DIAGNOSIS AND PROGNOSIS OF PORTUGUESE CONCRETE RAILWAY SLEEPERS DEGRADATION – A COMBINATION OF ASR AND DEF

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Abstract

During the winter of 2003 visible map cracking was detected in prestressed monobloc concrete sleepers in service in Portugal. Three types of sleepers were identified according to different degrees of visual deterioration in order to diagnose the causes and also to prognose the long-term behaviour of the deteriorated concrete sleepers.

This paper presents the results of the diagnostic analysis performed, that concluded the cracking was due to the occurrence of alkali-silica reaction (ASR) and delayed ettringite formation (DEF) in the concrete. The ASR was caused by the use of alkali reactive aggregates and the DEF by the employed steam heat-curing regime in combination with the high cement content used in the concrete mix design.

Finally the main reason for the concrete cracking was attributed to the DEF, this conclusion being supported by the results obtained on residual expansion tests.

Keywords: ASR, DEF, railway sleepers, diagnosis, prognosis

1 INTRODUCTION

During a routine inspection in the winter of 2003, the maintenance staff of a railway track in Portugal observed the occurrence of cracks running parallel to the prestressing wires in monobloc concrete railway sleepers and which were much more pronounced in the zone of the fastening inserts at both ends of the sleepers (Figure 1). After an initial visual inspection for the sampling of the sleepers, an important experimental program was conducted by Laboratório Nacional de Engenharia Civil (LNEC), a public institution of the Portuguese Ministry for Public Works, Transports and Housing.

This paper describes the mineralogical and microstructural analysis conducted in cracked and uncracked sleepers that were collected from a railway track in order to diagnose the causes of the cracking, as well as to forecast its evolution in order to estimate the long-term behaviour of the deteriorated railway sleepers.

2 MATERIALS AND METHODS

2.1 Concrete sleepers

The sleepers were produced by the same plant since 1992 and were in service since then. Three types of sleepers were used in this investigation as follows:

Type A - produced in July 1996, highly cracked, the maximum opening of the cracks being 4 mm in width and at the two end faces;

Type B - produced in June 1996 with small fine cracks (width < 1 mm) mainly in the their upper surface;

Type C – produced in December 1992 with no visible cracks.

The concrete of the sleepers was produced using an aggregate coming from alluvial deposits of the Tagus river (mainly quartzite) and a CEM I (Portland cement), which chemical composition was unknown and in a dosage of about 400-440 kg/m^3. The manufacturing process of the sleepers was kept constant during the entire production interval. Nevertheless, the steam heat-curing temperature regime (no records exist of the maximum temperature reached in the concrete) was not constant all the time. The maximum temperature reached varied with the air temperature around the sleepers and

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with the fresh concrete temperature, and it was speculated that a temperature between 70 and 80º C could be easily reached in some summer days.

2.2 Methods of examination and analysis

General

From each sleeper type a total of 17 core samples (73 mm in diameter and varying in length, depending of their location) were drilled for different tests (Figure 2). The samples were examined visually and by stereo-optical microscopy for signs of deposits [1]. Wet zones around the aggregates and white deposits in the air voids (Figure 3) were observed in the concrete cores of A and B sleepers types. The white deposits were scraped for further analysis by x-ray difractometry (XRD).

Determinations of sulphate and alkali contents in concrete were done respectively by gravimetric method and atomic absorption spectrometry (AAS).

In some cores the visualization of alkali-reaction products by the uranyl-fluorescence method [2] was applied.

The ASTM C 1260 method [3] was performed to ascertain the potentially alkali-reactivity of the aggregates employed.

Broken and polished concrete samples from all three type sleepers were prepared for observation by scanning electron microscopy (SEM) equipped with an energy-dispersive x-ray detector (EDX).

Several cores of each sleeper were tested for the determination of residual reactivity of concrete to alkali-silica reaction (ASR) and delayed ettringite formation (DEF), respectively according the LPC methods nº 44 [4] and nº 66 [5, 6, 7].

