DESIGN EVALUATIONS FOR THE TIME DEPENDENT CONTRACTIONS OF PRESTRESSED CONCRETE HIGH SPEED RAILWAY SLEEPERS

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ABSTRACT
Prestressed high performance concrete railroad sleepers are frequently used in ballasted high speed railways. There are strictly enforced dimensional production tolerance values for the concrete sleepers on the scale of millimeters. The creep and shrinkage of the prestressed high performance concrete sleepers within regions of low humidity have the potential to reduce their gauge lengths below their allowed tolerance values. The probability of rail abrasion, friction and derailment of a train under a given speed increases with the level of reduction of the gauge length that requires an evaluation of the time related dimensional changes of a sleeper before the finalization of its design. Ankara - Konya High Speed Railway located in Turkey is a ballasted railway that became operational in 2011. An analytical engineering evaluation that was conducted for the prestressed high strength B70 class sleepers showed that the cumulative dimensional changes of the sleepers due to the effects of prestressing, shrinkage and creep after demolding had the potential to reduce their shoulder length and the associated gauge length below the allowed tolerance within two months of their production. The sleeper molds were dimensioned to include an estimate for the time dependent contractions. The contractions of a number of sleepers produced by the adjusted molds were measured for two months, confirming the requirement to modify the production lengths of the sleepers to be used in high speed railways proposed along routes within arid climates.

INTRODUCTION
Sleepers align and secure the rails at a fixed distance apart and transfer the loads that are imposed onto the rails to the underlying supportive materials. They are exposed to cyclic and dynamic train loads under the effects of environmental conditions. The sleepers of a high speed railway line must be designed and produced to levels of precision higher than typical structural concrete elements. Attainment of this precision provides for the safe and reliable operation of a high speed line. Train speed is heavily dependent on the railway track qualities and the loads are generated by the interactions of the wheels with the rails. The interaction between the flanges of a train wheel with the railhead is among these interactions. The gauge length tolerances for normal speed railways are typically specified as +10 mm (+0.39 in) and -3mm (-0.12 in) (1). The gauge length tolerances for high speed railways built according to the international standards are typically specified as +2mm (+0.079 in) and -1mm (-0.039 in) (1). The desired contact condition between the wheel and the rail is between the top surface of the railhead and the bottom conical face of the rail as shown in figure 1 (2). However, due to gauge length variations, the interactions can take place between the flange and the inner side of the railhead as well, thereby increasing the number of possible points of contact between the wheel and the rail, provoking lateral and frictional forces, disturbing the ride comfort and ride stability and inducing wheel and rail abrasions (3).

FIGURE 1 Train wheel on a railhead.
Due to the conic design of the wheels, a laterally displaced axle with respect to the motion of a train is realigned along the rails. When the track gauge length is larger than the design value, sidesway motion of the train travelling at a certain speed, which is also known as the ‘Klingel Movement’ ([1], [4]), is provoked. As the train motion acquires a motion lateral to the direction of travel, the train begins to oscillate between the rails. These oscillations may seize and reach a point of stability under constant speed and linear train motion. However, as the train accelerates into higher speeds or moves along curvatures, these oscillations increase accordingly and the oscillating behavior develops into a recurring impact behavior when the flanges of the wheels begin to hit and rebound from the inner sides of the railheads known as the ‘Hunting Movement’ that induces lateral impacts onto the railheads ([1], [4]). The laterally induced motion generates a rotational behavior along the z–axis as well that is perpendicular to the x-y plane. Such rotations around the z-axis develop an angle ‘α’ referred to as the ‘angle of attack’ ([5]) along which the wheels tend to cut into the rail rather than smoothly roll along the rail. The laterally induced motions are represented through a sketch presented in figure 2. If the gauge lengths are larger than the intended values, these oscillations increase, which induce discomfort to the passengers before transforming into impact behavior. The coincidence of the developed frequency content of these increasing oscillations to the natural frequencies of the rolling stock reduces the stability of the train motion. If the gauge lengths are smaller than their design value, these oscillations quickly develop into producing forces due to lateral impacts that is increased by the developed angle α, developing friction forces at the instant of impacts.

