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Cold and moderate ambient temperatures effects on expansive pressure development in soundless chemical demolition agents

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Abstract:

This paper explores cool and moderate temperature (2°C-19°C) impacts on hydration heat and expansive pressure development in two commercial Soundless Chemical Demolition Agents (SCDAs). Experimental results showed (1) product-specific, linear relationships between the ambient temperature and time to peak hydration heat; (2) peak hydration heats to be consistently 1.5 times the ambient temperatures at 10℃-19℃; outside of this range the factor was greater; (3) a linear relationship between peak hydration heat time and the onset of expansive pressure development; (4) a largely proportional relationship between ambient temperature and volumetric expansion of 1.1-1.4 times the original volume.

Keywords: Soundless Chemical Demolition agent, Expansive cement, Ambient temperature, Expansive pressure, Dexpan, Bristar, Non-expansive demolition agent, Heat of hydration, Volumetric expansion

1. INTRODUCTION

Demolition in urban areas is challenging due to noise and vibration limits and prohibitions against explosive agents. Yet adoption of soundless chemical demolition agents (SCDAs), which avoid these and many other problems, remains highly limited. Arguably, the highly selective uptake of this nearly 50-year old technology is an outgrowth of the proprietary nature of the products and the absence of reliable usage guidelines for their application. Nowhere is this more crucial than with respect to cooler ambient temperatures. As such, this paper explores SCDA pressure development in cold and moderate ambient temperatures for two prominent brands.

2. BACKGROUND

The first non-explosive splitting of stone dates to ancient Greece where wooden wedges were inserted into cracks in marble blocks and then soaked with water. The surrounding material cracked with the wood's expansion. Chemicals were first investigated for this purpose in the 1890s, as part of Cardlot and Meaelis's discovery of ettringite in cement (Mather 1970).

SCDAs were first commercially marketed in the early 1970s. The typical SCDA is a grayish, powdery dry material that is naturally hygroscopic, non-combustible, and non-explosive (Etkin and Azarkovich 2006). SCDA usage involves pouring the SCDA in a slurry form into a predrilled hole. After fracturing occurs, the materials should be removable with a sledgehammer, pick, or mechanized removal equipment.

While there are numerous proprietary SCDAs on the market, they primarily contain calcium oxide (CaO) (often over 90%) and different amounts of ferrous oxide (Fe_2O_3),

magnesium oxide (MgO), silicon (SiO_2), aluminium oxide (Al_2O_3) and calcium fluoride (CaF_2). While CaO is the main SCDA ingredient, other materials have been added to change, postpone, enhance, or control the hydration procedure (Hinze and Brown 1994). For example, a higher CaO content leads to more reaction and, thus, heightened expansive pressures (Goto et al. 1988).

When water is added to an SCDA, the hydration reaction with the calcium oxide (CaO) generates heat and calcium hydroxide under the exothermic reaction described in eqn (1) as proposed by Goto et al. (1988):

$$CaO + H_2O \rightarrow Ca(OH)_2 + 15.2 \uparrow (kCal/mol) \tag{1}$$
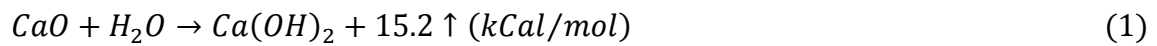
The SCDA's heat of hydration can reach 150°C, boil the mixture's free water, and cause blow outs (Swanson and Labuz 1999); however, during field applications heat dissipation into the surrounding environment makes this unlikely.

Eventually, hydration of the calcium oxide and formation of both calcium hydroxide and ettringite crystals generate a notable volumetric expansion. When confined, this leads to gradual stress development. If the strength of the surrounding material is less than the stresses forming inside the pre-drilled hole, cracks will initiate and propagate (Etkin and Azarkovich 2006).

Within a confined hole, compressive stress begins to develop along with tensile stress (Figure 1). Thus, fracture first occurs at the weakest section along the inside surface of the hole (Goto et al. 1988), at a point where this surface intersects the hole's opening.

