MICROSTRUCTURAL FEATURES OF RAILSEAT DETERIORATION IN CONCRETE TIES

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ABSTRACT: Deterioration has been observed in concrete railroad ties, producing a loss of up to 40 mm at the railseat and leaving a rough surface formed mainly by aggregates. This deterioration occurs largely in cold and wet regions of western Canada and northern United States. The purpose of the present investigation was to deduce the processes responsible for this deterioration. Proposed mechanisms included abrasion, erosion, hydraulic pressure, freeze-thaw cycles, and chemical deterioration. Microstructural features associated with each mechanism were explored using laboratory concrete subjected to known deterioration processes or through computer simulations. Microstructural studies utilized scanning electron microscopy and x-ray diffraction. Based on the microstructural evidence, it was concluded that the railseat deterioration is produced by a combination of abrasion and freeze-thaw or hydraulic pressure.

INTRODUCTION

In most countries of the world, there is a growing interest in the use of concrete railroad ties. Concrete ties are economical and their superior structural properties increase the stability and performance of the track structure. However, deterioration of concrete ties at the railseat has recently been observed in North America. In its preliminary stages, the deterioration produces a shallow imprint of the rail pad on the surface of the concrete tie. More severe deterioration causes loss of paste at this surface, which decreases stability of the fastening system. The damage appears to affect only the paste, leaving large aggregates generally intact and protruding after the paste has been removed. The worst cases have involved loss of as much as tens of millimeters of material from the railseat. The most severe deterioration has been observed in cold and wet climates such as that in western Canada and the northwestern United States and on graded and curved track.

Three processes were considered to explain the observed damage: (1) hydraulic pressure; (2) freeze-thaw; (3) abrasion; and (4) chemical deterioration. Hydraulic pressure would result from water trapped between the pad and the railseat being forced into the concrete pores due to high wheel loads (Fowler, personal communication, 1991). If the resulting pore pressure exceeds the concrete tensile strength, cracks may form. Freeze-thaw damage may occur if sufficient water between the pad and railseat is forced into the concrete to reach critical saturation (pores filled to at least 91% of their volume), causing the air-void system to become incapable of relieving the hydraulic pressures generated from freezing, and resulting in cracking of the paste (Powers 1945). The third process is abrasion by locomotive sand or metal filings. Locomotive sand is frequently applied to the rail in order to improve traction, and metal filings are produced during regular track grinding. If these materials accumulate under the pad, they may act as abrasive media to damage the railseat surface. Recent investigations of concrete railroad ties have focused on damage due to some combination of delayed ettringite formation (DEF) and alkali-silica reaction (ASR) (Shayan and Quick 1992). These are expansive processes that are known to produce cracks and deterioration in concrete.

To determine which process is responsible for the railseat deterioration, microstructural features of the deteriorated ties were compared to features of concrete subjected to various deterioration processes (freeze-thaw and abrasion). Because we were not able to reproduce damage due to hydraulic pressure, we developed a computer model to simulate microstructural features of this process. Microstructural examination was carried out in which we specifically looked for evidence of DEF and ASR.

We also studied erosion using a laboratory apparatus called a Jetmil that had been developed at Pandrol Ltd., Weybridge, United Kingdom to simulate railseat deterioration. The Jetmil sprays the concrete surface with water at high pressure, which reproduces visual features of the damage observed in the field. Based on the microstructural features produced by the Jetmil, we concluded that it operates by a process of erosion (abrasion due to water).

This study was described in more detail in the MS thesis of the first writer (Bakharev 1994).

EXPERIMENTAL PROCEDURES

Both laboratory concrete and unused concrete ties were exposed to a deterioration process (abrasion, erosion, or freeze-thaw) and investigated to determine the microstructural features of the deterioration. Microstructural features of concrete deteriorated in the field were also investigated. Microstructural examinations utilized a scanning electron microscope (SEM), primarily using backscattered electron imaging (BEI) of polished specimens to facilitate crack identification. Some polished specimens were also analyzed for qualitative chemical composition using an energy dispersive x-ray spectrometer (EDS) attached to the SEM. A few specimens were analyzed for mineralogical composition using X-ray diffraction (XRD).

Materials

One new tie, two field ties, and laboratory concrete were studied. The new tie was provided by CXT Corp., Spokane,

TABLE 1. Mix Proportions for Laboratory Concrete

Material (1)	Amount (2)
Type III cement	414 kg/m^3
Water	132 kg/m^3
Coarse aggregate	1,175 kg/m^3
Fine aggregate	802 kg/m^3
Air entraining agent	0.495 L
Superplasticizer	3.390 L
Water-cement ratio	0.34

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Wash. It was manufactured with a target air content of 5.5% and a compressive strength of 50 MPa. The two field ties had experienced railseat deterioration. One had been installed near Albreda, British Columbia, Canada, and the other near Pasco, Wash. The Albreda tie showed the more severe deterioration. Laboratory concrete beams for freeze-thaw tests were fabricated using a mix design (Table 1) developed to provide air content, workability, and strength properties typical of manufactured railroad ties.

Deterioration Tests

Jetmil

The Jetmil was clamped to the concrete specimen and used to spray water a high pressure (41 MPa) onto the test surface for 10 min (Fig. 1). The exposure left an eroded area 0.1 m in diameter with characteristics similar to the deteriorated railseats, in particular loss of mortar with the coarse aggregates left protruding from the surface.

Abrasion

A procedure was developed to reproduce abrasion using silicon carbide grit comparable in size to typical sand particles. The silicon carbide was applied on a 3.2-mm-thick polyethylene rubber pad, which acts as a deformable body allowing the grit to maneuver around aggregate particles and preferentially remove paste during the abrasion process. Propylene glycol was used as a lapping fluid. The dimensions of the concrete specimen were 40 mm by 25 mm. The specimen was pressed down by hand onto a rotating wheel (approximately 60 revolutions per min) while a mixture of silicon carbide grit and propylene glycol was applied to the rubber pad. Grinding continued until inspection showed that approximately 1 mm of material had been removed from the specimen surface.

