CRACKED PRESTRESSED CONCRETE RAILWAY SLEEPERS: ALKALI-SILICA REACTION OR DELAYED ETTRINGITE FORMATION

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Cracking of prestressed concrete railway sleepers in South Africa has so far only been recorded where potentially alkali-reactive aggregates, namely, quartzite and granite, have been used and not where non alkali-reactive aggregate, such as dolerite has been used. In the case of the two aggregates mentioned first, typical signs of ASR are present while ettringite formation is observed at the interfaces of cement paste with aggregates and steel.

INTRODUCTION

Longitudinal cracking of concrete railway sleepers in South Africa was first observed by maintenance staff in 1985 in the 861 km long Sishen/Saldanha line. This line was constructed between 1973 and 1976 to connect the vast iron ore deposits being mined at Sishen in the Northern Cape with the nearest suitable export harbour at Saldanha on the West Coast. Approximately 1,7 million heavy-duty FY type prestressed concrete sleepers were manufactured for this purpose, of which approximately 1,4 million were used in the construction of the line, while the remaining 300 000 were stockpiled at Saldanha for maintenance purposes.

Subsequently, the occurrence of longitudinally cracked sleepers in the Coal line to Richards Bay on the East Coast was reported in 1987 and from the De Aar/Noupoort line in the Karoo, in 1989 (1).

BACKGROUND INFORMATION

Manufacturing process

The sleepers were manufactured by the longline process. A brief outline of the production process follows:

The sleepers were cast in quadruple steel moulds in 100 m longline beds, 40 moulds, i.e., 160 sleepers, per bed. The moulds were cleaned and coated with a release agent. The prestressing wires were pulled into the bed and stressed by hydraulic jacks. The moulds were lifted in the "up" position and fastening components to be cast into the sleepers were placed in the moulds. The moulds were filled with concrete from a line feeder, vibrated by internal vibrators, covered within 15 minutes of casting with insulating covers and left for a minimum of two hours before heat curing commenced under the covers by introducing steam into two steel pipes of 100 mm diameter situated below the moulds. The rise in air temperature was controlled to a maximum of 10 °C per hour - the rise in temperature in the sleepers was 10 to 15 °C per hour during the first two hours and 5 to 8 °C thereafter - until an air temperature of 60 °C - which correspondeds to a temperature of ca.65 °C of the concrete - was reached. This maximum temperature was maintained for approximately 3 hours, the total heat curing period being about 8 hours. The rate of fall in air temperature was between 7 and 10 °C per hour for the cooling cycle. The heating process was totally dry as steam was enclosed in pipes and condensate was recycled. The only moisture available was the water driven off during the hydration under the covers in the line. The period for which the maximum temperature was maintained varied at the different factories because of the different cement sources. After cooling, the insulating covers were removed and the sleepers demoulded by pushing the moulds into the "down" position. The stress was transferred into the sleepers using the hydraulic jacks after checking the transfer strength of the concrete - minimum 28 MPa. The wires between sleepers were cut by flame torch and the sleepers removed from the beds. The protruding wires were cut off and the sleepers placed in storage stacks.

The reinforcing wire layout of the Saldanha sleepers is shown in Figure 1. Details of the materials and mixes used at the different factories are given in Table 1.

TABLE 1 - Materials and typical mixes for the concrete used at the different factories (Personal communication, Grinaker Precast, 1990)

		Saldanha factory	Nigel factory	Vryheid factory	De Aar factory
Stone, 19 mm	kg	1 350	1 160	1 400	1 290
Sand	kg	665	660	800	850
Cement	kg	545	450	480	385
Water	kg	215	180	190	160
Stone type		Granite	Quartzite	Dolerite	Dolerite
Sand type		Quartz Pit sand	Crushed quartzite	Quartz River sand	Crushed dolerite
Cement: Source/Type		Riebeeck West, RH	Slurry RH	Dudfield RH	Ulco RH*
Cement: % Na_2O-eq.		>1,0	ca. 0,45	ca. 0,35	ca. 0,50
% SO_3**		3,03	3,38	-	2,59