FIGURE 2 Lateral motion and rotation of an axle along the perpendicular axis.

The outcome of such lateral train behavior is either the high speed trains have to be operated at lower speeds to prevent this behavior ([6]) or the trains are operated with an increased risk of track and wheel abrasion or derailment. A gauge length smaller than the design value can increase the rate of development of friction between the flange and the railhead thereby increasing the probability of wheel and rail abrasion and derailment of a train travelling at a certain speed ([7], [8], [9]).

DIMENSIONAL ASPECTS OF PRESTRESSED CONCRETE SLEEPER DESIGN

Shrinkage and creep are two characteristics of concrete that result in changes in the dimensional aspects of a concrete structure ([10]). In prestressed concrete design, determination of prestressing losses is the primary concern since under extremely dry conditions these losses could be as high as 40%. Prefabricated high speed railway sleepers are prestressed structural elements that need to be evaluated within a scale that is much more precise than other structural elements. Therefore, along with the prestressing losses, the changes in the sleeper dimension must become a concern as well. The locations for the attachments of rails onto the sleepers are predetermined within millimeters and the value of the distance between the attached rails of a sleeper is set within a positive and a negative tolerance value, the precision of which is...
inversely proportional to the design speed of the train. International high speed railway structures with a shoulder length of 1813 mm (71.4 in) and a gauge length of 1435 mm (56.5 in) are accepted within tolerances of +2mm (+0.079 in) and -1mm (-0.039 in). The allowed positive tolerance is to limit the excessive lateral vibration which could also lead to derailment and the allowed negative tolerance is to limit the rail and wheel flange abrasion and the development of frictional forces that could also lead to derailment. The sleepers are designed and produced with established locations for rail attachments. In terms of production and construction efficiency, the sleepers are rapidly cast, cured and demolded within 1 to 3 days.

Even though a prefabricated prestressed high strength concrete sleeper attains the design strength and durability requirements within a month, its dimensional values have not yet stabilized due to the ongoing creep and shrinkage the majority of which lasts up to a year. The ambient humidity values along a proposed high speed line have a significant effect on their creep and shrinkage \( (10) \). The climatic conditions along a proposed route is unique and two routes that are identical in terms of geographical aspects, geological aspects, axle loads, train speed and operational frequencies is likely to require a unique mechanical and dimensional design for the sleepers due to the effects of climatic variances. The international high speed railway experience up to date have been mainly located in the Northern Hemisphere such as the Shinkansen of Japan, TGV of France, ICE of Germany, Acela Express of United States and AVE of Spain.

The climatic conditions; especially in Northern Europe and Japan where a major portion of the internationally applied design experience of high speed railways is located, are mainly humid, which may not apply for projects located within arid climates. It is determined analytically and experimentally that the time dependent contractions of prestressed concrete sleepers in countries where the climate is humid are within the allowed tolerance values. However, it was determined for the Ankara-Konya High Speed Railway that under the existing and projected local climatic conditions, the allowed tolerance for the sleepers had the potential to be surpassed within 2 months of production and was estimated to reach a level that was twice the allowed value within 1 year.