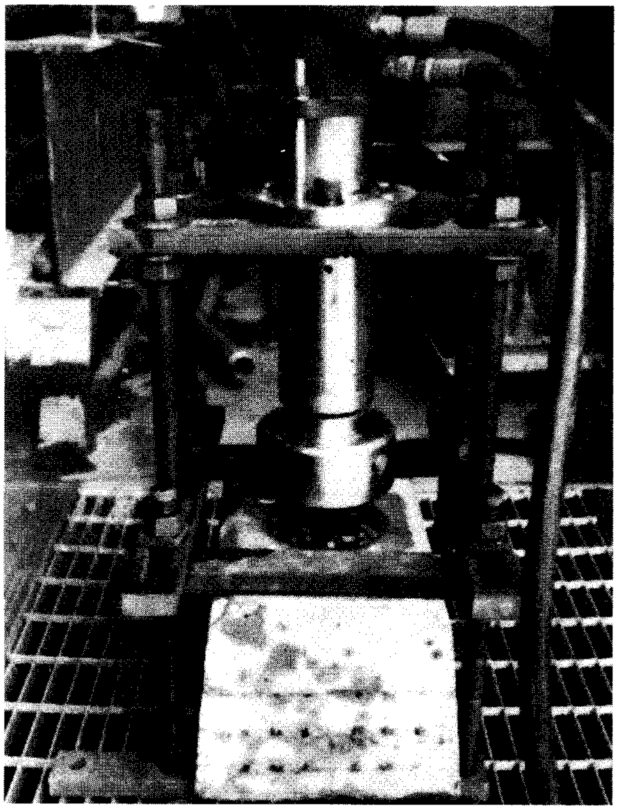

FIG. 1. Jetmil Apparatus

Freeze-Thaw

Freeze-thaw treatment followed ASTM C 666-84, procedure B (freezing in air and thawing in water). Concrete bars, 80 × 80 × 250 mm, were subjected to 300 cycles of freezing and thawing (−17.8°C and 4.4°C) with a cycle duration of 4 h.

Hydraulic Pressure

Preliminary efforts to simulate hydraulic pressure in the laboratory were not satisfactory. Concrete was exposed to 60 cycles of pressure (each cycle 2 min at a pressure of 7.9 MPa followed by 30 s of relief), the so-called Washington test (Almond and Janssen 1991). The test produced no observable deterioration. Therefore these efforts were discontinued and microstructural effects of hydraulic pressure were simulated using a computer model (described later).

Microstructural Studies

Specimens were cut from the concrete and examined for evidence of deterioration. The surface viewed in the microscope was perpendicular to the outer surface of the sample, allowing examination of both the outer surface and the subsurface microstructure. Each specimen was oriented such that a horizontal line in the micrograph was parallel to the outer surface of the sample.

Microstructural features were characterized using an SEM (Hitachi model S-582) equipped with an EDS (Princeton-Gamma-Tech IMAGIST 4000). Specimens were first impregnated with acrylic resin, polished, then examined using BEI. The impregnation is necessary to prevent damage during polishing. In this case, an impregnation technique was used that does not require drying of the specimen, thereby avoiding shrinkage cracks, which would otherwise have occurred (Struble and Stutzman 1989). Mineralogical compositions were determined using an automated XRD (Rigaku Geigerflex).

MICROSTRUCTURAL RESULTS

Jetmil

Although in visual appearance the Jetmil samples were very similar to the deteriorated railseats, the microstructural features of samples after the Jetmil test had essential differences compared to the field ties. The samples had a rough and eroded surface, with considerable pitting (Fig. 2) and voids to a depth of several millimeters, attributed to dissolution.

Abrasion

In visual appearance, the abraded samples were also very similar to the deteriorated ties. Samples had preferential loss

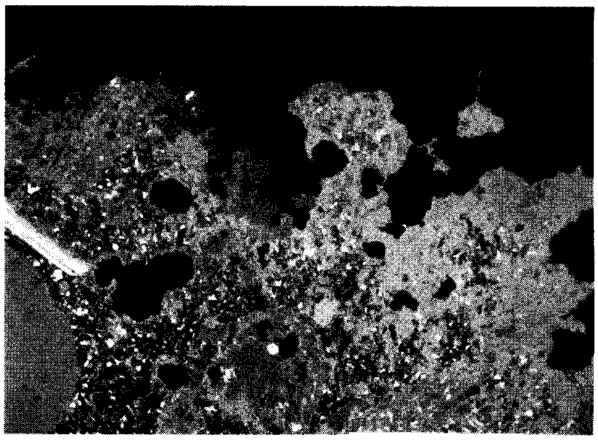

FIG. 2. BEI of Surface Region of Unused Tie Exposed to Jetmil

of cement paste from the surface, with little loss of fine and coarse aggregates due to their higher hardness. An abraded concrete sample is shown in Figs. 3 and 4. Characteristic features of the microstructure were: (1) microcracking along the interface between cement paste and aggregate (approximately 5 μm wide); (2) air voids open at the surface; (3) microcracks (<1 μm wide) extending inward approximately 20 μm) from air voids open at the surface, a rare feature in specimens exposed to abrasion but more frequent in deteriorated railseats (discussed later).