* RH = Rapid Hardening Portland Cement
* Average determined on cores from the sleepers

In the Sishen/Saldanha ore line only sleepers from the

Saldanha factory made with granite aggregate were used. In the Coal line, the number of sleepers from the Nigel factory made with quartzite aggregate comprised about 10 % and the balance came from the Vryheid factory and were made with dolerite aggregate. In the De Aar/Noupoort line, sleepers from the Nigel factory, made with quartzite aggregate, and from the De Aar factory, made with dolerite aggregate, were used.

The Problem

Sishen/Saldanha line. Cracks running parallel with the prestressing wires in sleepers of the Sishen/Saldanha line were first noticed by maintenance staff in 1985, between 9 and 12 years after construction of the line. Two years later the position had deteriorated to such an extent that a number of badly cracked sleepers were removed from the track for static and dynamic bending tests at Spoornet's Track Test Centre and for investigation by the CSIR. Spot checks of 100 sleepers per km were carried out by maintenance staff over the entire length of the line between January 1988 and January 1989 to dertermine the extent of the problem. It was found that 78 000, or 6 %, of the sleepers had cracks running along part of their length and 20 000, or 1,5 %, had cracks running the full length of the sleeper. Since April 1988 the growth rate of crack width in specific sleepers has been monitored on a three-monthly basis by means of a microscope with a 25x magnification and a measuring scale. The growth rate in width was found to be 0,04 mm/month (1).

Inspection of approximately 20 000 of the sleepers originally stockpiled for maintenance purposes at Saldanha Bay, revealed that the top and end layers, which were more exposed to the elements, showed the same type of cracking as found in the sleepers in the line. Sleepers further down in the stack did not show any cracking. In a particular case sleepers under a road-over-rail bridge were not cracked while those in the open on either side of the bridge, were cracked. In addition, no signs of cracking had so far been detected in those sleepers occurring in the line between 270 km and 800 km from Saldanha, a stretch running through country with a relatively low rainfall (1).

Richards Bay Coal line. By the middle of 1987 inspection reports were also being received about cracks appearing in the sleepers on the Richards Bay Coal line. The situation in this line is not as serious as in the Sishen/Saldanha line partly because these sleepers have been in service for a shorter period - seven years at that stage - and also, it is postulated, because only sleepers made with quartzite aggregate at the Nigel factory are affected. These sleepers constitute only 10 % of the total number of sleepers in service on this line. The remainder of the sleepers in this line were made in the Vryheid factory, using dolerite aggregate (1).

De Aar/Noupoort line. Towards the end of 1989, reports were also received of cracked FY sleepers on the De Aar/Noupoort line. These sleepers were cast in 1982 at the Nigel factory where Witwatersrand quartzite coarse aggregate was used.

STATIC AND DYNAMIC BENDING TESTS

To determine whether the structural strength of the sleepers was affected by the cracks, static and dynamic bending tests were carried out on the servo-hydraulic fatigue testing equipment at the Track Test Centre of Spoornet, according to the procedures described in its Manual for Railway Engineering which is similar to those of the American Railway Engineering Association (Special Committee on Railway Ties). Seventeen cracked sleepers from the Sishen/Saldanha line and three cracked sleepers from the Coal line were tested in 1988. The same tests were repeated in 1990 on sleepers with cracks running the full length; six came from the Sishen/Saldanha line and three from the De Aar/Noupoort line.

