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Li, Dan; Kaewunruen, Sakdirat

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Article

Effect of Extreme Climate on Topology of Railway Prestressed Concrete Sleepers

Dan Li [1,2] and Sakdirat Kaewunruen [1,3,*]

[1] Department of Civil Engineering, School of Engineering, University of Birmingham, Birmingham B152TT, UK; DXL561@student.bham.ac.uk
[2] Department of Civil Engineering, Tsinghua University, Beijing 100084, China
[3] Birmingham Centre for Railway Research and Education, School of Engineering, University of Birmingham, Birmingham B152TT, UK; S.Kaewunruen@bham.ac.uk
* Correspondence: s.kaewunruen@bham.ac.uk; Tel.: +44-121 414 2670

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Abstract: Railway networks are exposed to various environmental conditions. It is thus critical that infrastructure components can tolerate such effects by design. Railway sleepers are a critical safety component in ballasted track systems. Prestressed concrete is currently the most common material for railway sleepers due to its superior advantages in structural performance, low maintenance, sustainability, and construction. In practice, many prestressed concrete sleepers are installed in harsh environments that are subject to various changes in climate. Environmental conditions are, therefore, one of the most critical phenomena affecting the time-dependent behaviour of prestressed concrete sleepers. Hence, the impact of climate changes on the serviceability of railway infrastructure needs to be thoroughly investigated. Temperature and relative humidity are crucial aspects that have not been sufficiently studied so far with reference to prestressed concrete sleepers embedded in track systems. This study aims to investigate the effects of extreme climatic conditions on the performance and time-dependent behaviour of prestressed concrete sleepers using contemporary design approaches. The issue concerning the effects of climate uncertainties on creep and shrinkage is rigorously investigated on the basis of both environmental temperature and relative humidity. The outcome indicates that environmental conditions play a vital role in the time-dependent behaviour of prestressed concrete sleepers. The insights will be essential for assessing the long-term serviceability of prestressed concrete sleepers that have been installed in railway lines and are subjected to extreme environmental conditions.

Keywords: climate changes; railway infrastructure; prestressed concrete sleeper; time-dependent behaviour; relative humidity; temperature

1. Introduction

Climate uncertainty has become a significant issue around the world and is a social, economic, and political problem. The reasons for climate change could be derived from human activity, biotic processes, variations in solar radiation received by the Earth, and volcanic eruptions. In recent years, climate change has increased the frequency of extreme phenomena (IPCC, 2007) [1]. Consequently, the performance of railway infrastructure that is exposed to extreme environmental conditions can be directly influenced by climate change. "Extreme climate" is defined as unusual, unexpected, or unpredicted severe weather, based on historical records of the 10% most unusual cases [2,3]. The threshold of extreme climate percentiles shown in Figure 1 indicates that extreme events in both hot and cold climates can affect railway networks. Extreme weather may lead to pavement deterioration, rail buckling, and ground settlement, as well as increasing frequency of accidents, and so on.

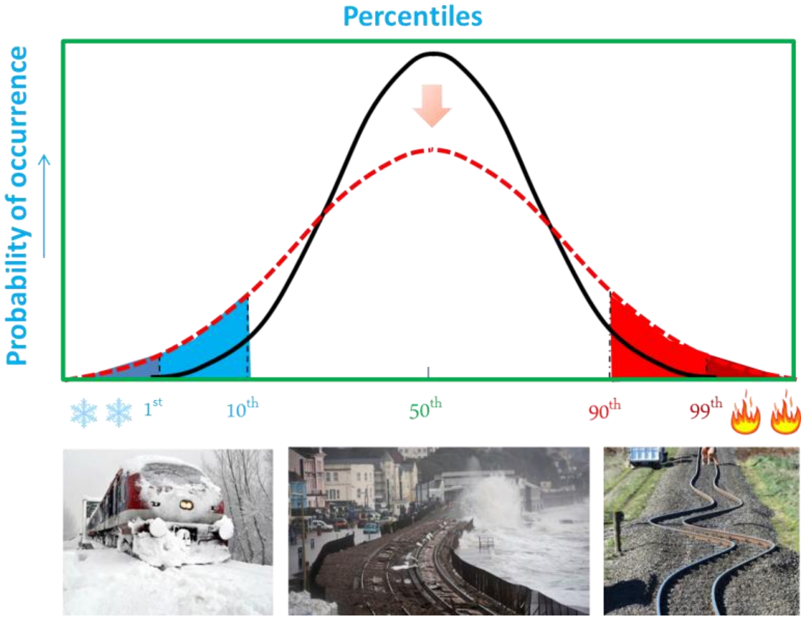


Figure 1. The threshold of extreme event percentiles and potential impacts.

In past decades, temperature and rainfall have gradually increased around the world. The damage to engineered structures caused by extreme weather patterns such as heavy storms, extreme temperatures, hurricanes, and so forth, should be considered in the future design of resilient infrastructures. The increasing frequency of rainfall caused by climate change may lead to severe flooding. In 1998, China experienced severe floods resulting in more than 4000 deaths and 15 million homeless, with many collapsed infrastructures and $24 billion in economic loss. The moisture content of soils decreases with the rise of climatic temperature, which accelerates the weathering process of soils in the event of heavy rain or wind. Millions of buildings will be damaged when global wind speeds increase by 6%, with huge consequences in terms of cost (up to $2 billion). In addition, the greenhouse effect will result in a carbon dioxide concentration increase that will accelerate carbonation of cement-based structures [4–7].

