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Technical Paper

Investigation on possible causes of expansion damages in concrete – a case study of sleepers in Indian Railways

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Abstract: Indian Railways uses factory made pre-tensioned pre-stressed concrete sleepers for its track. These sleepers start cracking after 6-9 years of their manufacturing in many areas of the Indian Railways. For the investigation of the premature cracking of sleepers, different categories of samples namely "Severely damaged", "Moderately damaged", and "Undamaged" are collected from different locations of Indian Railways. These samples are analyzed under Scanning Electron Microscope (SEM) and Energy Dispersive Spectroscopy (EDS). SEM images reveal that there is large ettringite deposition at the interfaces of aggregate and paste in case of "Severely damaged" and "Moderately damaged" sleepers, which could be a cause of deleterious expansion and subsequent cracking, whereas the interfaces of "Undamaged" sleepers were found to be intact. High temperature experienced by these sleepers in form of steam curing during their production in factories may lead to Delayed Ettringite Formation (DEF) and subsequent expansion and cracking. Temperature recorded in the concrete sleeper plant during steaming of the sleepers reveals that the temperature inside concrete exceeds 80℃, which is a critical temperature for the occurrence of damage due to DEF in future. Also, stress bench method of production of concrete sleepers, used in Indian Railways for older concrete sleeper plant, poses some structural deficiency which adversely affects the temperature of curing. Thus, DEF could be the possible cause of premature cracking of sleepers in Indian Railways.

Keywords: delayed ettringite formation (DEF), alkali-silica reaction (ASR), scanning electron microscope (SEM), energy dispersive spectroscopy (EDS).

1. Introduction

The objective of Railways is to provide a safe and economical transport system for the passengers as well as freight. Being a guided transport system, Railways should have tracks that ensure proper vertical and horizontal alignment in order to achieve the above objective. Sleepers are an important component of the railway track in the sense that they hold the rail in its position and transfer the load to the support structure below. Indian Railways uses factory made pre-tensioned pre-stressed concrete sleepers for its tracks. Two kinds of manufacturing processes of concrete sleepers exist in Indian Railways. Relatively older plants use "stress bench method" whereas newer one use "long line method". In many areas of Indian Railways, these sleepers start cracking after 6-9 years of their manufacture. Even sleepers that were never used in the track but just kept on the side of the track, also get cracked. Therefore, in addition to the issue of long term sustainability of the concrete sleepers, it also stands as a potential safety hazard since trains carrying passengers run on these sleepers. Thus, a proper investigation of premature cracking of concrete sleepers becomes essential for Indian Railways. Typical cracking patterns observed in the sleepers are shown in schematic diagram in Fig. 1. Typical map cracks are observed at the two ends of the sleeper where the pre-stress is minimum. These type of cracks occur due to some kind of expansive reaction in unrestrained concrete. Figure 2(a) shows the photographs of such cracking patterns. In the middle, cracks align in the longitudinal direction because concrete is not free to expand in the longitudinal direction as an effect of pre-stress. Figure 2(b) shows the photographs of such cracking pattern. Finally, at the location of inserts where load is transferred from the rails, failure cracks occur as a combined effect of internal damage and external

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rail loads. Figure 2(c) shows the photographs of such cracking patterns. The crack width ranges from just visible from naked eye i.e. around 0.3 mm to wide enough to cause failure cracks i.e. 10 mm. Maximum crack width generally occur in failure crack observed near insert location due to combined effect of external load due to trains and internal damage in concrete due to expansive reactions (Fig. 1 and Fig. 2(c)). In the present study cracks are only visually examined to categorize sleepers according to different levels of damage. The area, where cracks in sleepers are reported, has no proximity to sea; therefore chances of chloride attack can be eliminated. There is no corrosion related problem; hence there cannot be carbonation related problem. Also, freeze-thaw deterioration can be eliminated, since the region is not cold and snow never occurs. There is no overload or strength problem since the sleepers which were never loaded also get cracked. The environment is also not aggressive for chemical attack. Therefore, it is predicted that there is some expansive reaction taking place in the concrete that occurs typically after 6-9 years of manufacture of sleepers. So, systematic investigation of causes of premature cracking is need of the hour for Indian Railways.

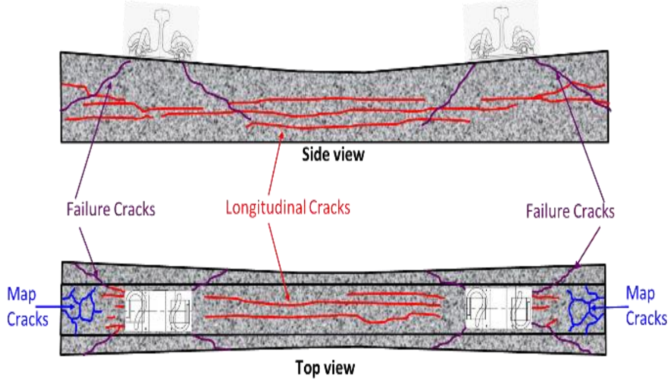


Fig. 1 – Schematic diagram of typical cracking pattern observed in concrete sleepers in Indian Railways

(a) Map cracks observed at the end of the concrete sleepers

(b) Longitudinal cracks observed at the middle of the concrete sleepers

(c) Failure cracks observed at the location of the insert in the concrete sleepers

Fig. 2 – Cracking patterns observed in the concrete sleepers of Indian Railways

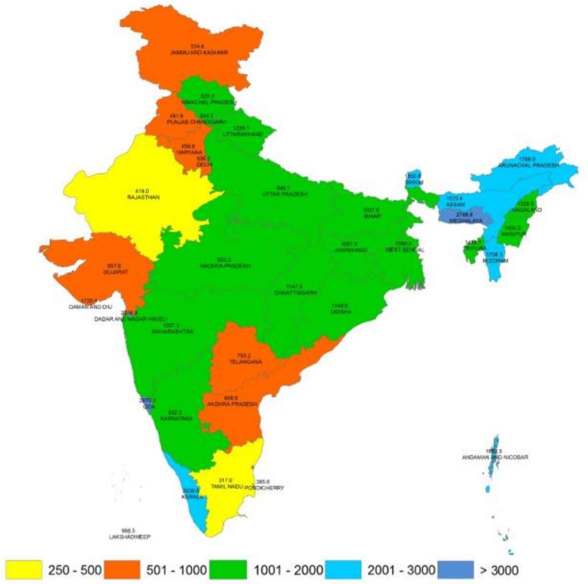


Fig. 3 – Average rainfall in India during monsoon period (June-September)

2. Previous studies on expansion damages of concrete

In the past, problems of premature cracking, as noticed in Indian Railways, were detected in other parts of the world as well. In 1980s, pre-stressed concrete railway ties, placed somewhere on the eastern coast of United States were reported showing distress within a few years of their installation (Mielenz et al. [1]). Between 1992 and 1996, a large number of railroad ties in Sweden had shown premature deterioration (Sahu and Thaulow [2]). The cause of distress in these cases was attributed to Delayed Ettringite Formation (DEF). But, Shayan A. and Quick G.W. [3] have attributed the main cause of damage in the concrete sleeper of Finnish Railways as Alkali-Silica Reaction (ASR) as against DEF in other cases. Therefore, it is predicted that the cause of damage in case of Indian concrete sleepers could be either DEF or ASR. Although the macroscopic cracking patterns observed in the concrete structures for both DEF and ASR induced damages are similar, but the mechanism involved in the expansive reaction for the two is quite different. DEF is expansion and cracking of concrete associated with delayed formation of the mineral ettringite which is a normal product of early cement hydration. The term DEF is commonly used to refer to the potentially deleterious reformation of ettringite in moist concrete, mortar, or paste after destruction of primary ettringite by high temperature. Scientific academia is not unanimous over the mechanism of DEF. Some of the mechanism proposed by different scholars are discussed here in brief. According to Ludwig et al. [4] ettringite (more specifically primary ettringite), one of the initial hydration product formed during hydration process of Portland cement, is decomposed during heat treatment at above 70℃. During this process a significant quantity of sulfate is absorbed in C-S-H (Calcium-Silicate-Hydrate) or present in pore solution. The reformation of ettringite during the service life at ambient temperature and exposure to moisture is called DEF. Since DEF takes place in a hardened paste it can cause heterogeneous expansion of concrete which subsequently causes cracking or spalling of concrete. In their explanation for the mechanism of DEF, Taylor H.F.W. et al. [5] concluded that expansion results from formation of ettringite crystal of sub-micrometer size in the paste. The larger crystal of ettringite that can be readily observed in the cracks and voids is a product of recrystallization. Collepardi [6] proposed a holistic approach for understanding DEF based on late sulfate release, micro-cracking and exposure to water as three necessary conditions for the DEF. On the other hand, ASR is a reaction which occurs over time in concrete between the highly alkaline cement paste and the reactive silica found in many common aggregates in the presence of moisture. This reaction causes the expansion of the altered aggregate by the formation of a swelling gel of C-S-H. This gel increases in volume with water, and exerts an expansive pressure inside the material, causing spalling and cracking. It is possible to identify these reactions by carefully observing microstructure of damaged concrete. Scanning Electron Microscope (SEM) and Energy Dispersive Spectroscopy (EDS) are powerful tool for identifying the hydration product and presence of ettringite, ASR gel or other substances in the microstructure of concrete that can cause distress in concrete. The same is adopted in this study for analyzing samples of concrete sleepers of Indian Railways.

