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Influence of surface abrasion on creep and shrinkage of railway prestressed concrete sleepers

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Abstract. Ballasted railway track is very suitable for heavy-rail networks because of its many superior advantages in design, construction, short- and long-term maintenance, sustainability, and life-cycle cost. The sleeper, which supports rail and distributes loads from rail to ballast, is a very important component of rail track system. Prestressed concrete is very popular used in manufacturing sleepers. Therefore, improved knowledge about design techniques for prestressed concrete (PC) sleepers has been developed. However, the ballast angularity causes differential abrasions on the soffit or bottom surface of sleepers. Furthermore, in sharp curves and rapid gradient change, longitudinal and lateral dynamics of rails increase the likelihood of abrasions in concrete sleepers. This paper presents a comparative investigation using a variety of methods to evaluate creep and shrinkage effects in railway prestressed concrete sleepers. The outcome of this study will improve the material design, which is very critical to the durability of railway track components.

Keywords: prestressed concrete, sleepers, crossties, creep, shrinkage

1. Introduction

The railway has been developed for decades and it's believed that the safest transportation system for transporting passengers and heavy haul. Two main components of rail track consist of superstructure and substructure. The superstructure contains rails, rail pad, fastening system, and sleepers. The ballast, sub-ballast (or capping layer) and subgrade form the substructure. The structure of typical ballasted rail track is shown in Figure 1. In superstructure of rail track, the sleepers distribute axle loads to substructure [1]. The sleepers can be manufactured using timber, concrete, steel or other engineered materials [2]. The main functions of sleepers are:

- to support rails and maintain the rail gauge

- to transfer and distribute load from rail to substructure

- to provide insulation between parallel rails

Prestressed concrete sleepers have been developed over 50 years and it is believed the most commonly used type of sleepers [3]. They have longer life cycle and lower maintenance costs in economic and technical aspects than reinforced concrete and concrete sleepers. Prestressed concrete sleepers provide high carrying capacity, stability, and safety, especially used in heavy freight transportation system [3].
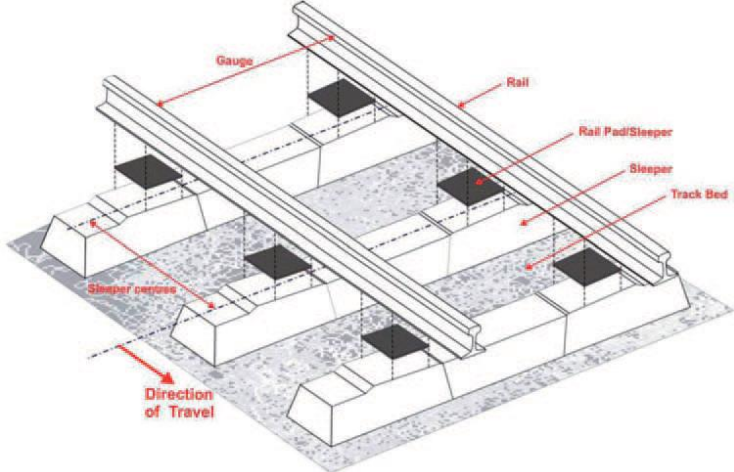

Figure 1: Typical ballasted railway track component [1]

Durability and long-term behaviours of railway prestressed concrete sleepers depend largely on their creep and shrinkage response. Many investigators have proposed various material models to predict creep and shrinkage but those were mostly based on general reinforced concrete concept. The popular uses of prestressed concrete in long span bridges, stadiums, silos and confined nuclear power plants have led to a concern of practitioners whether those predictive models could be realistically applied to prestressed concrete. Due to high initial elastic shortening in prestressed concrete, the creep and shrinkage effects should be critically re-evaluated in flexural members.

