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Thaumasite formation in a tunnel of Bapanxia Dam in Western China

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Abstract

A site investigation and sampling was carried out on a sulfate-attacked concrete structure in Bapanxia Hydraulic Power Plant in Western China. The concrete had been exposed to ground water containing substantial concentrations of salts (SO_4^{2-}, CO_3^{2-} and Cl^-) for about 6 years and was analyzed with X-ray diffraction (XRD), scanning electron microscopy (SEM), energy dispersive X-ray spectroscopy (EDX), laser-Raman spectroscopy and Fourier transform infrared (FTIR) spectroscopy. It is shown that a white mushy mixture consisting of thaumasite, ettringite, gypsum and calcite is present in the residual concrete. This paper reports the first instance of the thaumasite form of sulfate attack of concrete in China.

Keywords: Concrete (E); Thaumasite; Sulfate attack (C); Carbonation (C)

1. Introduction

Thaumasite is a naturally occurring mineral of the type $Ca_6[Si(OH)_6]_2(CO_3)_2(SO_4)_2{\cdot}24H_2O$, which has been found in metamorphosed rocks that have undergone hydrothermal changes over time [1]. Erlin and Stark [2] first reported its occurrence in concrete construction in sanitary sewer pipes and at the base of a core taken from an 11-year-old pavement. Since then, the thaumasite form of sulfate attack (TSA) has caused varying degrees of deterioration within a wide variety of cementitious building systems [3], the most notable of these being the 1998 discovery of TSA causing severe deterioration of the buried concrete foundations of several bridges on the M5 motorway in England [4]. As a result, the UK Government convened the Thaumasite Expert Group (TEG) and a report dealing with thaumasite sulfate attack was issued in 1999 [5]. Consequently, TSA has become recognized as a separate form of sulfate attack and has been found in different buildings of England, US, Canada, France, Switzerland, Germany, Norway and other places [3,6,7].

The preconditions for TSA [3,8] are (i) contact with sulfate solution, (ii) the presence of CO_3^{2-} from limestone-dust-filler in cement, limestone- and dolomite-aggregate in concrete, from carbonation of concrete or even from the environment [9], (iii) the presence of SiO_3^{2-}, mainly from CSH, the main OPC hydration phase. Lower temperatures (lower than 15 °C) can also favour the thaumasite formation and TSA attack. Notwithstanding the need for carbonate, these conditions would also be expected to lead to ettringite ($Ca_6[Al(OH)_6]_2(SO_4)_3{\cdot}26H_2O$) formation, which has been reported as the main product of sulfate attack [10]. Due to the similarity of XRD patterns of thaumasite and ettringite, it is quite likely that at least some previously reported cases of sulfate attack that were attributed to ettringite formation may have been TSA.

This paper presents a series of observations of field elements of the Bapanxia Hydraulic Power Plant on the Yellow River in Northwestern China, which is severely affected by sulfate attack. The attacked concrete was analyzed to identify the deterioration products and reaction mechanisms. X-ray powder diffraction (XRD), scanning electron microscopy (SEM) coupled with energy dispersive X-ray spectroscopy (EDX), laser-Raman

Table 1
Composition of the water sample (mg/l)

K^++Na^+	Ca^{2+}	Mg^{2+}	Cl^-	SO_4^{2-}	HCO_3^-
12 893	1026	524	17 801	6638	223

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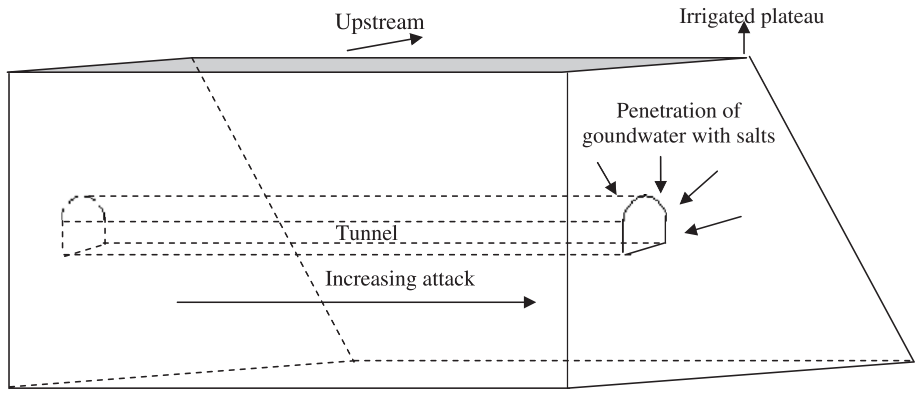

Fig. 1. Schematic diagram showing the concrete dam layout.

spectroscopy and Fourier transform infrared (FTIR) spectroscopy test methods were used.

