Study of Possible Causes of Premature Cracking Of Sleepers in Indian Railways

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Synopsis

Indian Railways uses pre-tensioned pre-stressed concrete sleepers for it's track. In many areas, these sleepers start cracking after 6-9 years of their manufacture. Samples of different categories were collected and examined under Scanning Electron Microscope (SEM). SEM images reveal large ettringite deposition in case of damaged sleepers especially at the interface of CSH gel and aggregate. 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°C, which is a very critical temperature for the occurrence of damage due to delayed ettringite formation (DEF) in future.

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

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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 it's position and transfer the load to the supporting structure below. Longer life, resistance to fire hazard and greater stability due to more weight makes concrete a better material for making sleepers compared to timber. Advances in design, quality and production of pre-stressed concrete gave a great impetus to the use of concrete sleepers which could now provide the desired resilience for repetitive railway load. Faster production of these sleepers in large numbers, in a factory set up, makes it possible to meet it's huge demand in the Railway tracks.

Indian Railways uses factory made pre-tensioned pre-stressed concrete sleepers for it's track. In many areas of Indian Railways, these sleepers start cracking after 6-9 years of their manufacture. Even sleepers 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, the aim of this study is to investigate the possible causes of pre-mature cracking of sleepers in Indian Railways. For the purpose of investigation, Scanning Electron Microscope (SEM) images are analysed. Field measurement of the concrete temperature during steam curing and also the manufacturing process of these sleepers are studied to find the possible causes of damage.

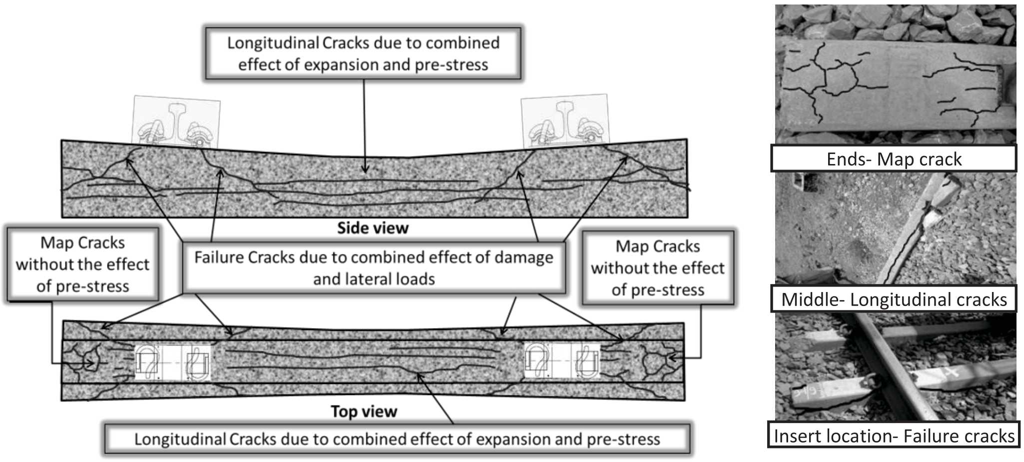
2 The Problem Of Premaure Cracking Of Concrete Sleepers In Indian Railways And Collection Of Samples

2.1 The problem with concrete sleepers

Typical cracking patterns observed in the sleepers are shown as photographs in Figure 1. Typical map cracks are observed at the two ends of the sleeper where the pre-stress is minimum. 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. 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 rail loads. 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. 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 (1995)). Between 1992 and 1996, a large number of railroad ties in Sweden had shown premature deterioration (Sahu and Thaulow (2004)). The cause of distress in these cases was attributed to Delayed ettringite formation (DEF). But, Shayan A. and Quick G.W. (1994) have attributed the main cause of damage in the concrete sleeper of Finnish Railways as alkali silica reaction as against delayed ettringite formation in other cases. Therefore, it is predicted that the cause of damage in case of Indian concrete sleepers could be either delayed ettringite formation (DEF) or alkali-silica reaction (ASR). Scanning Electron Microscope (SEM) is a powerful tool for identifying the hydration product and presence of ettringite or other substances that cause distress in concrete. The same is adopted in this study for analyzing samples of concrete sleepers of Indian Railways.