The tests were carried out on the rail seats of the sleepers using a support distance of 660 mm and comprised three separate bending tests (see Figure 2):

*A: Positive bending in compression
*B: Negative bending in compression
*C: Positive bending in compression and tension

In addition the centres of the sleepers were subjected to a negative bending test in compression at a support distance of 1 144 mm (see Figure 3). In all four tests, the sleepers were subjected to repeated loading in compression equivalent to 1,15 times the theoretical cracking moment of the sleepers for at least 5 million cycles. This is equivalent to approximately 10 years of service in the Sishen/Saldanha line. The standard acceptance test for concrete sleepers is carried out for 2 million cycles at the same loading. Table 2 gives some of the test results. In both cases, it was concluded that the positive closure of the cracks on completion of the repeated load tests indicated that the quality of concrete was still adequate and that the bond development between the concrete and the prestressing wires has as yet not been affected by the cracks in the concrete (1).

LABORATORY INVESTIGATION

During the first phase (April 1988) of the laboratory investigation, one cracked sleeper from the Sishen/Saldanha line and half a cracked sleeper from the Coal line, were received. Two years later, three 100-mm cores drilled from each of three sleepers in the Saldanha stockpile, three sleepers from the Sishen/Saldanha line, three sleepers from the De Aar/Noupoort line and three sleepers from the Coal line, were received for additional tests and investigation.

Visual Examination of Sleepers

Sishen/Saldanha line. A horizontal crack, 0,2 mm to 0,35 mm in width, running through the pinholes, occurred in both of the

TABLE 2 - Results of four-point loading static and dynamic tests done on sleepers from the Sishen/Saldanha and De Aar/Noupoort lines (1).

Line and Type of Test	Static Bending Moment kNm P1	P2	Crack Width on Completion of Repeated Load Test, mm	Test Result
Sishen/Saldanha				
Rail Seat, Positive	25,24	25,24	0,07	No defects
Rail Seat, Negative	20,17	20,62	0,06	No defects
Rail Seat, Positive Compression/Tension	22,23	22,23	0,10	No defects
Sleeper Centre, Negative	19,55	20,48	0,06	No defects
De Aar/Noupoort				
Rail Seat, Positive	23,54	23,93	0,07	No defects
Rail Seat, Negative	21,14	21,14	0,06	No defects
Sleeper Centre, Negative	16,94	17,21	0,05	No defects

P1: When a crack is detected optically
P2: When the crack extends to the bottom layer of prestressing wires, observed optically

long vertical and the two end faces, where it was wider, namely 0,4 mm. A distinct vertical crack, 2,5 mm wide in the end faces but quickly reducing to between 0,2 mm and 0,75 mm on the top face, was also present - see the photograph, Figure 4.

Coal line. A horizontal crack running through the pinholes was present. Crack widths on the surface were between 0,35 mm and 0,70 mm but reduced in width within about the first 2 mm. No vertical cracks were present.

Surface Treatment of Sleepers

The sleeper from the Sishen/Saldanha line was cut in half and one half treated with a water repellent which had previously been evaluated in terms of depth of penetration into concrete, active solids content and rate of water vapour and water transmission. Measuring anvils, 20 mm long were fixed in the concrete so that the measuring heads were flush with the surface, at spans of 50 mm, 100 mm and 200 mm, on both halves of the Sishen/Saldanha line sleeper as well as on the one half of the Coal line sleeper. The halves were exposed out of doors and measurements taken with a Demec gauge. From the results presented in Figure 5 it is seen that:

* the treatment effectively controlled expansion and the treated half shrank slightly during the first 30 months
* the untreated granite sleeper expands more than the untreated quartzite sleeper by a factor of about 10
* on the top face of the untreated half of the granite sleeper expansion across the width is about 10 times greater than along the length - expansion measured on the long vertical faces across the height was of the same order as that measured across the width of the top face.

Expansions recorded for the untreated quartzite sleeper across the width of the top face and the height of the long vertical faces, are respectively just more and just less than 0,10 % while it is less than 0,05 % across the length of the top face.

Crack widths in the treated granite sleeper have not changed although some spalling of crack walls is apparent. However, in the untreated granite sleeper crack widths have increased by a factor of between two and four. Crack widths in the untreated quartzite sleeper have remained practically unchanged.