THE ANKARA – KONYA HIGH SPEED RAILWAY

Ankara - Konya High Speed Railway Line; operated by the Turkish State Railroads (TCDD), connects the capital with a population of 4.8 million and the sixth largest city of the country with its 2.1 million inhabitants. It is the second high speed railway in the country after the Ankara – Eskişehir High Speed Railway which was completed in 2009 and the first railway to be constructed in the region outside the European Union. The construction of the double line, 212 km (131 mile) long high speed railway, which was designed for 22.5 Ton (49.6 kip) axle load commuter trains with a maximum train speed of 250 km/hour (155 mile/hour), began in late 2008 and the line became operational in late 2011 \( (11) \). It was a national high speed railway that was designed and constructed by a national company. An approximate count of 700,000 type B70 class sleepers was produced for the project. The prestressed pretensioned sleepers shown in figure 3 were produced in the city of Konya within confined and well insulated quarters by the circular production method, which is also known as the “caroussel method”, where the consecutive prestressed concrete production steps were applied to the mold sets that moved from one station to another along a closed loop until the sleeper was removed and the molds were returned back to the initial station where they were cleaned and the prestressing wires with the required attachments were inserted.
EVALUATION OF THE LOCAL CLIMATE AND HUMIDITY CONDITIONS

The Central Anatolia region of Turkey, where the line is located is an arid region within a climatic shift that is projected to end with desertification. The expected level of losses due to shrinkage and creep is 15% to 20% higher than the expected losses for the high speed railway lines located in Northern Europe and the sleepers were expected to be exposed to arid conditions estimated to produce dimensional contractions that had the potential to surpass the allowable tolerances. At the early sleeper design stages, it was determined that under the humidity conditions equal and below RH = 50%, the sleepers could contract more than 2 mm within a year (11). This was an issue that was not considered for the high speed railway projects located within humid conditions since the amount of contractions due to elastic shortening, creep and shrinkage are typically absorbed; sometimes unknowingly, within the 1 millimeter negative tolerance. However for this project, the prospect of derailment with high speeds acting on a gauge length with excessive contractions under the arid conditions was evaluated as a risk and remedial actions were reflected on the production dimensions of the sleeper shoulder length.

During the design of the sleepers, a meteorological investigation was conducted and the drought characteristics of the country were determined from the relevant sources (12). The drought characteristics of the country during 1971-2000 and for 2007 are shown in figure 4 and figure 5. The cities of Ankara and Konya are indicated with bold spots on the maps. The current level of humidity along the proposed route was determined to fluctuate annually between RH: 50% and RH: 85% with high levels of humidity between November and March, followed by an abrupt fall in humidity to arid levels between June and November. The expected level of decline in the near future was RH: 50% and perhaps below.
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FIGURE 4 Annual mean drought levels between 1971 and 2000.

FIGURE 5 Annual mean drought levels for 2007.

**ANALYTICAL EVALUATION OF THE TIME DEPENDENT CHANGES OF THE SLEEPER**

The B70 sleepers were designed with C65 grade concrete with design strength of 65 MPa (9.400 psi) and a mean strength of 73 MPa (10.580 psi). The concrete was cemented by CEM 52,5R type, high early strength white cement, with a cement compressive strength of 52,5 MPa (7.614 Psi). The concrete sleeper was pretensioned under a load of 350 kN (78.7 kips) applied through count-8, 7 mm (0.276 in) diameter high strength wires via plates anchored 30 mm (1.38 in) deep within the ends of the sleepers. Each sleeper was 260 cm (8.5 ft) long and weighed 280 kg (617 lb). The sleeper shoulder length was specified at 1813 mm (71.4 inch) with a tolerance value of +2mm and -1mm (+0.787 inch and -0.394 inch) (11).

Following the design of the concrete mixture for the sleeper and structural design of the prestressed section, the time related dimensional changes due to creep and shrinkage of the sleeper were analytically evaluated according to the Eurocode – 2 concrete standards (13, 14).
Creep

Eurocode – 2 includes a detailed qualitative and quantitative evaluation of creep. The “time dependent creep coefficient” is represented as a function of the “base creep coefficient” and the “time dependent variation of creep”.

\[ \varphi(t, t_0) = (\varphi_o) \cdot \beta_c(t, t_0) \]  

Time dependent creep coefficient: \( \varphi(t, t_0) = (\varphi_o) \cdot \beta_c(t, t_0) \)  

Base creep coefficient: \( \varphi_o = \varphi_{RH} \cdot \beta(f_{cm}) \beta(t_0) \)  

Time dependent variation of creep: \( \beta_c(t, t_0) = \left( \frac{(t-t_0)}{(\beta_{H} + t-t_0)} \right)^{0.3} \)

“Base creep coefficient” is represented as a function of “effect of relative humidity on creep”, “effect of concrete strength on creep” and “effect of concrete age during the transfer of prestressing on creep”.