2.2 Collection of samples according to the level of damage

For the investigation of premature cracking of sleepers, different categories of samples namely "Severely damaged", "Moderately damaged" & "Undamaged" were collected from Raipur division of Indian Railways which is approximately in the south east of central India. Samples of the "Severely damaged" category are collected from the sleepers which show 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 2 shows the photographs of concrete for the above three categories of samples.



3. Scanning Electron Microscope (sem) Image Analysis

3.1 Preparation of samples

Small pieces of samples from each of the three categories are embedded to resin solution. After hardening of the resin, these specimens are cut and the exposed surface is grinded by using polishing abrasives (Abrasive number 400, 800, 1200, 2000 and 4000 in sequence). Figure 2 shows such typical grinded specimen of the sleeper sample. Then the polished surface is coated with palladium which is needed to prevent the charging of specimen with electron beam. The conventional Scanning Electron Microscope (high vacuum and high voltage) is used for the analysis. Along with this, unpolished samples are also observed.

3.2 Results of SEM analysis and discussion

3.2.1 SEM images of "Severely damaged" sleeper samples

Figure 3 shows the typical SEM images for the polished and unpolished specimen of "Severely damaged" sleeper sample. Large ettringite deposition at the interface of aggregate is commonly noticed. Apart from this, ettringite is also present in the cracks within the paste (C-S-H gel). Very few aggregates seem to be porous and damaged. Unpolished samples also show large deposition of ettringite around the aggregates. Enlarged view shows typical needle like structure of ettringite.

Some of the samples of "Severely damaged" sleeper also show damage in the coarse aggregates. Also alkali-silica reaction (ASR) gel like substance is noticed. Although ettringite is also commonly noticed in the interface of aggregate and paste. Figure 4 shows SEM images of such polished specimen.

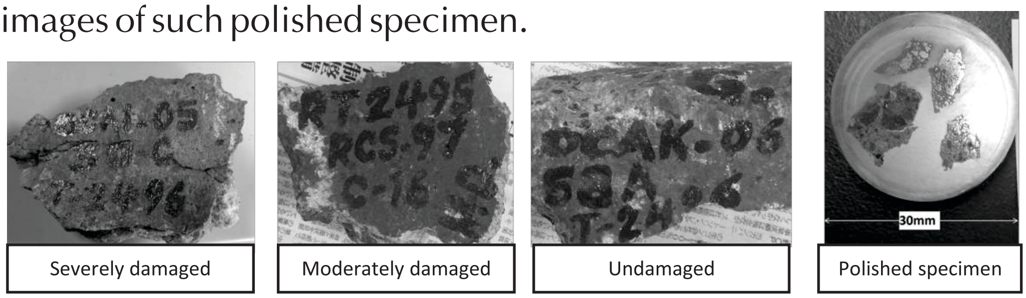


Figure 2. The three categories of concrete samples and typical polished specimen

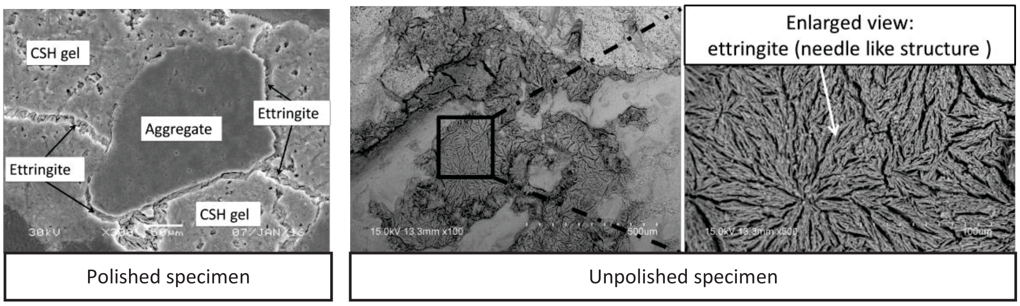


Figure 3. SEM image of polished and unpolished specimen of "Severely damaged" sleeper sample