Petrographic Examination

Petrographic thin sections were prepared of the cores drilled from the sleepers from the different lines for examination in transmitted light.

Sishen/Saldanha line. The coarse aggregate used was a Cape granite and the fine aggregate a quartz sand. The quartz content of the granite was between 30 % and 40 % with undulatory extinction angles of between 17^{o} and 38^{o}. The undulatory extinction angles of the quartz sand varied between 15^{o} and 25^{o}. Cracks occurred in the coarse aggregate, running into the mortar, and around the aggregate. Cracks could be empty, filled with isotropic ASR product or with ettringite needles or with both. ASR product was also present in voids.

Coal and De Aar/Noupoort lines. The coarse aggregate in the sleepers was typical of gold mine dump material and contained Witwatersrand quartzite, shale, greywacke and some lava. Quartz boundaries in the quartzite were scalloped and sutured and undulatory extinction angles ranged from 22^{o} to 36^{o}. Cracks occurred in the aggregate, in the mortar or skirted the aggregates. They were sometimes empty but were mostly filled with isotropic ASR product or ettringite or both. ASR product also occurred in voids.

Scanning Electron Microscopy

Examination of gold-coated fracture surfaces of concrete from sleepers of all three lines showed similar features. The ASR products were typical of those commonly found in concrete affected by the reaction, namely, mainly the rosette-type in voids and on aggregate surfaces and the gel-type at the interface between coarse aggregate and cement paste.

Ettringite bands, about 25 μm thick occurred at the coarse aggregate/cement paste interface. The ettringite had a typical acicular habit and could occur as fan-shaped bundles or with the needles perpendicular to the crack walls. Mats of ettringite crystals also occurred on aggregate surfaces and masses of smaller needles in the imprints of reinforcing bars.

Duggan Test

For the Duggan test (2) five cores, 22 mm in diameter and 60 mm long, were drilled from each sleeper. The results of this test are given in Table 3.

TABLE 3 - Results of Duggan Test Done on Cores Drilled From Sleepers Made With Three Different Types of Aggregate.

Source Factory Aggregate		Expansion, (%) at			
	1 day	3 days	6 days	9 days	20 days
Saldanha Stockpile, Un Saldanha, Granite	0,034	0,076	0,094	0,107	0,137
Saldanha Stockpile, Cr Saldanha, Granite	0,062	0,080	0,098	0,116	0,182
Saldanha Line, Un Saldanha, Granite	0 065	0,088	0,121	0,153	0,274
Saldanha Line, Cr Saldanha, Granite	0,099	0,151	0,212	0,246	0,362
Coal Line, Cr Nigel, Quartzite	0,063	0,078	0,100	0,116	0,151
De Aar/N. Line, Cr Nigel, Quartzite	0,074	0,097	0,117	0,127	0,163
De Aar/N. Line, Un De Aar, Dolerite	0,054	0,100	0,130	0,150	0,222
De Aar/N. Line, Un De Aar, Dolerite	0,063	0,090	0,106	0,120	0,153

Un = Uncracked; Cr = Cracked

According to the criterion of the test method an average expansion of 0,1 % and more indicates a deleteriously expansive concrete. According to the test results, the concrete of all the sleepers are potentially deleteriously expansive, even for those made with dolerite aggregate, which after more than 10 years of service do not show signs of cracking.

Expansion at 38 °C and 100 % Relative Humidity

To determine the potential for expansion due to ASR, two sets of measuring anvils were fixed 150 mm apart, on diametrically opposite sides of 100 mm diameter cores about 150 mm long. The cores were wrapped in moist paper towels and stored above water in sealed containers at 38 °C. Measurements were taken with a Demec fitted with a dial gauge capable of registering readings of 2 μm. Table 3 gives the results of those cores which have been measured for one year or more.

TABLE 4 - Results for Expansion of Cores Stored Above Water in Sealed Containers at 38 °C.