Freeze-Thaw

Visual examination of concrete subjected to 300 freeze-thaw cycles did not reveal any signs of deterioration. However,

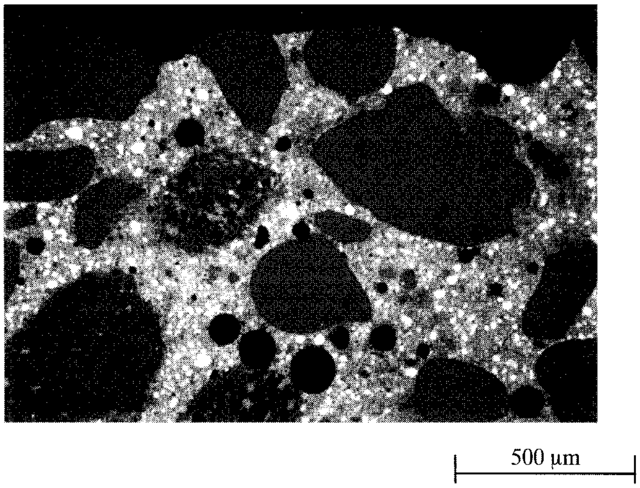

FIG. 3. BEI of Surface Region of Unused Tie Subjected to Abrasion

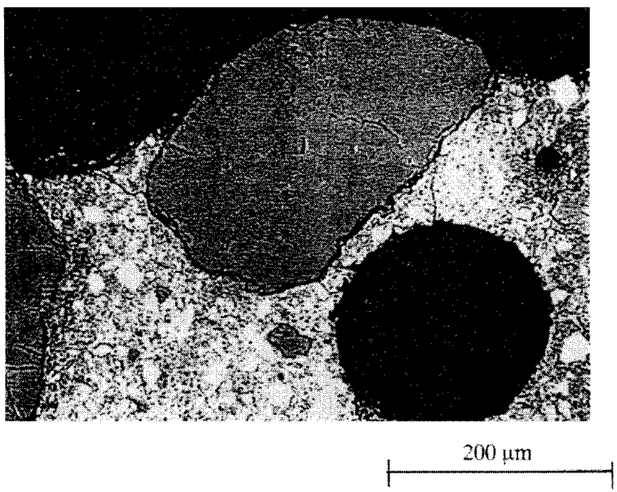

FIG. 4. BEI of Surface Region of Laboratory Concrete Subjected to Abrasion

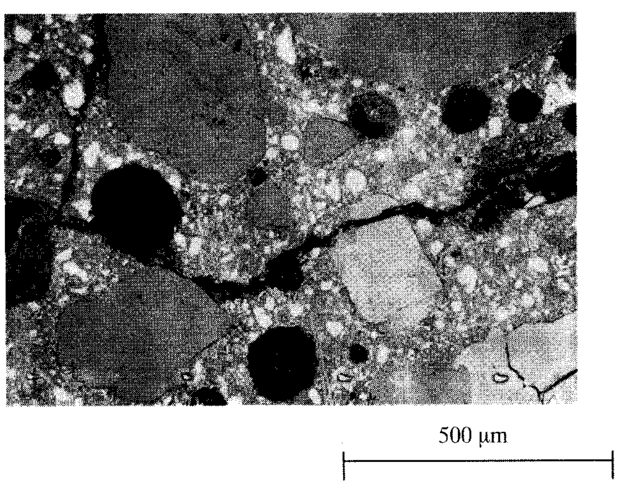

FIG. 5. BEI of Interior Region (5.2 mm from Surface) of Laboratory Concrete Subjected to Freeze-Thaw Cycles

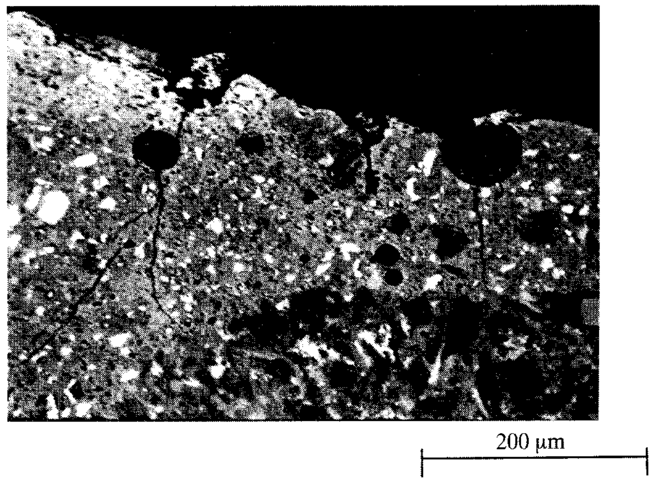

FIG. 6. BEI of Surface Region of Pasco Tie

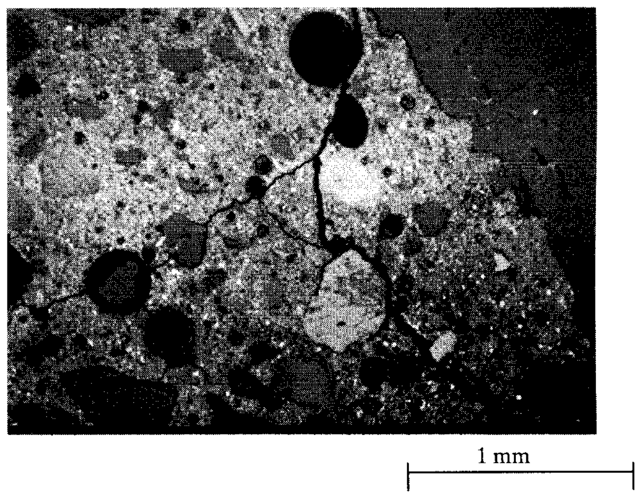

FIG. 7. BEI of Interior Region (15 mm from Surface) of Albreda Tie

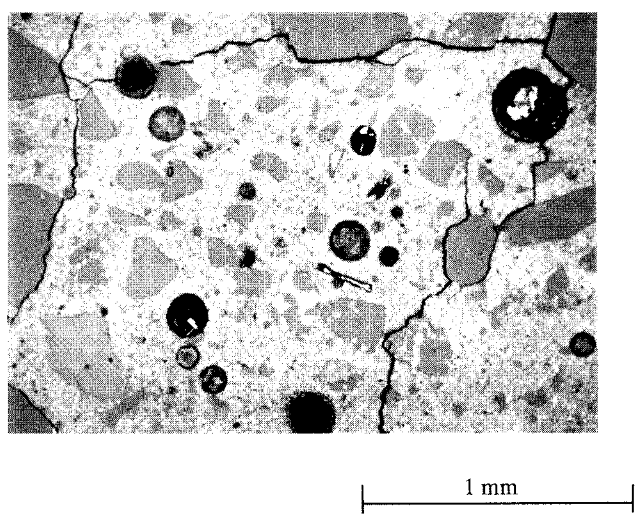

FIG. 8. BEI of Interior Region of Albreda Tie

SEM examination showed considerable microcracks (10–20 μm wide). The laboratory concrete contained vertical microcracks, extending from the surface to depths of 20 mm or more and spaced 10–15 mm apart. Horizontal microcracks were observed at depths of 5 or 6 mm (Fig. 5). The unused railroad tie had nearly vertical microcracks extending only 2–3 mm inward from the surface, spaced 20–30 mm apart, and horizontal cracks at a depth of 200 μm.

