Construction and Building Materials 176 (2018) 440–451

Contents lists available at ScienceDirect

Construction and Building Materials

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

Influence of alkali-silica reaction and crack orientation on the uniaxial compressive strength of concrete cores from slab bridges

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HIGHLIGHTS

- Extracted concrete cores from three severely ASR-damaged slab bridges were tested.
- The compressive core strength and Young's modulus are highly affected by ASR cracks.
- Strength parallel to ASR cracks can be higher than strength perpendicular to ASR cracks.
- The behaviour in compression is less anisotropic for increasing amount of ASR cracks.

ARTICLE INFO

Article history:
Received 10 February 2017
Received in revised form 11 March 2018
Accepted 12 March 2018
Available online 11 May 2018

Keywords:
Alkali-silica reaction
Slab bridges
Uniaxial compressive strength
Young's modulus
Crack orientation
Thin section examination
Failure mechanism

ABSTRACT

For a reliable structural analysis and risk assessment of concrete structures damaged by alkali-silica reaction (ASR), knowledge of the concrete compressive strength is essential.

This comprehensive study investigates the residual compressive strength of concrete cores drilled from three severely ASR-damaged flat slab bridges in service. Furthermore, the influence of the ASR-induced crack orientation on the compressive strength and the Young's modulus is investigated. Uniaxial compression tests, visual observations, and thin section examinations were performed on more than 100 cores drilled from the three severely ASR-damaged flat slab bridges. It was found that the orientation of ASR-induced cracks has a significant influence on the uniaxial compressive strength and the stress-strain relationship of the tested cores. The compressive strength in a direction parallel to ASR cracks can be significantly higher than the strength in the direction perpendicular to ASR cracks. It is proposed that for an increasing amount of ASR-induced cracks in the extracted cores the anisotropic concrete behaviour in compression will be reduced.

1. Introduction

Alkali-Silica reaction (ASR) is a well-known deterioration mechanism in Denmark. In Denmark, most aggregate sources contain reactive silica minerals both in the fine and in the coarse aggregate fraction. Opaline and calcareous opaline flint were found as the main reactive aggregate types in the country [1]. The reactive aggregate types are characterized as fast reactive, which can cause deleterious cracking within a few years in the structure [2].

ASR is a complex physical and chemical reaction between alkalis (Na^+, K^+) present in the concrete pore solution, usually originating from the cement but also supplied from outside sources such as de-icing salts, certain types of reactive aggregates containing reactive silica minerals, and moisture [3]. The reaction produces an alkali-silica gel that can absorb water and expand. With a sufficient amount of reactive aggregates in the concrete, the reaction can generate expansion and internal pressure that causes serious cracking in concrete structures [3].

A large percentage of the Danish concrete bridges and tunnels contains a critical amount of ASR reactive aggregates. The Danish Road Directorate has estimated that approximately 600 concrete bridges have the potential to develop ASR [4]. In addition to the 600 bridges owned by the Danish Road Directorate an unknown amount of municipal bridges are built with ASR reactive aggregates. The majority of the 600 Danish road bridges were built during the 1960s and 1970s. Local ASR reactive aggregates were used in the construction of these bridges as a part of the fast developing

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https://doi.org/10.1016/j.conbuildmat.2018.03.096
0950-0618/

Danish infrastructure at that time [4]. Today, some of these bridges are severely damaged with considerable extent of ASR cracking. In Denmark, the majority of the cases with ASR-damaged concrete structures are related to reactions in the fine aggregate fraction. To the authors' knowledge, four slab bridges in Denmark have at recent time been demolished due to ASR cracking and uncertainties regarding the residual load-carrying capacity and safety requirements for these bridges. The major concerns are regarding the shear-carrying capacity for flat slabs without shear reinforcement. The load-carrying capacity for existing structures is often assessed by conventional calculation methods based on the compressive strength of concrete. However, for structures with extensive ASR cracks, the extracted cores are often broken into small pieces during the in-situ drilling procedure. Consequently, the in-situ drilled cores are rarely in a size to perform compressive strength tests. Therefore, the assessment of the load-carrying capacity of the Danish ASR-damaged bridges has mainly been based on in-situ visual inspections of the structure, combined with petrographic examination of drilled cores.

In order to conduct a better and more reliable assessment of the ASR-damaged concrete structures knowledge about the influence of ASR and ASR crack orientation on the compressive strength is essential.

Several experimental studies on the effect of ASR on the compressive strength of concrete have been published [5–19]. The majority of these studies were based on experiments with small-scale laboratory specimens accelerated to a free expansion without restraints [5–9,14,16]. Here, the ASR-induced cracks were typically orientated randomly, because the expansion is not restrained in any direction [20]. Generally, these studies conclude that the compressive strength is only slightly affected by ASR. The reduction in the tensile strength and the Young's modulus can be significantly higher than the reduction in the compressive strength.