Presently, railway transportation is becoming increasingly important, and railway engineering needs to improve the performance of railway infrastructure under extreme weather [8–14]. Conventional railway infrastructure can be divided into a superstructure and a substructure (shown in Figure 2) [15]. The superstructure consists of sleepers, rail pads, fastening systems, and rails. The substructure includes ballast, sub-ballast, and formation. Rail sleepers are a major component of railway structures as they transfer vertical loads from rails to the foundation and they maintain rail gauge [16]. Prestressed concrete is the most commonly used material in railway sleepers around the world because of its good structural performance and low maintenance cost. Prestressed concrete sleepers are often applied in harsh environments, but often excessive loads are applied that can induce damage [17]. Therefore, railway engineers need to improve the performance of prestressed concrete sleepers, especially to improve functionality under extreme weather. The time-dependent behaviour of prestressed concrete sleepers largely depends on environmental factors [18].

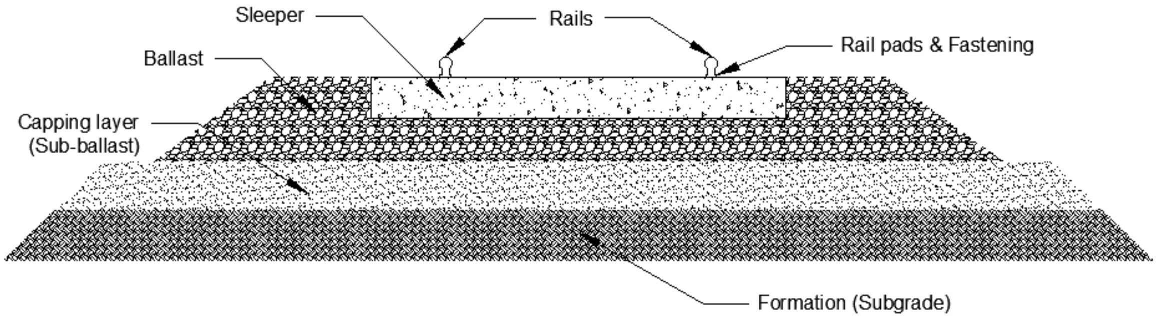


Figure 2. Conventional railway structure.

Like any other structural concrete product, prestressed concrete sleepers can be affected by changes in various factors over time. The failures of prestressed concrete sleepers are more likely due to cumulative damage rather than to any one single extreme event [19]. You et al. [20] have identified the time-dependent limitations of a concrete sleeper, which accumulates various damages progressively over years until it reaches a critical state. The main objective of this study is to address the time-dependent behaviour of railway prestressed concrete sleepers under extreme climatic conditions. Climatic effects on prestressed concrete sleepers are very important [21]. Changing environmental factors will significantly influence the performance of prestressed concrete sleepers. In this study, open literatures have been comprehensively reviewed for investigating the topology of prestressed concrete sleepers, and experimental data was obtained from previous research in order to study the climatic changes that influence the performance of prestressed concrete sleepers. Material prediction models are used to identify influential effects, and are essential for structural geometric analysis. The material prediction models are based on existing design codes used for the analytical calculation. The analysis results from this study have been compared with design standards and base operating conditions (BOCs) to get a comprehensive insight into the design and maintenance of railway prestressed concrete sleepers.

2. Global Climate Trends

The fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC) identified global climate change trends. The IPCC stated that the warming of climate systems is obvious and definite. The summary of the IPCC pointed out that the rise in global temperature has increased from 0.0045°C per decade to 0.177°C per decade over the past 150 years [22]. Therefore, extreme events are likely to happen more frequently due to atmosphere and ocean warming, polar iceberg melting, and greenhouse gas emissions. A variety of reports by the Rail Safety and Standard Board (RSSB) have revealed similar trends to the IPCC (shown in Figure 3) [23–25]. The ongoing increase of hot weather spells is confirmed by the tail of the statistical distribution, which indicates that extremely hot events are going to take place more frequently in the future. According to Zhu et al. [26,27], hot days and heat wave events are increasing significantly, by more than 10% in China over the past decade. High temperatures can be influenced by factors such as air pollution, the intensity of sunlight, velocity of wind, and human activities.

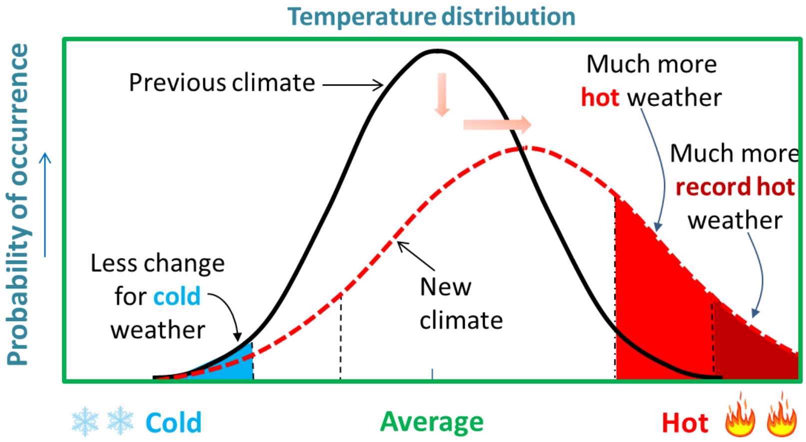


Figure 3. The temperature change between previous years and recent years [1].

According to the IPCC, the CO_2 concentration has increased by 36% (from 280 parts per million to 380 parts per million) over the past 250 years [1]. Figure 4 indicates the global temperature and carbon dioxide relation, in which red bars indicate a temperature that is higher than the long-term average, and blue bars show a temperature that is lower than the long-term average. From the graph, it can be seen that the average global temperature has increased yearly by more than 1.5˚F (0.8˚C) since 1880. In recent decades, global warming has been caused primarily by human activities, and it will continue to change in the coming decades. The magnitude of climate change mainly depends on heat-trapping gas emissions. Emission levels determining a rise in temperature are shown in Figure 5. In the US, climate change results in increasingly heavy downpours and heat waves that have become more frequent and intense [28].