This is the point where surrounding confinement is lowest. The phenomenon can be described by elastic theory, even though the tensile stress in the tangential direction of the hole is caused by expansive pressure. At the opening's edge, the stress is at its maximum and reduces in proportion to the square of the distance from the edge (Chatterji and Jeffery 1966). Therefore, the tensile stress generated by the SCDA expansion is responsible for the fracturing. The applied stresses fracture the surrounding mass without producing noise, vibration, or airborne debris.
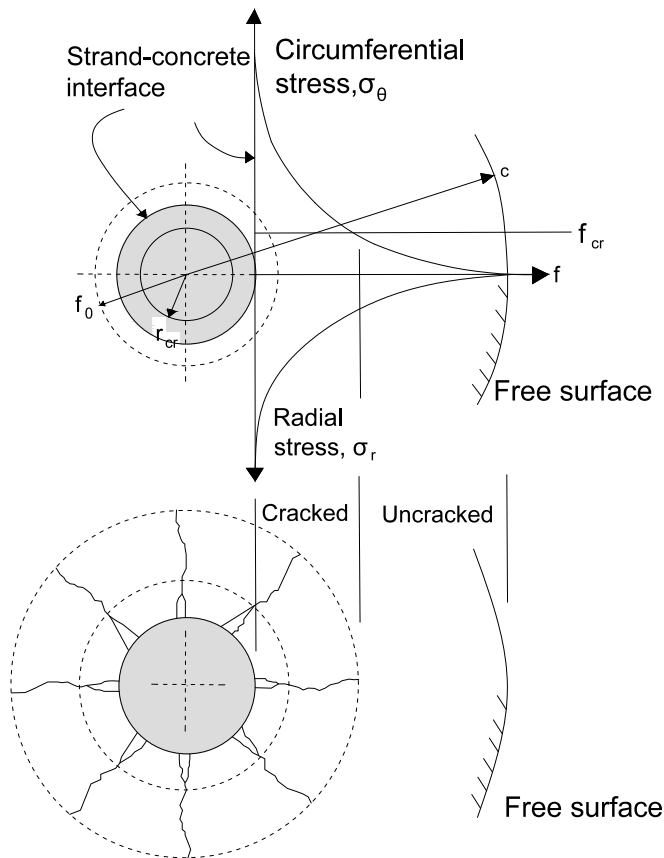

Figure 1: Deformation mechanism of drillhole by demolition agent (Zhongzhe et al. 1988)

Notable expansive pressure may be generated in a few hours or across a much longer duration depending upon the SCDA type, surrounding material, and ambient tempera-

ture (Hinze and Brown 1994). At an ambient temperature of 20°C, Soeda et al. (1994) recorded expansive pressure generation for more than one year when testing two types of SCDAs (one for warm and one for cold temperatures). However, in most applications cracking is desired within hours, if possible, as material removal may delay other construction activities.

SCDAs are designed to be used over a wide range of ambient temperatures, with most manufacturers confining application to environments of 0°C to 40°C, although some claim applicability in temperatures as low as -8°C or as high as 50°C (Connolly 2013). Notably, some manufacturers recommend a specific product within particular temperature ranges, with selection based on the lowest temperature likely to be encountered. As most applications are outdoors, temperatures can change significantly over 24 hours (S. Natanzi and Laefer 2014).

Ambient temperature has been shown to significantly influence a variety of SCDA performance factors. For example, Huynh and Laefer (2009) demonstrated that the Time to First Crack (TFC) and the Minimum Demolition Time (MDT) [moment at which there is sufficient cumulative cracking width for non-percussive, mechanical material removal] occurred sooner under warmer temperatures. Laefer et al. (2010) showed specifically that for 0.67 m³ concrete blocks with small aggregate that increasing the ambient temperature from 24℃ to 38℃ decreased the MDT by 4 hours and the TFC by 13 hours. When Hinze and Brown (1994) increased ambient temperatures from 20°C to 30°C in samples in steel tubes, a doubling in the expansive pressure was documented. Similarly, Onada (1980) demonstrated in thin-walled steel cylinders with Bristar that under a 10° temperature reduction (from 25°C to 15°C), a 30% decrease in expansive pressure at 24

hours and a 10% decrease at 48 hours were observed. Additionally, research by Laefer et al. (2010) demonstrated that products designed for colder temperatures could be used in warmer environments to accelerate cracking and that heating the mix water was another approach to hastening the cracking process.

Soeda and Harada (1993) provided a basis for this when they found that higher ambient temperatures contributed more to the exothermic reaction of the hydration reaction, thereby increasing $Ca(OH)_2$ generation. They also observed that a lower water/SCDA ratio resulted in less $Ca(OH)_2$. Subsequent experimental work by Soeda et al. (1994) directly linked greater hydration level formation increases to expansive pressure development.