X-ray powder diffraction (XRD)

The white materials removed from concrete voids were gently pulverized in an agate mill and put directly with adding acetone in a silicon substrate specimen holder, transparent to x-rays. Operating conditions of the Philips PW3710 X-ray diffractometer were set to 35 kV and 45 mA, using Fe-filtered CoKα radiation of wavelength λ=1.7903 Å. Diffractograms were recorded from 3-74 °2θ, in 0.05 °2θ increments with 1 s counting time per increment, in effect 0.05 $°2\theta \cdot s^{-1}$.

Sulphate and alkalis analysis of concrete

About 250 g of concrete was crushed and dried in a closed cabinet at 40 ºC for 1 day and was reduced by manual splitting to ~50 g to fill a porcelain vibratory ball-mill for pulverization. The sulphur was determined gravimetrically by the precipitation of the sulphates by barium chloride solution [8]. Alkalis determination was conducted following the methodology developed by Bérubé et al. [9], the sodium and potassium contents being determined separately on a GBC 906AA atomic absorption spectrometer (AAS).

Visualization of ASR products in concrete by the uranyl-fluorescence method

Freshly sawed concrete surfaces were employed for the application of a uranyl acetate solution. The observations of the treated surfaces were performed by a ultra-violet (UV) light in a dark room. The presence of ASR products is revealed in UV light by a yellowish-green fluoresce glow.

Potential alkali-reactivity of the aggregate

The aggregate that was employed in the concrete railway sleepers was tested according the ASTM C 1260 test method. Mortar bars with 25 x25 x 285 mm and made with a CEM I Portland cement type were kept in a container with a 1N sodium hydroxide solution at 80º C during 14 days. In this test the aggregate is judged alkali reactive if the expansion at 14 days is more than 0.20%.

Scanning electron microscopy and x-ray microanalysis (SEM-EDX)

Scanning electron microscopy observations were performed on a scanning electron microscope (SEM) JEOL JSM-6400 coupled with an OXFORD energy dispersive spectrometer x-ray detector (EDX), both on polished surfaces (with backscattered electrons – BSE images) and freshly fracturated surfaces (using secondary electrons – SEI images) that were sputtered with carbon in a JEOL JEE-4X vacuum evaporator.

Residual alkali-silica reactivity of concrete

Concrete cores, 73 mm diameter and 160 mm length, were tested according the LPC nº 44 test method [4] (similar to the ASTM C 1293). In this method, the specimens, previously wrapped in absorbent paper and polyethylene sheet, are put in a closed metallic container, containing a few centimetres of water, and placed in a climatic chamber at 38° C. Some of the cores were tested with external supply of alkalis, i.e., stored over a solution of 1M KOH solution in sealed containers at 38° C. The measurements were made at various intervals until 1 year, with a gauge length comparator (0.001 mm resolution) adapted to the shape of the reference studs installed in the ends of each core. One core of each sleeper type was broken at 1 year to be analysed by SEM-EDX.

Residual internal sulphate reactivity of concrete

Concrete cores, with the same dimensions of the previously mentioned, were tested according the LPC nº 66 test method [5, 6, 7]. In this method the expansion is obtained by lateral length measurements in three equally spaced lines of two gauge reference studs each, with a distance of 100 mm between the two studs of a given line, so permitting three readings per core. The specimens are immersed in tap water at 20 ± 2 ºC. The measurements were made at regular intervals with a gauge length comparator adapted to the reference studs installed in the three laterals lines of each core. As in the ASR residual reactivity, after one year of immersion, one core of each concrete sleeper type was analysed by SEM-EDS.

3 RESULTS

X-ray powder diffraction (XRD)

The XRD patterns of the white materials removed from the concrete voids indicates, besides the quartz, the presence of some reflections (6.6 Å and 2.9 Å) that can correspond (Figure 4) to minerals mountainite ($(Ca,Na_2,K_2)_2Si_4O_{10}.3H_2O$) and rhodesite ($(Ca,K,Na)_{7,5}Si_{16}O_{40}.11H_2O$), which are referred by Cekulaire [10] as a possible ASR minerals-group.