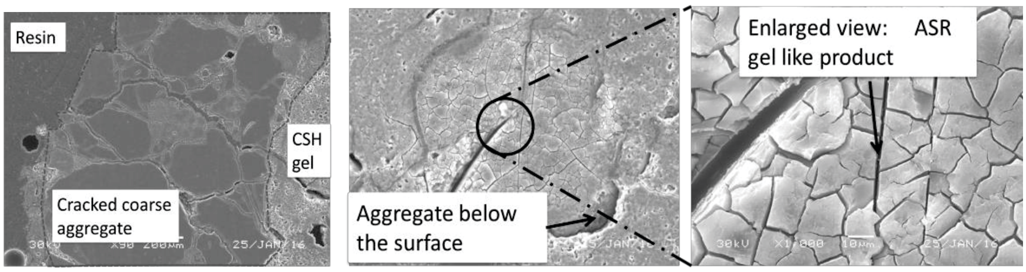


Figure 4. SEM image of polished specimen of "Severely damaged" sleeper sample

3.2.2 SEM images of "Moderately damaged" sleeper samples

Figure 5 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. Also, ettringite could be noticed inside the paste. Few coarse aggregate also show some porosity and cracks inside them but alkali-silica reaction (ASR) gel like substance is not noticed. Also, the locations with ettringite deposition are fewer in this case as compared to "Severely damaged" case. Unpolished specimen also confirms ettringite deposition and also a typical needle like structure of ettringite could be noticed in an enlarged view.

3.2.3 SEM images of "Undamaged" sleeper samples

Figure 6 shows the typical SEM images of polished and unpolished specimens of "Undamaged" sleeper samples. Interface of aggregate and paste seems to be intact and no ettringite formation 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.

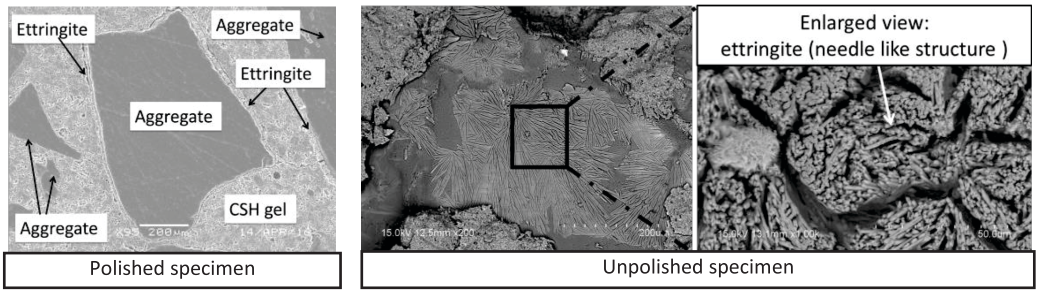


Figure 5. SEM image of polished and unpolished specimen of "Moderately damaged" sleeper sample

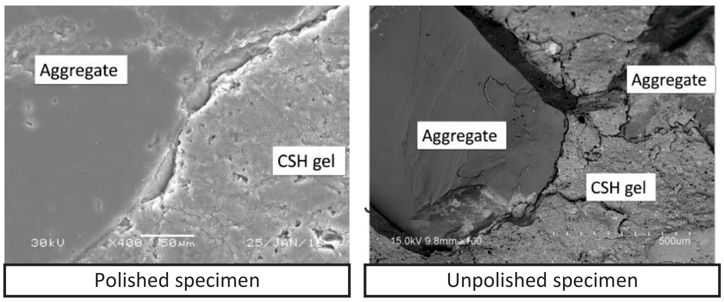


Figure 6. SEM images of polished and unpolished specimen of "Undamaged" sleeper sample