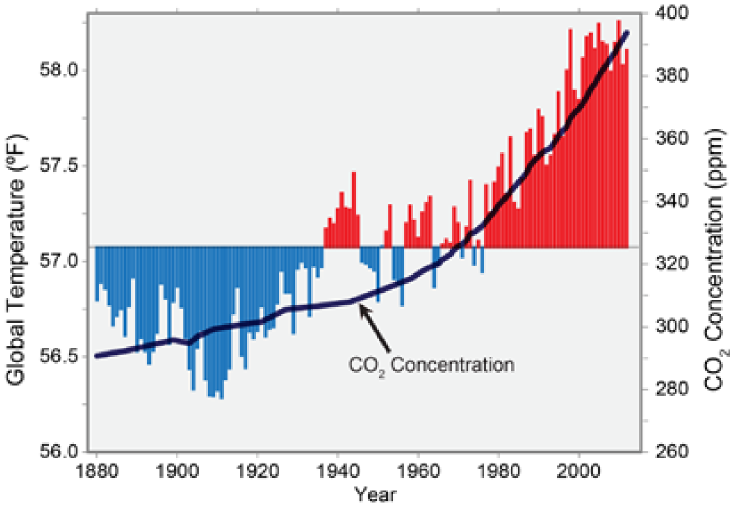


Figure 4. Mean temperature and carbon dioxide concentration in the past 100 years [28].

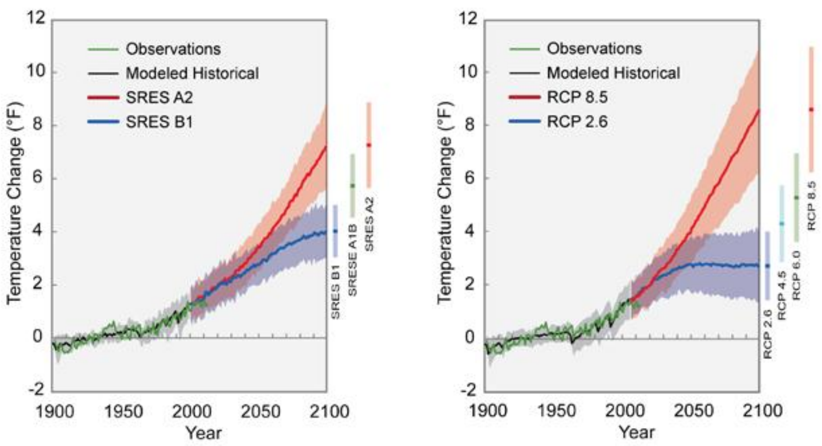


Figure 5. Emissions and temperature [28].

3. Methodology

Durability can be defined as the capability of a structure to resist various damages such as deterioration, cracks, corrosion, and other afflictions over its lifetime [29]. Throughout the lifetime of railway infrastructures, all components will experience various environments, and the effects of extreme climate could pose a series of problems to the durability of prestressed concrete sleepers. In an extremely cold climate, cracks could occur in sleepers as the volume of water in the concrete's pores expands when it freezes. The flexural strength of concrete will decrease under the extreme temperature. In addition, an extremely warm climate could increase a chemical attack on prestressed concrete. For example, the concentration of CO_2 will increase in a warm climate, which increases the possibility of carbonation on concrete sleepers [30–33]. It is thus necessary to account for durability that fulfils the performance requirements demanded during a sleeper's service life.

The serviceability limit state is a limit state in which concrete sleepers are beginning to impose some tolerances on the operational capacity of the track, such as deformations, vertical displacement, rail cant dynamics, etc. [20]. The time-dependent behaviour of concrete has been investigated for more than a century. Besides elastic shortening, the gradual in-time development of deformations is due to creep, shrinkage, and thermal strains. In the long term, the deformation of prestressed concrete sleepers will lead to losses of prestress, which reduces performance and serviceability. Creep strain is a strain that increases with time under constant stress. Shrinkage is not relevant to stress and results primarily from several factors such as loss of water, chemical reactions, capillary tension, and so on. With increasing temperatures, relative humidity will reduce, which significantly influences creep and shrinkage. Creep and shrinkage can cause undue axial deformation, excessive pre-camber, and loss of prestress. Excessive deflection and excessive shortening are often caused by creep and shrinkage [34,35].

In this study, a review of the literature was conducted in order to investigate the influence of climate change on prestressed concrete. Also, the influential factors of time-dependent behaviour were studied in order to find influential factors relevant to climate change. The experimental data obtained from previous research relevant to environmental change were used in calculating the effect of climate change on the topology or structural geometric change of prestressed concrete sleepers. The results were calculated based on material prediction models in accordance with Eurocode 2.