Compared to the laboratory concrete, the unused railroad tie had vertical cracks that were much shorter and more widely spaced, and horizontal cracks that were situated much closer to the surface. Because the water-cement ratio of the laboratory concrete and the unused tie were the same, the differences are attributed to the effects of heat treatment during curing of the railroad tie.

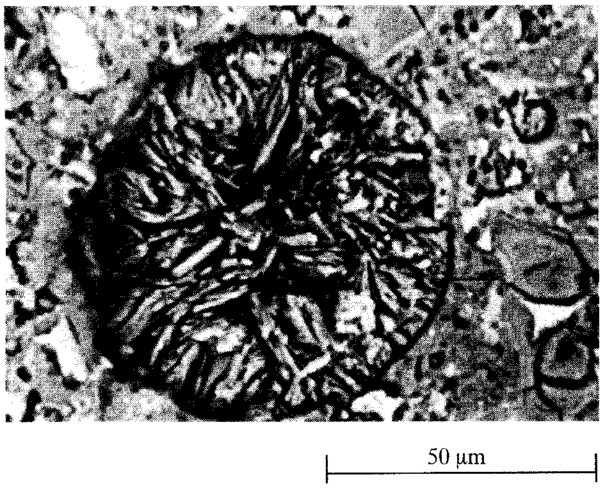

FIG. 9. BEI of Interior Region of Albreda Tie Showing Ettringite Crystals in Air Void

Pasco Tie

The surface layer of the Pasco tie (up to 1 mm inward) was quite dense, while the interior was more porous (Fig. 6), with this porous region extending more than 10 mm inward from the surface. Air voids were observed that were open at the surface (Fig. 6). The tie had vertical microcracks extending inward, often more than 15 mm from the surface. No horizontal cracks were observed. The main features of deterioration at the surface resembled those of the abraded samples: cracks along the interface between paste and aggregate, air voids open to the surface, and cracks extending inward from surface air voids. However, the vertical cracks were many times deeper than those observed in the abraded specimens.

Albreda Tie

The Albreda tie showed vertical microcracks extending more than 15 mm deep into the concrete (Fig. 7) and horizontal microcracks at a depth of 6 mm (Fig. 8). These cracks were typically about 10–20 μm wide. This combination of cracks was similar to that observed in the freeze-thaw specimens.

Many air voids, both near the surface and deep in the specimens, were filled by needle-shaped crystals (Fig. 9) contain-