Effect of relative humidity on creep: \( \varphi_{RH} = \left[ 1 + \frac{1-RH/100}{0.1 \cdot 3.0} \right] \cdot \alpha_1 \cdot \alpha_2 \)  

\[ \alpha_1 = \left[ \frac{35}{f_{cm}} \right]^{0.7} \] and \[ \alpha_2 = \left[ \frac{35}{f_{cm}} \right]^{0.2} \]  

\[ h_o = \frac{2A_c}{u} \]  

Effect of concrete strength on creep: \( \beta(f_{cm}) = \frac{16.8}{\sqrt{f_{cm}}} \)

Effect of concrete strength during prestressing transfer on creep: \( \beta(t_0) = \frac{1}{(0.1 + t_0^{0.2})} \)

Where, \( h_o \) = Representative dimension of the concrete strength, \( A_c \) = Concrete cross section area, \( u = \) Concrete cross section perimeter, \( \beta(f_{cm}) = \) Effect of concrete strength on creep constant, \( f_{cm} = \) Mean concrete strength at the end of 28 days, \( \beta(t_0) = \) Effect of concrete age at the instant of loading on the creep constant.

The time dependent variation of creep is a function of, humidity, representative cross section dimension, concrete strength and concrete age.

\[ \beta_H = 1.5[1 + (0.012RH)^{18}]h_o + 250\alpha_3 \]

\[ \alpha_3 = \left[ \frac{35}{f_{cm}} \right]^{0.5} \]  

\[ t_o = t_r \cdot \left( \frac{9}{2 + t_{0,T}^{1.2}} + 1 \right)^{\alpha} \geq 0.5 \]

\[ t_r = \sum_{i=1}^{n} e^{-\left( \frac{4000}{[273 + T \Delta t_i]} \right)^{13.65}}, \Delta t_i \]

Where, \( \beta_H = \) Constant based on relative humidity, representative element dimension and concrete strength, \( t_o = \) Age of concrete based on the ambient temperature during prestressing (days), \( t = \) Age of concrete (days), \( t_r = \) Effective concrete age, \( T(\Delta t_i) = \) Temperature in terms of centigrade within \( \Delta t_i \), \( \Delta t_i = \) Number of days when the temperature is \( T \), \( h_o = \) Representative dimension of the concrete element,
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\[ f_{cm} = \text{Average concrete cylinder strength, } f_{ck} = \text{Characteristic concrete cylinder strength, } R = \text{Rapidly hardening high early strength cement, } N = \text{Normally hardening cement, } S = \text{Slowly hardening cement.} \]

The total creep shortening is determined by the multiplication of the elastic shortening by the time dependent creep coefficient.

\[ \text{Total shortening due to creep: } \varepsilon_{\text{creep}} = \varphi(t, t_0) \left( \frac{\sigma_{\text{pressure}}}{E_{\text{concrete}}} \right) \]  

An analytical evaluation of the expected contraction within the shoulder length of the sleeper was conducted. The sleeper is a non-prismatic section. To this end, the sleeper shoulder length is represented within three regions as shown in figure 6. The representative sections within these regions are: section A, B and C, which are the sleeper rail region, the sleeper transition region and the sleeper central region respectively. The cross sections are presented in figure 7.