3.1. Creep Prediction

Neville [36] stated that the concrete under loads at which strain increases over time are due to creep. Therefore, creep can be defined as the increase in strain under a sustained stress, which can be several times larger than the initial strain. Creep is a considerable factor in a concrete structure. Bhatt [37] stated that the deformation of concrete is different from other materials like steel. When a load is applied to steel, the deformation will not change with time if the load is constant. Like steel, concrete deforms as soon as a load is applied. This is known as elastic deformation. However, the displacement of concrete gradually increases over time when a load is left in place. This displacement can reach a value as large as three to four times the immediate elastic deformation. The inelastic deformation with a constant load is known as creep deformation. "Creep is defined as the increase of strain with time when the stress is held constant." [37] As a rule, creep increases when the water–cement ratio increases, or when the cement content increases. On the other hand, creep decreases when the aggregate content increases. According to Martin [38], creep occurs very slowly after the immediate elastic strain has happened. If the load is removed, the strain decreases immediately due to elastic recovery, but the gradual recovery is incomplete because of creep. This behaviour is shown in Figure 6. When creep is taken into account, its design effects are always evaluated under the quasi-permanent combination of actions irrespective of the design situation considered, i.e., persistent, transient, or accidental.

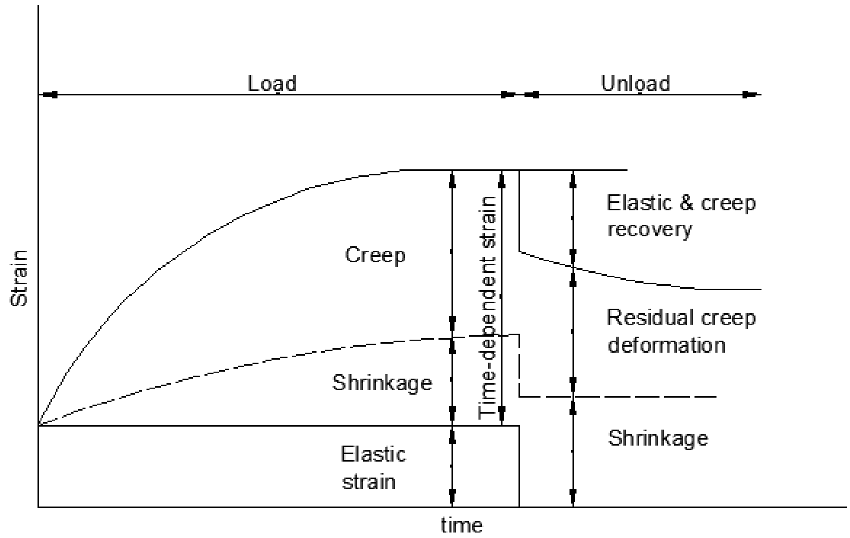


Figure 6. Creep strain after loading.

The total creep strain ε_{cc} (∞, t_0) of concrete due to the constant compressive stress of σ_c applied at the concrete at age of t_0 is given by Eurocode 2 (material prediction models):

$$\varepsilon_{cc}(\infty, t_0) = \varphi(\infty, t_0) \times \frac{\sigma_c}{E_c} \quad (1)$$

where $\varphi(\infty, t_0)$ is the final creep coefficient, and E_c is the elastic modulus of concrete.

$$\varphi(\infty, t_0) = \varphi_{RH} \times \frac{16.8}{\sqrt{f_{cm}}} \times \frac{1}{(0.1 + t_0^{0.20})} \quad (2)$$

$$\varphi_{RH} = 1 + \frac{1 - 0.01 \times RH}{0.1 + h_0^{0.333}}, f_{cm} \leq 35MPa \quad (3)$$

$$\varphi_{RH} = \left(1 + \frac{1 - 0.01 \times RH}{0.1 + h_0^{0.333}} a_1\right) \times a_2, f_{cm} \leq 35MPa \quad (4)$$

$$a_1 = \left(\frac{35}{f_{cm}}\right)^{0.7}, a_2 = \left(\frac{35}{f_{cm}}\right)^{0.2} f_{cm} = f_{ck} + 8MPa$$

$$h_0 = \frac{2A_c}{u}\ in\ mm$$

$$t_0 = t_{0,T} \times \left(\frac{9}{2 + t_{0,T}^{1.2}} + 1\right)^{\alpha} \geq 0.5, \alpha = \{-1(S), 0(N), 1(R)\} \quad (5)$$

where RH is relative humidity in percentage; A_c is the cross-sectional area; u is the perimeter of the member in contact with the atmosphere; and S, R, and N refer to different classes of cement.

3.2. Shrinkage Prediction

Bhatt [27] stated that both creep and shrinkage are influenced by the same material parameters. Shrinkage is not an entirely reversible process like creep and can also be also influenced by relative humidity, surface exposure to the atmosphere, compressive strength of concrete, and type of cement. Shrinkage usually can be divided into four components, including plastic shrinkage, drying shrinkage, chemical shrinkage, and thermal shrinkage. Plastic shrinkage occurs in wet concrete before setting, and high-strength concrete is prone to plastic shrinkage in which significant cracking may occur before and during the setting process. Drying shrinkage is caused by loss of water during the drying process, which results in a reduction in volume. Various chemical reactions with the cement paste lead to chemical shrinkage. Thermal shrinkage is the contraction that results in the first few hours (or days) after setting, as the heat of hydration gradually dissipates [34]. In theoretical prediction, the total shrinkage strain can be calculated by combining drying shrinkage and autogenous shrinkage. The total shrinkage strain ε_{cs} can be given by Eurocode 2:

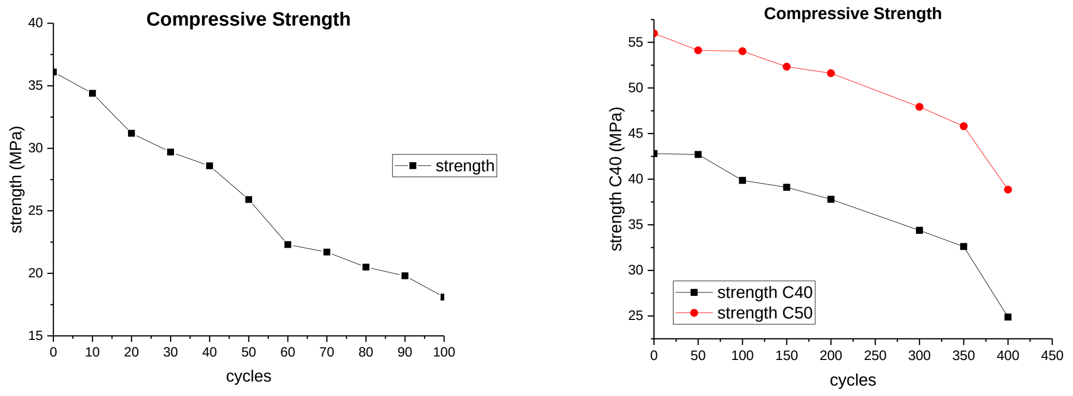
$$\varepsilon_{cs} = \varepsilon_{ds} + \varepsilon_{as} \quad (6)$$

where ε_{ds} is drying shrinkage strain, and ε_{as} is autogenous shrinkage strain.

4. Results for the Effects of Climate

4.1. Extreme Temperature Impact

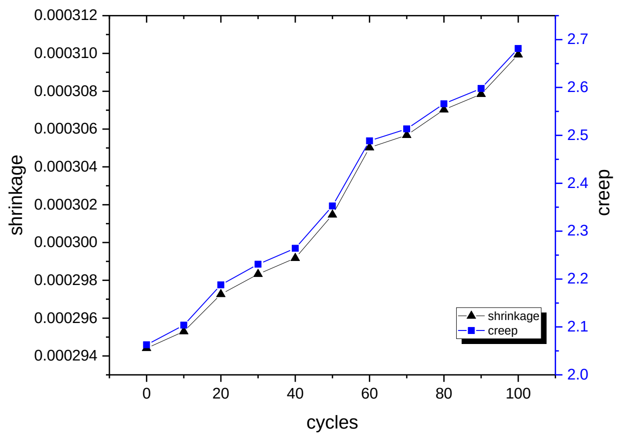
Previous research conducted by Solatiyan et al. [30] simulated a freeze–thaw situation. The research indicated that freeze–thaw cycles influence concrete properties significantly. In their experiment, C35 was used for concrete pavement. The initial compressive strength of concrete was 36.1 MPa with 7.5% air content. The concrete used in Solatiyan's experiment had relative high air entrapment. Plain concrete tends to have less freeze–thaw resistance in comparison with air-entraining concrete [39]. The fast freeze–thaw cycle experiment conducted by Shang et al. also tested C40- and C50-strength concrete through 400 cycles [40]. Figure 7 shows the compressive strength of concrete change after a number of freeze–thaw cycles. As shown in Figure 7a, the concrete compressive strength decreased sharply up to 50.2% (from 0 to 100 cycles). Figure 7b shows a 41.9% and 30.6% strength reduction for C40 and C50, respectively (from 0 to 400 cycles). According to this result, a low temperature can also influence the time-dependent behaviour of prestressed concrete sleepers. Figure 8 shows the effects of freeze–thaw in an aspect of time-dependent behaviour. The results of time-dependent behaviour were analysed based on concrete strength reduction due to extreme cold weather. Both the shrinkage strain and the creep coefficient still increased significantly as the freeze–thaw cycles increased, which implied that the total strain would also increase. More deformation can cause cracks due to a loss of prestress. As a consequence, pore pressure increases and favours further cracks.



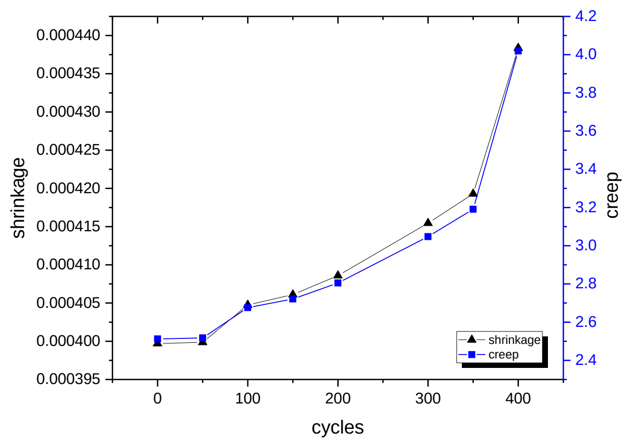
(**a**) Concrete strength C35 (100 cycles)

(**b**) Concrete strength C40 and C50 (400 cycles)

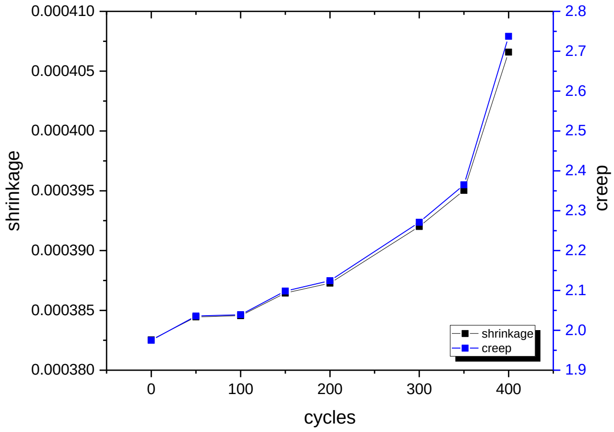
Figure 7. Compressive strength changes of concrete samples in association with freeze–thaw cycles.