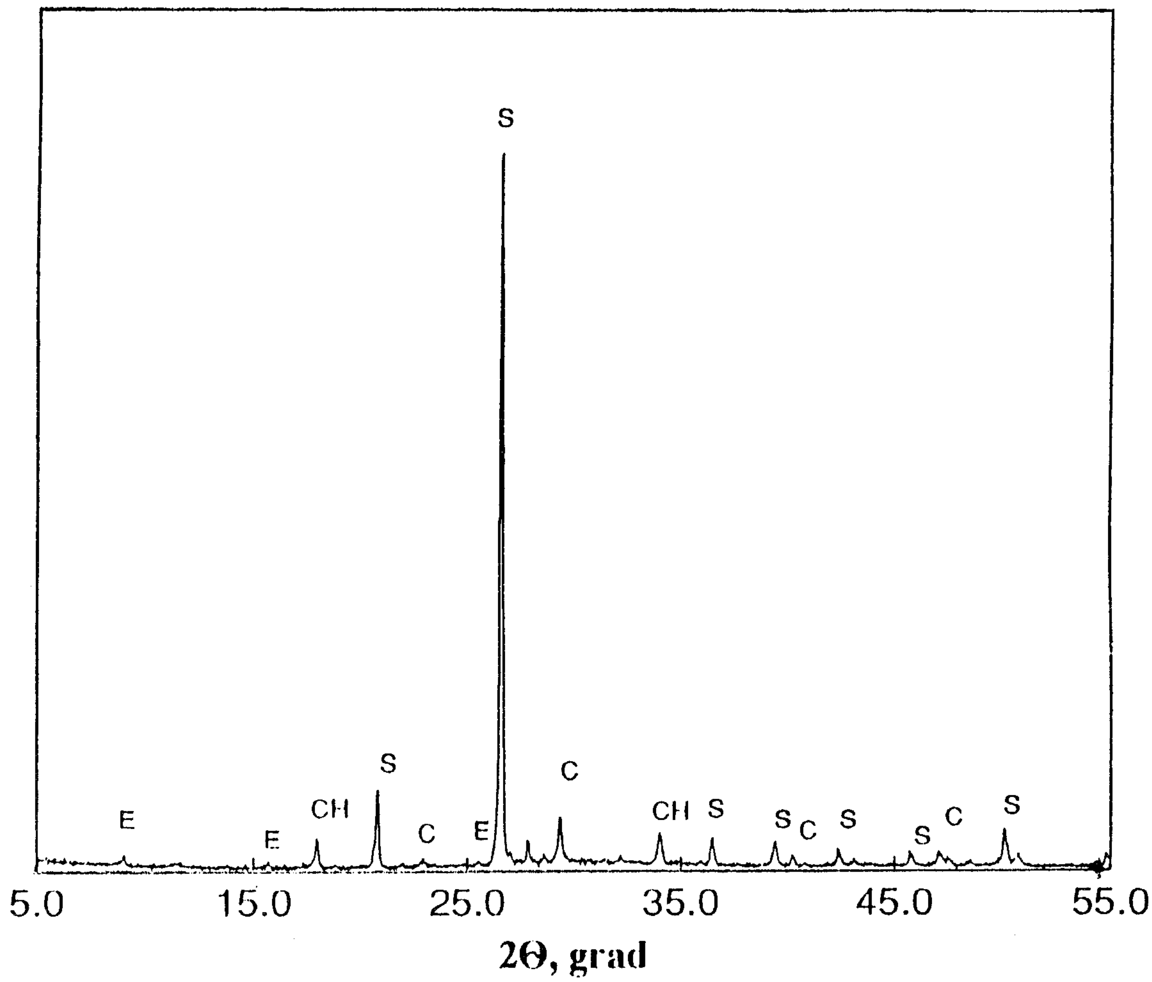

FIG. 10. XRD Spectrum of Mortar from Deteriorated Surface of Albreda Tie—E-Ettringite, CH-Calcium Hydroxide, S-Silica (Quartz), C-Calcium Carbonate (Calcite)

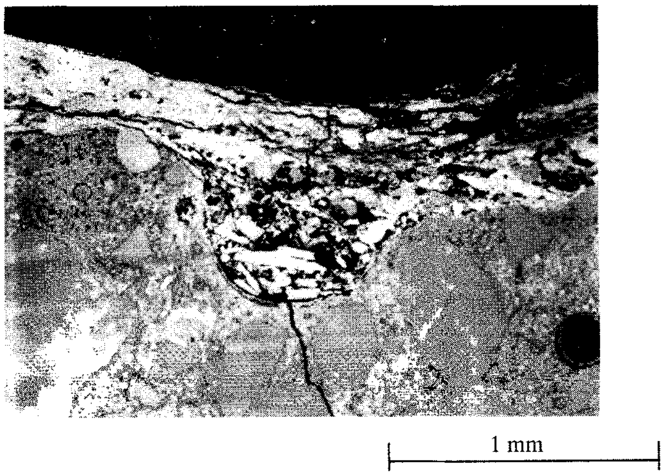

FIG. 11. BEI of Surface Region of Albreda Tie

ing primarily Ca, Al, and S (by EDS). The XRD analysis showed the presence of considerable ettringite in this concrete (Fig. 10). Thus it appears that the crystals filling these air voids is ettringite. Similar crystals were also observed in vertical cracks deep in the specimen. Examination from the surface to a depth of 15 mm from the surface showed that ettringite had precipitated in most air voids.

A white band, approximately 2 mm thick, was observed on the railseat surface of the Albreda tie (Fig. 11). An EDS analysis of this band showed the presence of Ca and Si (major), Al and Fe (minor), and Mg and S (trace). It does not appear to be a carbonated layer but it clearly has a different composition and microstructure from ordinary cement hydration products. On the underside of this band in the center of Fig. 11 there is a depression on the concrete surface containing large, very bright, elongated crystals. EDS analysis of these crystals revealed only Fe, suggesting that the crystals may be metallic iron, iron oxide, or iron hydroxide. The material probably came from the rail.

New Ties

The unused tie showed no cracks or other signs of deterioration. An EDS analysis of air voids did show some accumulation of potassium. No ettringite was observed by SEM or XRD.

HYDRAULIC PRESSURE

Because efforts to reproduce hydraulic pressure in the laboratory were not successful, a computer model was developed to predict microstructural features of the deterioration.

Stress Distribution at the Railseat

Talbot and coworkers in the 1920's carried out an experimental investigation of the distribution of pressures in railroad ties and ballast (Zaremski et al. 1980). For a section of tie one unit long, the vertical unit pressure at the edge was assumed to P_0, and the vertical unit pressure at a distance x from the edge was P. If the total load on the tie is P, and l is the length of the tie, then the total load that can be carried by a section of tie without being forced into the ballast is

$$\frac{P}{l} = \frac{2P_0 k}{f \cos\theta} \exp\left(fb \cos\frac{\theta}{2k} - 1\right) \quad (1)$$

where k = constant; θ = angle between the load and the direction normal to the tie surface (the angle of repose); f = coefficient of friction between the tie and the ballast; and b = width of the tie. The maximum pressure occurs at some point away from the edge of the tie, and the ultimate supporting power of the tie increases rapidly with its width.

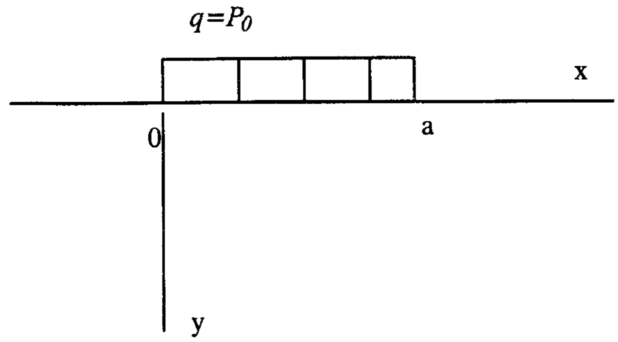

FIG. 12. Cross Section of Tie Showing Simplified Diagram Used for Modeling

Although the distribution of hydraulic pressure is not uniform along its length or width, to analyze the load beneath the rail and rubber pad one can assume uniform distribution of pressure, because the pad width is less than the tie length or width. Stress from the train wheel is conducted through the rubber pad to the concrete tie, producing a uniformly distributed load. The pressure applied to any water under the pad is the same as the pressure applied to the surface of the tie, P_0. So the following boundary conditions are valid in concrete beneath the rubber pad

$$q = P_0 \text{ and } P = P_0 \qquad x \in [0, a] \quad (2)$$

$$q = 0 \text{ and } P = 0 \qquad x \notin [0, a] \quad (3)$$

where a = width of the rubber pad; q = uniformly distributed load on the track; and P = pressure on the surface of concrete and the water. Because the tie is much longer than a pad, the tie is assumed to be a semiinfinite body for the purposes of analysis. The orientation of axes are as follows: z is parallel to the long dimension of the tie, x is parallel to the rail, and y is the vertical direction (Fig. 12).