**FIGURE 6** Regions along the shoulder.

**FIGURE 7** Sleeper cross sections.

The cross section areas of the sections A, B and C are \( A_A = 49.233 \text{ mm}^2 (7.631 \text{ in}^2) \), \( A_B = 37.400 \text{ mm}^2 \), \( A_C = 33.425 \text{ mm}^2 (5.181 \text{ in}^2) \), their perimeters are \( U_A = 884 \text{ mm} (34.8 \text{ in}) \), \( U_B = 780 \text{ mm} (30.7 \text{ in}) \), \( U_C = 737 \text{ mm} (29 \text{ in}) \) and \( h_{0A} = 111 \text{ mm} (4.4 \text{ in}) \), \( h_{0B} = 96 \text{ mm} (3.8 \text{ in}) \), \( h_{0C} = 91 \text{ mm} (3.6 \text{ in}) \). The creep characteristics for RH=75%, which was the mean indoor humidity level reported for the experimental measurement presented in the next section, can be evaluated through the numerical analysis presented in Appendix A.
Shrinkage

The shrinkage characteristics are presented in Eurocode-2 (13). Total “concrete shrinkage” is related to “drying shrinkage” and “autogenous shrinkage”.

Drying Shrinkage:

\[ \varepsilon_{cd,0} = \beta_{ds}(t_s, t) \cdot \varepsilon_{cd,0} \]  

\[ \beta_{ds}(t_s, t) = \left( \frac{(t-t_s)}{(t-t_s)+0.04} \right)^{0.5} \]  

\[ \varepsilon_{cd,0} = 0.85 \left( 220 + 110. \alpha_{ds1} \right) e^{-\frac{f_{cm}}{f_{cm0}}} \cdot 10^{-6} \cdot \beta_{RH} \]  

\[ \beta_{RH} = 1.55 \left[ 1 - \left( \frac{RH}{RH_0} \right)^3 \right] \]

\( f_{ck} = 65 \text{ MPa (Characteristic cylinder strength), } f_{cm} = \text{ Average concrete strength = 73 MPa, } f_{cm0} = 10 \text{ MPa, } t_s = \text{Time of cure termination (t_s =0.5 Days), } t = \text{Time (Days), } RH = \text{Relative humidity (%) and } RH_0 = 100\% 

\[ \alpha_{ds1} = \begin{cases} 3 & \text{for S type cement} \\ 4 & \text{for N type cement} \\ 6 & \text{for R type cement} \end{cases}, \quad \alpha_{ds2} = \begin{cases} 0.13 & \text{for S type cement} \\ 0.12 & \text{for N type cement} \\ 0.11 & \text{for R type cement} \end{cases} \]

Autogenous Shrinkage:

\[ \varepsilon_{ca}(t) = \beta_{as}(t) \cdot \varepsilon_{ca}(\infty) \]  

\[ \beta_{as}(t) = 1 - e^{-0.2t^{0.5}} \]  

\[ \varepsilon_{ca}(\infty) = 2.5(f_{ck} - 10)10^{-6} \]

Estimate of Total Elastic and Time Dependent Contractions

The evaluation of the development of creep and shrinkage can be determined through the use of spreadsheets. Tables 2 and 3 that are presented in Appendix A, show the development of creep and shrinkage along the shoulder of the sleeper under a relative humidity of 75%. Such tables are constructed for varying levels of relative humidity and the resultant variations in time summarized in a single figure. Figure 8 shows that under relative humidity conditions of 80% and less, the expected time dependent contractions within the shoulder, exceed the 1 mm negative tolerance within 1 month of the application of prestressing.
EXPERIMENTAL EVALUATION OF ELASTIC AND TIME DEPENDENT CONTRACTIONS

Prior to the production of the sleepers for the Ankara - Konya high speed railway, the sleeper molds were produced according to the numerically estimated time dependent contractions for the designed sleeper. The numerical estimate for the annual time dependent dimensional change for RH = 50% was 2 mm which was 100% higher than the allowed negative tolerance of -1 mm. Based on the estimates and the allowed tolerances of +2 mm and -1 mm, the molds were dimensioned for a shoulder length of 1814.5 mm that was 1.5 mm longer than the required design value of 1813 mm. In order to test the numerical contraction estimates, 24 sleepers from the daily production of May 27, 2009 was selected and measured indoors, with a calibrated digital gauge under a reported indoor humidity mean level of RH=75%. Figure 9 shows the shoulder length measurements of an array of sleepers with the calibrated digital gauge.

