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Non-Delayed Heat Application Effects on The Strength of Concrete For Railway Sleepers

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Abstract

Precast concrete sleepers production requires the application of low-pressure steam curing to accelerate the early age strength development. In this curing process, heat is gradually applied to the sleepers after 2 hours from casting. A typical production specification for concrete sleepers limits the rate of temperature rise to 24°C per hour and the maximum temperature to 70°C. However, it is not usual to consider heat application immediately after casting to achieve improved productivity to meet the supply demand. This paper reports the results of an experimental investigation into the effect of non-delayed heat application on the early age and later age compressive strength for the typical concrete mixes used for the production of concrete sleepers in Australia. The mixes had either ordinary Portland cement or high early-age strength Portland cement with the low calcium fly ash as binder materials. The results showed that the compressive strength after 8 hours and 28 days were significantly reduced when non-delayed heat application was carried out. Delayed ettringite formation (DEF) could be one of the reasons for the strength reductions and a delayed period up to 4 hours is beneficial in controlling the strength loss.

Keywords: Concrete sleepers; curing; compressive strength; heat treatment; delayed ettringite formation

1. Introduction

The role of a railway structure is to provide safe and economical train transportation. The railway track must serve as a stable guide way with appropriate vertical and horizontal alignment. Sleepers, an important structural component of the railway track system, play an important role in the successful operation of a track structure. The main function of the sleepers and ballast is to transfer the train load to the formation by progressively distributing the load over an ever increasing area. In addition, the sleepers must fulfil the following functions in the track [1]: (a) hold the rail to the correct gauge and inclination within the specified tolerances; (b) not to rollover sideways under the traffic loading; (c) not to move sideways under either centrifugal or thermal forces and resist buckling; (d) not to move longitudinally under traction, breaking or thermal forces, and (e) electrically insulate the two rails from each other.

Traditionally, timber sleepers have been used in Australia. More recently, concrete sleepers have replaced the timber sleepers, providing improved strength, durability and cost savings. Crowford [2] showed that the life cycle emissions of reinforced concrete sleepers are up to six times less than the emissions associated with timber sleepers. Australian Transport Safety Bureau (ATSB) investigation report [3] on the safety of rail operation between Melbourne and Sydney indicated that from the point of views of the availability and resistance to misalignment during hot weather, concrete sleepers were preferred to replace the timber sleepers. Australian Rail Track Corporation (ARTC) considered a complete replacement using concrete would reduce operational delays in the long term, since the requirement for track access to do maintenance is less for concrete than timber.

2. Delayed ettringite formation and concrete specification

Precast concrete sleepers production involves the application of low-pressure steam curing to achieve high early-age strength, even though the later age strength of concrete is reduced [4]. The lack of supplementary wet-curing following the steam curing cycle was considered as the primary cause, although increased porosity, internal cracking and heterogeneity of the paste were also contributing to the strength reduction.

The micro-structural studies on steam-cured concrete [5] showed that in concrete cured at or above 60^{o}C, 20% to 30% of the C-S-H had a dark inner zone and lighter outer shell which were not present in room temperature, and up to 80% of the Hadley grains had distinct hydrate product rims, many being partially or completely infilled with either ettringite or mono-sulphate-type hydrates. As the curing temperature was increased the proportional of ettringite-type hydrates decreases while those associated with mono-sulphate became more predominant.

Heinz and Ludwig [6] reported that ettringite, one of the initial cement hydration products formed prior to steam curing at a temperature of 70°C or above, is destroyed during heat application and further formation of ettringite is inhibited. During this process, a significant amount of sulfate is absorbed in the C-S-H or present in the pore solution [7]. The subsequent formation or reformation of ettringite during the service life of the concrete at ambient temperature and exposure to moisture is known as delayed ettringite formation (DEF) which causing expansion and cracking. DEF was being identified as cause for severe cracking of pile caps of bridge piers in Sri Lanka [8] where the concrete temperature during the very early ages was well above 80^{o}C.

DEF was found to be responsible for the premature deterioration of more than 50 structures [9] in France and for the failure of concrete sleepers in Finland [10] and Sweden [11]. Cracking was observed at the locations where the temperature differentials have been greatest and at the weak aggregate-cement paste interface. To minimize the risk of DEF, Lawrence et al. [12] recommended the following specification requirements for the production of concrete sleepers: (a) a maximum fresh concrete temperature of 30^{o}C; (b) a maximum curing temperature of 60^{o}C; (c) application of steam curing after 3 to 4 hours of delay from the time of casting; and (d) maximum heating rate of 20^{o}C per hour.

Sahu and Thaulow [11] had reported that the DEF could occur even below 60^{o}C due a combination of the following factors related to the cement: (a) high cement content; (b) high alkali content; (c) high sulphate content; (d) high magnesium oxide content; and (e) high reactivity of ferrite phase.

