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Field performance of concrete exposed to sulphate and low pH conditions from natural and industrial sources

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ABSTRACT

Laboratory investigations have been used to derive a high number of important details on sulphate attack on hardened concrete, but are not able to forecast the performance of this material under field conditions. In order to obtain reliable information on the long term behaviour of concrete, a survey is presented that looks at sulphate and sulphide containing environments in a particular region in mid-Europe. Twenty concrete structures have been sampled and analyzed.

The classical idea of sulphate attack considering the migration of sulphate ions from ground or river water into concrete with subsequent phase transformation and damage has not been confirmed. This kind of exposure was found to be rare and no serious deterioration has been observed in connection with it. However, concrete is liable to be destroyed when in contact with sulphide bearing environments or if intimately mixed with gypsum. Disintegration and serious expansion requiring immediate repair has been observed. Information on all investigated structures are presented in this article and in more detail in a separate report.

1. Introduction

Concrete is a material that is used for many purposes in construction without the need of maintenance during the life time of the structure. However, it can be damaged by a number of chemical reactions that are often due to the ingress of certain reactive species in the microstructure. Such reactions are carbonation, chloride induced steel corrosion and sulphate attack, among others. Attack from an aggressive species is considered during concrete production by selecting cements that exhibit superior resistance in the relevant exposition.

Research into performance and durability of hydraulic limes and cements has a long tradition, starting in the 18th and 19th century with investigations reported by Blezard [1]. A high number of research programs have been conducted in the 20th century, acquiring knowledge on the nature of sulphate attack mechanisms. Monographs and review articles on this issue are available [2–7] and design of concrete exposed to sulphate attack is supported by standards and guidelines.

Upon the contact of concrete with sulphate containing environments, a diffusion of sulphate and potentially of other ions in the hardened cement paste takes place. Some of the phases in the microstructure are sensitive to an interaction with sulphate. Calcium hydroxide reacts with sulphate ions to gypsum, AFm phases are converted to ettringite, and C–S–H is potentially transformed into thaumasite. All of these reactions induce a modification of the microstructure of the hardened cement paste. Most often, expansion and micro-cracking are observed, although softening and disintegration have been reported as well. In order to avoid these deterioration processes, mix design properties such as water/cement-ratio and cement content are modified and sulphate-resisting cements or binders are used. Susceptibility is reduced by restricting the amount of the clinker phase C_3A in the cement and by adding mineral admixtures such as blast furnace slag and coal fly ash. These information and many other details have been derived from the results of a great number of experimental investigations carried out under laboratory conditions. Experimental investigation in laboratories benefit from the fact that the test conditions can be carefully controlled whereas real field situations are much more complex. It has been proved difficult to compare the outcome of laboratory scaled investigations with experiences of the performance of hardened concrete under field conditions. This is mainly due to the limited number of studies addressing field situations. Most of the latter have been focused on the cause of damage in a special case [8–24,34], whereas more general studies are rare. Information related to the distribution of sulphur bearing environments and the performance of concrete in these conditions would be helpful to identify correlations and differences between lab and field behaviour. Only a few publications are available on this topic. A systematic survey of concrete structures in the UK damaged by the thaumasite form of sulphate

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attack (TSA) has been reported recently [5]. The performance of concrete is currently being tested in situ by exposing a number of different concretes to the aggressive environment that has been identified in the aforementioned study [25]. Information on the distribution of sulphate containing environments is hardly available [5,26,27]. Field concretes exposed to sulphate have been studied by SEM [28].

The current study has been set up in order to add supplementary data on the nature and distribution of sulphate and sulphide containing environments in a specific area in mid-Europe. Twenty structures exposed to these environments have been examined by visual inspection and core drilling of hardened concrete followed by testing of the obtained samples with different analytical techniques. Information on the long term performance of the structures under examination have been derived from strength data and the depth of the damaged surface layer. The obtained data can be used to discuss the relevance of laboratory investigations with respect to kind and frequency of different types of expositions, correlation of attack mechanisms between laboratory and field, extent of damage, and other questions.

The investigations reported in this paper are restricted to a special region in Germany with a broad range of sulphate related expositions. However, the spectrum is not exclusive and other conditions can be met elsewhere. Most relevant are aride soils and sulphide containing clays that are not abundant in the region under discussion.

2. Laboratory examination and testing

Most of the concretes investigated in this study have been sampled by core drilling (diameter 100 mm). These samples were tested with respect to compressive strength, carbonation depth (phenolphthalein test) and phase transformation. The latter comprised SEM on polished sections and fracture surfaces, thin section light microscopy and qualitative XRD. The chemical composition of the aggressive environments has been analyzed by wet methods and ICP–OES. Data on the original composition of the concrete was included in the evaluation where available.

