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Petrographic identification of alkali–silica reactive aggregates in concrete from 20th century bridges

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ABSTRACT

Cracks and white coatings have been observed in a number of concrete bridges constructed during the 20th century. The observed damage phenomena have been attributed to the alkali–silica reaction (ASR) after following detailed macroscopic examination. Several analytical approaches – optical microscopy of thin sections, petrographic image analysis and SEM/EDS study – were employed in order to: (1) quantify the extent of the damage (volume percentage of alkali–silica gel); (2) determine the causes of the damage. The presence of alkali–silica gels is controlled by the petrography of aggregates where monomineral quartz aggregates, metagreywacke, pellite and metasedimentary rock fragments contribute significantly to ASR development. Other phases (feldspars) and fragments of magmatic native rocks (granite, diorite, and volcanic rocks) have not been shown to have any influence on ASR. The volume of alkali–silica gels in the studied concrete samples (ranging from 0.1 to 0.9 vol.%) increases with increasing age of the bridge.

1. Alkali–silica reaction damage in concrete

The alkali–silica reaction (ASR) originates in concrete in which aggregates containing reactive forms of SiO_2 react with alkalis (sodium and potassium) and form amorphous alkali–silica gels. Alkali–silica gel develops in the aggregate particles or at its margins. It absorbs water molecules, increases in volume and exerts pressure. The internal pressure may exceed the consistency limits of the concrete, leading to mechanical failures e.g. [1,2]. Open air cracks, crushing and white coatings represent typical phenomenon of the alkali–silica reaction observed macroscopically on the concrete surface e.g. [3,4]. All these signs are calculated in the damage ratio index of the concrete. More advanced methods use a digital image analysis, which enables quantitative analysis of the cracking in the concrete [5–7]. Different approaches from laboratory techniques including petrographic study, chemical tests, and dilatometric evaluation are used to evaluate the ASR potential of aggregates.

ASR occurs only when three principal factors act simultaneously: (1) a sufficient amount of alkalis, (2) the presence of reactive forms of silica in the aggregate, and (3) sufficient moisture e.g. [1,8]. The alkalis can be derived from cement, from the aggregate and/or from an external source. A critical factor consists, however, in the presence of aggregate containing disordered (poorly crystalline) forms of silica, like opal, cristobalite or tridymite in, e.g., sedimentary or volcanic rocks, or highly strained quartz in some types of metamorphic rocks e.g. [9,10].

1.1. Recent developments in petrographic techniques for study of the alkali–silica reaction

Analytical techniques such as scanning electron microscopy with energy dispersive spectroscopy (SEM/EDS) and/or X-ray diffraction (XRD) together with standard petrographic examination are widely used methodologies in the identification of damaging processes in construction materials e.g. [11–13]. In contrast, petrographic methods have been employed for concrete samples more recently, since the 1980s e.g. [1,14]. In identifying damaging mechanisms in concrete, they improve the identification of reactive components e.g. [15–17]. The identification of reactive forms of silica is, however, a very difficult task, as these cannot be easily separated from other forms by optical microscopy e.g. [1]. This was one of the reasons for the introduction of dilatometric testing to evaluate the reactivity of aggregates e.g. [18–21] and combination of the mortar dilatometric bar tests with petrographic methods [22].

Petrographic examination can also facilitate determination of mechanisms of concrete damage even where ASR is accompanied by other processes like frost weathering [23]. In some cases, detailed petrographic examination helped detect the mechanism of concrete damage – e.g. sulphate attack [24] and formation of ettringite instead of the originally proposed mechanism of ASR [25,26].

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1.2. Aims of the study

This study presents part of a project focused on the experimental evaluation of petrographic factors enhancing ASR in concrete structures. The aims of this study were to correlate two methods, macroscopic observation "in situ" and petrographic identification of ASR using optical microscopy and SEM/EEDS, to identify the aggregates causing ASR and, finally, to find whether the year of the bridge construction is correlated with the occurrence of ASR.

Thirteen different bridges were selected that exhibited the following characteristics: (1) extensive signs of ASR were first observed in the 1990s, (2) repair work was performed in 1995, (3) protective coatings were used, (4) in 2005, control samples from the most damaged parts were examined to evaluate the quality of the repair work and to examine the remnants of previous ASR, (5) the signs of ASR were repeatedly observed macroscopically. Cracking and spalling were considered to be pre-indicators of ASR. The total amount of alkali–silica gels was accepted as reference value for ASR in concrete.

2. Experimental

2.1. Sampling sites

The concrete samples were taken from eight concrete bridges located at various places in the Czech Republic. The road bridges were constructed in the 1924–1982 period and have been considered to be "safe" from the point of view of ASR for a number of years or decades. During inspection in the 1990s, extensive signs of ASR were, however, identified on these structures and repair followed in the late 1990s. About five years after the repair work (in 2005), control samples were taken from the most damaged parts in order to evaluate the quality of the repair work and to examine the remnants of previous ASR. Visual examination of the damage ratio was carried out macroscopically "in situ" (according to the Czech National Standard ČSN 736221, [27]) by Pontex Ltd. All the bridges exhibit functionless protective coatings and large surface parts damaged by cracks (see Fig. 1). More detailed descriptions of the identified damage are given in Table 1.

2.2. Sampling and preparation of thin sections

The sampling consisted of diamond-core drilling carried out by Pontex Ltd. The cores are 80 and/or 100 mm in diameter depending on the location of the drill and have a length from 300 to 400 mm. 1–2 drill cores were taken at each site. The size of the cores allowed preparation of 6–23 thin sections from each specimen in order to take into account the heterogeneity of the material. The remainder was stored for other analyses.

Two sets of petrographic thin section have been prepared. The first one (thin sections with dimensions of 50 $\times$ 50 mm) was employed for the optical microscopy and image analysis. The second set (thin sections with dimensions of 35 $\times$ 28 mm) was designed for the analytical study by SEM/EDS.

Fig. 1. In situ observation of ASR. (a), (b) cracks through the face-side (indicated by black arrows), (c) detailed view of the net of cracks, (d) detailed view of the spandrel panel over the pillar, (e) front of the pillar damaged by concrete spalling, (f) cracks through the landing front.