Source		Factory	Aggregate	Expansion, %, 386 days		
				a	b	Aver
Saldanha Stockpile,	Un	Saldanha	Granite	0,031	0,026	0,029
Saldanha Stockpile,	Cr	Saldanha	Granite	0,042	0,067	0,055
Saldanha Line,	Un	Saldanha	Granite	0,016	0,030	0,023
Saldanha Line,	Cr	Saldanha	Granite	0,057	0,083	0,070
Coal Line,	Cr	Nigel	Quartzite	0,027	0,014	0,020
De Aar/N. Line	Cr	Nigel	Quartzite	0,037	0,026	0,032

Un = Uncracked; Cr = Cracked

From the results, it appears that uncracked granite sleepers from the stockpile and the railway line do not have the potential to expand further but that cracked sleepers do. The results of measurements taken on the untreated granite sleeper exposed out of doors showed that the concrete is still expanding and expansions of more than 1,5 % are being recorded. The concrete from the cracked quartzite sleepers don't seem to have the potential for further expansion, although the untreated quartzite sleeper from the Coal line exposed out of doors shows expansions as high as 0,10 %.

Tests done in South Africa on concrete specimens made with a wide range of cement/aggregate combinations which were exposed under ASTM C 227 conditions as well as out of doors, showed that the amount of alkali required to cause expansion due to ASR, expressed as Na_2O equivalent in kg/m^3 of concrete, is 4,5 for the Cape granites and 2,0 for the Witwatersrand quartzite (3). Dolerite used in the manufacture of the sleepers, is not potentially alkali reactive. Based on the figures given in Table 1, the Na_2O equivalent/m^3 of the concrete made with the two types of aggregate, would have been respectively about 5,5 and 2,0 and therefore, both combinations would have been potentially deleteriously expansive due to ASR.

SUMMARY

1. Cracking of heat-cured, prestressed concrete railway sleepers was noticed between seven and 12 years after installation.

2. Static and dynamic bending tests done on cracked sleepers from the different lines indicated that the structural

strength was still adequate.

3. In sleepers made with granite coarse aggregate both horizontal and vertical longidutinal cracks were present but in sleepers made with quartzite aggregate only horizontal longitudinal cracking occurs.

3. Cracking was observed only in sleepers made with potentially alkali-reactive granite and quartzite coarse aggregate but not in those made with innocuous dolerite aggregate. Petrographic and scanning electron microscopic examination of cores drilled from sleepers revealed the presence of typical features of ASR only in those made with granite and quartzite coarse aggregates. This seems to favour ASR as the reason for the cracking of the sleepers. Ettringite needles were observed as bands at the coarse aggregate/cement paste interface, as mats on aggregate surfaces and in the imprints of reinforcing bars in sleepers containing granite and quartzite aggregate. The latter two features were also well developed in sleepers containing dolerite aggregate. Although it is possible that delayed ettringite expansion played a contributory role in the overall expansion of cracked sleepers, it appears that ASR is a prerequisite for this to occur.

6. Treatment of one half of a cracked granite sleeper with a water repellent, effectively stopped expansion under out of doors exposure conditions, compared with the untreated half.

7. According to the results of the Duggan test done on cores drilled from sleepers, concrete made with all three types of aggregate was potentially deleteriously expansive. There is, however, doubt whether the results of this test have any significance. Measurements taken on 100 mm cores stored under ASTM C 227 conditions, indicated that some of the sleepers still had the potential to expand.

REFERENCES

1. Brand, J.H.B., 1991, "Alkali-Aggregate Reaction in Concrete Sleepers", Railways, 37.

2. Duggan, R. and Scott, F., 1986, "Potential New Test for Alkali-Aggregate Reactivity", ICAAR Seventh Conference Proceedings 319, Ottawa, Canada.

3. Oberholster, R.E., 1989, "Alkali-Aggregate Reaction - A Problem for the Concrete Industry", Holderbank Eigth Stone and Ready-Mixed Conference, Mabula, South Africa.