However, expansive pressure generation cannot be explained exclusively by CaO hydration. Performance can vary widely depending upon the product, confinement geometry, and percentage and temperature of the mix water (Laefer et al. 2010), with ambient temperature arguably the controlling factor. Thus, SCDA users have to date been unable to estimate demolition time based on manufacturers' information and the published literature. This paper aims to begin to overcome this knowledge gap.

3 PROJECT SCOPE, METHODOLOGY, AND MATERIALS

Presently, there is no systematic published research explicitly on SCDA heat development. Knowing this development is important, as hydration heat development is indicative of expansive pressure development and can result in additional thermal stresses (Ishida et al. 2005). Furthermore, SCDA performance at ambient temperatures below

20°C has not been studied systematically, yet most field work occurs in that temperature range. This paper investigates these issues with two commercial SCDAs: Dexpan II and Bristar 150. According to the manufacturers, the Bristar 150 is designed for temperatures up to 20℃ and Dexpan II for temperatures 10℃ to 25℃. Each product was tested at 7 different ambient temperatures (2℃, 5℃, 7℃, 10℃, 13℃, 17℃, 19℃). This paper examines the relationship between ambient temperature, heat of hydration, and expansive pressure in two types of SCDAs at cool and cold temperatures.

3.1 Set up

The SCDAs were mixed according to the manufacturer's recommendations (tap water at 15°C; 30% by weight). The slurry was poured into seamless, stainless steel pipes with a funnel. To control the ambient temperature, the filled pipes were placed into a temperature-controlled environment. The heat of hydration produced during the SCDA reaction with water was measured throughout the testing period using thermocouples embedded in the SCDA. The expansive pressure was measured by strain gauges affixed to the outside of the pipe. Tangential strain and temperature were recorded in intervals of 0.1 s and 1 s, respectively.

3.2 Methods

The expansive pressure was calculated using theory of elasticity. Radial and tangential stresses in a thick walled cylinder under a uniform internal and external load is known to be a function of pressure (Timoshenko and Goodier 1951):

$$\sigma_r = \frac{R_i^2 P_e - R_e^2 P_e}{(R_e^2 - R_i^2)} - \frac{(P_i - P_e)R_i^2 R_e^2}{(R_e^2 - R_i^2)r^2} \qquad (2)$$

$$\sigma_\theta = \frac{R_i^2 P_i - R_e^2 P_e}{(R_e^2 - R_i^2)} + \frac{(P_i - P_e)R_i^2 R_e^2}{(R_e^2 - R_i^2)r^2} \tag{3}$$

where σ_r and σ_θ are the radial and tangential stresses respectively, and r is the radial distance to the point of interest. The terms P_i and P_e are the internal and external pressures, respectively, while R_i and R_e are the internal and external radii, respectively. The strain gauges were placed on the external boundary where $\sigma_r = 0$. During testing there was no external pressure on pipe ($P_e = 0$). Therefore the tangential stress on the external boundary ($r = R_e$) is:

$$\sigma_\theta = \frac{2P_i R_i^2}{(R_e^2 - R_i^2)} \tag{4}$$

The tangential strain on the external boundary of the cylinder is as follows:

$$\varepsilon_\theta = \frac{1}{E}(\sigma_\theta - \sigma_r) = \frac{\sigma_\theta}{E} = \frac{2P_i R_i^2}{E(R_e^2 - R_i^2)} \tag{5}$$

Expansive pressure is represented by eqn (6):

$$P_i = \frac{\varepsilon_\theta E(R_e^2 - R_i^2)}{2R_i^2} \tag{6}$$

The tangential strain ε_θ is the output given by the strain gauges employed in this testing, $R_e = 21\ mm\ and\ R_i = 18\ mm$, and the modulus of elasticity of the steel was E=180 GPa.

The pipe was considered a thick-walled steel cylinder, based on Hertzberg's criteria (Hertzberg 1996):

$$\frac{b-a}{a} > \frac{1}{20} \tag{7}$$

where a is the internal and b is the external radii. An internal diameter of 36 mm was selected to match traditional drillhole size in concrete (Gambatese 2003). The external diameter of 42 mm was chosen to satisfy the thick-walled criterion (eqn 7 resulted in a value of 0.167 for the selected experimental arrangement).