(**a**) Concrete strength C35



(**b**) Concrete strength C40

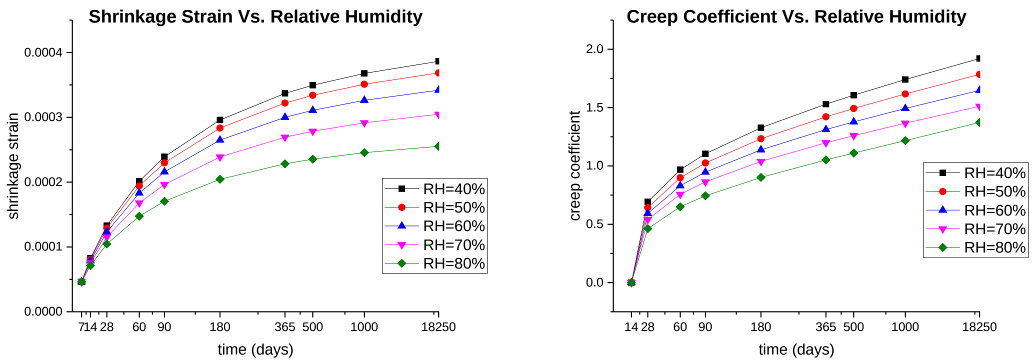


(**c**) Concrete strength C50

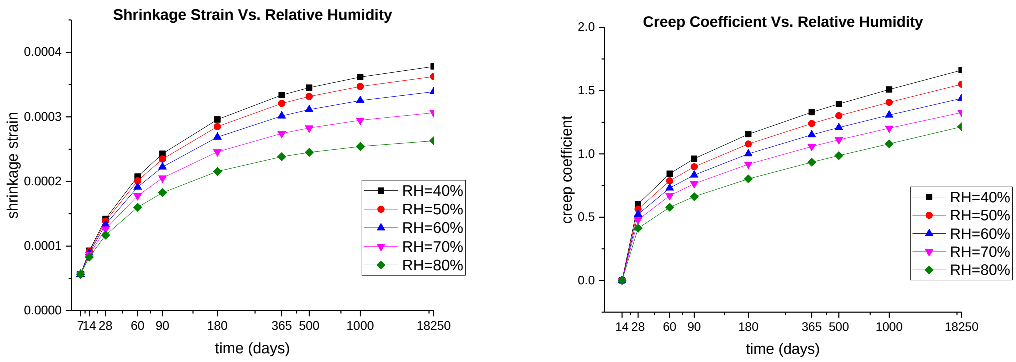
Figure 8. Effect of freeze–thaw on the time-dependent behaviour of prestressed concrete sleepers.

4.2. Extreme Humidity Impact

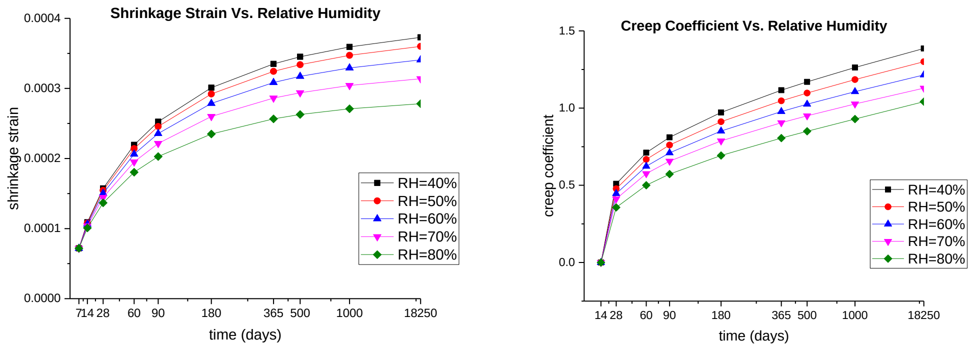
The performance of prestressed concrete sleepers is also influenced by temperature and relative humidity. Drying shrinkage is affected by certain factors that influence concrete drying, such as water content, the water–cement ratio, and relative humidity. Shrinkage will increase when the temperature rises, accelerating drying. Creep also depends on drying factors, and is greater when relative humidity decreases. According to Li et al. [18], relative humidity is a key parameter in estimating time-dependent behaviour. An Australian-manufactured prestressed concrete sleeper was used for investigation. The sleeper was 2700 mm long with a concrete strength of 55 MPa and a 1600 mm track gauge. Both the creep and shrinkage were significantly influenced by relative humidity. Figure 9 shows the results of the creep coefficient and shrinkage strain between 40 and 80% relative humidity. The figure indicates that either creep or shrinkage will increase when relative humidity decreases. The difference of shrinkage between 40 and 80% relative humidity even reached 51.3%. The concrete strength C65 and C80 were also investigated as a parametric study, which showed a similar trend that lower relative humidity had more influence on the time-dependent behaviour of prestressed concrete sleepers.



(**a**) Concrete strength C55



(**b**) Concrete strength C65



(**c**) Concrete strength C80

Figure 9. Effect of relative humidity on the time-dependent behaviour of prestressed concrete sleepers.

5. Discussion of the Effects of Climate Uncertainty

High temperatures increase the deformability of cement paste and accelerate concrete drying, thus influencing the time-dependent behaviour of prestressed concrete. Rusch et al. [35] stated that time-dependent behaviour is more significant at elevated temperatures, and is far less significant between temperatures 0 and 20˚C. For example, creep at the mean temperature 40˚C could be 25% higher than at 20˚C. Figure 10 shows that the relationship between relative humidity and temperature is inversely proportional. Extremely high temperatures could result in low relative humidity, and the time-dependent behaviour of prestressed concrete sleepers will be impacted.