In reality, the ballast is tamped by dynamic action at the railseat areas. Therefore, the bottom of sleepers (or called 'soffits') may experience the aggressive abrasive force, wearing out the materials in the region [4-6]. Most of the previous work revealed the dynamic behaviours, but long-term behaviours of prestressed concrete sleepers with abrasion were not fully investigated, especially when the sleepers are deteriorated by excessive wears [7-11]. The typical wears of prestressed concrete sleepers are shown in Figure 2.
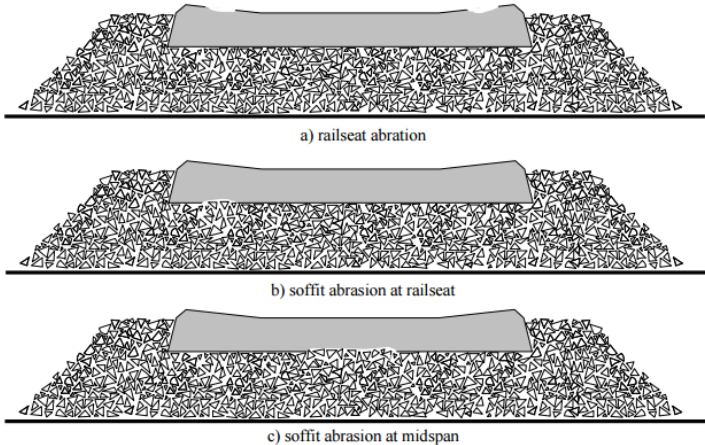

a) railseat abration

b) soffit abrasion at railseat

c) soffit abrasion at midspan

Figure 2: Typical wears of prestressed concrete sleepers

This study will investigate methods to evaluate creep and shrinkage effects in railway prestressed concrete sleepers when the sleepers are deteriorated by excessive wears. Comparison between design codes of EUROCODE2 and AS2009-3600 will provide the insight into the durability of concrete sleepers. The outcome of the project will help rail track engineers to better design and maintain railway infrastructure, improving asset management efficacy.

2. Prediction for creep and shrinkage

2.1. Creep Prediction

The concrete under load that strain increases with time is due to creep. Therefore, creep can be defined as the increase in strain under the sustained stress and it can be several times as large as the initial strain [12]. If the load is removed, the strain decreases immediately due to elastic recovery and a gradual incomplete recovery due to creep. This behaviour is shown in Figure 3.
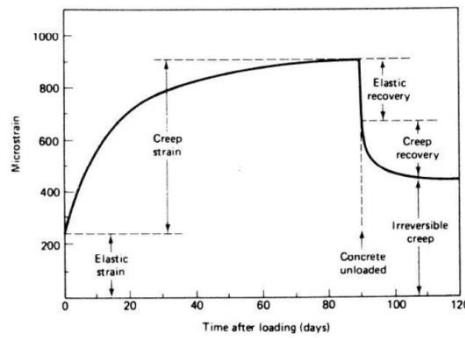

Figure 3: Time dependent creep

When creep is taken into account, its design effects are always evaluated under quasi-permanent combination of actions irrespective of the design situation considered, i.e. persistent, transient or accidental.

2.1.1. Eurocode 2

The total creep strain ε_{cc} (∞, t_0) of concrete due to the constant compressive stress of σ_c applied at the concrete age of t_0 is given by :

$$\varepsilon_{cc}(\infty, t_0) = \varphi(\infty, t_0) \times \frac{\sigma_c}{E_c}$$

Where (∞,$_0$) is the final creep coefficient, which the value of σ_c does not exceed $0.45f_{ck}$ (t_0). Ec is the tangent modulus.