Sulphate and alkali content of concrete

The water soluble alkali content as well as the acid sulphate content of the concrete were determined in order to enable the assessment of any changes in the contents of these ions in the 3 type concrete railway sleepers, and to know if they are enough to promote the ASR and internal sulphate reaction (ISR). Results are presented on Table 1.

Despite the differences between the sleepers due to the sampling, it was verified that the higher alkali soluble and sulphate contents were obtained in the A type sleepers, where the cracking is more intense. Taking into consideration the values obtained the possibility of ingress of these ions from the external environment was not considered.

Visualization of ASR products in concrete by the uranyl-fluorescence method

The tests revealed the occurrence of products of the ASR in all the concrete cores, mostly located in the paste/aggregate interfaces and also in some of the aggregates. The detection of ASR gels by this method showed that the C type concrete sleeper, that has not yet presented cracking, is also affected by ASR. A possible explanation for this fact could be that the concrete of these sleepers, witch are normally placed bellow bridges or tunnels, has been protected from moisture, a necessary condition for the acceleration of ASR.

Potential alkali-reactivity of the aggregate

The application of the ASTM C 1260 test method to the concrete aggregate shows an expansion of 0,35% at 14 days and 0,53% at 28 days. The aggregate is considered alkali reactive according the expansion limits of this test method.

Scanning electron microscopy and x-ray microanalysis (SEM-EDX)

The SEM/EDX study showed that in all concrete sleepers types, even in the non-cracked C type but in much lesser degree, the existence of ASR products (gels and semi-crystallized forms). Figure 5 shows representative morphological features of ASR products observed. The extent of ASR observed by SEM does not appear to have been sufficient to produce cracking of sleepers.

However, besides the ASR products shown in Figure 5, large amounts of ettringite were detected, but only in A and B types cracked sleepers. The morphological features of the ettringite detected are presented in Figure 6. The morphological aspect of the ettringite detected, mainly in compressed or compact forms, was attributed to an internal sulphate reaction or delayed ettringite formation (DEF) caused by cement type, concrete mix design and curing temperature. The observation of DEF and ASR prompted an investigation on the residual reactivity of the concrete to alkalis and DEF to prognose the long-term behaviour of the deteriorated concrete sleepers.

Residual alkali-silica reactivity of concrete

The results of the tests for the assessment of residual ASR expansion are presented in Table 2. It can be concluded that the concrete does not show residual expansion due to alkali-silica reaction. Nevertheless, the specimens placed in saturated relative humidity without external supply of alkalis experienced higher values of residual expansion that those with alkali supply. These results can be explained if DEF is the main process of deterioration [11].

Residual internal sulphate reactivity of concrete

The results of the tests for the assessment of residual DEF expansion are presented in Table 3. The tests showed, unlike registered in testing of the residual alkali-silica expansion, a very different behaviour between the 3 types of sleepers tested. It appears that the residual DEF expansion is, in general, much higher than those obtained in the tests of alkali-silica residual reactivity. It appears that the values of residual DEF expansion increase with the rank of damage, which may indicate again that the main cause for the degradation is due to the occurrence of DEF.

4 DISCUSSION

All the 3 types of sleepers tested in this investigation were collected from the same railway track and have thus been exposed to similar loading service conditions. Only A and B sleeper types manufactured during the summer had presented macroscopic damage.

The soluble alkali content of the concrete sleepers was about 2.5-3.3 kg/m^3, that is slightly higher than the safe threshold 2.5 kg/m^3 for alkali-silica reactive aggregates [12]. Since the aggregate that was used in the concrete was classified as reactive according the ASTM C 1260 test method, these railway sleepers exposed outdoors to moisture may suffer distress by ASR. Examination of the railway sleepers on laboratory specimens supports this deduction, but the observations by ultra-violet light and SEM shows that the extent of ASR was similar between the three A, B and C sleeper types used in this investigation. This suggests that other factors could have been involved in the cracking process of the sleepers A and B types.