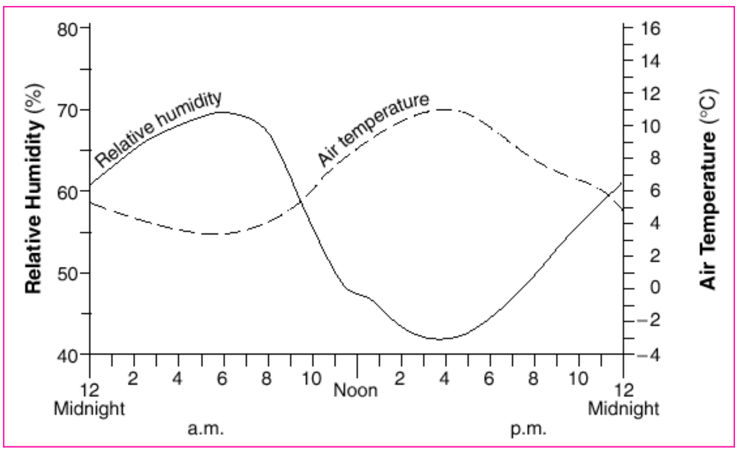
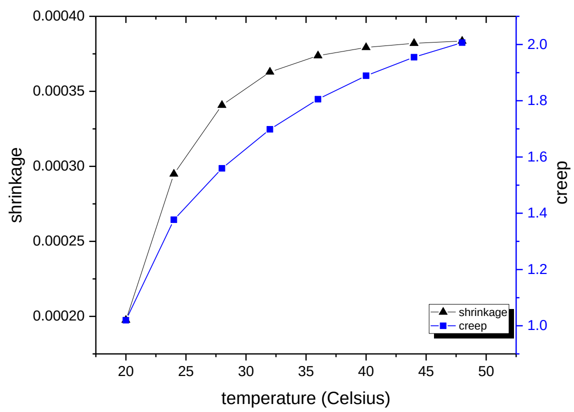


Figure 10. Relationship between relative humidity and temperature.

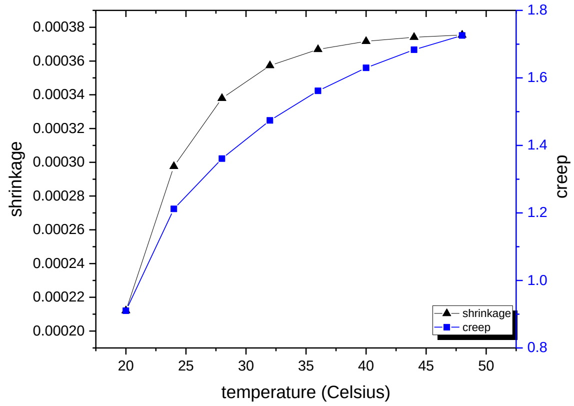
According to Zhu et al. [26], the prediction model relating relative humidity and temperature was converted from the Goff–Gratch vapour pressure formula (shown in Equations 8 and 9). Relative humidity can be calculated using observed vapour pressure (e), saturation vapour pressure (e_s), and temperature (T). This formula is valid from -45 to 60˚C. The relationship between temperature and the time-dependent behaviour of prestressed concrete sleepers can be predicted by inputting the Goff–Gratch vapour pressure formula into prediction codes. By using prediction models, material behaviour can be attained for further structural analysis [41]. The principle of solid mechanics has been used to demonstrate the time-dependent behaviour of the safety-critical structural component, railway prestressed concrete sleepers. Figure 11 shows the effect various temperatures had on the time-dependent behaviour of prestressed concrete sleepers between C55, C65, and C80, with a temperature range from 20 to 48˚C. With the same conditions, the creep coefficient increased by 94.74% and shrinkage strain increased by 94.16% when the temperature was raised to 28˚C. In this calculation, the vapour pressure and dew point were assumed as constant. The effect of varying temperatures on concrete strength was investigated as a parametric study. Figure 12 illustrates the time-dependent behaviour of C55, C65, and C80 concrete sleepers. The higher-strength concrete had less creep under extreme temperatures. However, higher-strength concrete sleeper also had more shrinkage under 30˚C. This is because higher strength concrete has more autogenous shrinkage [41]. The results of shortening the sleeper and rail gauge are shown in Figure 13. The total shortening of the full-scale sleeper due to time-dependent behaviour at 48˚C was 2.77 mm, which was 95.76% higher than the shortening at 20˚C. The largest rail gauge change reached 1.64 mm.

$$e_s(T) = 6.112e^{17.62T/(243.12+T)} \tag{7}$$

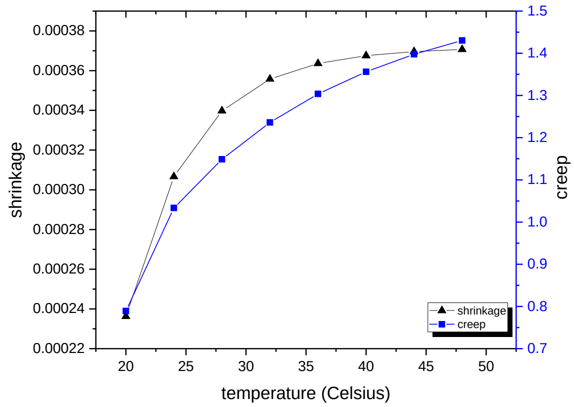
$$RH = 100 \times \left(\frac{e}{e_s}\right) \tag{8}$$



(**a**) Concrete strength C55



(**b**) Concrete strength C65



(**c**) Concrete strength C80

Figure 11. Effect of temperature on the time-dependent behaviour of prestressed concrete sleepers.