The first measurements were conducted 1 day after demolding at 08.00 AM of the following day when the external humidity was at its daytime high, followed by a monthly measurement and a final measurement at the end of 60 days at the early day hours before the routine daily shift progressed. The measurement values are presented in figure 10.
The measurements were statistically evaluated based on the Gauss Distribution. The mean values were determined, followed by the determination of the variance and the values for the 95% and the 99% confidence intervals. After the comparison of the mean, the 95% CI value and the 99% CI value with the theoretical estimates, it was determined that the numerical estimates was approximately in 100% agreement with the 99% CI values. The numerical evaluations of the time dependent contractions over-estimated the measured 2 month mean contraction values by 30% and the 2 month 95% CI value by 14%. The statistical values are presented in figure 11.

The 2 mm shoulder analytical contraction estimate for RH=50% was revised to 1.5 mm (0.06 in) and the shoulder production length was set at 1814.5 mm (71.44 mm). The random measurements from the railroad gauge length taken a year after panel placement yielded values 1435 mm ± 0.3 mm. (56.5 in ± 0.012 in).
CONCLUSIONS
Although a dimensional shift on the scale of millimeters could be considered to be irrelevant for an ordinary civil engineering concrete structure, for a high speed railway; the components of which should be considered more as a mechanical piece rather than a structural element, it is an important design variation that could jeopardize the high speed operations of the railway or cause structural damage and failure. The issue of time dependent gauge length shortening was raised for the Ankara-Konya High Speed Railway, which was not previously addressed for other high speed railway lines. The presented numerical analysis and the measurements provide evidence for the initiative to maintain the dimensional quality of the high speed railway sleepers in arid climates.

The measurement of the dimensional changes along the sleepers were not pursued beyond two months based on an understanding that estimates were indicative and the allocations for the expected time dependent dimensional changes were sufficient.

In conclusion, the following are proposed for the design of a prestressed concrete sleeper destined for use in a high speed railway proposed within an arid climate:

1. The existing and the projected humidity levels for the proposed locations of the high speed railways must be established.
2. The shrinkage and creep characteristics of the sleeper design concrete must be experimentally determined along with its strength and stiffness parameters.
3. Under RH values equal and below 75%, the -1 mm shoulder tolerance is determined to be lost in two months to time dependent contractions
4. The mold shoulder length must be dimensioned to include the estimated time dependent contractions for projects proposed in countries with arid and desert conditions.
5. Further studies for wheel and rail interaction is required.
APPENDIX A

Curing time for the sleepers: 7 hours (0.3 days), waiting time until transfer of prestress to the sleepers: 5 hours (0.2 days)

\[ t_T = 0.3 \cdot e^{-\frac{4000}{(273+50)^{1.35}}} + 0.2 \cdot e^{-\frac{4000}{(273+28)^{1.35}}} = 1.35 \]

\[ t_o = t_T \left( \frac{9}{2+0.5 t_T} + 1 \right)^{\alpha} = 1.35 \left( \frac{9}{2+1.35^{1.2}} + 1 \right)^{1} = 4.9 \geq 0.5 \text{ (High early strength cement: CEM 52.5 R)} \]

\[ \beta(t_0) = \frac{1}{0.1+0.5 t_0^2} = 0.678 \text{ (High early strength cement: CEM 52.5 R)} \]

\[ \beta(f_{cm}) = \frac{16.8}{\sqrt{f_{cm}}} = \frac{16.8}{\sqrt{73}} = 1.97 \]

\[ \alpha_1 = \left[ \frac{35}{f_{cm}} \right]^{0.7} = \left[ \frac{35}{73} \right]^{0.7} = 0.598 \text{ and } \alpha_2 = \left[ \frac{35}{f_{cm}} \right]^{0.2} = \left[ \frac{35}{73} \right]^{0.2} = 0.863 \]