The manufacturing process of the monobloc concrete sleepers included, after the casting of concrete, a steam curing during all the production period on appraisal. Nevertheless, the steam heat-curing temperature regime (no records of the maximum temperature reached in the concrete are available) was not constant during the entire time of production. The maximum temperature reached varied with the external air ambient temperature, and it was speculated that a temperature between 70 and 80º C could have been easily reached in some summer days. These circumstances suggest that these sleepers might have been deteriorated by DEF. The observation of DEF prompts to investigate the amount of SO_3 content of the cement used, which was about 2.0-3.0 % that is not very high. We must mention that the SO_3 content is not the only factor that influence DEF occurrence, others cement parameters, such as, fineness, C3S, C4AF, C3A, MgO, as well as permeability and environmental conditions are important as well in its formation mechanism [1]. Unfortunately the chemical composition of the cement is not known.

The SEM examination performed on these 3 sleeper types shows that there is a large amount of compressed ettringite in the heavily damaged type A concrete sleepers. The same is observed but in a lesser extent in the type B sleepers. In the type C sleepers no ettringite filling the gaps around aggregate particles or in the voids or in the paste was observed by SEM. Therefore, the secondary ettringite formation is probably the main reason of the concrete sleepers deterioration. This conclusion was supported by the supplementary SEM-EDX observations performed in specimens taken, after one year testing, from concrete cores tested according LPC nº 44 and LPC nº 66 residual expansion methods. The observations done confirmed the presence of ASR products but at a low level in all 3 sleepers types, while the compressed ettringite was present in huge quantities in the specimens taken from type A concrete sleepers and in a much less extent in the others two sleepers types.

According to the obtained results of the residual reactivity to alkalis and sulphates and SEM-EDX observations performed in concrete specimens after these tests, only the type A concrete sleepers presents a high potential to expand in near future due to internal sulphate reaction. However, it is likely that the other types will later develop cracking during their service life.

5 CONCLUSIONS

The residual expansion test results as well as the microscopic observations allow us to conclude that the cracking of the concrete sleepers was mainly due to DEF. This reaction was a consequence of the use of a non-controlled steam heat-curing regime in combination with the high cement content of the concrete mix. The progress of this reaction was increased due to the penetration of moisture into concrete together with ASR, creating a further expansion and cracking. The ASR was caused by the use of alkali reactive aggregates.

An important research program is now in progress, aiming for the study of diverse solutions to control the expansion of the affected railway sleepers.

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TABLE 1: Alkali and sulphate contents of the concrete.

Railway sleeper type	*Soluble alkali content (kg/m³)*	*Sulphate content (%SO_3)*
A	3,3	0,47
B	2,8	0,41
C	2,5	0,32

TABLE 2: Residual alkali-silica expansion.

Saturated environment conditions	*Railway sleeper type*	*Residual expansion (μm/m)*	
		Max.	*Min.*
Over water at 38º C	A	183	110
	B	146	110
	C	183	146
Over 1M KOH solution at 38º C	A	73	73
	B	146	0
	C	26	22

TABLE 3: Residual internal sulphate expansion.

Immersion condition	*Railway sleeper type*	*Residual expansion (μm/m)*	
		Max.	*Min.*
Water at 20º C	A	5074	4928
	B	237	186
	C	110	0

Figure 1 – End view of a cracked concrete railway sleeper.

Figure 2 – View of the concrete sleeper A type after core drilling.