In actual reinforced concrete structures, the development and orientation of the ASR-induced cracks are influenced by the structural boundary conditions and the reinforcement configuration. In the presence of reinforcement the expansion is, depending on the reinforcement degree, elastically restrained in the reinforcement direction leading to tensile stresses in the reinforcement bars and suppression of the concrete expansion in the main reinforcement direction [21]. Consequently, the ASR-induced cracks form parallel to the main reinforcement direction as seen in bridge slabs in service without shear reinforcement [21]. Therefore, the conclusion from the experiments without restraints cannot be generalised to actual reinforced concrete slabs. Few experimental studies of small scale laboratory accelerated specimens are based on more realistic restraints of the ASR expansion [11–13,15]. Here, the specimens were accelerated with uniaxial compressive stresses applied to the specimens and the ASR-induced cracks were formed parallel to the compressive stresses. These experimental studies conclude that the compressive strength and the Young's modulus in the direction parallel to the ASR cracks were greater than in the direction perpendicular to the ASR cracks. Additionally, the influence of crack orientation on the Young's modulus was found to be greater than the influence on the compressive strength.

Limited studies investigate the influence of drilling orientation on the compressive strength of concrete cores extracted from reinforced elements [13,17–19]. The results from these experimental studies are contradictory. Three out of four studies show [13,17–18] that the drilling orientation has an influence on the compressive core strength. However, these studies do not agree on whether the compressive strength in the direction parallel or perpendicular to the crack orientation is the largest. Additionally, Allard et al. [18] reported no statistically significant differences between the compressive strength of cores drilled vertically and horizontally from accelerated thick concrete beams. These contradictions may be caused by differences in the amount of ASR cracks at the time of testing, reinforcement configuration, type of reactive aggregate types and the conditioning of the reinforced beams. Consequently, these differences result in significant challenges in the interpretation and comparison of experimental studies. Furthermore, since the studies are based on laboratory manufactured and accelerated reinforced beams, the authors may argue that the ASR cracking is not representable for Danish bridge slabs reinforced in the longitudinal and transversal direction without shear reinforcement. The differences in ASR crack orientation due to differences in reinforcement configuration and exposure conditions between reinforced slabs in service and laboratory accelerated beams are illustrated by Hansen et al. [22].

To the authors' knowledge, there exists no studies that investigate the influence of ASR and the orientation between the ASR cracks and the loading on the compressive strength and the Young's modulus of concrete cores extracted from flat slab bridges in service. This paper presents a comprehensive study on the influence of ASR and ASR crack orientation on the compressive strength and the Young's modulus of drilled concrete cores from three severely ASR-damaged flat slab bridges. Additionally, an explanation of the effect of ASR cracks on the failure mechanism of the concrete cores during compressive loading is presented.

2. Studied structures

All the examined slab bridges are reinforced with two layers of horizontal reinforcement nets and are not provided with shear reinforcement. Consequently, the vertical expansion is not restrained by any reinforcement.

2.1. Slab bridge A

Slab bridge A, also known as Vosnæsvej bridge, was built in 1976 and consists of three spans. The total bridge length is 54.5 m, and the width is 10.0 m. The bridge was built with two prestressed beams and an integrated slab (a double T structure). According to records, the design 28-day concrete compressive strength of the slab was 30 MPa.

In 2012, a visual inspection of the bridge showed comprehensive fine wet longitudinal ASR cracking combined with gel exudation at the cantilevered part of the slab.

For determination of the mechanical properties of the ASR-cracked concrete cores were drilled from 12 1.3-m-long beams. The thickness of the beams varied from 0.27 to 0.45 m. The beams were cut from the cantilever part of the slab; six beams were cut from the western bridge end, and six beams from the eastern bridge end. The distance between the eastern and western ends was approximately 30 m. The beams were cut during the preparation for an in-situ test of the load carrying capacity of the slab. The results of these tests were reported by Schmidt et al. [23] and further analysed by Hansen et al. [24].

2.2. Slab bridge B

Slab bridge B, also known as Gammelrand bridge, was built in 1976 and consisted of three spans. The width of the bridge slab was 9.1 m, and the total length was 30.5 m; the longest span was 14.0 m. The entire bridge was constructed as a concrete slab. According to records, the design 28-day concrete compressive strength of the slab was 35 MPa.

Visual inspections of the bridge and drilled cores showed that the entire 0.7-m-thick slab was cracked due to ASR. In 2010, the bridge was demolished due to uncertainties regarding the residual load-carrying capacity. Beforehand, four 7.65-m-long and 0.6-m-