3. Results

Thuringia is a region in Germany, mid-Europe, with about 2 million inhabitants residing on about 16,000 km^2. A few small mountains with a maximum altitude of approximately 1000 m are located in this region. Ores and other resources have been exploited by mining for more than 500 years. Due to its geographic history, marine evaporates such as gypsum and rock salt are at or close to the earth crust in some places. The climate is humid with a medium temperature of approximately 8 °C and a medium rainfall of 400–500 mm per year.

The classical model of sulphate attack relies on the idea that sulphate ions migrate from an aggressive environment into concrete leading to phase transformation and structural damage. The extent of deterioration depends on the sulphate ion concentration itself and the kind and concentration of accompanying ions. Subsequently, exposition classes depending on the sulphate ion concentration in the water have been introduced in standards for the production of concrete, and measures are suggested to increase the resistance of the material. Most prominent are the decrease of the water/cement-ratio and the use of more resistant cement types. However, standards and guidelines are developing over time and differ between nations.

This study discusses the nature and distribution of sulphate related environments in a special region and the performance of concrete in these conditions. Classification of the exposure types is different from the one suggested by the currently valid standard EN 206. The following grouping in five classes has been found appropriate. Exposition types 1–3 consider attack by dissolved sulphur species in combination with different accompanying ions, types 4 and 5 are relevant for environments containing undissolved sulphur bearing minerals.

- Type 1: Mobile water may contain sulphate ions due to the dissolution of other minerals such as gypsum, and exposition class 1 considers elevated sulphate ion concentrations at a neutral pH in the absence of harmful accompanying ions.
- Type 2: In contact with pyrite, increased sulphate ion concentrations in connection with low pH values in mobile water may lead to a faster progress of deterioration.
- Type 3: This class includes highly concentrated brines with a salt content ranging from 50 to approximately 300 g salt/kg solution. Such brines are found in the vicinity of stockpiles and waste tips from salt mining.
- Type 4: A direct contact of hardened concrete with sulphate containing soil and rock is discussed in this exposition class.
- Type 5: Rock and soil with reduced sulphur in the form of sulphide is considered in class 5. Relevant minerals are pyrite, markasite, and pyrrhotite.

For each exposition type, occurrence details are discussed in combination with results from the examination of concrete structures that were exposed to this particular environment.

3.1. Elevated sulphate concentration in mobile water

Concrete structures in contact with mobile water such as bridges and dams are mostly located on rivers. The sulphate ion concentration of most rivers in the region under consideration is monitored by local authorities. Depending on rainfall, the sulphate concentration rises and falls over the course of the year. There is a tendency to lower sulphate ion concentrations in wet seasons due to a dilution with rainwater. An example presented in Fig. 1 shows data collected over 6 years from one particular sampling point. There is also a second variation of sulphate ion concentration between different sampling points on the same river.

The number of rivers falling in three categories with differing sulphate ion concentrations is presented in Fig. 2. A majority of test sites indicate sulphate ion concentrations never exceeding 400 mg/l. In contrast to this, a medium sulphate concentration of approximately 600 mg/l is encountered for only a few very small rivers. Both categories correspond to exposition class XA0 or the lower range of XA1 according to EN 206. It is unlikely that such low sulphate ion concentrations are able to damage hardened concrete and subsequently only three bridges exposed to low sulphate ion

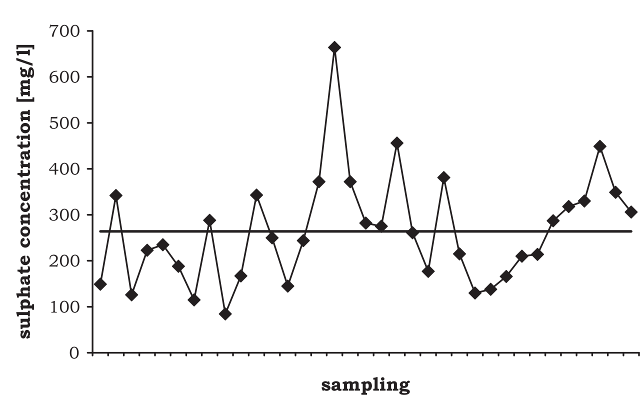

Fig. 1. Variation of sulphate ion concentration in a particular river over time (mean value is indicated by the horizontal line).