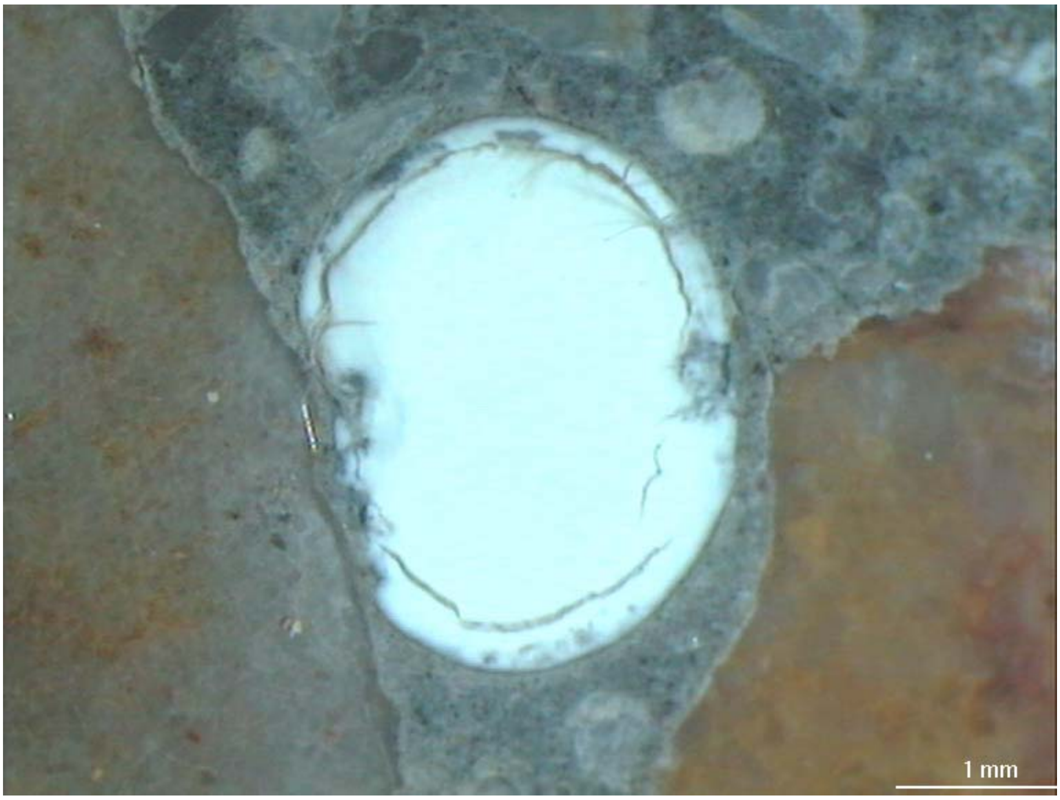

Figure 3 – View of a polished section of concrete showing a white deposit filling an air void.

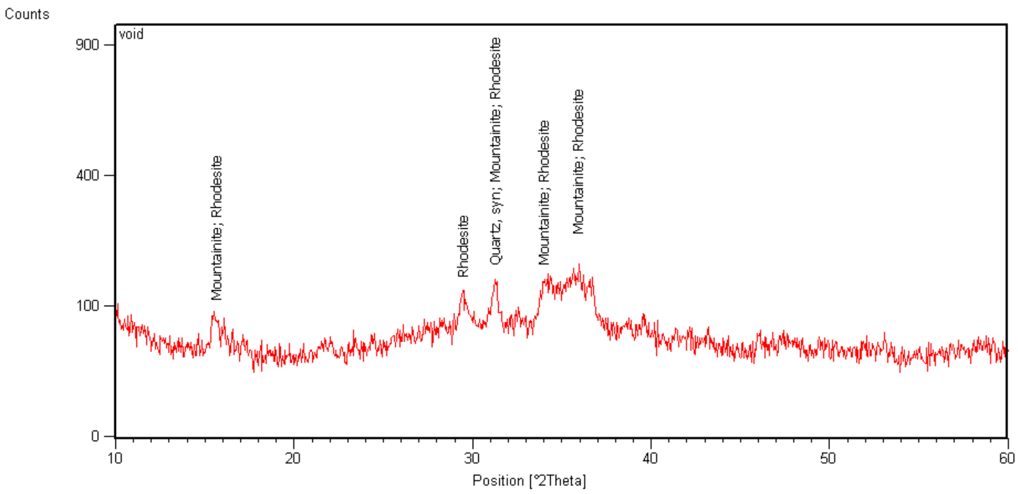

Figure 4 – XRD pattern of a white material removed from a concrete void.