3.2.4 Discussion

The frequent occurrence of ettringite deposition in case of "Severely damaged" and "Moderately damaged" 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 also cannot be denied. Mechanism of Delayed ettringite formation has been explained by Ludwig et al (1986). They have shown that ettringite (more specifically primary ettringite), one of the initial hydration product formed during hydration process of Portland cement, is destroyed during heat treatment above 70°C. During this process a significant quantity of sulfate is absorbed in C-S-H or present in pore solution. The reformation of ettringite during the service life at ambient temperature and exposure to moisture is called delayed ettringite formation (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 delayed ettringite formation (DEF) Taylor H.F.W. et al (2001) 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. 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 (2001). The cracks are found in the paste and interfaces filled by ettringite shows that uniforms 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. Collepardi (2003) proposed a holistic approach for understanding DEF based on late sulfate release, micro-cracking and exposure to water as three necessary conditions for the Delayed ettringite formation. In case of Indian concrete sleepers, steam curing is done at a temperature of 70-75°C which can be a possible cause of late sulfate release and use of high early strength cement, containing higher content of gypsum ($CaSO_4.2H_2O$) compared to Ordinary Portland cement, might be ensuring the ample availability of sulfate, micro-cracking might be existent due to high temperature steam curing or excessive and non-uniform stress distribution due to pre-stressing, presence of water is ensured from rainfall (Indian subcontinent receives heavy rain fall from June to September during monsoon period). On the other hand, the cracks across the aggregates filled with alkali-silica gel (ASR) gel like product, in case of some of the "Severely damaged" sleeper samples, agree with the findings of Thomas et al (2008) and suggest that ASR might have taken place. Coexistence of alkali-silica reaction gel and ettringite, similar to that is observed in some of the "Severely damaged" cases, was explained by Brown and Bothe (1993). 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. So, possibility of alkali-silica reactivity causing damage cannot be denied and further investigation is necessary to reach to a conclusion.

Apart from other factors which cause pre-stressed concrete sleepers to become more vulnerable to DEF attack, the one which is the most significant is the early age temperature experienced by concrete in form of steam curing. Ghorab et al (1980), 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 development of ettringite X-ray peak with time in case of heat cured sample. Similarly, Heinz and Ludwig (1987) have shown that large expansion occurs in specimen treated above 75℃ temperature. Hanehara & Oyamada (2010) confirmed that the boundary temperature conditions for occurrence of DEF are between 60℃ and 70℃. The steam curing cycle adopted in Indian Railways specifies the maximum temperature that is to be attained during steam curing as 70-75℃ for at least 4 hours. This makes Indian concrete sleepers vulnerable to DEF induced damages. Temperature may further increase over and above the curing temperature due to the heat released during the hydration process of cement. To confirm the actual temperature attained by the concrete during steam curing, temperature measurement has been performed in the concrete sleeper plant in India.

4. Temperature Measurement Inside The Sleepers During Production

4.1 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 the same as shown in Figure 7. The sleeper plant uses stress bench method and curing chambers of dimension approximately 12.8m x 8.5m x 4.8m 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 7 also shows the typical arrangement of curing chamber and position of the sleeper for which temperature measurement was done. Three sleepers viz. 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 is expected and one just outside that point. Two sets of field measurements are 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. Figure 8 shows the arrangement of thermocouples, Figure 9 and Figure 10 shows the results of the field measurement-1 and field measurement-2 respectively.

