Development of safe construction temperature ranges to avoid blow-ups in Ultra-Thin Concrete Pavements

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Abstract. After the construction of an ultra-thin concrete pavement, ambient temperatures may induce an axial force within the pavement due to thermal expansion that can lead to the formation of a blow-up failure. By analysing the mechanism of a blow-up, temperature differentiates at which a blow-up failure in ultra-thin concrete pavements may occur were identified. Safe construction temperature range graphs were produced for different ultra-thin concrete pavements to serve as a guideline that would potentially limit the occurrence of blow-ups.

1 Introduction

The South African road network is an ageing part of the country's infrastructure. With 70 % of the network exceeding the 20 year design life, innovative repair and construction methods were required to rectify this problem [1].

Ultra-Thin Continuously Reinforced Concrete Pavements (UTCRC) were developed as one such solution. The most significant difference between UTCRC and conventional Continuously Reinforced Concrete Pavements (CRCP) is the thickness of the pavement structure. While CRCP typically varies between 150 mm up to 300 mm, UTCRC is typically 50 mm thick. In addition, UTCRC utilizes concrete with a very high strength (exceeding 80 MPa compressive strength) and a high percentage of steel (usually 50 x 50 x 5.6 mm steel mesh), while it also contains a large volume of steel fibres and also polypropylene fibres [2].

During the early development of UTCRC, the potential of using thin concrete in low volume roads was identified and this led to the development of Ultra-Thin Reinforced Concrete Pavements (UTRCP). UTRCP differs from UTCRC in that a lower volume of steel (typically 100 x 100 x 4 mm steel mesh) and lower strength concrete (typically 30 MPa compressive strength) is used [3].

The failure modes of ultra-thin concrete pavements were interrogated during initial heavy vehicle simulator testing [1]. Unfortunately the trial strips were generally short, did not always incorporate anchor end stops and failure modes were mainly load associated cracking and potholing. These conditions did not favour thermal expansion related failures and accordingly it did not receive significant research attention. The focus of this investigation is blow-ups, also referred to as pop-ups, as

typically shown in Figure 1, in UTRCP. There is general consensus that blow-ups are caused by axial compressive forces within the pavement structure. The axial forces are induced into the pavement through a rise in temperature or moisture changes [4].

Figure 1 : Typical example of a buckling blow-up failure in an ultra-thin concrete pavement

The blow-ups are typically accompanied with transverse cracks or joints in the pavements. The thermal expansion of the pavement is critical to activate this mechanism. Thermal expansion is dependent not only on temperature of the pavement, but also the moisture within the pavement. The increase or decrease of the moisture within the pavement may be represented by an equivalent increase or decrease of temperature [5]. This is due to the thermal expansion coefficient increasing or decreasing with a corresponding increase or decrease in moisture [6].

The use of safe temperature construction limits is well known in the road construction industry, with authorities restricting the construction of bituminous seals to warmer periods of the year. The calculation of safe construction temperature ranges to prevent thermal buckling failure is primarily used in rail construction [7].

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It is of crucial importance for Continuously Welded Rails (CWR) to ensure that excessive tension and compression forces are not present in the rail to avoid either rail breaks or kick-outs. This investigation attempts to establish such temperature ranges for the construction of UTRCP pavements.

2 Background Theory

The development of safe temperature construction range graphs for ultra-thin concrete pavements, UTRCP, may reduce the occurrence of blow-ups within the pavement. If a pavement is constructed and adheres to the temperature limits prescribed, it should ensure that no excessive strain is developed in cold weather or excessive axial forces are induced by warm weather.

The blow-ups of CRCP pavements have been extensively researched [8]–[17]. The analysis of the phenomenon focuses on the axial force induced into the concrete pavement by a rise or fall in temperature and/or moisture. Research conducted by Kerr [4], [5], [18] identified three modes (cases) of buckling of a concrete pavement as indicated in Figure 2:

- continuous pavement with no joint, also referred to as unhinged;
- continuous pavement with a joint or crack, hinged;
- continuous pavement adjoining a rigid structure, typically at an anchor beam.

Figure 2 : The three modes investigated by Kerr (Kerr, 1997)

Kerr confirmed that the most critical case is where a joint or a large spalling crack is located in a continuous pavement (Case II). As continuously reinforced concrete pavements are designed without joints but with regular narrow (less than 0.5mm in width) transverse cracks, a load case somewhere between an unhinged (Case I) and hinged (Case II) is applicable for the current study.