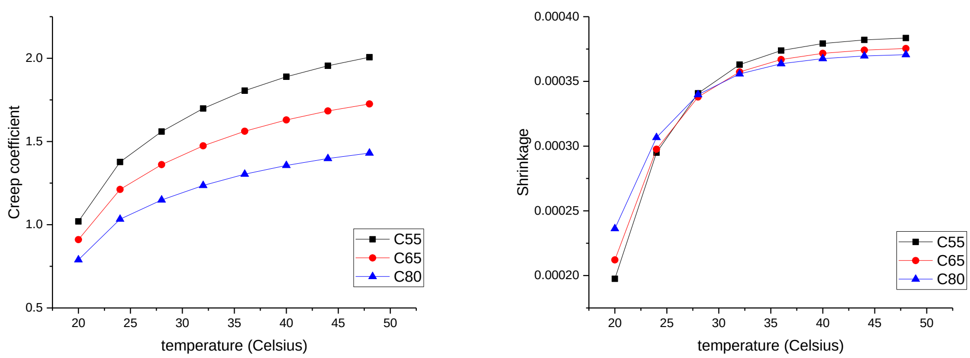
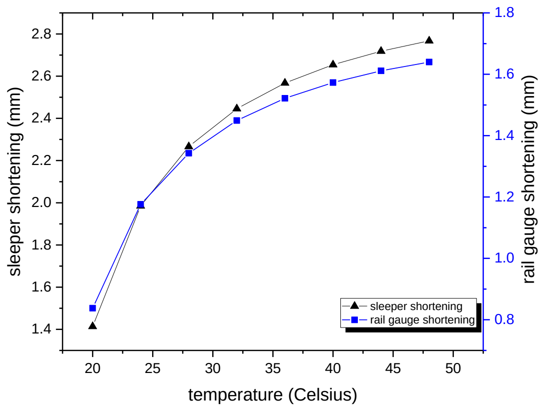
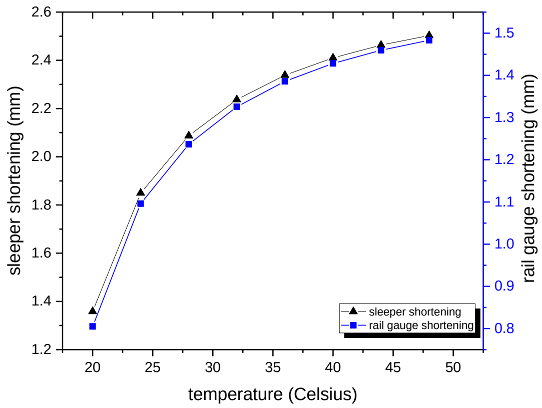


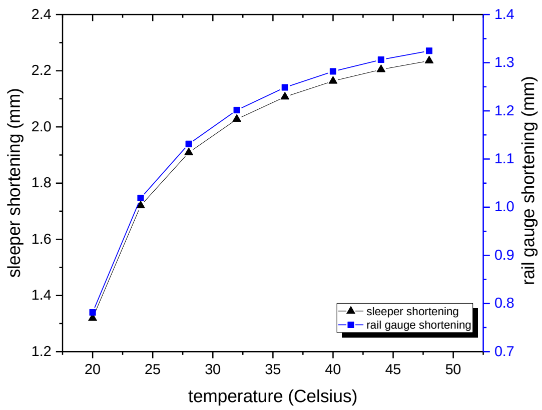
Figure 12. Effect of temperature on the strength of prestressed concrete sleepers.



(**a**) Concrete strength C55



(**b**) Concrete strength C65



(**c**) Concrete strength C80

Figure 13. Total shortenings of prestressed concrete sleeper and rail gauge.

6. Conclusions

Prestressed concrete sleepers have gained a reputation for their satisfactory structural performance and its associated benefits. The service life of railway prestressed concrete sleepers is usually designed for 50 years, but it can be vary largely depending on time-dependent behaviour.

Railway concrete sleepers always experience aggressive environments, including impact load, abrasion, chemical attack, and so on. Many railway sleepers cannot meet the design requirements because of aggressive environments. Material degradation over time leads to premature failure before reaching the design service life. However, our critical review revealed that extreme climate will accelerate the accumulation of damage. The time-dependent behaviour results in material degradation, deflection, deformation, change of rail gauge, and other problems. The effects of environmental factors on concrete properties are very significant, which influence service life and raise the risk potential.

This paper presents some critical considerations on the effect of extreme climates on the topology or influential geometrical changes of railway prestressed concrete sleepers. In order to evaluate the effect of extreme climate on the topology of railway sleepers, the impact factors need to be found relevant to time-dependent behaviour. In this study, the climate data was derived from the IPCC and different countries' authorities, together with previously published studies related to the time-dependent behaviour of concrete. This study indicates that extreme high temperature and low relative humidity increase the creep and shrinkage of railway sleepers. Cold weather can cause a reduction of concrete compressive strength that influences the time-dependent behaviour of the structural component. The effect of extreme climate on railway prestressed concrete sleepers will also cause a loss of prestress, which could result in cracks and a worsening of performance and service life. The results indicate that environmental factors can influence material properties, structural performance, and service life. Material prediction models in accordance with Eurocode 2 were employed to determine the material parameters that are essential for analytical calculations of the time-dependent behaviour of prestressed concrete sleepers. The outcome of this research provides a new insight into prestressed concrete sleepers used in aggressive environments. It enables decision making towards serviceability design requirements for railway concrete. This study also provides an innovative solution and new knowledge that could lead to improvement in the durability of concrete, such as concrete mixes for extreme climate or new material that could be applied in concrete sleepers to resist extreme climatic conditions.

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