Construction and Building Materials 162 (2018) 253–264

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Characterization of concrete affected by delayed ettringite formation using the stiffness damage test

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HIGHLIGHTS

- The *Stiffness Damage Test* (*SDT*) can reliably assess DEF-damaged concrete.
- SDI and PDI indices have a near-linear correlation to DEF expansions up to 0.40%.
- *SDT* may characterize DEF damage more effectively than ASR damage.
- The statistical significance of *SDT* analyses by SDI and PDI is confirmed by ANOVA.
- Future work should consider combined ASR and DEF damage, and correlating *SDT* to DRI.

ARTICLE INFO

Article history:
Received 28 March 2017
Received in revised form 14 October 2017
Accepted 2 December 2017

Keywords:
Concrete
Stiffness damage
DEF
Delayed ettringite formation
ASR
Damage characterization

ABSTRACT

The stiffness damage test (SDT) may provide more information than conventional mechanical tests used to assess concrete affected by expansive reactions. A new approach to analyzing SDT data involving the calculation of stiffness damage and plastic damage indices (SDI and PDI) has successfully characterized the expansion of concrete affected by alkali-silica reaction (ASR). This study is the first to implement SDI and PDI to characterize concrete affected by delayed ettringite formation (DEF). The SDI and PDI parameters have a nearly linear relationship to expansions under 0.40%. ANOVA confirms the statistical significance of the SDI and PDI parameters and that they provide information not available from standard elastic modulus tests.

1. Introduction

Extraction and testing of core samples from concrete structures is extremely useful in the diagnosis and evaluation of structures affected by durability-related problems, such as alkali-aggregate reactions (AAR), cyclic freezing and thawing damage, and delayed ettringite formation (DEF). Core sampling is akin to taking a biopsy in medicine – an invasive procedure that generally does little harm to the structure. Cores are typically subjected to mechanical tests and petrographic examination to determine the type and severity of the distress, and to determine whether the structure has sufficient load-carrying capacity. Compressive strength, though an important indicator of concrete quality and a critical input for structural analyses, is not affected as much as stiffness, tensile strength, or flexural strength in concrete suffering from internal swelling reaction mechanisms (ISR) such as AAR and DEF [1–3]. Compressive strength testing is also destructive to the specimen and precludes also performing petrographic examination of the same specimen. The stiffness damage test (SDT), however, was found to provide useful information on the degree of damage in concrete, such as reduction in stiffness and extent of microcracking damage; it is thus considered a more complete technique than a simple elastic modulus test [4,5]. Moreover, it has been found that when loads of 40% or less of the compressive strength of the concrete area used, the SDT remains a non-destructive test of the concrete, even at very high levels of deterioration from ISRs [5]. Hence, the SDT can be coupled with further chemical or microscopic

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https://doi.org/10.1016/j.conbuildmat.2017.12.012

evaluations performed on the same specimens, to obtain maximum information about the condition of the structure [4–11]. It is worth noting that the non-destructive character of the SDT is an asset, although the most important aspect of this mechanical testing procedure is its ability to quantify the amount of inner distress of damaged concrete, which requires the application of loads of at least 30% (ideally 40%) of the compressive strength of the concrete.

SDT attempts to quantify damage to concrete from AAR and other mechanisms by analyzing stress vs. strain data obtained when cyclic loads are applied to core samples. Several versions of the test and associated data analyses have been proposed, but the basic principle remains the same; compared to sound concrete, damaged concrete will have a reduced stiffness and will accumulate more plastic strain and thus dissipate more energy during the test. While the use of SDT as a tool for characterizing the effects of AAR on concrete structures has been widely-described and reported in the literature [5,12–17] and most extensively for alkali-silica reaction (ASR), there are only limited reports of its use for characterizing DEF-affected concrete [4,18]. Recent research on the use of SDT for ASR-damaged concrete has resulted in new methods of data analysis [5,8,10,11], which are now applied to prior SDT data generated for DEF-affected concrete in this paper.