Railcorp specification in Australia [13] specifies the following design information for prestressed precast concrete sleepers: length of 2.39 to 2.50 m; base width of 220 and 255 mm; and depth at the central of rail seat 230 mm (maximum) for heavy duty sleeper and 180 mm (maximum) for medium duty sleeper. Concrete mix for the sleepers requires a minimum characteristic strength of concrete of 50 MPa and a minimum compressive strength 30 MPa at the transfer of pre-stress force. The low-pressure steam curing applied to sleepers complies with the following specification requirements: the relative humidity of curing atmosphere of over 95%; the concrete temperature below 70^{o}C; the maximum heating rate of 24^{o}C per hour; and the maximum cooling rate of 15^{o}C per hour.

The time between casting and steam application (i.e. delay period) is dependent up on many factors, namely characteristics of cement, initial concrete temperature, water content, rate of temperature change during the delay period and rate of concrete temperature rise. Specification for prestressed concrete sleepers (AS 1085.14) states the following: (a) if the temperature within the sleeper exceeds 70^{o}C, there is potential for delayed ettringite formation; and (b) the curing cycles are controlled by adjusting the curing atmosphere temperature profile once the correlation between concrete temperature profile and curing atmosphere profile has been established for the particular manufacturing center and mix design.

3. Research significance

Specification for prestressed concrete sleepers production requires a delay period of at least 2 hours after casting for the application of steam curing, with a maximum concrete temperature of 70^{o}C. However, considering the flexibility allowed by the specification, the concrete sleeper producers are often request for approval to have a reduced or no delay period prior before the application of steam curing to increase the production target. The significance of this research is to evaluate the effects of heat application immediately after casting on the compressive strength after 8 hours and 28-days for concrete mixes used in the concrete sleeper productions in Australia.

4. Experimental investigation

4.1 Materials and mix compositions

A typical concrete mix used for precast concrete railway sleepers in Australia was produced. Two identical mixes were produced with either General purpose Portland cement (Type GP) or high-early strength Portland cement (Type HE). Low calcium fly ash was used in both mixes and its quantity was about 11%, by weight, of the total cementitious materials in the mixes. The coarse aggregate was crushed river gravel whereas the fine aggregate was river sand. Superplasticiser was used to obtain sufficient workability for mixing and casting. The water to cementitious materials ratios of the mixes were 0.40 and 0.34 for Mix 1 and Mix 2, respectively. Table 1 shows the details of the two concrete mixes.

TABLE 1: COMPOSITION OF THE CONCRETE MIXES

Materials	Mix 1 (Type GP)	Mix 2 (Type HE)
Cement	331	331
Fly ash	40	40
20 mm Coarse aggregate	810	810
10 mm Coarse aggregate	460	460
Fine aggregate	670	670
Water (l/m^3)	145	125
Superplasticiser (l/m^3)	4.97	4.97
Water to (Cement + Fly Ash)	0.39	0.37

4.2 Casting, curing and testing of concrete

The concrete was mixed in a pan-type mixer and the fresh concrete was tested for its slump. For each mix, a total of 18 Nos. of 100mm diameter by 200mm long cylinders were cast in standard steel moulds and full compaction for the specimens was achieved using a vibrating table.

A total of three curing history were used for the concrete cylinders. Immediately after casting, six sealed cylinders were placed in a pre-heated oven to the temperature of 65^{o}C and left for 6 hours. After a delay period of 2 hours from casting, six sealed cylinders were placed in a heated oven to 65°C for 4 hours. At the end of the heating period, the cylinders were removed from the oven and allowed to cool in the laboratory environment. They were then stripped from the moulds and tested at the age of 8 hours and the rest of them were stored in water at 20°C until the age of 28 days.

The temperature of the concrete was monitored using embedded thermocouples and Figure 1 shows the temperature development n concrete during the period of heating. The temperature was increased gradually and took approximately 2 hours to attain the required temperature.

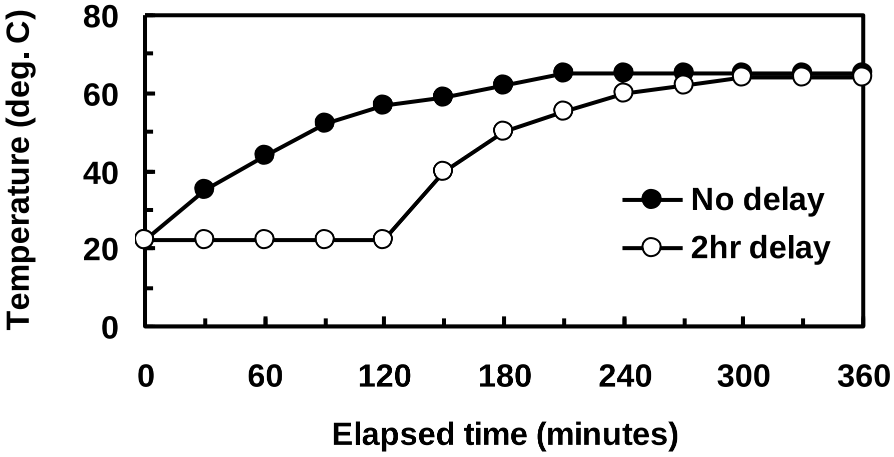

Figure 1. Temperature history of the heated concrete cylinders

The last set of six cylinders was not subjected to heat application and three of them were removed from the moulds at the age of 8 hours and tested for the compressive strength. Other three cylinders were removed from the mould after 24 hours and subjected to standard water curing at the mean temperature of 20°C until the age of 28 days. All the concrete cylinders were tested in direct compression according to the procedures outlined in AS 1012.