Water filling microcracks and pores may be assumed to obey Darcy's law for laminar flow through a porous medium (Young 1988)

$$V = K\nabla P \quad (4)$$

where V = rate of flow; K = permeability constant; P = pressure; and $\nabla = (\partial/\partial x) + (\partial/\partial y) + (\partial/\partial z)$. If all the voids are filled with water, then mass conservation governs flow

$$\nabla V = \frac{\partial V}{\partial x} + \frac{\partial V}{\partial y} + \frac{\partial V}{\partial z} = 0 \quad (5)$$

Substitution of (4) into (5) gives

$$K\left(\frac{\partial^2 P}{\partial x^2} + \frac{\partial^2 P}{\partial y^2} + \frac{\partial^2 P}{\partial z^2}\right) = 0 \quad (6)$$

If $K \neq 0$, then $(\partial^2 P/\partial x^2) + (\partial^2 P/\partial y^2) + (\partial^2 P/\partial z^2) = 0$. The solution of this equation is

$$P(x, y) = \frac{P_0}{\pi}\left[\arctan\left(\frac{x}{y}\right) - \arctan\left(\frac{x-a}{y}\right)\right] \quad (7)$$

Fig. 13 shows the distribution of pressure calculated using (7).

Stress Distribution due to Uniformly Distributed Load

For the boundary conditions given by (2) and (3), the distribution of stresses due to a uniform load applied on some length to an elastic semiinfinite body (Fig. 12) is the following (Amenzade 1979):

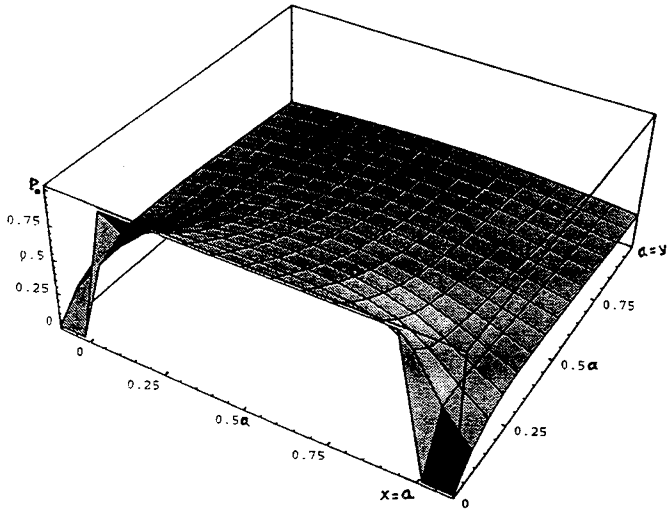

FIG. 13. Distribution of Stresses (σ_1/a in x-Direction, σ_2/a in y-Direction, and σ_3/P_0 in z-Direction) due to Application of Hydraulic Pressure at Railseat

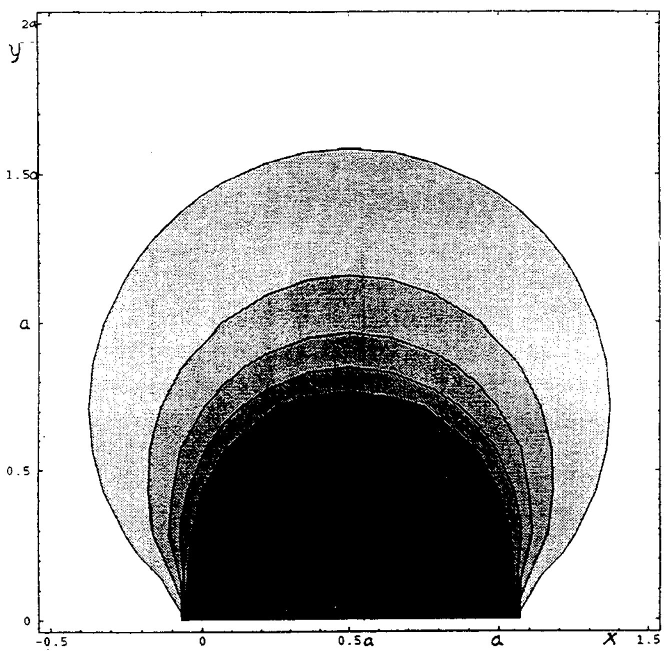

FIG. 14. Distribution of Main Stress (σ_1/a) through Tie

$$\sigma_{xx} = \frac{-P_0}{\pi}\left[Q_2(x, y) - Q_1(x, y) - \frac{\sin 2Q_1(x, y) - \sin 2Q_2(x, y)}{2}\right] \tag{8}$$

$$\sigma_{yy} = \frac{-P_0}{\pi}\left[Q_2(x, y) - Q_1(x, y) + \frac{\sin 2Q_1(x, y) - \sin 2Q_2(x, y)}{2}\right] \tag{9}$$

$$\sigma_{xy} = \frac{P_0}{\pi}[\cos 2Q_2(x, y) - \cos 2Q_1(x, y)] \tag{10}$$

where $Q_1(x, y) = \arctan(x/y)$; and $Q_2(x, y) = \arctan[(x - a)/y]$. Stresses along the z-axis are assumed to be determined by the prestress

$$\sigma_{zz} = f_{ps} < -P_0 \tag{11}$$

By convention, the principal stresses along the main axes are $\sigma_1 > \sigma_2 > \sigma_3$. Then

$$\sigma_1 = \frac{\sigma_{xx} + \sigma_{yy}}{2} + \sqrt{\left(\frac{\sigma_{xx} - \sigma_{yy}}{2}\right)^2 + \sigma_{xy}^2} \tag{12}$$

$$\sigma_2 = \frac{\sigma_{xx} + \sigma_{yy}}{2} - \sqrt{\left(\frac{\sigma_{xx} - \sigma_{yy}}{2}\right)^2 + \sigma_{xy}^2} \tag{13}$$

$$\sigma_3 = f_{ps} < -P_0 \tag{14}$$

Distribution of σ_1 is shown in Fig. 14.