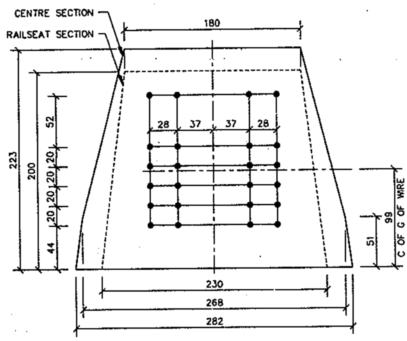

Figure 1 Reinforcing wire layout of Saldanha sleepers, 24 x 4 mm wires

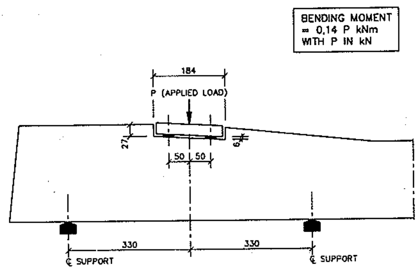

Figure 2 Support for rail seat repeated load test

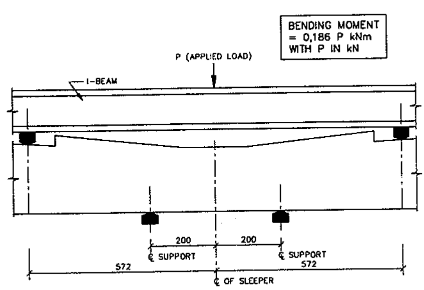

Figure 3 Support for sleeper centre repeated load test

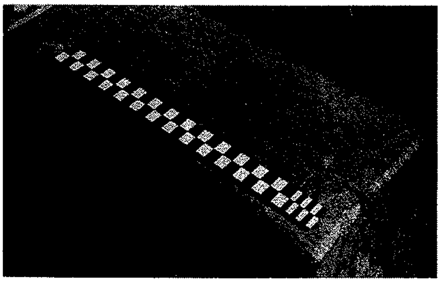

Figure 4 Photograph of top face of cracked Saldanha sleeper

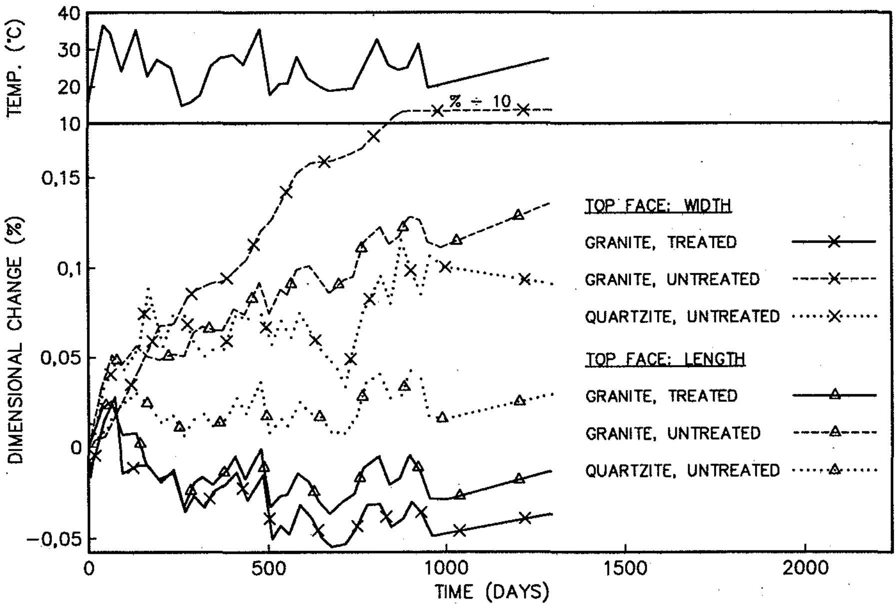

Figure 5 Dimensional changes measured on the top faces of untreated halves of sleepers and one half that was treated with a water repellent