The 170mm long pipe (Figure 2) was selected based on that length being sufficient to crack a rock or concrete specimen to a depth of around 250mm according to a 70% depth rule developed by Huynh and Laefer (2009). Lastly, the cylinder was closed at one end to simulate field conditions. The steel cylinder had a threaded end, which allowed a cap to be screwed securely to its bottom, which facilitated post-test cleaning. A simple clamp was attached to a heavy plate to hold the cylinder upright during testing.

Two sets of 5 mm long strain gauges with an original resistance of 120 ohms were affixed to opposite sides of the steel cylinder to measure tangential strain. The strain gauges were placed in the middle of the cylinder to ensure capturing a representative response and included tangential strain gauges and a dummy gauge to correct for thermal

expansion using a Wheatstone bridge circuit arrangement (Figure 2). A further dummy

gage was not deemed necessary, as the strain gages on each pipe were calibrated through

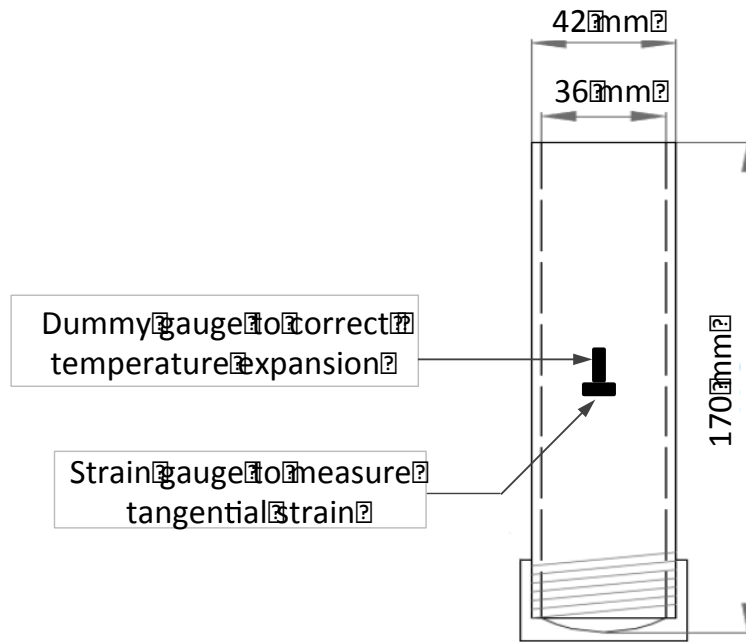physical testing in the lab through controlled loading.

Figure 2: Steel pipe dimensions and strain gauge orientations

The heat of hydration was monitored during testing with a thermocouple located mid-

height in the SCDA in the steel pipe. The SCDA expansive pressure and hydration heat

development was investigated for a minimum of a two-week period for each ambient

temperature. At the end of testing, vertical expansion of the material was measured with

vernier calipers. A pre-attached aluminium collar prevented any material loss. Radial

pipe expansion was negligible.