2. Site investigation

Bapanxia Hydraulic Power Plant is located on the Yellow River in Xigu District of Lanzhou City, China and was constructed between 1969 and 1975. The area is mountainous, with undulating bedrock covered by silty aeolin deposits known as loess [11]. These bedrocks are orange-red sandstones and tan-red mudstones, the upper portion of which is gypsiferous [12]. Sandstone is of relatively low permeability [13], which results in the permeating water flowing slowly and dissolving a mass of soluble salts during the pervasion. This results in the groundwater typically containing significant amounts of sulfate, chloride and a substantial mass of carbonate. A sample of the groundwater from the northern side of the dam (the most severely attacked) was analyzed and the result is shown in Table 1.

Fig. 1 shows the general layout of the dam, looking upstream. The irrigated plateau is situated on the north bank of the dam along the river, where the soil and the groundwater contain a high concentration of sulfate. Observations within the tunnel suggest that the run-off water, which is rich in sulfate, percolates from the outer surface through cracks and preformed ducts to reach the tunnel, where it collects in the drainage channel. At the points of entry, the tunnel wall concrete is also seriously attacked, particularly at the northern end which is closer to the irrigated plateau. In some areas, deep deposits of white crystalline salts were also seen deposited on the tunnel walls, confirming the flow of mineralized water through the concrete into the tunnel.

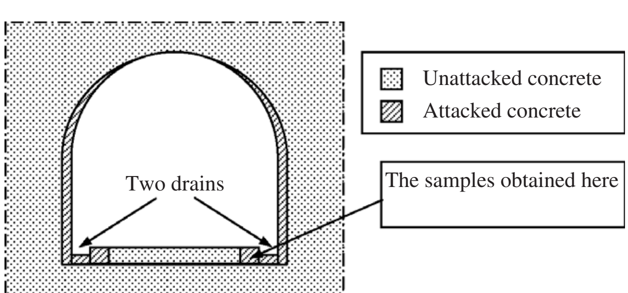

Fig. 2. Schematic illustration of the tunnel and areas most affected by TSA.

Fig. 2 shows a cross-section of the tunnel in the dam and highlights specific areas where damage has been observed. The damage is predominantly in the drainage channels but is also observed on the walls and roof in localities where the water enters the tunnel. The deepest effects appear to penetrate to around 100 mm from the surface. However, a full core analysis is recommended to determine the actual depth and type of attack observed at greater depths.

Fig. 3 shows a general view across the dam to the mountain, from where the aggressive salts originate. The lighter-coloured areas above the dam in Fig. 3 are, in fact, sulfate salt deposits on the surface of the soil. Consequently, the water penetrating the tunnel has enough sulfates (Table 1) to cause severe sulfate attack and is equivalent to a Class DS-5 sulfate solution [14]. Within the tunnel, temperatures range between 4 and 10 °C with a continuous relative humidity of more than 85%. Additionally, carbonated concrete in the tunnel, dissolved CO_2 in the water and dissolved carbonates in the water would appear to be a likely source of CO_3^{2-}. Thus, conditions favourable to TSA are present.

The northern side tunnel is the most severely damaged by sulfate attack and has been repaired every few years since the dam was constructed. The last restoration was in 1997, when all the damaged surface concrete was replaced with a high-quality cement concrete made with ordinary Portland cement and a

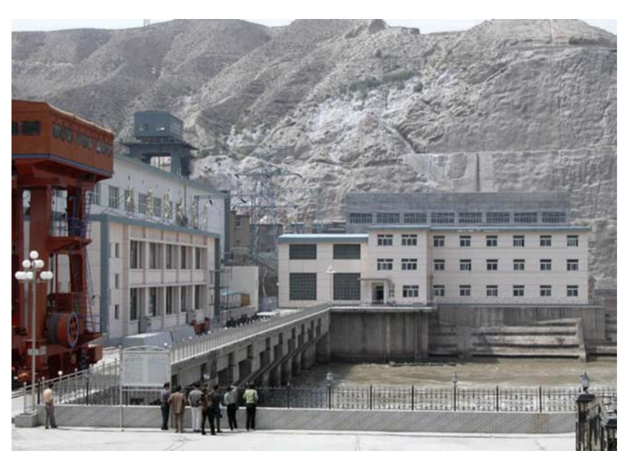

Fig. 3. Profile of Bapanxia Hydraulic Power Plant.