless, the 60 °C temperature method is reported to cause reduced expansion compared to that achieved when exposed to 38 °C temperature [13,14]. Some reasons for the reduced expansion at 60 °C are [13,14] (i) increased leaching of alkalies; (ii) change in pore solution chemistry owing to the reduced concentration of hydroxyl ions; and (iii) drying of prisms at higher temperature. Another unusual observation reported in the study [14] of ASR conducted at 60 °C was that non-reactive fine aggregate had a "dramatic effect" on reducing the expansion and increasing the variability in expansion measurements [14].

Considering the complexity associated with interpretation of the response of ASR-affected concrete specimens conditioned at 60 °C, Folliard et al. [13] performed a series of concrete prism tests at 49 °C, which is an intermediate value between 38 and 60 °C. While the ultimate expansion decreased with an increase in temperature, this effect was more pronounced for the temperature increment from 49 to 60 °C than from 38 to 49 °C. The ultimate expansions corresponding to 60 °C (0.09%) were markedly less than those corresponding to 49 °C (0.17%) and 38 °C (0.20%). A non-linear effect of the two temperature increments was also observed in terms of alkali leaching. Alkali leaching was more pronounced for the temperature increment from 49 to 60 °C than from 38 to 49 °C. These findings indicate that the accelerating temperature for investigating the performance of large specimens should be limited to around 50 °C.

An increase in temperature accelerates the rate of ASR by thermoactivating two processes involved in ASR [15]. Firstly, an increase in temperature accelerates the dissolution of silica in aggregates. For instance, the rates of dissolution of three types of silica particles measured at 25 °C in 3 M NaOH solution for 3 days were 71%, 8% and 7%, whereas these amounts were, respectively, 100%, 66% and 31% when measured at 80 °C [16]. In another study [17], the dissolution of silica at 80 °C was reported to be 6–7 times more than at 60 °C. Secondly, increased temperature accelerates the rate of formation of reaction products [15]. Results from an experimental study [18] on concrete conditioned at temperatures ranging from 23 to 58 °C confirmed that both processes follow the Arrhenius law of chemical reaction [15]. Based on the formulas for two time constants for the two processes [15], the rate of expansion is approximately doubled when the temperature is increased from 38 to 50 °C. As per the formulas proposed in another experimental study [19], the rate of reaction can be increased by approximately 1.7 times when the temperature is increased from 38 to 50 °C. These findings indicate that the test duration can be significantly reduced by choosing 50 °C instead of 38 °C as the accelerating temperature for large concrete specimens.

Recently, an accelerating temperature of 50 °C was chosen in a large-scale project aimed at investigating the consequences of ASR on existing structures [20]. The project involved several large unreinforced and reinforced concrete specimens with thickness ranging from 75 to 254 mm and length of up to 1.5 m. Even though the accelerating temperature was 50 °C, the study had to rely on the vast knowledge of ASR gained mainly through experiments performed at 38 °C. For example, the reactivity of aggregate to be used for casting the specimens was decided based on the expansion of concrete prisms tested at 38 °C. To evaluate the effect of temperature increment from 38 to 50 °C on expansion, which is one of the key performance indicators for reactive concrete, a study was necessary to compare the expansion results at the two temperatures. Moreover, the specimens were designed to be monitored for the performance of concrete in terms of cracking and degradation of mechanical properties. However, most of the performance indicators for ASR damage are either unavailable or inadequate for tests at 50 °C. The damage rating index (DRI) is one such indicator that quantitatively assesses the damage due to ASR based mainly on the cracks it develops in concrete. The DRI method has been extensively applied on field samples and on specimens conditioned at 38 °C [21–24]. In order to assess DRI as a performance indicator for ASR-affected concrete, Sanchez [25] performed DRI analysis of twenty concrete mixtures made with a variety of reactive aggregates. The study discussed the influence of concrete strength and different types of reactive aggregates on DRI. However, all the experiments were performed at 38 °C, and hence, the effect of temperature on damage was not investigated. An increase in temperature can lead to greater damage despite having identical ultimate expansion as indicated by a recent numerical study [26]. While expansion mainly depends on the amount of reaction product formed and not on its rate of formation, microstructural damage is influenced by the creep effect which in turn is influenced by the rate of reaction [26]. Thus, a study comparing DRI of identical concrete specimens conditioned at 38 °C and at 50 °C is essential before DRI can be used as a performance indicator for the concrete specimens conditioned at 50 °C. Furthermore, to better understand the influence of increasing temperature on the damage of concrete, the degradation of mechanical properties should be compared at the two temperatures.

This paper compares the consequences of ASR on identical concrete prism specimens conditioned at 38 °C and at 50 °C. Both test sets (one at 38 °C and the other at 50 °C) include reactive and non-reactive (control) mixes of concrete. Longitudinal expansion of the prism specimens from the two tests is compared. Prism specimens from the two tests are analyzed by the DRI method. The results are discussed to compare the damage between the two tests, to elucidate the evolution of ASR damage, and also to highlight some limitations of the DRI method. The degradation of dynamic modulus of elasticity and modulus of rupture of the prism specimens is measured. Based on the findings from the tests, a conclusion is made regarding the implication of increasing the accelerating temperature from 38 to 50 °C.

2. Materials and methods

2.1. Concrete mix design and materials

The mix design was based on the concrete prism test as per ASTM C1293 [6], and is shown in Table 1. The water-to-cement ratio was 0.44. High alkali general use (GU) cement was used with a total alkali content of 0.99% Na_2O equivalent by mass of cement. The chemical composition of cement is shown in Table 2. The alkali