\[ \varphi_{at A} = \left[ 1 + \frac{1-\frac{100}{0.1 \cdot \sqrt{h_{OA}}} \cdot \varphi_{at A}}{1} \right] \cdot \varphi_{at A} = \left[ 1 + \frac{1-\frac{75}{0.1 \cdot \sqrt{111}}}{0.598} \right] \cdot 0.598 = 1.151, \text{ and } \]

\[ \varphi_{at B} = 1.146 \text{ and } \varphi_{at C} = 1.132 \]

\[ \varphi_{O} = \varphi_{RH} \cdot \beta(f_{cm}) \cdot \beta(t_0) \]

\[ \varphi_{OA} = 1.151 \cdot 2.08 \cdot 0.678 = 1.623 \varphi_{OB} = 1.146 \cdot 2.08 \cdot 0.678 = 1.616, \varphi_{OC} = 1.132 \cdot 2.08 \cdot 0.678 = 1.596 \]

\[ \Delta_{s} = 0.76 \text{ mm.} \]

**TABLE 1** Elastic Shortening Values Along the Sleeper

<table>
<thead>
<tr>
<th>Elastic shortening within the shoulder</th>
<th>Region on sleeper</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
</tr>
<tr>
<td>E&lt;sub&gt;at transfer&lt;/sub&gt; (MPa)</td>
<td>33.000</td>
</tr>
<tr>
<td>F (kg)</td>
<td>35.714</td>
</tr>
<tr>
<td>Cross section (cm&lt;sup&gt;2&lt;/sup&gt;)</td>
<td>334</td>
</tr>
<tr>
<td>Cross section perimeter (mm)</td>
<td>400</td>
</tr>
<tr>
<td>Δ(mm)</td>
<td>0.127</td>
</tr>
<tr>
<td>Total Δ (mm)</td>
<td>0.47</td>
</tr>
</tbody>
</table>

For RH = 50%:

\[ \Delta_{s,A} = 1.623 \cdot 0.13 = 0.21 \text{ mm,} \]
\[ \Delta_{s,B} = 1.616 \cdot 0.18 = 0.29 \text{ mm,} \]
\[ \Delta_{s,C} = 1.596 \cdot 0.18 = 0.28 \text{ mm} \]

Total expected creep for RH=50%, Δ<sub>s</sub> = 0.76 mm.
TABLE 2 Creep and Shrinkage Between the Shoulders for RH = 75%

<table>
<thead>
<tr>
<th>INTERVAL</th>
<th>Percentage of regional total</th>
<th>Strain</th>
<th>Shortening (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
<td>C</td>
</tr>
<tr>
<td></td>
<td>Strain</td>
<td>Total</td>
<td>Strain</td>
</tr>
<tr>
<td>Time</td>
<td>Region on sleeper</td>
<td>Strain</td>
<td>Strain</td>
</tr>
<tr>
<td></td>
<td>Strain</td>
<td>Strain</td>
<td>Strain</td>
</tr>
<tr>
<td>t&lt;sub&gt;e&lt;/sub&gt; (end of cure)</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1 Day</td>
<td>1</td>
<td>17,3%</td>
<td>17,2%</td>
</tr>
<tr>
<td>1 Month</td>
<td>30</td>
<td>46,9%</td>
<td>46,6%</td>
</tr>
<tr>
<td>2 Months</td>
<td>60</td>
<td>56,5%</td>
<td>56,1%</td>
</tr>
<tr>
<td>1 Year</td>
<td>365</td>
<td>82,0%</td>
<td>81,7%</td>
</tr>
<tr>
<td>5 Years</td>
<td>1825</td>
<td>95,0%</td>
<td>94,8%</td>
</tr>
<tr>
<td>40 Years</td>
<td>14600</td>
<td>100,0%</td>
<td>100,0%</td>
</tr>
</tbody>
</table>

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