One of the significant factors for DEF induced damages to occur in the future is attributed to early age high temperature (>70℃) experienced by the concrete. Ghorab et al. [7], in their pioneering work, have done extensive experimentation with German high-early-strength cement and concluded that the delayed expansion occurred if specimen were cured above 80℃. With X-ray analysis, they have shown the development of ettringite X-ray peak with time in case of heat cured sample. Similarly, Heinz and Ludwig [8] have shown that large expansion occurs in specimen treated above 75℃ temperature. Hanehara and Oyamada [9] confirmed that the boundary temperature conditions for occurrence of DEF are between 60℃ and 70℃. Lawrence at al. [10] have studied the effect of duration of heat treatment on subsequent expansion. Specimens that were heat treated for 16 hours, rather than 3 hours showed a reduction in the time to start the expansion. Therefore, they have concluded that the start of expansion occurs early in case of a specimen heated for longer duration. Höhlig at al. [11] have devised a new method for heat treatment of concrete by radio waves to avoid DEF. It was found that a maximum temperature of 60℃ should not be exceeded because higher temperatures cause severe DEF.

In case of Indian concrete sleepers, steam curing is done at a temperature of 70-75℃ which can be a possible cause of late sulfate release, microcracking might be existent due to high temperature steam curing or excessive and non-uniform stress distribution due to pre-stressing and presence of water is ensured from rainfall (Indian subcontinent receives heavy rain fall from June to September during monsoon period). Figure 3 shows average rainfall in India during monsoon period. It can be seen that most of India receive rainfall of 800 mm to 1,500 mm during above period. Therefore, three necessary preconditions for DEF, as mentioned by Collepardi [6] in his holistic approach, may exist in case of sleepers of Indian Railways. Hence, in case of Indian Railways concrete sleepers, there is possibility of DEF induced damages. Possibility of DEF induced damages are higher in South Asian countries because of their hot and humid climate. Nanayakkara [12] discussed about severe cracking in some of the pile caps of bridge piers in southern highway project in Sri Lanka and the main cause for cracking in those pile caps was found to be DEF. Since, high temperature experienced by the concrete in its early age is very critical factor for DEF induced damages to occur in the future, the temperature measurement of concrete is performed in the setup of Indian sleeper manufacturing plant. This aspect is dealt with in the next section. Indian concrete sleeper plant uses “high early strength cement” in the production of sleepers. Table 1 shows the typical composition cement used in sleeper plant. Although composition of cement can also affect the deleterious reaction in concrete like ASR and DEF [13], the study of the same is beyond the scope of current study. Other parameters like initial micro cracking due to high temperature curing [14], relative humidity [15] and size of aggregates [16], that can also affect DEF, are not studied under the present work.

Table 1 – Typical composition of cement used in sleeper plant

Sl No.	Characteristics	Requirement as per IS 12269-2013	Typical test results of cement used in concrete sleeper plant dated 09.08.2015
1	Ratio of percentage of lime to percentages of silica, alumina and iron oxide, when calculated by the formula: $\frac{CaO - 0.7SO_3}{2.8SiO_2 + 1.2Al_2O_3 + 0.65Fe_2O_3}$	0.8-1.02	0.96
2	Ratio of percentage of alumina to that of iron oxide, *Min.*	0.66	1.44
3	Insoluble residue, percent by mass, *Max.*	4	0.71
4	Magnesia, percent by mass, *Max.*	5.0	2.32
5	Total sulphur content calculated at sulphuric anhydride (SO3), percent by mass, *Max.*	4.0	2.22
6	Loss on ignition, percent by mass, *Max.*	4.0	1.67
7	Chloride content, percent by mass, *Max.*	0.1	0.01
8	Tricalcium aluminate content, percent by mass, *Max.*	10	7.50
9	Tricalcium silicate, percent by mass, *Min*	45	58.85

3. Investigation on manufacturing condition of sleepers in Indian Railways, collection of samples and preparation of specimens

3.1 Experimental set up for field measurement of temperature in the sleeper plant

To know the temperature rise inside the concrete during steam curing, field measurement of temperature using thermocouples and data-logger was performed in a concrete sleeper plant in India. The curing cycle adopted by the sleeper plant is shown in Fig. 4. The sleeper plant uses stress bench method and curing chambers of dimension approximately 12.8 m x 8.5 m x 4.8 m that are used for steam curing. The steam is supplied from the bottom and there are 7-8 chambers in a tank where the bench holding the sleepers is inserted for curing. In a chamber sleepers are stacked in 8 layers one over the other. Figure 5 shows the typical arrangement of curing chamber and position of the sleeper for which temperature measurement was done. Three sleepers namely bottom most, middle (5th from the bottom), and top most were chosen for temperature measurement to study the effect of deep curing chamber used in stress bench method. For a sleeper, temperature was measured at two points, one inside the sleeper where maximum temperature was expected and one just outside that point. Two sets of field measurements were performed. The first measurement was done with the normal concrete sleepers for the track and the second was done with the sleepers used for point and crossings. Figures 6 and 7 show the arrangement of thermocouples for field measurement-1 and field measurement-2, respectively, Figures 8 and 9 show the results of the field measurement-1 and field measurement-2, respectively.