Superposition of Stresses

The stress in the vicinity of the railseat is determined by the superposition of stresses due to uniform load and hydraulic pressure. To evaluate the effect of superposition on concrete failure, let us apply Griffith's theory. Any pore in the material may be assumed to have an elliptical shape with $c >> \rho$, where ρ is the radius of the pore (at the crack tip) in the direction most susceptible to cracking (Fig. 15).

$$\sigma_t = \sigma_1' \quad \text{if } 3\sigma_1' + \sigma_3 > 0 \tag{15}$$

and

$$\sigma_t = \frac{-(\sigma_1' - \sigma_3)^2}{8(\sigma_1' + \sigma_3)} \quad \text{if } 3\sigma_1' + \sigma_3 < 0 \tag{16}$$

where

$$\sigma_1' = P(x, y) + \sigma_1 \tag{17}$$

Because σ_3 is constant, determined only by precast stresses, development of cracks is determined by σ_1'. After substituting (7) and (12) into (17)

$$\sigma_1'(x, y) = \frac{\sqrt{2}P_0}{2\pi}\sqrt{1 - \cos[2Q_2(x, y) + 2Q_1(x, y)]} \tag{18}$$

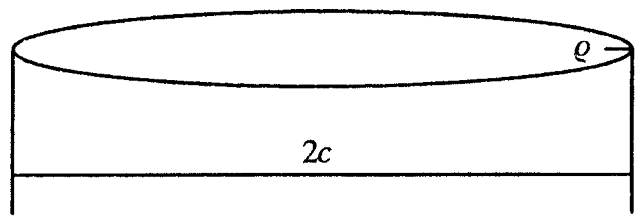

FIG. 15. Diagram of Elliptical Crack Showing Length (2c) and Radius of Curvature (ρ)

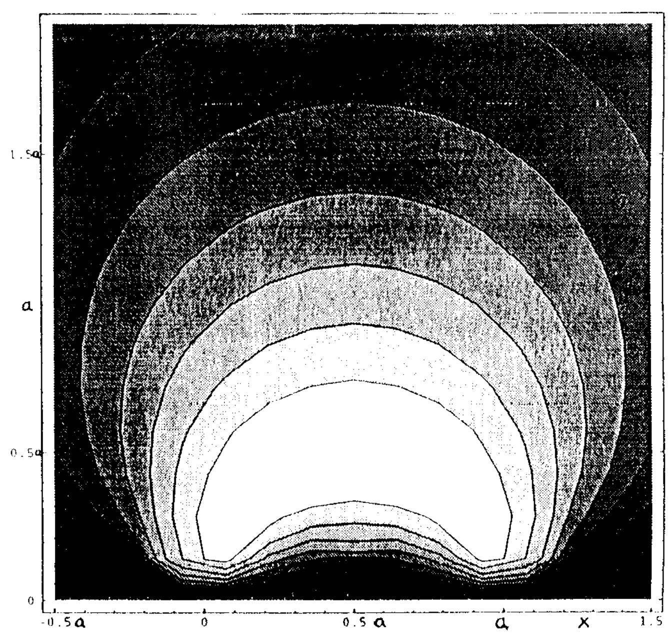

FIG. 16. Distribution of Stresses (σ_1/a and σ_2/a) due to Superposition of Compression Load and Hydraulic Pressure

This function is positive for all (x, y) and has a maximum equal to P_0/π on the arc with diameter a and center at the point (a/2, 0) (Fig. 16).

The region most susceptible to cracking due to hydraulic pressure is where maximum principal stresses occur. That region is on the arc (Fig. 16) where the effective stresses are tensile ($\sigma_1' > 0$) and equal to P_0/π. The most dangerous zone is in the arc region between $a/3$ and $2a/3$, beneath the surface.

These stresses are especially damaging to concrete because they are cyclical (one cycle for each wheel passing the tie) and therefore may cause fatigue failure. Repeated loading of concrete at about 55% of its static strength is known to cause fatigue failure (Mindness and Young 1981, p. 373). However, the growth rate of cracks filled with water is restricted by the velocity with which water moves through the network of cracks. Therefore crack propagation may be slowed by reducing permeability of the upper layer of concrete on the railseat.

ANALYSIS

Based on microstructural evidence, it appears that deterioration in the Jetmil is quite different from railseat deterioration in the field. In the Jetmil, water has obviously removed material from the concrete surface by erosion and has flowed into the concrete and caused dissolution of paste and soluble portions of the aggregate.

Abrasion reproduced several features observed in the deteriorated ties. Abrasion created microcracks near the surface in paste and around aggregates. It caused preferential loss of paste to a depth of 0.5–1 mm. Finally, it caused air voids to be exposed at the surface. However, a more powerful mechanism is needed to explain the creation of microcracks to a depth of 20 mm.

Based on mathematical modeling, hydraulic pressure, in particular cyclic pressure in combination with mechanical load, is expected to cause deep vertical cracks, normal to the surface. Such cracks were observed in the Pasco tie. But this process does not explain the horizontal cracks observed at some depth beneath the surface in the Albreda tie.

The cracking observed in the Albreda tie, the combination of vertical cracks extending from the surface and horizontal cracks at some depth, were observed in concrete subjected to freeze-thaw cycles. Because the depth of damage was much greater in the Albreda tie than in the unused tie tested in the laboratory, it is suggested that the field tie was more fully saturated with water when freezing occurred, perhaps due to the simultaneous action of hydraulic pressure.

The observation of ettringite in air voids and cracks of the Albreda tie raises the possibility that DEF is responsible for the railseat deterioration. Delayed ettringite has been observed in many deteriorated precast concrete structures (Heinz and Ludwig 1987).