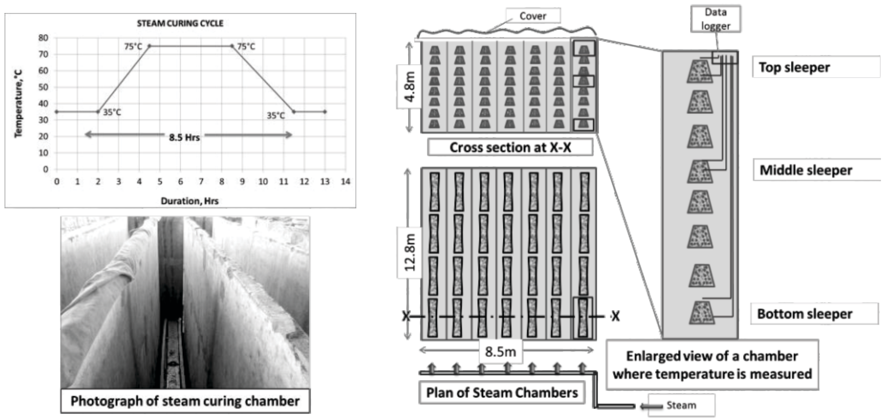


Figure 7. Steam curing cycle and arrangement of steam curing chambers in sleeper plants in India

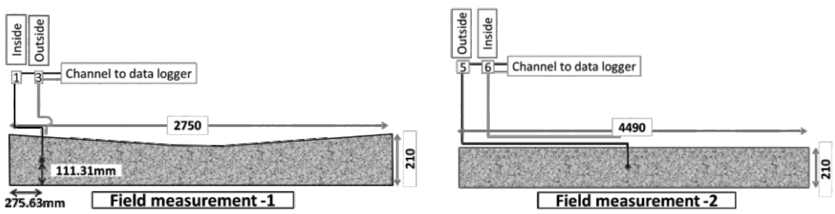


Figure 8. Arrangements of thermocouples in longitudinal direction (figure not to the scale)

4.2 Discussion

4.2.1 Maximum temperature inside the concrete during field measurement

Field measurement of temperature reveals that the maximum temperature reached inside concrete is 80.7°C and 84.9°C for the bottom-most sleeper in field measurement-1 & field measurement-2 respectively (Figure 9 and Figure 10). It is very well established that concrete temperature is beyond the critical temperature for the occurrence of DEF problem (Ghorab et al (1980), Heinz and Ludwig (1987), Hanehara & Oyamada (2010)). 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.

4.2.2 The cooling curve is excessively prolonged

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 (Figure 9 and Figure 10). 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 (Figure 7). 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. 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, Lawrence et al (1990) concluded that the start of expansion occurs early in case of a specimen heated for longer duration.