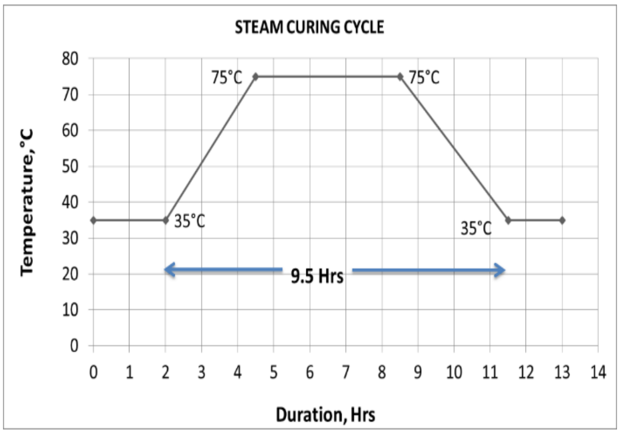


Fig. 4 – Steam curing cycle adopted

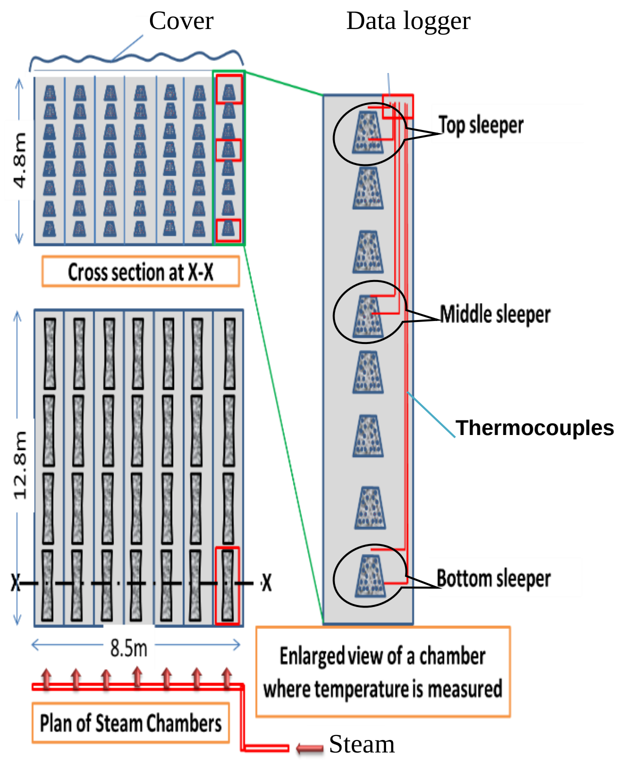


Fig. 5 – Schematic diagram of curing chambers adopted in stress bench method

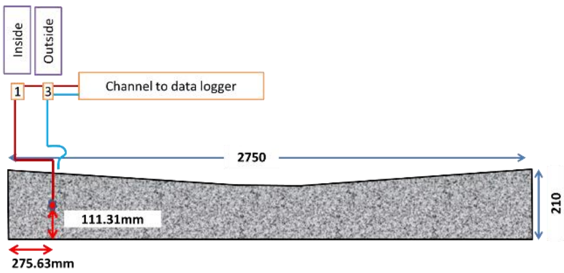


Fig. 6 – Typical arrangement of thermocouple in field measurement-1

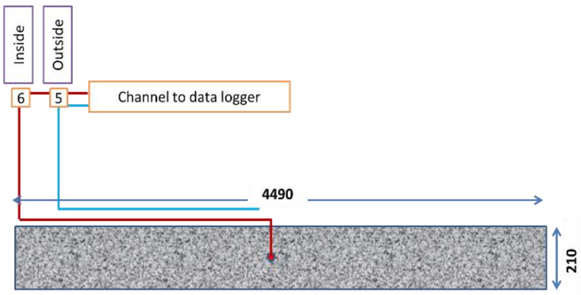


Fig. 7 – Typical arrangement of thermocouple in field measurement-2

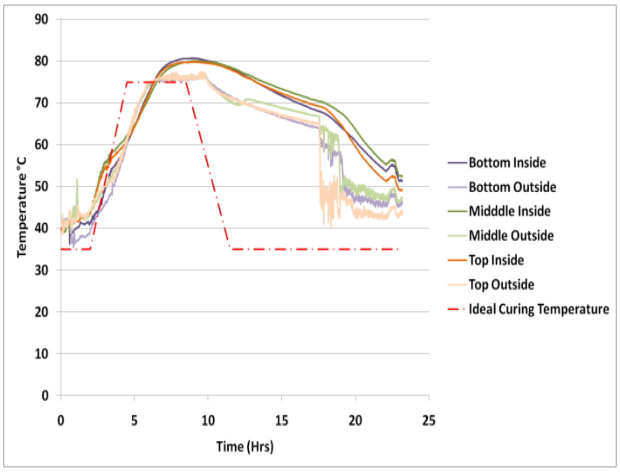


Fig. 8 – Results of temperature measurement-1 in sleeper plants in India

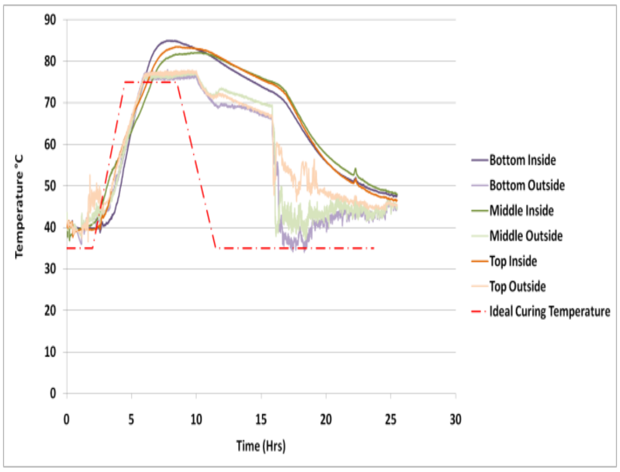


Fig. 9 – Results of temperature measurement-2 in sleeper plants in India

3.2 Results of field measurement of tempera ture in the concrete sleeper plant

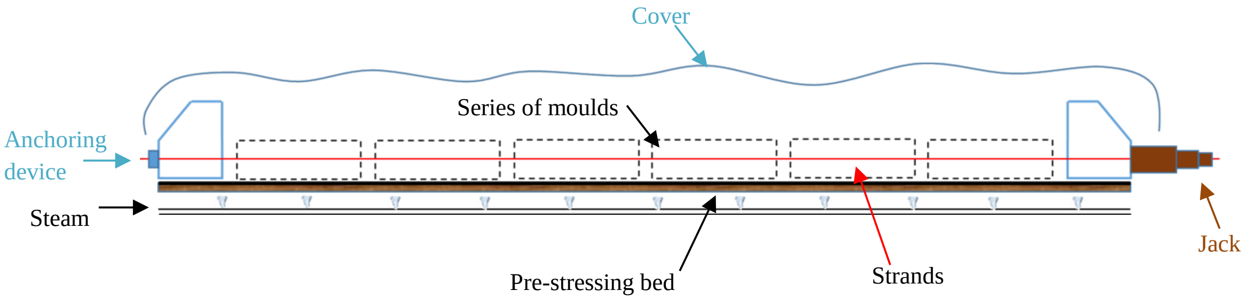
Field measurement of temperature reveals that the maximum temperature reached inside concrete is 80.7℃ and 84.9℃ for the bottom-most sleeper in field measurement-1 and field measurement-2, respectively (Figs. 8 and 9). Therefore, it is very well established that concrete temperature is beyond the critical temperature for the occurrence of DEF problem (as mentioned by Ghorab et al. [7], Heinz and Ludwig [8], Hanehara and Oyamada [9]). The temperature inside concrete generally follows the trend of temperature outside concrete but becomes more than the outside temperature after approximately 6 and 1/2 hours of casting. This depicts the effect of heat of hydration in addition to the outside curing temperature. In the two cases of field measurement the bottom most sleepers reached the maximum temperature. This shows that heating is not uniform in a deep steaming chamber when steam is supplied only from bottom.

Rise of temperature inside the concrete is very close to the ideal curing curve but the fall of temperature greatly deviates from the ideal curve (Figs. 8 and 9). This may be due to the layout of curing chambers adopted in stress bench method. In contrast to long line method, where only one line of sleeper is casted and cured at a time, in stress bench method there are series of 7 to 8 chambers inside one big tank. Depth of chambers is such that around 8 benches of sleepers can be kept one over the other (Fig. 5). The chambers are separated by thin brick wall through which heating of a chamber can rise the temperature in adjacent chamber. Therefore, if the adjacent chambers are not synchronized for the curing cycle, the heating effect of one chamber does not allow dropping the temperature of other. Figure 10 shows the schematic diagram depicting differences between long line method and stress bench method. Therefore, stress bench method of prestressing poses some structural deficiency which adversely affects the curing cycle. It is also observed that sleeper plant works in two shifts of 12 hours and if laborers of one shift do not turn up, the benches are removed when the next shift of laborers come. This also adversely affects the cooling cycle. Although absolute maximum temperature is most important factor for DEF problem, as mentioned in section 2, Lawrence et al. [10] concluded that the start of expansion occurs early in case of a specimen heated for longer duration. Therefore, Indian concrete sleepers are exposed to high early age temperature more than 80℃ and availability of moisture is ensured from heavy rainfall during monsoon period, which can lead to DEF induced damages in the sleepers as observed in the field. Hence, there is a need to revise curing cycle for the production of concrete sleepers in India so that temperature inside concrete should always below critical temperature for DEF which is around 70℃. To achieve this, maximum curing temperature can be kept between 55℃ to 60℃ after taking due care of heat of hydration. Trials can be done to arrive at optimum curing cycle which also suits to the production set up in factories. More care should be taken for the sleepers produced by "stress bench method" since it adversely affects the curing cycle. Local issues like non removal of sleepers from curing chambers should be avoided as it adversely affects the curing cycle. For the new sleeper plant "long line method" should be adopted instead of stress bench method. Another area which can be dealt with as a preventive measure is that of "precuring time and rate of rise and fall of temperature". In case of Indian sleeper production, pre-steaming period is 2 hours, rate of rise of temperature is 16℃ and rate of fall of temperature is 13.3℃.

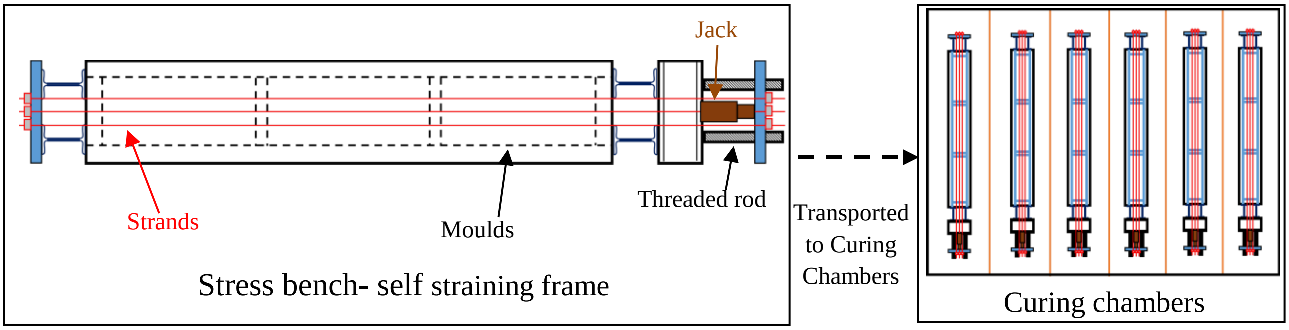
Sylla [17] did extensive field and laboratory study on pre-mature cracking of rail road ties in West Germany and concluded that the factors responsible for the problems were a rapid production cycle with short pre-curing times before the application of heat and excessive temperatures of the concrete during curing. Similarly, Neck [18] suggested 3 hour pre-cure with a maximum curing temperature of 60℃ for exterior exposure contact with the earth. As a result European Committee for Standardization, in 1989, responded with more stringent specifications for heat treatment of concrete. The specifications were as follows:

- the concrete temperature cannot exceed 30℃ during the first 3 hours of curing and cannot exceed 40℃ during the first 4 hours of curing;
- the rate of temperature rise cannot be greater than 20℃/hr; and
- the cooling rate after heat-treatment cannot exceed 10℃/hr.

Other guidelines called new German guidelines limited pre-steaming period to minimum 3 hours and rate of rise of temperature to 10-15℃/hr. Therefore in Indian case, apart from controlling maximum temperature of curing for concrete sleeper production, pre-steaming period can be increased to around 3-4 hours, rate of rise of temperature can be maintained in between 10℃/hr to 15℃/hr and rate of fall of temperature can be maintained at around 10℃/hr to yield better results. Another countermeasure can be blending cement with determined percentages of slag or fly ash since these materials proved to be very effective in improving interface characteristics of aggregates and paste [19].