The use of conventional beam-buckling theorem, to determine the force at which the concrete pavement will buckle, is considered as erroneous. This is because beam-buckling does not account for the resistance to buckling provided by the self-weight of the pavement that influences the solutions significantly [18].

The analysis of Kerr represented the concrete pavement as a rectangular beam on a rigid base as indicated in Figure 3. The axial force induced by a temperature increase is represented by N_t , the reduced axial force after a blow-up is represented by $\tilde{N}_t$ in the lift-off region of $2l$. In the adjoining regions, the axial force, N , varies due to the shearing resistance to axial displacements. The joint in the centre of the illustration is also the point x , where the largest lift-off may be expected after a blow-up.

Figure 3 : Axial forces in a concrete pavement after a blow-up [18]

The temperature at which a blow-up could occur was determined by further analysis of this model. The maximum temperature without a blow-up occurring was presented by ΔT_L . The temperature increase in the pavement was represented by ΔT_0 . Thus, for a range $0 < \Delta T_0 < \Delta T_L$, no blow-up in the concrete pavement is expected, but any instance at which $\Delta T_0 > \Delta T_L$, a blow-up is possible.

For ultra-thin concrete pavements, the formulas used to represent the mode of failure for a concrete pavement without a joint/crack were the following [18]:

$$\lambda l = 4.4934 \quad (1)$$

$$\alpha \Delta T_0 - \tilde{N}_t / EA = \sqrt{((2r_0) / \mu EA \ln(\cosh\{\mu(\alpha \Delta T_0 - \tilde{N}_t / EA)l - J\}))} \quad (2)$$

Where

$$J = 0.001023 q^{*2} l^7 \quad (3)$$

$$\lambda = \sqrt{((\tilde{N}_t (1 - \nu^2)) / EI)} \quad (4)$$

$$q^* = (q_0 (1 - \nu^2)) / EI \quad (5)$$

With

α = coefficient of linear thermal expansion for the concrete ($\alpha = 9 \times 10^{-6}/^{\circ}\text{C}$)

E = Young's modulus for the concrete (GPa), refer to Table 1

A = cross sectional area of the pavement (b x h; with b the width of the pavement and h the height of the pavement, typically 50 mm for UTRCP)

r_0 = sliding frictional resistance at the interface of the pavement and the base per unit length and width of pavement

μ = curve fitting parameter for the sliding frictional resistance to test data ($\mu = 1000/\text{m}$)

$\tilde{N}_t$ = axial force in the pavement

q^* = unit weight of the pavement per meter length

γ = unit weight of the pavement material ($\gamma = 23.6 \text{ kN/m}^3$)

l = half the length of the lift-off region of the pavement since the uplift is symmetric

The Young's Modulus of the concrete differs for UTRCP, as it is not the same for all the design codes. For the analysis the values given by Euro code [19] was used. Alkali-silica reactions have not been included in the study as it is assumed that care will be taken to avoid such aggregates when constructing ultra-thin concrete pavements.

Table 1: Concrete Modulus of Elasticity

Cube Strength (MPa)	Young's Modulus (GPa)			
	Euro code [19]	SANS 10100 [20]	BS 8110-1:1997 [21]	ACI 318M-05 [22]
25	30	26	21	21
30	31	28	23	23
35	32	29.5	24	25

The expected vertical displacement of the pavement can be calculated by using equation (6). For the maximum deflection of the pavement, x is equal to zero since the maximum deflection occurs in the middle of the lift-off region.

$$w_l(x) = (q^*/2\lambda^4) [2\lambda l (\cos\lambda x - \cos\lambda l)/\sin\lambda l + (\lambda x)^2 - (\lambda l)^2] \quad (6)$$

With the above equations, a positive value is assumed for the axial force within the pavement. With

the now known axial force, lambda (λ) can be calculated along with l (length), the term J and a solution can be found for ΔT_0 through equation (2). From the solution of the equations over a multitude of axial forces, graphs can be developed for a concrete pavement without a joint.