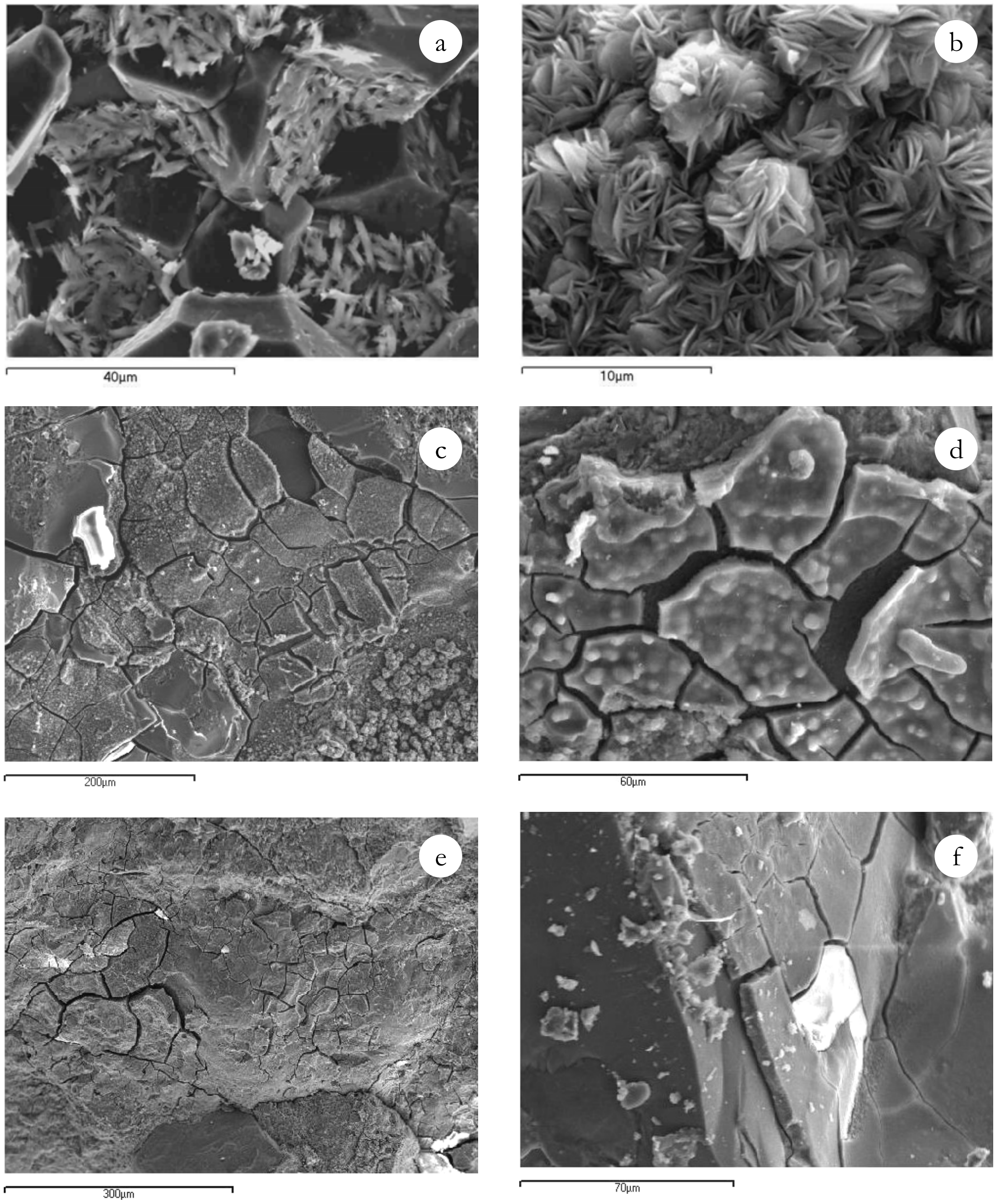

Figure 5 – SEI images showing various forms of ASR products (): (a) lamellar crystals in a quartzite grain, (b) rosette-like crystals, (c-d) concomitance of bump-shaped gel and botryoïdal products, (e-f) smooth gel.