(a) Long line method of pre-stressing

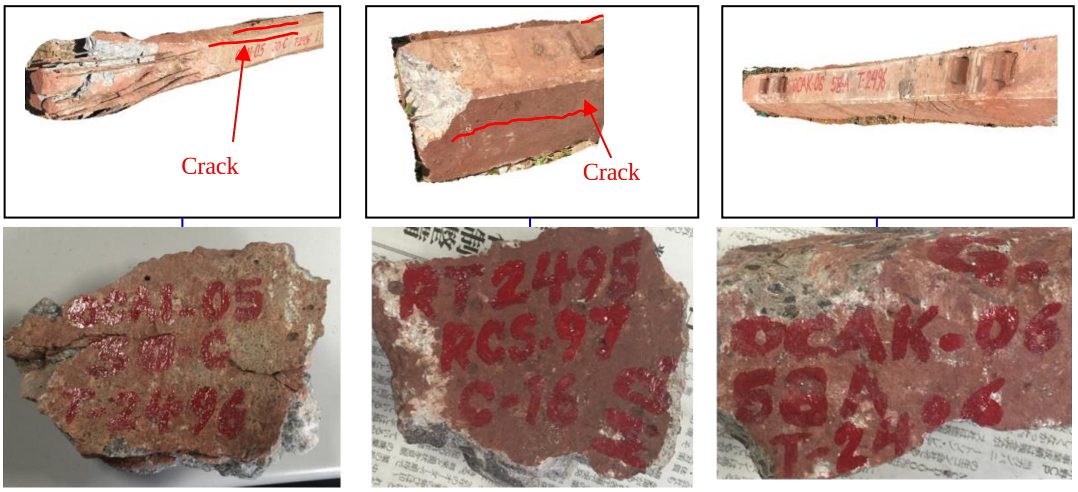


(b) Stress bench method of pre-stressing

Fig. 10 – Schematic diagram showing “long line method” and “stress bench method” of pre-stressing

3.3 Collection and preparation of samples for SEM analysis

Premature cracking of concrete sleepers was reported from different parts of India. For the investigation of premature cracking of sleepers, different categories of samples namely “Severely damaged”, “Moderately damaged”, and “Undamaged” were collected from different parts of India. Details of these samples are given in Table 2. Samples of the “Severely damaged” category were collected from the sleepers which showed maximum damage like long visible cracks and which were in service earlier but were removed since they could no longer able to hold the rails. Samples of “Moderately damaged” category show some visible cracks but the distress is not as severe as in the case of the samples of “Severely damaged” category. Samples of “Undamaged” category are collected from the sleepers which are in sound condition and do not show any kind of distress. Figure 11 shows the photographs of concrete for the above three categories of samples. Results of SEM and EDS analysis for some of the typical samples of each category are discussed in the next section.



(a) Severely damaged (b) Moderately damaged (c) Undamaged

Fig. 11 – Typical concrete sample

Table 2 – Details of sample collected

Sl. No.	Sleeper number	Label of manufacturing plant	Year of manufacturing	Level of damage	Abbreviated name
1	OCAI 02 51 C T2496-60	OCAI	2002	Severely damaged	D
2	OCAI-05 30C T-2496	OCAI	2005	Severely damaged	D1
3	OCAB-06 47 A T-2496	OCAB	2006	Severely damaged	D2
4	OCAB-06 53 D T-2496	OCAB	2006	Severely damaged	D3
5	OCAK-06 46 D T-2496	OCAK	2006	Severely damaged	D4
6	OCAB-06 C-22 T-2496	OCAB	2006	Severely damaged	D5
7	OCAB-06 18-B T-2496	OCAB	2006	Severely damaged	D6
8	OCAI-02 54-C T-2496	OCAI	2002	Severely damaged	D7
9	OCAK-06 100-B T-2496	OCAK	2006	Severely damaged	D8
10	OCAI-02 11-C T-2496	OCAI	2002	Severely damaged	D9
11	OCAB-06 72 A T-2496	OCAB	2006	Severely damaged	D10
12	OCAI-02 30B T-2496	OCAI	2002	Severely damaged	D11
13	OCAI-05 41 D T-2496	OCAI	2005	Severely damaged	D12
14	RCS-05 4183	RCS	2005	Severely damaged (Not loaded)	N1
15	RCS-05 4182	RCS	2005	Severely damaged (Not loaded)	N2
16	SEJ OCP 05 123 C 4149	OCP	2005	Severely damaged (Not loaded)	N3
17	RCS 05 4183 314	RCS	2005	Moderately damaged	M
18	OCAI-02 7-C T-2496	OCAI	2002	Moderately damaged	M1
19	RCS-97 C-16 RT 2495	RCS	1997	Moderately damaged	M2
20	OCAL 92 32A A-12 52 Kg	OCAL	1992	Undamaged	G
21	RCS-98 22 A RT-2495	RCS	1998	Undamaged	G1
22	OCAK-06 56 A T-2496	OCAK	2006	Undamaged	G2
23	RCS-98 66-B RT 2495	RCS	1998	Undamaged	G3
24	OCAK-06 58 A T-2496	OCAK	2006	Undamaged	G4
25	T-2496 RCS 12	RCS	2012	Undamaged (Relatively New)	GB1
26	T-2496 OCAK-12 120B	OCAK	2012	Undamaged (Relatively New)	GB2
27	T-2496 OCAK-12 66B	OCAK	2012	Undamaged (Relatively New)	GB3
28	RT 2496 01A MCP06 Km 83/0-83/1	MCP	2006	Severely damaged	DU1
29	RT 2496 21B MCP06 Km 84/5-6	MCP	2006	Severely damaged	DU2
30	RT 2496 61C MCP06 Km 84/7-8	MCP	2006	Severely damaged	DU3
31	RT 2496 113D MCP06 Km 82/9-83/0	MCP	2006	Severely damaged	DU4
32	RT 2496 14C MCP06 Km 84/6-7	MCP	2006	Severely damaged	DU5
33	DCT-04 27B	DCT	2004	Severely damaged	DS1
34	PUI-04 28B	PUI	2004	Severely damaged	DS2
35	PUI-04 RT 2496	PUI	2004	Severely damaged	DS3

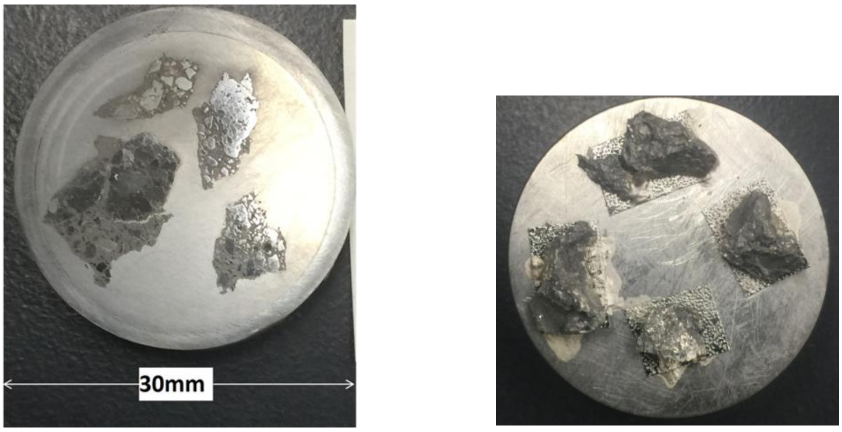
(a) Small pieces of concrete samples

(b) Samples embedded into epoxy resin

(c) Cutting the specimen

(d) Polishing with abrasive

Fig. 12 – Sequence of operation for preparation of polished specimens



(a) Polished specimen

(b) Unpolished specimen

Fig. 13 – Typical Specimens used for SEM analysis

Both polished and unpolished specimens were observed under SEM. The polished specimens were prepared by embedding small pieces of samples (approximately 10 mm x 10 mm x 10 mm) from each of the three categories into epoxy resin. Epoxy resin facilitates mounting of small pieces of concrete samples, which are polished to view the microstructure of concrete under SEM. Figure 12 shows these sequences of operation. After hardening of the epoxy resin, these specimens were cut and the exposed surface was grinded by using polishing abrasives (Abrasive number 400, 800, 1200, 2000 and 4000 in sequence).

Figure 13 shows such typical polished and unpolished specimens of the sleeper sample. Then the polished surface was coated with platinum, which was needed to prevent the charging of specimen with the electron beam. Along with the polished specimen, unpolished specimens were also observed. Unpolished specimens are also important because it can give 3-D information about microstructure of concrete. Unpolished specimens are just small broken pieces of concrete so unlike polished specimen, aggregates are not cut but break occurs generally at the interface of aggregates and paste for the obvious reason that it is weakest. Therefore, unpolished specimens can furnish additional information about the microstructure of concrete and its interface characteristics. The conventional SEM (high vacuum and high voltage) is used for the analysis.

4. Analysis of material composition of concrete

4.1 SEM analysis

Figure 14 shows the typical SEM images for the polished and unpolished specimen of “Severely damaged” sleeper sample ‘D’. Large ettringite deposition, i.e. ettringite patches of around 1 cm^2 area which can also be seen with naked eyes as white patches, are commonly noticed at the interface of aggregate and paste. Apart from this, ettringite is also present in the cracks within the paste (C-S-H gel). Unpolished samples also show large deposition of ettringite around the aggregates. Enlarged view shows typical needle like structure of ettringite. Unpolished specimen also reveals that there is layer of ettringite at the interface of aggregate and paste. There is similarity in pattern of the ettringite deposition in the samples from different locations of India i.e. a rim of ettringite forms around the aggregates and is joined by cracks in the paste filled by ettringite.