Ettringite is a normal product of cement hydration and does not usually cause the concrete to deteriorate (Scrivener and Taylor 1993). It forms due to the reaction between C_3A, $C\bar{S}H_2$, and water, and serves to slow the hydration of C_3A and thereby prevent flash set. After some time (several hours or a few days), the $C\bar{S}H_2$ is typically used up and any remaining C_3A reacts with already formed ettringite to produce calcium monosulfoaluminate ($C_4A\bar{S}H_{12}$). If this monosulfoaluminate later reacts with external sulfate ions to produce ettringite, the concrete deteriorates (a process known as sulfate attack).

Ettringite is not stable at high temperatures, and is not found in concrete cured at temperatures of 70°C or greater. In such concrete, the alumina and sulfate occur as monosulfoaluminate or in a highly substituted calcium-silicate-hydrate. At cooler temperatures these phases slowly release their alumina and sulfate, allowing ettringite to precipitate. It is this delayed ettringite that is responsible for the deterioration described by Heinz and Ludwig (1987). Delayed ettringite appears to occur only in concrete that is water saturated and has been subjected to repeated cycles of wetting and drying, ASR, or some other deterioration process.

Delayed ettringite formation has been observed in precast concrete made of high-strength concrete and heat treated during production. Some precast structures have shown damage characterized by cracks emerging from the edges of the building components and by loss of bond between cement paste and coarse aggregate. It was found that the reaction may be suppressed by reducing the molar ratio of SO_3 and Al_2O_3 to 0.55 and limiting the SO_3 to 2.5% in the cement. Heinz et al. (1989) concluded that to prevent subsequent damage due to DEF the temperature of steam curing should not exceed 70°C, and the ratio of $(SO_3)^2$/(active Al_2O_3) should be below 2. Active Al_2O_3 refers to that which is bound in the aluminate phase and not in the ferrite phase.

By means of scanning electron microscopy, Heinz and Ludwig (1987) showed that the new phases are formed and degradation originates in the contact zone between paste and aggregate. They also observed that a heat-treated mortar with a water-cement ratio of 0.5 does not expand when the content of air voids is increased by the use of an air-entraining agent. The delayed formation of ettringite that occurs in the air voids does not appear to cause a crystallization pressure (Heinz and Ludwig 1987, Fig. 8).

There are a number of investigations (Shayan and Quick 1992; Regourd et al. 1981; Jones and Poole 1987) in which ettringite and ASR gel have been found to exist together, but it is not clear which mechanism was primarily responsible for the observed deterioration. Shayan and Quick suggested that differential expansion and microcracking due to ASR preceded formation of ettringite in several Australian railroad ties.

Delayed ettringite was observed in the present study, both in air voids and in microcracks in the Albreda tie. However, no deposition of ettringite was observed at paste-aggregate interfaces. From these microscopical observations, we conclude that DEF was not a factor in railseat deterioration of the ties.

Although it appears that ettringite did not contribute directly to the development of stresses, it is likely that air voids filled with ettringite were rendered ineffective, making the concrete more susceptible to freeze-thaw damage. The coincidence in the Albreda tie of DEF in air voids and in cracks that were apparently produced by freeze-thaw cycles supports this hypothesis.

The occurrence of DEF in the Albreda tie but not in the Pasco tie suggests that some factor other than field exposure is involved in DEF. The XRD analysis of the new tie revealed the presence of monosulfoaluminate, and EDS analysis showed a concentration of potassium in air voids. Such juxtaposition of monosulfoaluminate and alkali may reflect a link between alkalies and DEF, as has been suggested in other cases of railroad tie deterioration.

It is probably worth noting how difficult it usually is to deduce what is responsible for deterioration of concrete in the field. Field concrete is exposed to a number of deterioration processes. Evidence for a particular process does not mean that the process caused the deterioration.

Based on microstructural observations, railseat deterioration may be divided into the following three levels:

1. Minor deterioration with no deep cracking is attributed to abrasion.
2. Intermediate deterioration is attributed to hydraulic pressure superposed with mechanical load, or freeze-thaw. Deterioration is characterized by cracking of the cement paste near the surface and visible loss of particles. As it progresses, deeper cracks are produced and material is lost from the railseat.

3. Major deterioration with deep cracking accompanied by loss of a significant amount of material at the railseat is attributed to hydraulic pressure or freeze-thaw. It is possible that water saturation due to hydraulic pressure allows damage on freezing.

Microstructural modifications can improve the durability of concrete railroad ties. Additional research is necessary to find the paste microhardness, proportion of entrained air, and minimum permeability needed to provide resistance to abrasion, freeze-thaw cycles, and hydraulic pressure.

CONCLUSIONS

The main processes responsible for railseat deterioration railroad ties are abrasion, hydraulic pressure, and freeze-thaw cycles.

Deterioration in the Jetmil is caused by erosion. Erosion in a high-pressure water spray is associated with formation of a very rough surface and creation of voids at some depth (mm). The Jetmil test does not reproduce the processes responsible for railseat deterioration.

Concrete abrasion against a resilient body causes formation of a rough surface with preferential loss of paste. Such abrasion is characterized by small microcracks around aggregates and in the paste, and exposure of air voids at the surface. Abrasion contributes to deterioration of railroad ties in wet conditions and may be the main mechanism in dry climates.

On the basis of mathematical modeling, hydraulic pressure is expected to cause deep vertical cracks, normal to the surface, probably originating from air voids. Modeling the superposition of compressive load and hydraulic pressure suggested the existence of a maximum tensile stress at some depth from the surface. Such features were observed in the Pasco tie.

The microstructure of freeze-thaw deterioration is characterized by deep vertical cracks and horizontal cracks some distance from the surface. These features were observed in the Albreda tie.

Railseat deterioration is attributed to the combined effects of abrasion, freeze-thaw, and/or hydraulic pressure. The net contribution of each mechanism is probably a function of specific field conditions.

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