The formulas used to represent the mode of failure for a concrete pavement with a joint/crack were the following, with equation (2), (4) and (5) unchanged:

$$\lambda l = 2.3311 \quad (7)$$

$$J = 0.0063 q^{*2} l^7 \quad (8)$$

$$w_l(x) = (q^*/2\lambda^4) [\cos\lambda x + [(\sin\lambda l - \lambda l)/\cos\lambda l] \sin\lambda x - 1 + (\lambda x)^2/2 - (\lambda l)^2/2] \quad (9)$$

For each of the modes of failures, a minimum temperature increase to cause lift-off, i.e. a blow-up, can be determined for different thicknesses.

3 Determination of Blow-up Failure Temperatures

The relationship between temperature and vertical displacement has a parabolic shape representing the post-buckling equilibrium displacements as indicated in Figure 4 and Figure 5, where h denotes the thickness of the concrete. The equilibrium branch to the left of the minimum value represents the unstable mode of failure that may occur described as a shattering blow-up.

The equilibrium branch to the right represents the stable failure mode or a buckling blow-up. Shattering type blow-ups are more likely to occur in UTRCP pavements due to the lower compressive strength concrete used, with buckling blow-ups more common in UTRCP pavements. Figure 6 and Figure 7 indicate the relationship between the axial force and vertical displacement and confirm high axial compressive forces with minimal up lift for shattering blow-ups.

Figure 4: Equilibrium branches for UTRCP with a joint/crack

Figure 5: Equilibrium branches for UTRCP without a joint/crack

Figure 6: Axial forces, $\tilde{N}_t$, for UTRCP without a joint/crack

Figure 7: Axial forces, $\tilde{N}_t$, for UTRCP with a joint/crack (left) and without a joint/crack (right)

The relationship between concrete thickness and the maximum safe allowable temperature increase that the pavement can experience before a blow-up, is indicated in Figure 8. It is clear that the temperature increase required to cause a blow-up in an ultra-thin concrete pavement is considerably lower than for conventional CRCP pavements.

The temperature increase required for a blow-up in ultra-thin concrete pavements with a thickness of 50 mm, can be less than 15 °C as indicated in Figure 4. It is

therefore of importance for the designer of an ultra-thin concrete pavement to take into consideration the minimum temperature increase required to cause a blow-up and limit the construction temperature accordingly.

The deterioration of cracks in an ultra-thin concrete pavement may further increase the risk of a blow-up at even lower temperatures than that of a newly constructed (without a joint/crack) pavement. Transverse cracks in an ultra-thin concrete pavement can occur and reduce the bending stiffness of the concrete, depending on the depth of the crack.

For rectangular shapes, an 8 mm deep crack in a 50 mm thick pavement will incur a 40 % reduction in bending stiffness in the concrete used, as an example. This implies only about 60 % remaining bending stiffness if a crack nearly one sixth the depth is present within the pavement.

This will cause the temperature increase for a blow-up to occur, to lie between the above-mentioned values with and without a joint. The effect of 40% bending stiffness due to a possible crack in the pavement is shown in Figure 8.

Figure 8: Pavement thickness influence on safe temperature increase for different bending stiffness situations

4 Safe Temperature Ranges

In rail track design, more specifically the design of Continuously Welded Rails (CWR), the rails need to be fixed and destressed within certain temperature ranges. This will ensure that tension and compression forces within the rail are limited to reduce the risk of buckling failures.

With ultra-thin concrete pavements being prone to temperature related failures, the need to identify possible safe temperature ranges for casting of the concrete was recognized. With bridge construction, the maximum daily air temperature of the day before, and the minimum night time air temperature for the morning of the casting a concrete expansion joint is used to determine the installation temperature [23]. A similar approach to the construction temperatures of UTRCP is proposed where the average of the two values is taken as the installation temperature.

The lower construction temperature limit is currently dependent on axial thermal expansion forces within the pavement while the upper temperature limit is dependent on concrete regulations with regard to maximum casting

temperatures. It must be noted that daily thermal expansion of the pavement can cause large movements exceeding that caused by shrinkage [24].

Temperature rise during construction in thin, exposed members are usually small, regardless of the mixture or type of cement used. The temperature of the concrete will be slightly above the ambient air temperatures and the stable installation temperature of the concrete will approximate the geographical annual average air temperature [25].

4.1 Upper Temperature Limit

The main factor influencing the upper construction temperature limit is strain within the concrete. If the concrete pavement exceeds the allowed strain in thermal contraction, the pavement may not be able to recover the strain and therefore create a permanent defect.