Figure 15 shows polished specimen of sample DU1, where ettringite deposition at the interface of aggregate and paste can be noticed. There is some porosity and hair cracks in coarse aggregate but ASR gel like substances are not noticed. Figure 16 shows SEM image of Sample DS1. Ettringite deposition can also be noticed at the interface of aggregate and paste in this sample.

Contrary to above, in the matrix of sample DS1, white brittle material is also noticed (Fig. 17). The SEM image of the sample shows alkali-silica gel like substance. Typical glassy surface of gel can be observed in the SEM images. The sample was also analyzed for EDS (details are explained in the next section), which shows only substance in the material is silica. Therefore, ASR or combined effect of ASR and DEF cannot be denied in some of the sleepers and further investigation is required in this regard.

Figure 18 shows the typical SEM images of polished and unpolished specimen of "Moderately damaged" sleepers. As in the case of "Severely damaged" sleeper samples, SEM images of "Moderately damaged" sleeper also reveal that there is ettringite deposition around the interface of aggregate and paste. Ettringite could be noticed inside the paste as well. Few coarse aggregates also show some porosity and cracks inside them but ASR gel like substance is not noticed. It is observed that the locations with ettringite deposition are fewer in this case as compared to "Severely damaged" case. Unpolished specimen also confirms ettringite deposition and a typical needle like structure of ettringite could be noticed in an enlarged view.

Figure 19 shows the SEM image of "Undamaged" sleeper sample 'G'. In such relatively older sleeper samples, for example sample G (year of manufacturing: 1992), interface of aggregate and paste seems to be intact and no ettringite deposition has been noticed either in the C-S-H gel or at the interface of aggregate and paste. Apart from this, no ASR gel like substance is noticed. Figure 20 shows SEM image of "Undamaged" sleeper sample 'GB1'. Unlike in "Undamaged" old sleeper sample like 'G', in relatively newer sleeper samples like 'GB1' (year of manufacturing: 2012), ettringite deposition similar to the case of "Severely damaged" and "Moderately damaged" case is noticed, however the sleeper does not show macroscopic cracks or damage. This indicates that the expansive reaction in these sleepers is in progress, but till now it is not large enough to cause macroscopic cracks. However there are high chances that in future these sleepers may become "Severely" or "Moderately" damaged.

4.2 Discussions on the results of SEM analysis

The frequent occurrence of ettringite deposition at the cracks found in the paste and at the interfaces of aggregates and paste, in case of "Severely damaged" (Figs. 14-16) and "Moderately damaged" (Fig. 18) sleepers, suggests that delayed ettringite formation might be the cause of premature damage in the concrete sleepers in India. However, occurrences of alkali-silica reaction cannot be denied. The microstructure of the aggregates and paste in "Severely damaged" and "Moderately damaged" samples are in good agreement with those proposed by Taylor H.F.W. et al. [5]. The cracks are found in the paste and also the interfaces are filled by ettringite. This shows that uniform expansion of the paste might have occurred due to delayed ettringite formation and large crystals of ettringite might have deposited in the gaps and cracks formed by such expansion. According to Thomas et al. [20] DEF results in expansion of cement paste and increase in volume of paste in relation to aggregates which results in separation between them or, in other words, this will lead to gaps or opening between paste and aggregates, which become sites for deposition of larger crystals of ettringite. The SEM images observed in "Severely damaged" and "Moderately damaged" samples (Figs. 14 and 18) show ettringite filled gaps around aggregates which matches very well with the SEM images observed by Thomas et al. [20] for the case of DEF damaged concrete. Similarly, Scrivener et al. [21] also noted that, in case of DEF, gaps form as a consequence of relatively uniform expansion of paste in all directions.

On the other hand, ASR gel like product, in one of the "Severely damaged" sleeper sample (DS1, Fig. 17), suggests that ASR might have taken place. Coexistence of alkali-silica reaction gel and ettringite, similar to that observed in one of the "Severely damaged" case, was explained by Brown and Bothe [20]. According to them cracks resulting from expansive reaction of ASR may provide space where ettringite crystallizes. The formation of alkali-silica gel decreases the alkali concentration of the pore solution. Development of ettringite is favored in low alkali solutions and ettringite may form in areas close to alkali-silica gel. Also, there are evidences that high early age temperature in concrete triggers both ASR and DEF [20, 23].