DEF is a form of internal sulfate attack in concrete, driven by curing temperatures in excess of 65–70 °C and unfavorable cement chemistry [19–21]. Cement hydration and formation of C-S-H is greatly accelerated with increased curing temperatures. With sustained temperatures above 65 to 70 °C, ettringite becomes thermodynamically unstable; hydration reactions are unable to form ettringite, and previously-formed ettringite decomposes and returns to solution [22]. The rapidly-growing “inner” C-S-H traps dissolved sulfates and alumina before they can react to form ettringite [20,21,23]. After temperatures decrease to levels more commonly experienced by concrete in service, thermodynamics again favor the formation of ettringite. Trapped sulfates and alumina may be released from the C-S-H and react with water and monosulfate to form ettringite; this can lead to deleterious expansion and cracking of the concrete [20]. Similar to AAR, the microscale characteristics of DEF include extensive microcracking. In contrast to AAR (especially ASR), where microcracking extends through both the paste and aggregate particles, microcracking from DEF is primarily limited to the cement paste, which expands away from the aggregate particles. The resulting gaps and microcracks are often filled with recrystallized ettringite deposits instead of ASR gel. More importantly, because DEF damage development is not intrinsically linked to the mineralogy of the aggregates or the distribution of reactive phases, as is the case in ASR [24], it is possible that SDT could be more generally useful as a tool to diagnose and characterize the extent of damage from DEF.

2. Background on SDT

The stiffness damage test (SDT) was originally developed by Crouch and Wood [12] and involved applying five cycles of 5.5 MPa compressive load to a core specimen and measuring its stress–strain response. In ASR-damaged concrete, the elastic modulus decreases, while the stress–strain hysteresis loops increase in size, and increasing amounts of plastic strain accumulate during the course of the test [12,13]. Chrisp et al. [13] placed emphasis on the elastic modulus, plastic strain and size of the hysteresis loops of the second through fifth cycles and largely discarded the data from the first load cycle, primarily because they believed that the first cycle induced new damage in the concrete. They also proposed calculating a non-linearity index (NLI), defined as the secant modulus at half the maximum load divided by the secant modulus at the maximum load; this was thought to account for the orientation of cracking in damaged concrete.

Further development of the test method by Smaoui et al. [14] resulted in a recommended loading level of 10 MPa and identified the area of the first hysteresis loop and the accumulated plastic strain over all five cycles as the most important parameters. They proposed that a linear relationship between these parameters and ASR expansion could be established using laboratory specimens or core samples extracted from larger specimens of known expansion levels [14,15]. They also noted that concrete made with different reactive aggregates will exhibit varying responses in the stiffness damage test; that is, linear relationships must be established for multiple reactive aggregate types in order to estimate the expansion of a variety of field structures. Fig. 1 shows typical stress–strain data obtained using this version of the test for an undamaged sample and one damaged by ASR.

The 10 MPa version of the test has been adopted by the US Federal Highway Administration [25]. Several papers describe the application of this version of the SDT to field structures damaged by ASR [26–29], but no studies have been published regarding the use of SDT to characterize damage from DEF or a combination of ASR and DEF using the updated procedure and analysis developed by Smaoui et al.

More recent works by Sanchez et al. [5,8,10,11,30] suggest that the maximum applied stress in the test should not be a fixed value because useful data can only be obtained if it is at least 30% of the compressive strength. If the load is less than 30% of the compressive strength, which would be greater than 10 MPa for concrete stronger than 33.3 MPa, and greater than 5.5 MPa for all but the weakest concretes, then it is very difficult to quantify ASR damage with SDT. As a result, Sanchez et al. [10,11] recommended conducting the test at 40% of the current strength, which would be the same load specified for the determination of the static modulus of elasticity by ASTM C469 [31].

3. Scope and research significance

This paper presents a study of the use of SDT to characterize two sets of concrete cylinders, made with different aggregates and conditioned to increasing levels of expansion and damage from DEF. The results of standard secant modulus of elasticity tests and compressive strength tests on the same specimens are also presented and analyzed for their utility in characterize the progress of damage. The notable improvement over earlier work to characterize DEF-affected concrete is the use of analytical tools developed by Sanchez and coworkers that seek to correlate SDT damage indices to petrographic damage features quantified through the Damage Rating Index (DRI) [5–11,32]. The SDT data are also analyzed using tools previously developed by Smaoui et al. [14]. Finally, ANOVA analysis of the data is presented to identify the most significant variables influencing the test results.

4. Materials and methods

Two sets of 100 × 200 mm cylinder specimens were fabricated for this study. The specimens made use of the same concrete mixtures used by Giannini and Folliard [16] in a parallel study on the mechanical properties of ASR-affected concrete; however, the conditioning regime (described in Section 4.2) was designed to limit the development of ASR and promote the development of DEF.

4.1. Materials and mixture proportions

Table 1 presents the aggregates used in this study, and Table 2 shows the proportions for the two concrete mixtures. Mixture 1 contained aggregates C1 and F1, and Mixture 2 contained aggregates C2 and F2. Aggregates C1 and F2 are considered non-reactive with regards to ASR; the 1-year expansion in ASTM C1293 testing for these two aggregates tested together is 0.01% [20]. When tested per ASTM C1293, reactive aggregates C2 and F1 have been documented to exhibit 1-year expansions