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A new approach to evaluate alkali-silica reactivity using loss in concrete stiffness

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HIGHLIGHTS

- Loss of concrete stiffness occurs at 4 weeks, and significantly increases at 26 weeks.
- Loss of concrete stiffness at 26 weeks of more than 18% is considered as reactive.
- Loss of concrete stiffness between 4 and 26 weeks of more than 9% is treated as reactive.
- The proposed limits of loss in concrete stiffness shows a good ASR prediction.

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ABSTRACT

This paper reports the loss of concrete stiffness due to the adverse effect of alkali-silica reactivity (ASR). The concrete cylinders prepared with fourteen aggregate groups were immersed in water at 20 °C (68°F), and in the 1.0 N NaOH at 80 °C (176°F). The percent loss in stiffness (PLIS) between water- and alkali-cured cylinders was determined at 4 and 26 weeks, and was correlated with the expansion of the mortar bars (immersed in the 1.0 N NaOH at 80 °C (176°F)) containing the companion aggregate source at the test durations of 2, 4 and 8 weeks. The results concluded that the loss in stiffness of the concrete cylinders occurred at 4 weeks, and it significantly increased at 26 weeks. The study also suggested that the ASR classification of the aggregates based on the expansion limits of mortar bars showed a good correlation with that produced from the proposed limit of stiffness loss of concrete.

1. Introduction

Alkali-silica reaction (ASR) is one of the most recognized deleterious phenomena in concrete and has been a major concern in more than fifty countries of the world [53]. It is a chemical reaction between the reactive forms of silica in some aggregates and hydroxide ions in the alkalis, mostly come from cementitious materials [50,38]. The ASR reaction forms an alkali-silica gel, which swells by extracting water from the surrounding cement paste, thereby inducing expansion and cracking the aggregate and surrounding paste [13]. The atomic structure, physical characteristic and mineralogy of aggregates are mainly responsible for forming ASR-induced expansive gels in concrete [51]. However, the crystal structure of silica present in aggregate plays an important role in alkali-silica reactivity [14]. The durability, serviceability, and the safety of the installation eventually can be deteriorated by ASR, which tends to disturb the internal forces and deform the overall structures [6,35,33]. The total losses in the engineering properties of concrete affected by ASR depend on the physical and chemical characteristics of aggregate present in concrete [52,17]. However, the deterioration caused by reactive aggregates can also be controlled by using proper mitigation techniques [28,29].

The mechanical properties of concrete involve a thermally-activated reaction, known as hydration, and the development of hydration is a function of time. The increase in the rate of hydration in concrete is prominent at the beginning of concrete casting, and is relatively slow at later ages [27]. The surrounding environmental factors, such as the temperature and the relative humidity of air, affect the hydration rate as well [43]. The increased temperature accelerates hydration reactions at the early age [43]. Alternatively, the effect of low temperature on cement hydration is quite different. In such circumstances, the hydration reactions in the initial periods are slow and they increase with an increase in the test duration. The ultimate compressive strength of concrete cylinders

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increases with an increase in the curing temperature to a maximum at about 26 °C, and then decreases rapidly until a certain temperature is reached, after which they remain nearly constant [36].

Stiffness is the elastic characteristics of a material. The hydrated cement paste and aggregate show linear elastic properties, but their combined material (concrete) displays nonlinearity [39]. The slope of the relation between stress and strain of concrete under uniaxial loading gives the static modulus of elasticity, but the term Young's modulus can be applied strictly only to linear categories [34]. Due to the nonlinearity of curve, secant modulus can be used in computing the modulus of elasticity, where the origin of the line is drawn from a point representing a longitudinal strain of 50 μ in/in to the point that corresponds to 40 percent of the ultimate load. Since the stiffness is defined as the ratio between the applied stress and instantaneous strain within assumed proportional limit, the stress induced by strains associated with the alkali-silica reactions plays a vital role.

A number of past investigations showed that the compressive strength is little affected during the early stages of alkali-silica reaction [42,52,40,23,27]. Some research studies [40,1] disputed the idea; they stated that compressive strength is not a good indicator of ASR. The compressive strength of concrete initiates to decrease as soon as the alkali-silica reaction takes place at the micro-structural level. Nixon and Bollinghaus [42] demonstrated that the loss in concrete strength becomes an indication when the cracking turns into severe at later stages. The effect of compressive strength of a concrete on ASR reaction is a function of time, and loss in compressive strength increases with an increase in test duration [9,51,32,1,27]. The strain of concrete begins to increase due to the micro-cracking that develops as soon as alkali-silica reactions take place, and it increases significantly with increasing the curing age [27]. As such, the combined effects of decreased compressive strength and the increased strain result in the loss in stiffness of concrete. The loss in compressive strength due to the adverse impact of ASR could be as high as 40–60% [51].