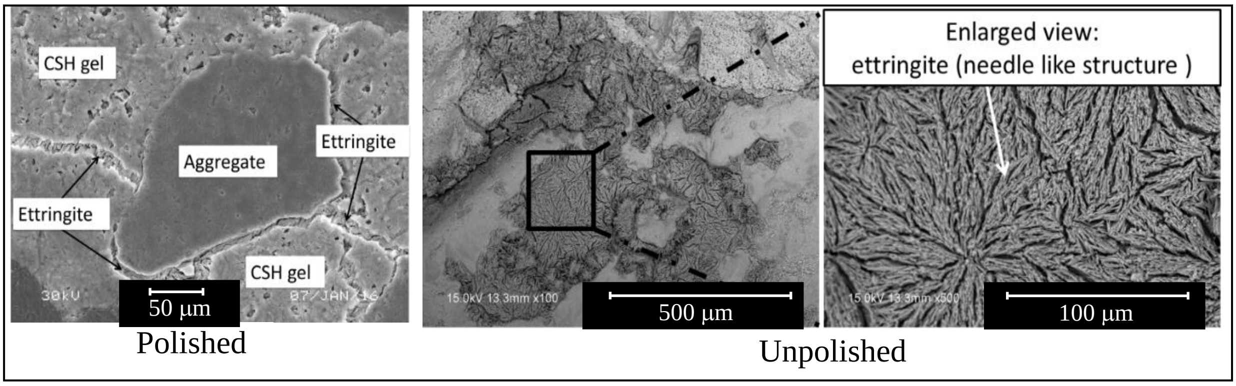


Fig. 14 – Polished and un-polished specimen: Sample D

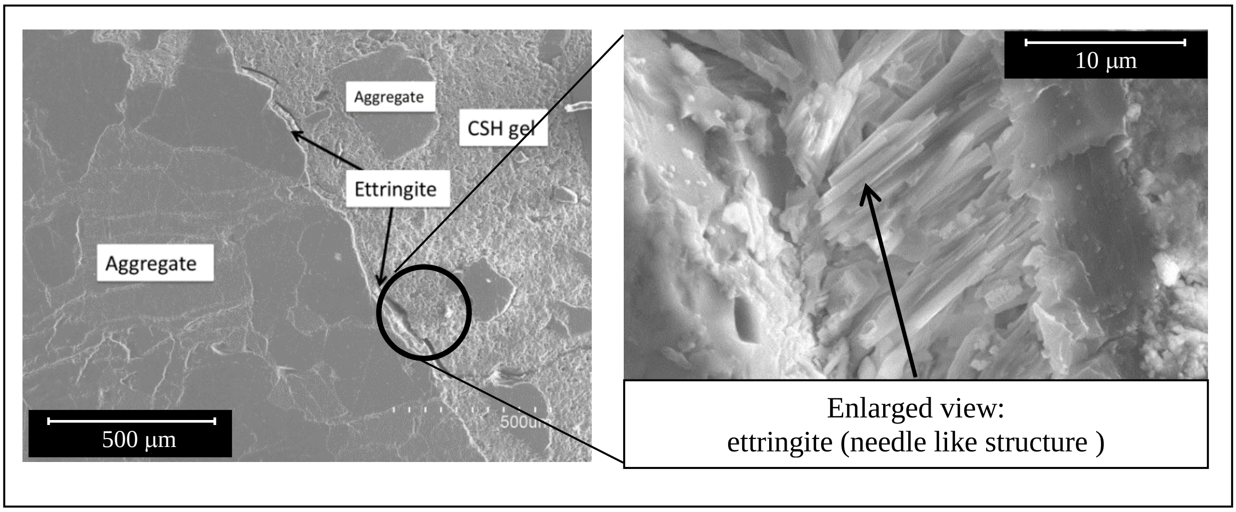


Fig. 15 – Polished specimen: Sample DU1

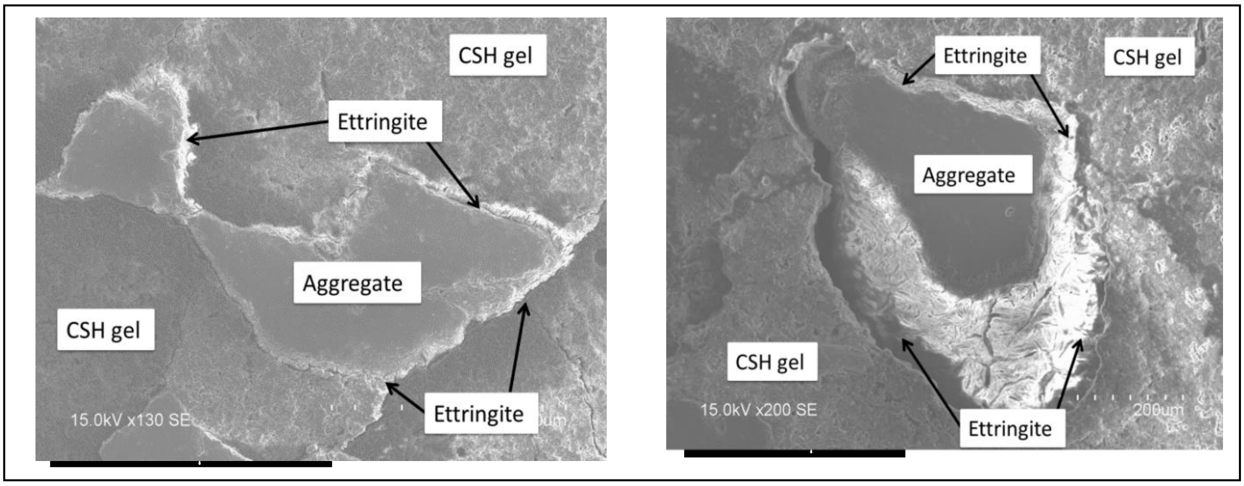


Fig. 16 – Polished specimen: Sample DS1

Therefore, possibility of ASR or combined effect of ASR and DEF cannot be denied in some cases and further investigation is necessary to reach to a conclusion. However, in case of ASR damaged concrete, Thomas et al. [20] have found reacting aggregates or cracks through aggregates some of which were partially filled with alkali-silica gel. Such type of reacting aggregates are not observed in the samples investigated in present study.

On the other hand, in case of relatively old "Undamaged" sleeper samples (Sample G, Fig. 19), the absence of ettringite indicates that expansive reaction has not taken place. However, some of the relatively newer sleeper samples (GB1, Fig. 20) have the similar microstructure as in the case of "Severely damaged" and "Moderately damaged" case, where ettringite deposition is commonly noticed. This indicates that an expansive reaction in these relatively newer

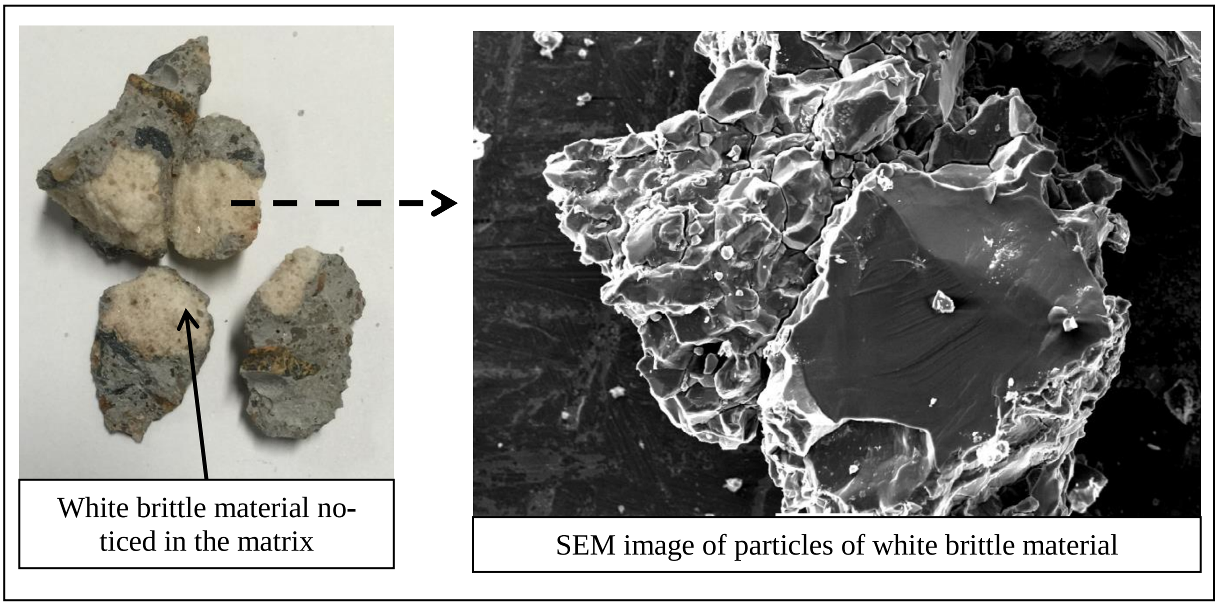


Fig. 17 – Unpolished specimen: Sample DS1

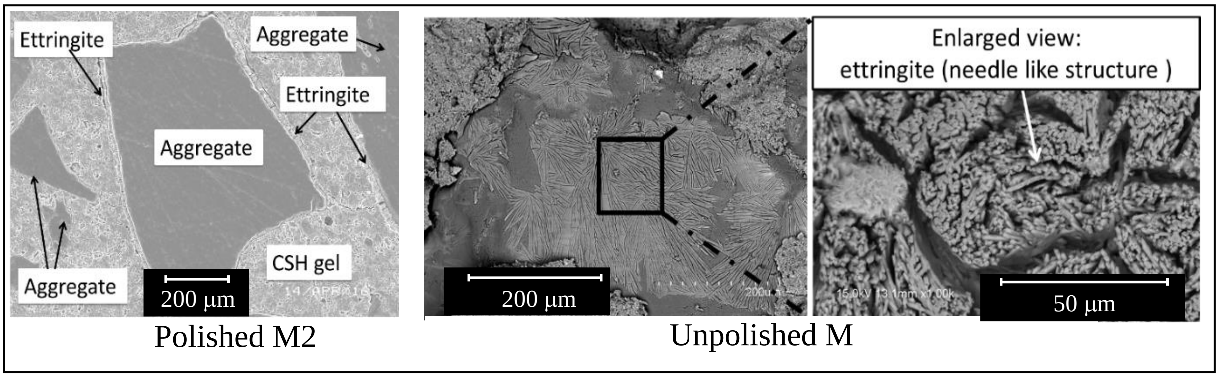


Fig. 18 – Polished and unpolished specimen: Sample M2 and M

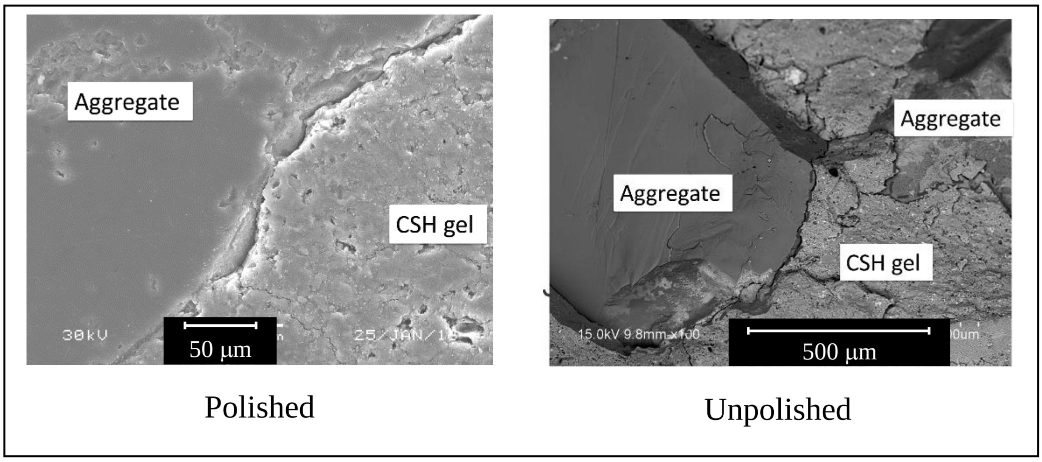


Fig. 19 – Polished and Unpolished specimen: Sample G (Year of manufacture: 1992)

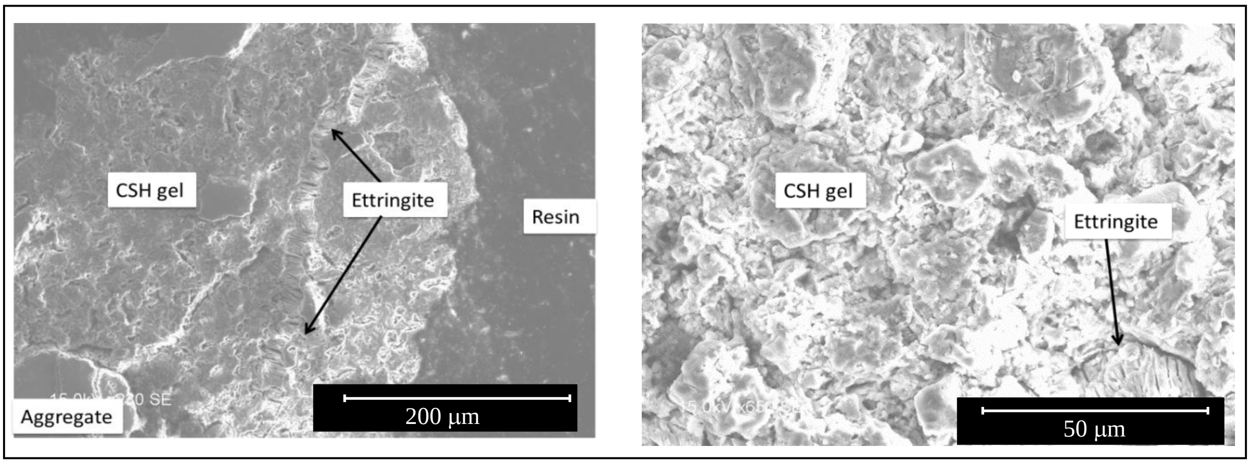


Fig. 20 – Polished specimen: Sample GB1 (Year of manufacture: 2012)

Fig. 21 – Typical specimen for EDS analysis

samples is in progress and in future there are high chances that these sleepers will also get damaged.