$$\varphi(\infty, t_0) = \varphi_{RH} \times \frac{16.8}{\sqrt{f_{cm}}} \times \frac{1}{(0.1 + t_0^{0.20})}$$

$$\varphi_{RH} = 1 + \frac{1 - 0.01 \times RH}{0.1 + h_0^{0.333}}, \quad f_{cm} \leq 35MPa$$

$$\varphi_{RH} = (1 + \frac{1 - 0.01 \times RH}{0.1 + h_0^{0.333}}\alpha_1)\alpha_2, \quad f_{cm} > 35MPa$$

$$\alpha_1 = (\frac{35}{f_{cm}})^{0.7}, \quad \alpha_1 = (\frac{35}{f_{cm}})^{0.2} \quad f_{cm} = f_{ck} + 8MPa$$

$$t_0 = t_{0,T} \left(\frac{9}{2 + t_{0,T}^{1.2}} + 1 \right)^\alpha \geq 0.5,$$

$$\alpha = \{-1(S), 0(N), 1(R)\}$$

Where: RH = relative humidity in %, h_0 = 2Ac/u mm, Ac = cross sectional area, u = perimeter of the member in contact with the atmosphere, S, R and N refer to different classes of cement.

The final creep will be larger and final creep coefficient (∞,0) is multiplied by a factor k_σ if the compressive stress applied at the age of t_0 exceeds 0.45f$_{ck}$(t0) as can happen during prestress transfer process. The Table 1 shows the value of k_σ. The factor k_σ is given by:

$$k_\sigma = \exp\left[1.5 \times \left(\frac{\sigma_c}{f_{ck}(t_0)} - 0.45 \right)\right]$$

Table 1 Value of $\boldsymbol{k_\sigma}$ in terms of f$_{ck}$

$\dfrac{\sigma_c}{f_{ck}(t_0)}$	k_σ
0.5	1.078
0.6	1.252
0.7	1.455
0.8	1.691
0.9	1.964
1.0	2.282

The creep coefficient at any age t can be given by empirical solutions [6, 10-12].

2.1.2. Australian Standard 3600-2009
The creep coefficient at any time φ_{cc} can be determined by:

$$\varphi_{cc} = k_2 k_3 k_4 k_5 \varphi_{cc.b}$$

Where k_2 is the development of creep with time; k_3 is the factor which depends on the age at first loading τ (in days); k_4 is the factor which accounts for the environment; and k_5 is the factor which accounts for the reduced influence of both relative and humidity and specimen size.

For the development of creep with time k_2 can be calculated by:

$$k_2 = \frac{\alpha_2(t - \tau)^{0.8}}{(t - \tau)^{0.8} + 0.15t_h}$$

$$\alpha_2 = 1.0 + 1.12e^{-0.008t_h}$$

$$t_h = 2A_g/u_e$$

Where t is any time in days; t_h is the hypothetical thickness; A_g is the cross-sectional area of the member; u_e is the portion of the section perimeter exposed to the atmosphere plus half the total perimeter of any voids contained within the section.

For factor k_3 which depends on the age at first loading τ can be shown as:

$$k_3 = \frac{2.7}{1 + \log(\tau)} \; (for \; \tau > 1 \; day)$$

For the factor k_4 which accounts for the environment:

$$k_4 \quad = 0.7 \; for \; an \; arid \; environment$$
$$= 0.65 \; for \; an \; interior \; enviroment$$
$$= 0.60 \; for \; a \; temperate \; enviroment$$
$$= 0.5 \; for \; a \; tropical \; or \; near-coastal \; enviroment$$

For the factor k_5 is given by:

$$k_5 \qquad = 1.0 \qquad when \; fc' \leq 50MPa$$
$$k_5 \quad = (2.0 - \alpha 3) - 0.02(1.0 - \alpha 3)f'c \; when \qquad 50MPa \leq f'c \leq 100MPa$$

Where $\alpha 3 = 0.7/(k_4 \alpha_2)$. The basic creep coefficient $\varphi cc.b$ is shown table below:

f'_c (MPa)	20	25	32	40	50	65	80	100
$\varphi_{cc.b}$	5.2	4.2	3.4	2.8	2.4	2.0	1.7	1.5

2.2. Shrinkage Prediction

Both of creep and shrinkage are influenced by the same parameters. Shrinkage is not an entirely reversible process like creep and it can be also influenced by relative humidity, surface exposed to atmosphere, compressive strength of concrete and types of cement. Shrinkage can be divided by two parts [13]:

(1) Plastic shrinkage: it happens in few hours after concrete placed.