TABLE 2: MEAN COMPRESSIVE STRENGTH (MPA) OF CONCRETE

Curing Conditions	Mix 1		Mix 2	
	8-hour	28-day	8-hour	28-day
Standard	1.00	46.8	1.10	57.7
Non delay	11.4	38.6	22.5	50.5
2-hr delay	14.5	40.6	24.1	51.7

5. Results and Discussion

Mix 1 and Mix 2 had sufficient workability with the slump of 60 mm and 50 mm, respectively. Table 2 summarizes the compressive strength of concrete mixes at the ages of 8 hours and 28 days for all three curing regimes. The following observations could be made from the strength results.

For standard curing, both concrete mixes had very low compressive strength after 8 hours. The concrete mix with high-early strength cement (Mix 2) showed an improved strength after 28 days compared to the corresponding strength for the concrete mix with general purpose Portland cement (Mix 1). The 28-days strength for Mix 2 is 57.7 MPa compared to 46.8 MPa for Mix 1. This corresponds to an increase of about 23%. This may be due to the combined effects of cement type and water to cementitious materials ratio. The water to the cementitious materials ratio for Mix 1 and Mix 2 was 0.39 and 0.37, respectively.

The application of heat immediately after casting for 6 hours had increased the strength after 8 hours from 1.00 MPa to 11.4 MPa for Mix 1 and from 1.10 MPa to 22.5 MPa for Mix 2. When the heat application was delayed by 2 hours, the 8-hour strength was further increased from11.4 MPa to 14.5 MPa for Mix 1 and from 22.5 MPa to 24.1 MPa for Mix 2. In relative terms, 2 hours delay in the heat application has caused the strength gains of 27.2% for Mix 1 and 7.1% for Mix 2. This could be due the reduced amount of microfissures due to the delay in the heat application. The improvement in early age strength with heat treatment for both mixes compared to the standard curing at room temperature is due to the increased maturity of concrete, associated with the increased degree of cement hydration.

The results also show that the effect of 2 hours delay prior to the heat application has increased the 28-days strength from 38.6 MPa to 40.6 MPa for Mix 1. This corresponds to the strength improvement of 5.2%, while the corresponding strength gain for Mix 2 was only 2.4% (increase from 50.5 MPa to 51.7 MPa).

In relation to the standard water curing condition, both mixes showed losses when the heat was applied with or without the delay period. For the Mix 1, the compressive strength at 28 days was 46.8 MPa for standard curing condition compared to 38.6 MPa for heated concrete with no delay period and 40.6 MPa for heated concrete with 2 hours delay. In relative terms, the strength losses were 17.5% and 13.2% with non-delayed and delayed heat application, respectively. The corresponding strength losses for Mix 2 were 12.5% and 10.4% for non-delay and delayed heat application, respectively. These observations indicate that concrete with high early age strength Portland cement is less sensitive to the non-delay in heat application compared to the similar concrete with the general purpose Portland cement.

In mass concrete, where the concrete temperature could be over 70^{o}C at early ages, the strength losses were also reported by others. Sri Ravindrarajah and Beggs [14] reported that effect of curing temperature history on the development of strength for concrete with blast furnace slag cement used in the construction of 27 m by 21m by 5 m ANZAC bridge pile caps in Sydney, Australia. The 90-days compressive strength for water cured concrete at 84^{o}C for 28 days followed at 20^{o}C was 53.8 MPa compared to 63.5 MPa for the same concrete water cured at 20^{o}C for the same duration. The strength loss of 15% after 90 days was due to high temperature curing at early ages. Similarly, Nanayakarra [8] reported a strength loss of 10% at 28 days when the concrete was subjected to a temperature match curing regime with the maximum temperature of 80^{o}C compared to the constant water curing at 30^{o}C.

6. Concluding Remarks

Application of steam curing is necessary for the concrete sleepers to increase the development of early age strength in concrete, necessary for the production of precast concrete sleepers. The effect of application of heat immediately after casting on the early and later age strengths were evaluated for concrete mixes used for the prestressed concrete sleepers production. The results clearly showed the application of heat had the beneficial effect of increasing the 8-hour strength with the negative consequence of reducing the strength at 28 days.

The strength results also have shown that the application of heat immediately after casting compared to 2-hours delay period has caused noticeable reductions in compressive strength at the ages of 8 hours and 28 days. The concrete mix with high-early age strength Portland cement was less sensitive to the delay period compared to the mix with the general purpose Portland cement.

Even though, the strength reduction may be acceptable by having non-delayed heat application, the experience had shown that this practice should be allowed from the point of view of increased potential of the delayed ettringite formation which had been reported as main cause for the premature failure of concrete sleepers in Finland and Sweden.

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