4.3 Energy Dispersive Spectroscopy (EDS) and characteristic X-Ray Maps

Samples for EDS analysis were prepared in similar fashion as in the case of SEM analysis. The preparation of samples for SEM has been discussed in section 3.3. Both polished and unpolished samples were tested for EDS. Figure 21 shows picture of typical polished sample used for EDS analysis.

Two kinds of spectrum were analyzed for concrete sleeper samples. Firstly spot EDS of ettringite, hydration product, and other deleterious substances were analyzed. Secondly, X ray maps were obtained for various regions of the samples, thus identifying hydration product, ettringite etc.

4.3.1 EDS spectrum of different spots in a da-m aged sample of sleeper

A standard specimen of synthesized ettringite was obtained from Japan Cement Association. To identify ettringite, first EDS pattern of synthesized ettringite was obtained and compared with EDS response of the spots in the sample. Figure 22 shows the standard synthesized ettringite and its EDS pattern.

EDS patterns of ettringite obtained from different specimens of concrete sleepers (EDS pattern of one such typical specimen of sample 'D' is shown in Fig. 23) show that its intensity pattern matches with the standard synthesized specimen of ettringite (Fig. 22), which confirms that substance deposited in the cracks and in the interface between aggregate and paste is ettringite.

4.3.2 Characteristic X-Ray maps of concrete samples

Characteristic X-ray mapping provides images of elemental distributions in a sample. While SEM images can show variations in composition in a sample, characteristic X-ray maps can show which elements are responsible for the variation.

For the purpose of identification of hydration products, ettringite and other substances in overall matrix in concrete samples, characteristic X-ray maps were plotted. Figures 24 and 25 show typical characteristic X-Ray maps of "Severely damaged" and "Undamaged" concrete samples.

Ettringite is crystal of Ca (Calcium), S (Sulfur) and Al (Aluminum). Therefore wherever ettringite is present all of these three elements are present. C-S-H gel is Ca and Si (Silicon) hydrates, so peaks of only Ca and Si without any presence of S in certain area in microstructure of concrete indicates that it is C-S-H gel. High intensity peaks of only Si suggests that it is Quartz aggregate and peaks of Si and K (Potassium) together suggests that it can be Feldspar aggregate.