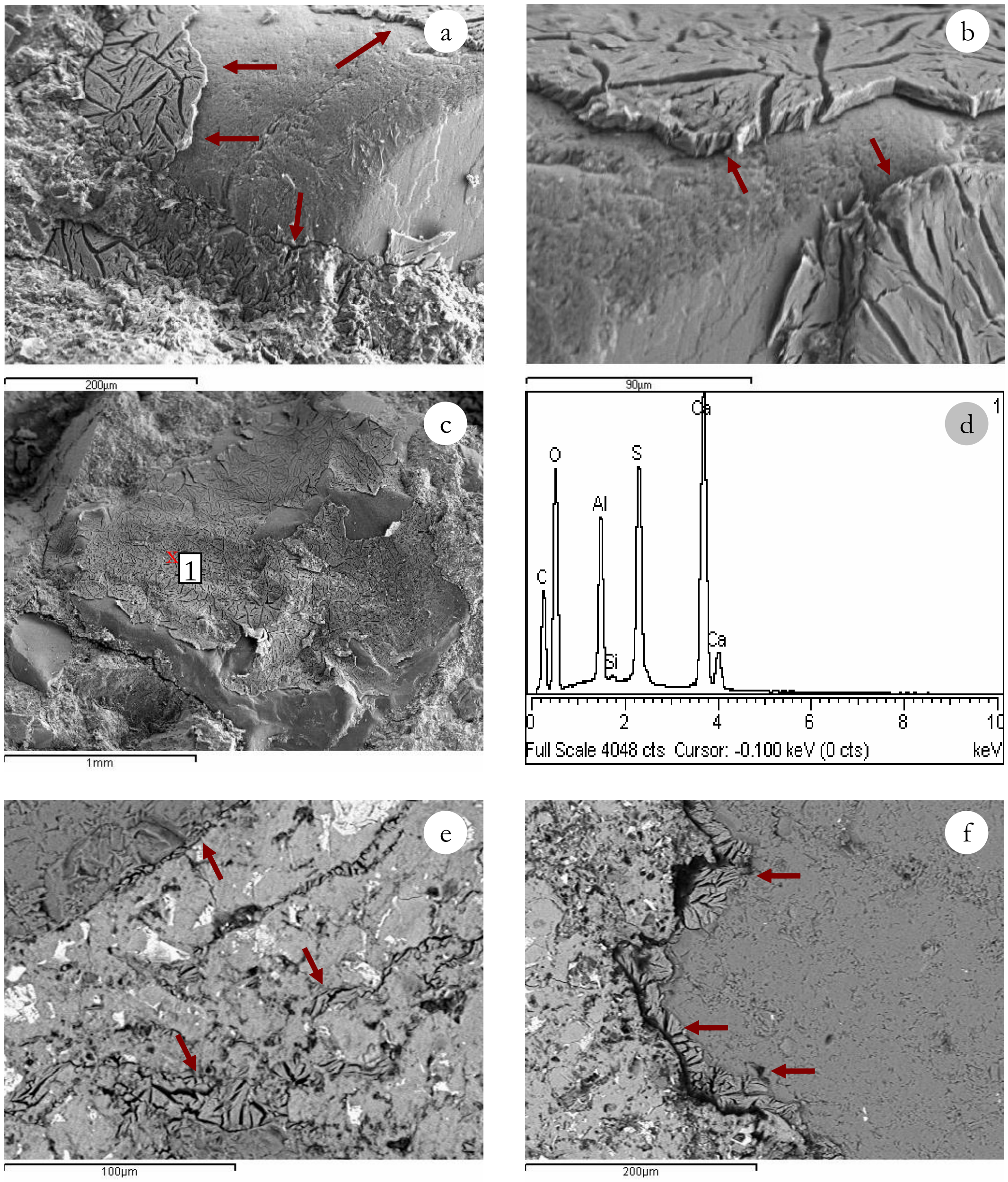

Figure 6 – Different aspects of ettringite formation in the cracked sleepers A and B types: (a-c) SEI images of compressed ettringite on aggregate particles, (d) EDX spectra of ettringite marked in Figure 2c, (e-f) BSE images of compressed ettringite in the paste and around aggregate particles.