(2) Dry shrinkage: evaporation leads to loss of water.

2.2.1. Eurocode 2
The total shrinkage strain εcs can be given by:

$$\varepsilon_{cs} = \varepsilon_{ds} + \varepsilon_{as}$$

Where ε_{ds} is drying shrinkage strain; and ε_{as} is autogenous shrinkage strain.

2.2.2. Australian Standard 3600-2009
The total shrinkage strain ε_{cs} is shown below:

$$\varepsilon_{cs} = \varepsilon_{cse} + \varepsilon_{csd}$$

Where ε_{cse} is autogenous shrinkage strain; ε_{csd} is drying shrinkage strain.

The autogenous shrinkage εcse is given by:

$$\varepsilon_{cse} = \varepsilon'_{cse}(1.0 - \exp\{-0.1t\})$$

$$\varepsilon'_{cse} = (0.6f'_c - 1.0) \times 50 \times 10^{-6} \ (f'_c \ in \ MPa)$$

$$\varepsilon_{csd.b} = (1.0 - 0.008f'_c) \times \varepsilon'_{csd.b}$$

Where $\varepsilon'_{csd.b}$ depends on the quality of the local aggregates and may be taken as 800×10^{-6} for concrete supplied in Sydney and Brisbane, 900×10^{-6} in Melbourne and 1000×10^{-6} in elsewhere.

The drying shrinkage strain ε_{csd} after the beginning of drying $(t - \tau_d)$ can be estimated:

$$\varepsilon_{csd} = k_1 k_4 \varepsilon_{csd.b}$$

Where k_1 is the factor which describes the development of drying shrinkage with time; and k_4 is the factor which accounts for the environment [13-15].

3. Material Properties

The effects of various abrasions for estimating creep, shrinkage strain will be evaluated. The fundamental engineering properties of prestressed concrete sleeper used for calculation are based on previous research by Remennikov et al. [1]. The parametric results are generated for comparisons between Eurocode 2 (EC2) and Australian standard 3600-2009 (AS). Figure 4 shows the cross section at rail seat of the prestressed concrete sleepers.
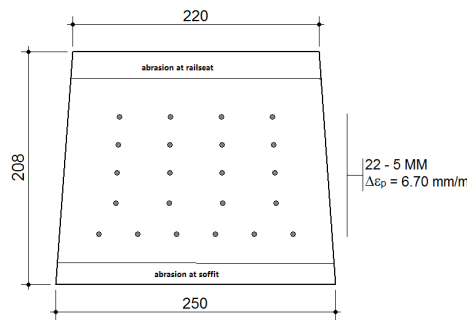