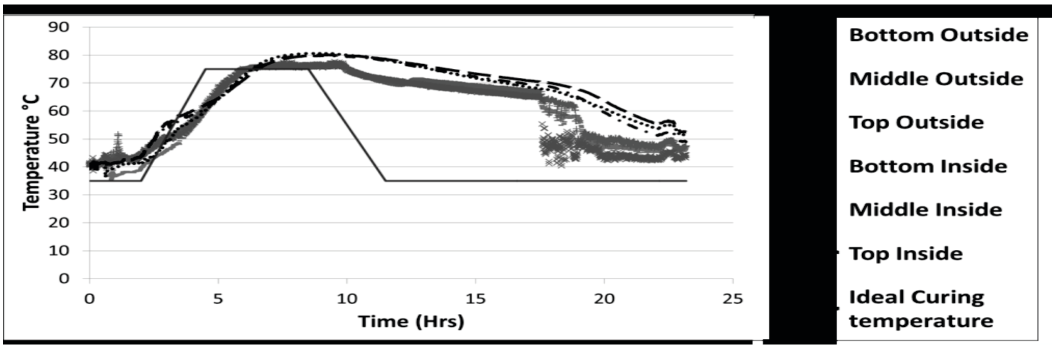


Fig 9. Results of temperature measurement-1 in sleeper plants in India

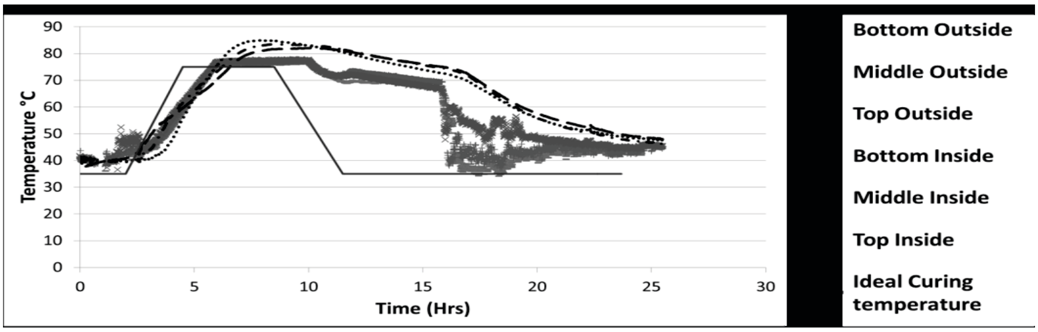


Fig 10. Results of temperature measurement-2 in sleeper plants in India

5 Conclusions

1. Analysis of SEM images shows that there is large ettringite deposition in the damaged samples from Indian concrete sleepers.
2. 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 delayed ettringite formation (DEF) induced damage in the future.
3. In some cases alkali-silica reaction or combined effect of alkali-silica reaction and delayed ettringite formation cannot be denied and further investigation is to be done to reach to any conclusion.

References

- Brown, P.W., Bothe, J.V., (1993), "The stability of ettringite", Adv. Cem. Res., Vol. 5, no. 18,pp. 47-63.
- Collepardi M., "A state-of-the-art review on delayed ettringite attack on concrete", Cement & Concrete Composites 25 (2003) 401–407
- Ghorab H.Y., Heinz D., Ludwig U., Meskendahl T. and Welter A. (1980), "On the stability of calcium aluminate sulphate hydrates in pure systems and in cements", 7th Intnl. Congr. Chem. Cem., Vol IV, 496-503,1980
- Hanehara S. & Oyamada T. (2010), "Reproduction of delayed ettringite formation (DEF) in concrete and relationship between DEF and alkali silica reaction", Monitoring and Retrofitting of Concrete Structures- B. H. Oh, et al. (eds)ⓒ 2010 Korea Concrete Institute, Seoul, ISBN 978-89-5708-181-5
- Heinz D. and Ludwig U.(1987), "Mechanism of secondary ettringite formation in mortars and concretes subjected to heat treatment", American Concr. Inst., SP 100-105, Detroit, 2059-2071, 1987
- Lawrence C.D., Dalziel J.A. and Hobbs D.W., "Sulphate attack arising from delayed ettringite formation", Interim Technical Note, 12, British Cement Association, Wexham Springs, Slough, U.K., May, 1990
- Ludwig U. and Heinz D., "Mechanism of subsequent ettringite formation in mortars and concretes after heat treatment", 8th International Congress on the Chemistry of Cement, Rio de Janeiro, 1986, vol. 5, Abla Grafica e Editora Ltda, Rio de Janeiro, 1986, pp. 189–194.
- Mielenz R.C., Marusin S.L., Hime W.G. and Jugovic Z.T. (1995) "Investigation of prestressed concrete railway tie distress", Concrete Int 1995;17(12):62–8
- Sahu Sadananda and Thaulow Niels (2004), "Delayed ettringite

formation in Swedish concrete railroad ties", Cement and Concrete Research 34 (2004) 1675–1681

- Shayan A. and Quick G.W. (1994), "Alkali-aggregate reaction in concrete railway sleepers from Finland",
- 16th international conference on cement microscopy, Duncanville, TX: 69-79
- Taylor H.F.W, Famy C. and Scrivener K.L.(2001), "Review- Delayed ettringite formation", Cement and Concrete Research 31 (2001) 683-693
- Thomas M., Folliard K., Drimalas T. and Ramlochan T.(2008), "Diagnosing delayed ettringite formation in concrete structures", Cement and Concrete Research 38 (2008) 841–847

Acknowledgement:

This work is supported by Council of Science, Technology and Innovation (CSIT), Cross-ministerial Strategic Innovation Promotion Program (SIP), "Infrastructure Maintenance, Renewal, and Management Technology" (Funding agency: JST)