Compared to the loss in compressive strength of concrete due to the harmful ASR reaction, the stiffness is a more sensitive and reliable indicator of concrete deterioration [12,23,2,11]. The concrete stiffness is vulnerable to variations in the ratio of crystalline and non-crystalline parts in the structures, while strength is comparatively insensitive to such variation [41]. Alkali-silica reaction reduces concrete stiffness significantly [31,32,40,1,17,49,18,10]. The reduction is mainly due to micro-cracking rather than ASR-induced expansion [52,44].

The stiffness of water-cured cylinders at low temperature increases with an increase in test duration [2], and decreases with raising temperature [46]. The relationship of the normalized stiffness of concrete (E_{cr}/E_c) in compression with the temperature (T) ranging from 20 °C (68°F) to 120 °C (248°F) can be expressed in Eq. (1) [8]. Excluding the aggregate reactivity and the influence of test duration, the loss in stiffness depends on mixture design, aggregate type, and storage environment etc.

$$E_{cr}/E_c = -0.00165 * T + 1.033 \tag{1}$$

where: E_r is concrete stiffness at 20 °C (68°F); E_{cr} is concrete stiffness at T°C; and T is temperature in degree celsius.

A variety of standard methods can be conducted to evaluate the alkali-silica reactivity of an aggregate. Among them, the ASTM C 1260 (accelerated mortar bar test, known as AMBT) is very popular throughout the world. In the AMBT, the specimens are kept in the strong alkali solution of 1 N NaOH maintained at 80 °C for a minimum of 2 weeks. A number of expansion limits of mortar bars at different ages have been suggested to describe potentially ASR reactions. The most conservative approach is the 2-week failure limit of 0.10%, proposed by ASTM C 1260, have led the additional expansion limits of 0.33% at 4 weeks and 0.48% at 8 weeks, proposed by Hooton [20,21], and Hooton and Rogers [22]. Islam [23,24] and Islam and Ghafoori [25,26] proposed that the aggregates producing the 2-, 4- and 8-week mortar expansions of 0.10%, 0.28% and 0.47%, respectively, are considered reactive, and those producing the expansions of less than the above-mentioned proposed expansion limits can be classified as innocuous. The aggregates having the mortar expansions in the range of 0.10–0.30% experienced 20–50% loss in stiffness of concrete [45]. The modulus of elasticity of concrete cylinders containing highly reactive aggregates decreased at the early age, while that of containing modestly reactive aggregates decreased at later ages [2]. The study conducted by Marzouk and Langdon [37] showed that about 52% loss in stiffness was observed at 12 weeks for the cylinders prepared with moderately reactive aggregates.

The influence of ASR-induced expansion on concrete stiffness is a vital topic, which has been incorporated in many previous studies. However, none of the existing investigations offer failure criteria of ASR evaluation of an aggregate based on the loss in concrete stiffness due to the adverse effects of alkali-silica reactivity. As such, an experimental study with advanced statistical analysis is needed whether the stiffness loss can accurately predict alkali-silica reactivity of an aggregate when compared to the results obtained by the expansion limits of mortar bars and aggregate mineralogy.

2. Research significance

Previous investigations were mostly limited with a general agreement that a substantial loss in concrete stiffness is experienced due to the alkali-silica reactivity. However, they often contradicted at what age and the limit of loss in stiffness due to alkali-silica reactivity occurred. The past investigations were also lack of establishing failure limits of loss of concrete stiffness for which the ASR of an aggregate can be evaluated. This study proposes failure limits of loss in concrete stiffness below which an aggregate behaves as innocuous or reactive otherwise. The evaluations are made from the statistical correlations of the loss in stiffness of concrete cylinders made with fourteen aggregate groups and the ASR-induced expansions of mortar bars prepared with the companion aggregates. The model proposed herein can also be utilized with the existing standard tests for evaluating alkali-silica reactivity of an aggregate.

3. Experimental procedures

The identification, chemical composition, and rock type of the fourteen investigated aggregate groups used in this study are shown in Table 1. The potential ASR reactivity of the investigated aggregates was also determined based on the findings of major rock types (mineralogy) susceptible to alkali-silica reaction, recommended by the studies conducted by Islam [23], Ghafoori and Islam [16], and Islam and Ghafoori [25], and the results are also presented in Table 1. Type V Portland cement with 21% of SiO_2, 3.6% of Al_2O_3, 3.4% of Fe_2O_3, 63.1% of CaO, 4.7% of MgO, 0.84% of Na_2O_{eq}, 2.6% of SO_3, and 1.3% of LiO was utilized to prepare mortar bars specimens. An appropriate amount of sodium hydroxide pellets was added in the mixing water to raise the cement alkali from 0.84% to 1.25% Na_2O_{eq}, and used to cast cylinder specimens.

3.1. Mortar bars

The mortar specimens were prepared from a specific gradation of crushed coarse, water-to-cement ratio (by weight) of 0.47, and the aggregate to cement ratio of 2.15 as per the requirements of