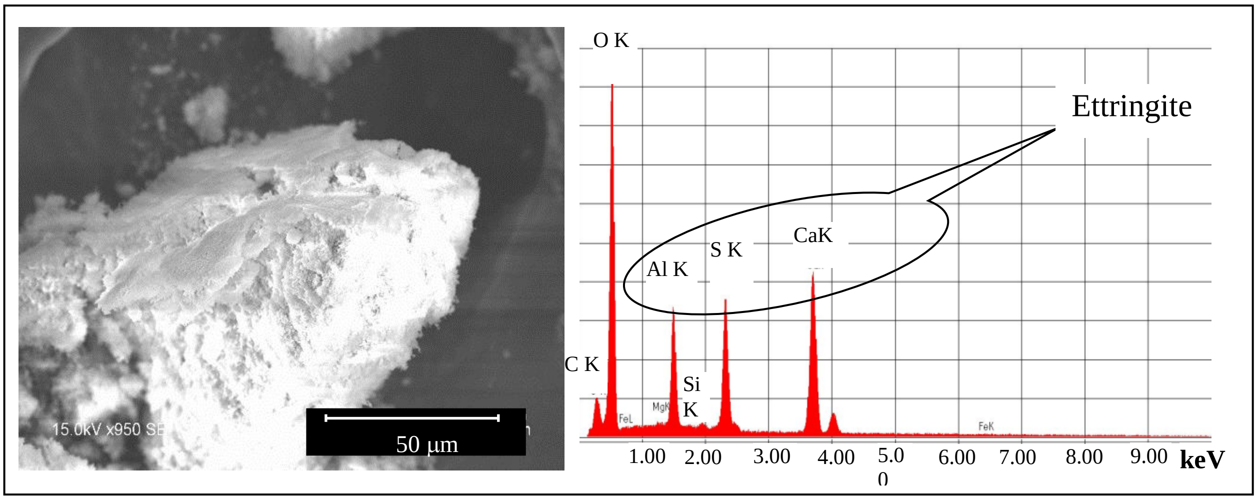


Fig. 22 – Standard synthesised specimen of ettringite

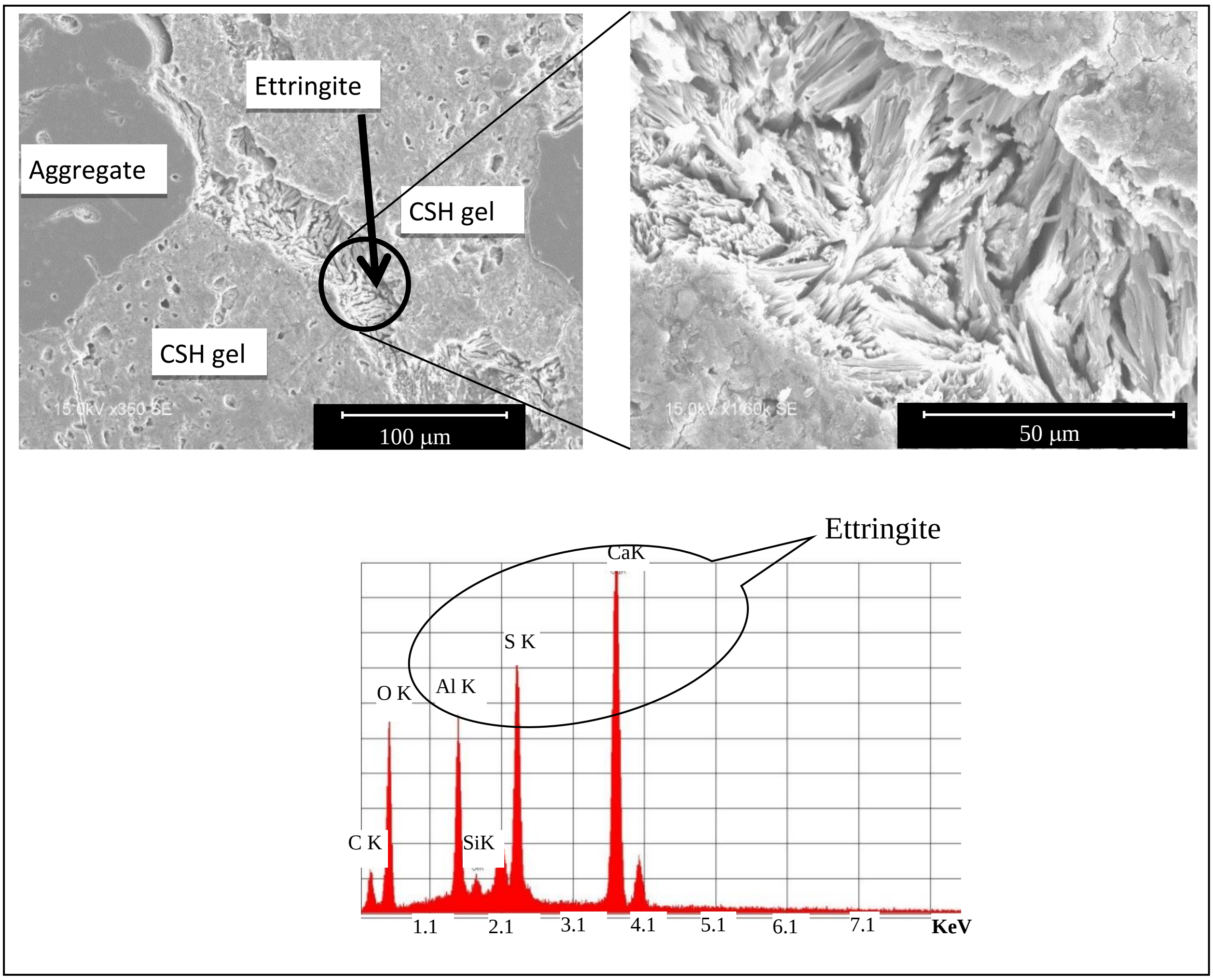


Fig. 23 – Polished specimen: Sample D

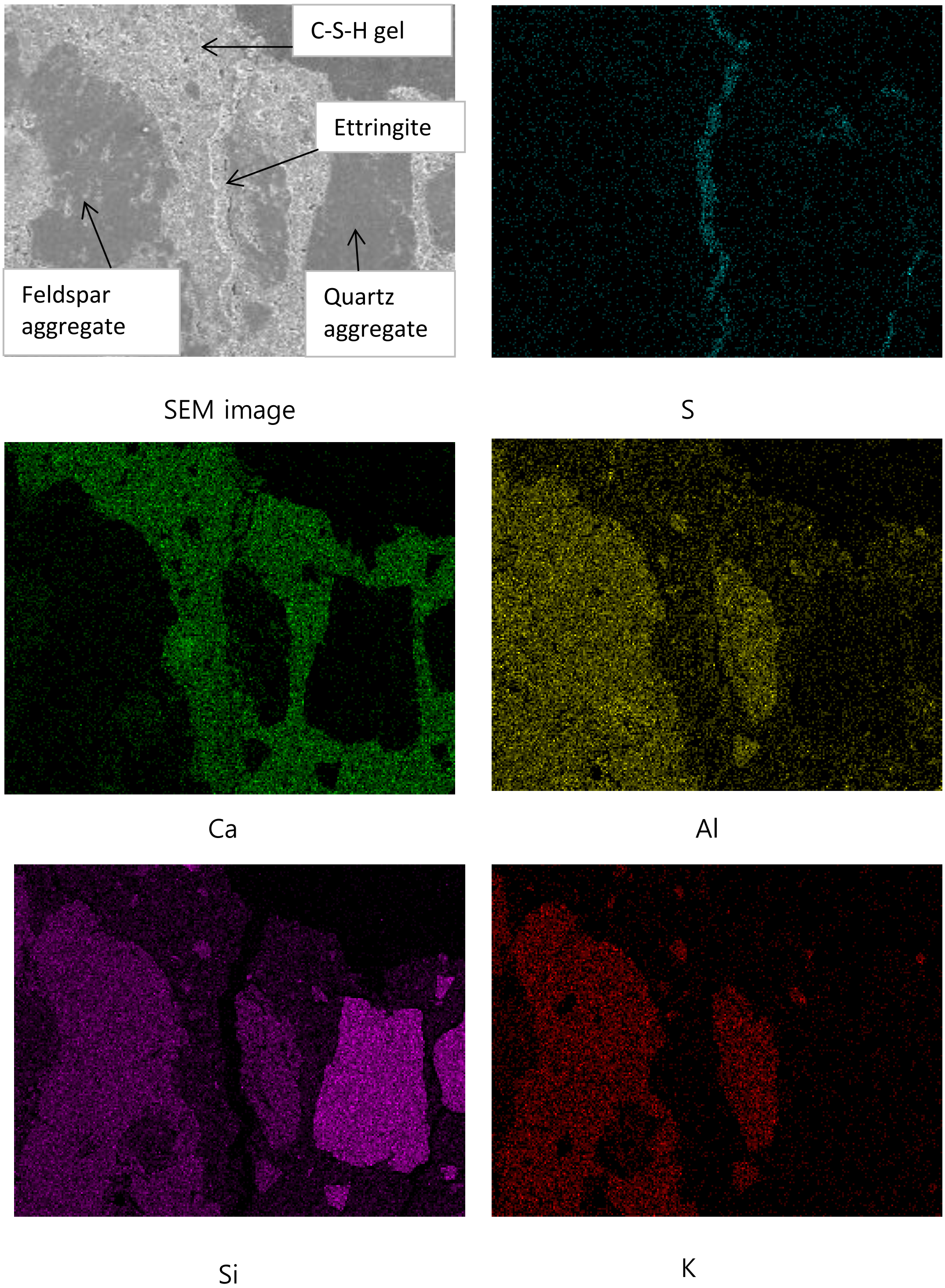


Fig. 24 – Characteristic X-ray map of sample D1

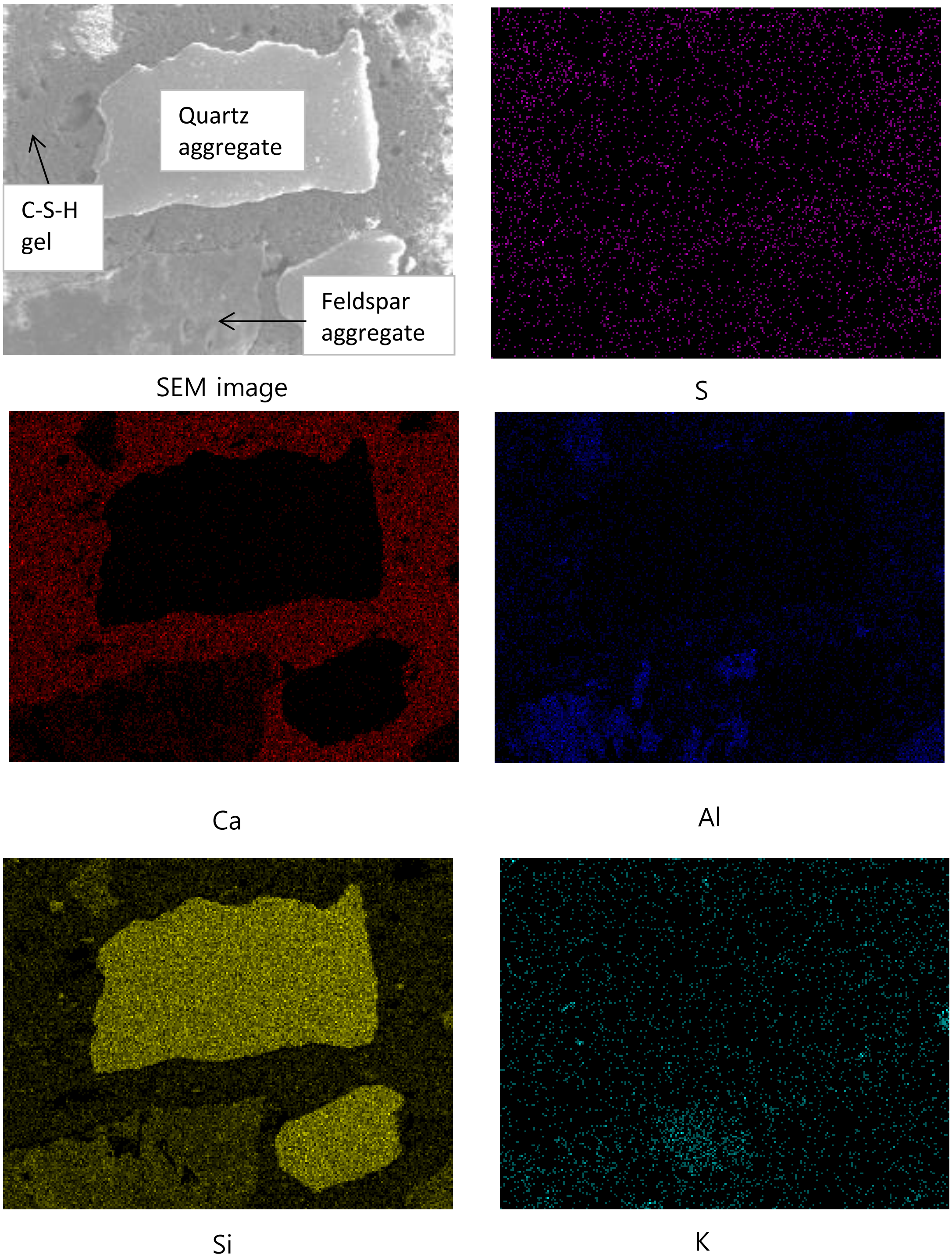


Fig. 25 – Characteristic X-ray map of sample GD3

Characteristic X-ray maps of damaged sleeper sample D1 in Fig. 24 reveal that ettringite is deposited in the crack and around aggregate (peaks of Ca, Al, and S together can be seen at the location of cracks and around aggregates). Feldspar aggregate (containing peaks of K and Si) and quartz aggregate (No peak of K and only peaks of Si) are distinctly identified. Also, C-S-H gel containing peaks of Ca and Si is identified.

Characteristic X-ray maps of undamaged sleeper sample GD3 in Fig. 25 reveal that no ettringite deposition is present in the matrix. Quartz aggregate, feldspar aggregate and C-S-H gel can be identified.

5. Conclusions

(1) Field measurement confirms that temperature inside the concrete during steam curing reaches 80.7℃ and 84.9℃ respectively for the two measurements performed in the setup of concrete sleeper plant in India. Therefore, damaged sleepers are exposed to a condition that may cause DEF induced damage in the future. Also, deep curing chambers separated by thin brick wall, used in stress bench method of prestressing in production of concrete sleepers in Indian Railways, adversely affects the curing cycle in the way that the actual observed cooling curve greatly deviates from the ideal one. Apart from this, there are local issues like non removal of sleepers after the end of curing cycle which also affects cooling curve.

(2) Analysis of SEM images shows that there is large ettringite deposition in "Severely damaged" and "Moderately damaged" samples from Indian concrete sleepers. In contrast to this, relatively old "Undamaged" sleeper samples do not show any ettringite deposition similar to damaged sleeper samples and interfaces between aggregate and paste are intact. However, some of the relatively new "Undamaged" sleepers (year of manufacture: 2012) also show large ettingite deposition in them.

(3) EDS analysis reveals the composition of 'needle like deposited material' as delayed ettringite. Characteristic X-Ray maps of damaged and undamaged samples reveal that the matrix of damaged concrete contains ettringite deposition around aggregates and inside cracks while there is no such ettringite deposition present in undamaged samples.

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