**Figure 4:** Cross section of railway sleepers

## 4. Results and discussions

4.1. Creep evaluations

To investigate relationship between abrasion and creep, the 15 cases have been analysed in different abrasion (railseat 10, 20, 30mm, soffit 15, 30, 45mm and both of railseat and soffit abrasion), which are plotted in Figure 5. The data of creep coefficient are calculated by EC2 and AS codes respectively. All the cases are estimated from 1 day up to 18250 days (50 years) in the same conditions (uniform dimension of sleepers, 70% relative humidity, steam curing etc.).
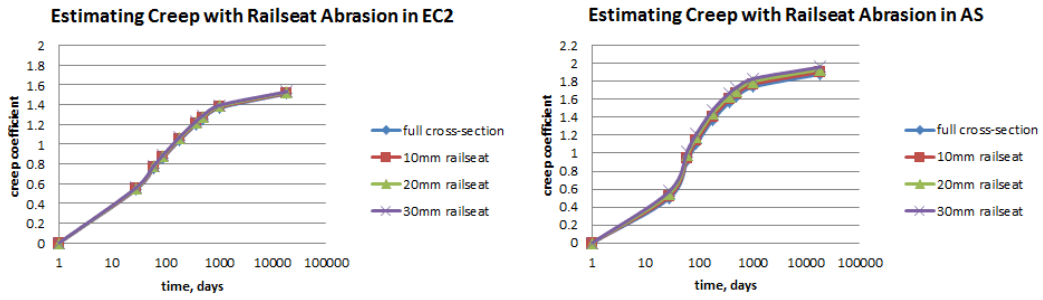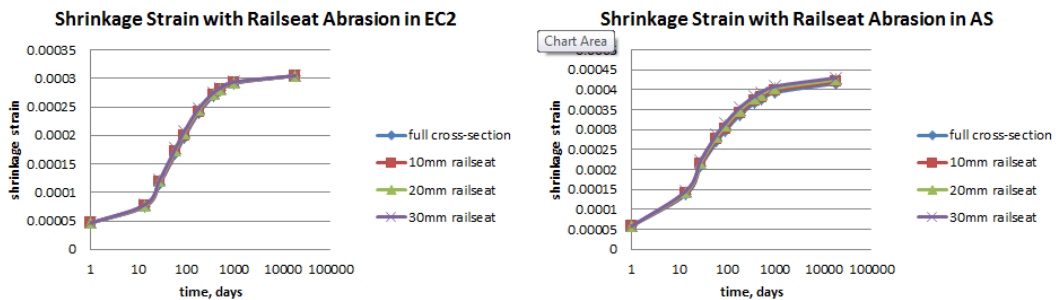
(a) Railseat abrasion
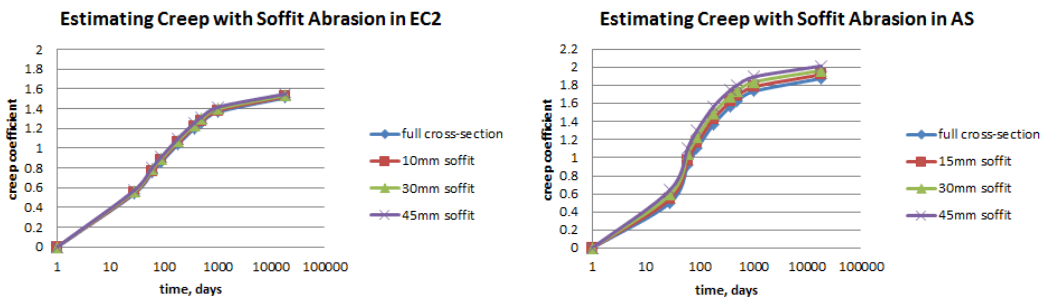
(b) Soffit abrasion
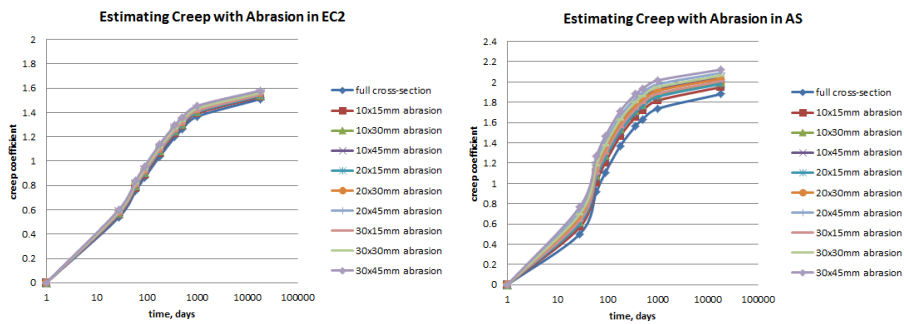
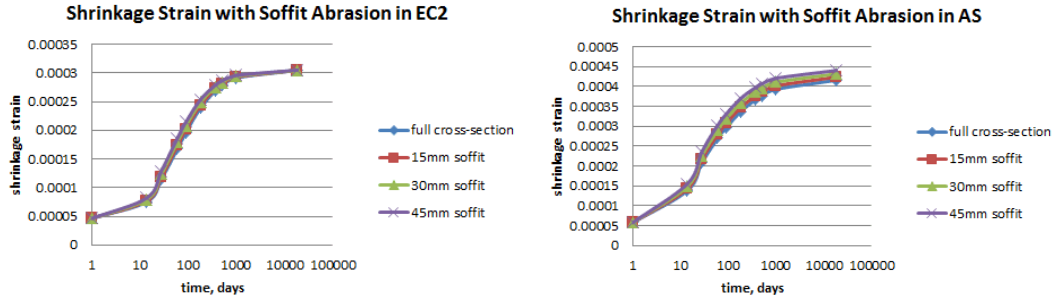(c) Both of railseat and soffit abrasion