Most of the shrinkage occurs in the initial drying of the concrete, where a large part cannot be recovered [26]. The CSIR guideline for ultra-thin concrete pavement construction allows for construction joints between two adjacent sections of pavement that are cast later than 48 hours apart [27]. However, this would reduce the amount of recoverable shrinkage since the length of the earlier cast pavement is reduced due to the time it has been allowed to shrink. Since most of the shrinkage will occur at the free end of the pavement, this reduces the recoverable shrinkage capacity of the pavement [26].

Accordingly, an upper construction limit of 35°C can be seen as the maximum permissible temperature for local conditions as per the South African National Standard 878:2012 [28]. Hot weather concreting at temperatures above 35°C is in any event usually not permitted as water evaporation and early age cracking becomes a problem [29].

4.2 Lower temperature limit

To determine the lower temperature limit, the expected maximum temperature of the pavement needs to be known. While asphalt pavement maximum temperatures are well documented in South Africa, limited information on concrete pavement temperatures are known. Ambient temperatures are generally slightly lower than that of the pavement surface due to concrete's thermal absorptivity from the sun's radiation [6]. A relationship between ambient temperature and surface temperature of concrete pavements has not been established, and due to the thickness of ultra-thin concrete pavements, ambient temperatures were assumed for concrete temperatures in this study.

If the maximum temperature that an ultra-thin concrete pavement can experience on a specific site is assumed to be 40 °C, as indicated by SCT 22 [30], the lower limit (LL) is determined as follows:

$$LL = MaxT - \Delta T_L \quad (10)$$

As shown earlier, for a 50 mm thick ultra-thin concrete pavement with a transverse crack, approximately 13 mm deep, (40 % reduced stiffness) the value of ΔT_L is equal to 20.5 °C for UTRCP. The lower construction temperature limit is equal to 19.5 °C. The sensitivity of the pavement to temperature and the condition thereof is clear from this analysis.

5 Discussion

Following the analysis above, a safe construction temperature graph for a 50 mm thick ultra-thin concrete pavement can be produced as shown in Figure 9 for an illustrative site. Note that the highest expected temperature of 40°C represents the highest expected concrete temperature of the pavement during the hot summer months at this illustrative site.

Figure 9: Safe construction temperature range graph indicating the range of temperatures at which ultra-thin concrete pavements should be constructed to minimize the risk of a blow-up failure for the illustrative site considered

The specifications supplied by the Standard Specifications for Road and Bridge Works for State Road Authorities (COLTO) as well as South African National Standard 878:2012, state that concrete may be placed at temperatures as low as 5 °C [31], [28]. This was adopted for UTRCP [27]. Although such low temperatures may be expected on site and even lower, to construct the ultra-thin concrete pavement at such temperatures may lead to significant blow-ups occurring within the pavement.

The above analysis was repeated for different possible site temperatures and a range of possible pavement construction thicknesses to establish a guide for minimum construction temperatures as shown in Table 2. The use of a reduced bending stiffness of 40% was applied to represent possible defects that may occur within the pavement and considered appropriately conservative for design.

Table 2 : Minimum construction temperatures for UTRCP associated with the maximum expected site temperature and pavement thickness

Pavement thickness [mm]	Maximum expected site temperature [°C]				
	24	28	32	36	40
50	5	8	12	16	20
60	5	5	9	13	17
70	5	5	7	11	15
80	5	5	5	9	13
90	5	5	5	7	11
100	5	5	5	5	9

6 Conclusion and Recommendations

With an increase in temperature, an axial force is induced within a concrete pavement. The axial force may then lead to a blow-up in the pavement where there is a vertical displacement of the pavement over a certain length. The magnitude of the temperature increase, consequent induced axial force and magnitude of displacement was calculated for ultra-thin concrete pavements.

An interim guideline was developed that will allow designers in future to specify the minimum safe construction temperature for UTRCP pavements for specific site temperatures. The safe temperature range can also be referred to as a neutral temperature range where the pavement is not in danger of experiencing excessive temperature induced axial forces or excessive strain with a temperature decrease. The lowest allowable construction temperature as stated by COLTO [31] and SANS 878:2012 is 5°C, but to construct ultra-thin pavements at this temperature could be detrimental and may lead to blow-up failures.

The temperatures at which blow-ups occur need to be confirmed by laboratory and/or full scale testing to substantiate the analysis done. The validation of the calculated low construction temperatures is the focus of a study that is currently being undertaken by the authors on a number of recent blow-up failure sites.

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