Figure 5 Abrasion-creep effects

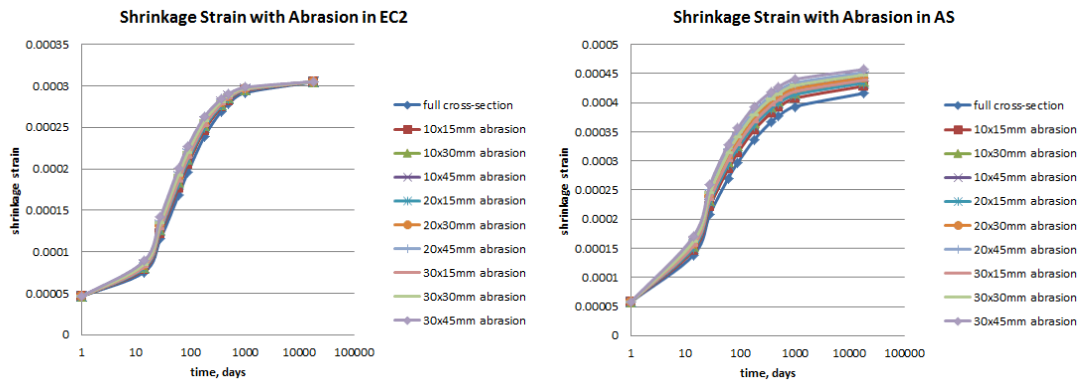*4.2. Shrinkage evaluations*

Figure 6 shows 15 cases of different abrasion on the shrinkage effect. The data of shrinkage stains are calculated by EC2 and AS3600-2009 codes respectively.

(d) Railseat abrasion

(e) Soffit abrasion

(f) Both of railseat and soffit abrasion

Figure 6: Abrasion-shrinkage effects

The results are based on parametric analysis and we found that creep and shrinkage in prestressed concrete sleeper can be significantly influenced by abrasion. Abrasion in the top of a sleeper (railseat) has less influence for both of creep and shrinkage than the bottom of a sleeper (soffit). Comparison full cross-section and 30mm abrasion on railseat of creep and shrinkage, the results are very close which just 1.41% and 0.05% respectively. However, the difference is up to 12.80% when abrasion happens in both of railseat and soffit.

5. Conclusions

There are two main duties for railway prestressed concrete sleepers (or railroad ties) that must successfully perform: first, to carry wheel loads from the rails to the ground; and second, to secure rail gauge for dynamic safe movements of trains. In many cases, an inappropriate design of the time-dependent behaviours of railway concrete sleepers due to their creep, shrinkage and elastic shortening responses of the materials affect significantly the rail gauge control. In addition, the concrete sleepers are often modified on construction sites to fit in other systems such as cables, signalling gears, drainage pipes, etc. This paper highlights constitutive models of concrete materials within the railway sleepers under different environmental conditions over time. The comparison has been carried out by a variety of reputable methods to evaluate shortening effects in railway prestressed concrete sleepers. Based on the sensitivity analyses, we found that creep and shrinkage in railway sleeper depend largely on the cross-section. According to the obtained data, the both of creep and shrinkage strains are

influenced by abrasion. This insight will improve the material design and structural restraints, which are very critical to the durability of railway track components.

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