4 EXPERIMENTAL RESULTS

4.1 Heat of Hydration

The time to peak SCDA temperature (herein referred to as peak hydration heat) development was faster under higher ambient temperatures (Figure 3). At 19℃, this occurred after about 6 hours for both Dexpan and Bristar. As shown in Figure 3, the 17 ℃ and 13 ℃ tests showed delayed response, with the peak hydration heat occurring for the Dexpan after 8.2 and 8.8 hours (respectively) and for the Bristar at 6.6 and 9.28 hours (respectively). At the lowest ambient temperature (2℃), the peak hydration heat appeared after 13.5 hours for Dexpan and 22.5 hours for Bristar. The time to peak hydration heat development showed virtually no difference between the two products at the highest temperature but a nearly 9 hours difference under the coolest temperature. The onset of peak hydration heat seems to decrease linearly with increasing ambient temperature but at distinctively different rates depending upon the product, with the Bristar experiencing a rate of change about half that of the Dexpan (Figure 3).
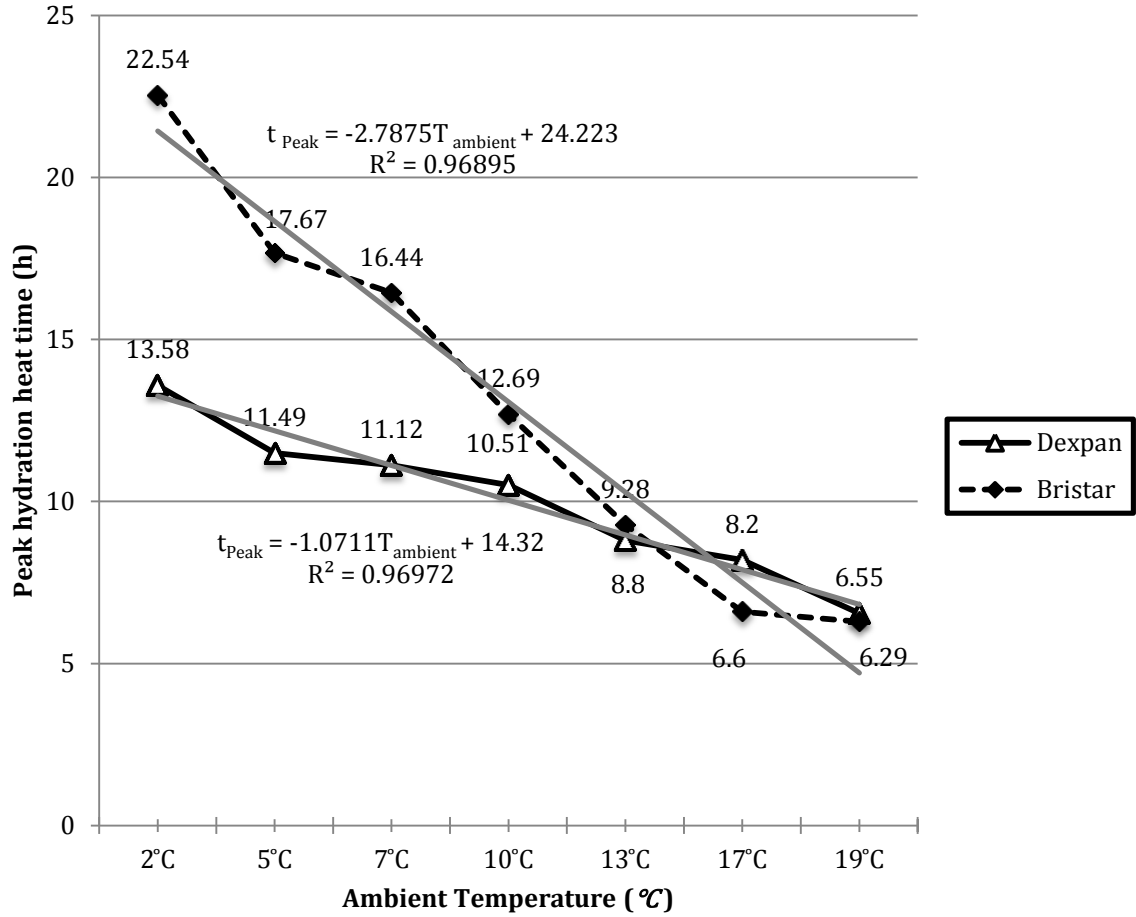
Figure 3: Time to peak hydration heat

Ambient temperature also influenced the level of peak hydration heat, with higher peaks occurring under greater ambient temperatures (Table 1). At 19 ℃ maximum hydration heats of 26.19 ℃ and 26.42 ℃ were observed for Dexpan and Bristar, respectively. The 17 ℃ test showed levels of peak hydration heat close to those occurring at 19 ℃, with 25.95 ℃ and 26.11 ℃ for Dexpan and Bristar, respectively. For the 13 ℃ test, the peak hydration heat dropped at a rate of more than double the decrease in the ambient temperature (17.94 ℃ for Dexpan and 16.73 ℃ for Bristar). The peak hydration heat loss rate then slowed (Figure 4). At the lowest ambient temperature (2 ℃), the peak hydration heat was more than 300% greater than ambient temperature and nearly indistinguishable between products: 6.06 ℃ for Dexpan and 6.86 ℃ for Bristar. Above 10 ℃, the SCDAs typ-

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ically generated peak hydration rates 50% higher than the ambient temperatures irrespective of temperature or product. At temperatures below 10℃, peak hydration heats were significantly lower but represented a greater multiplier with respect to the surrounding temperature. Below 10℃, the Bristar typically produced 15% more peak heat than the Dexpan, which is not altogether surprising, as the Dexpan was only formulated for temperatures of 10℃ or more.

Table 1: Peak hydration heat temperature

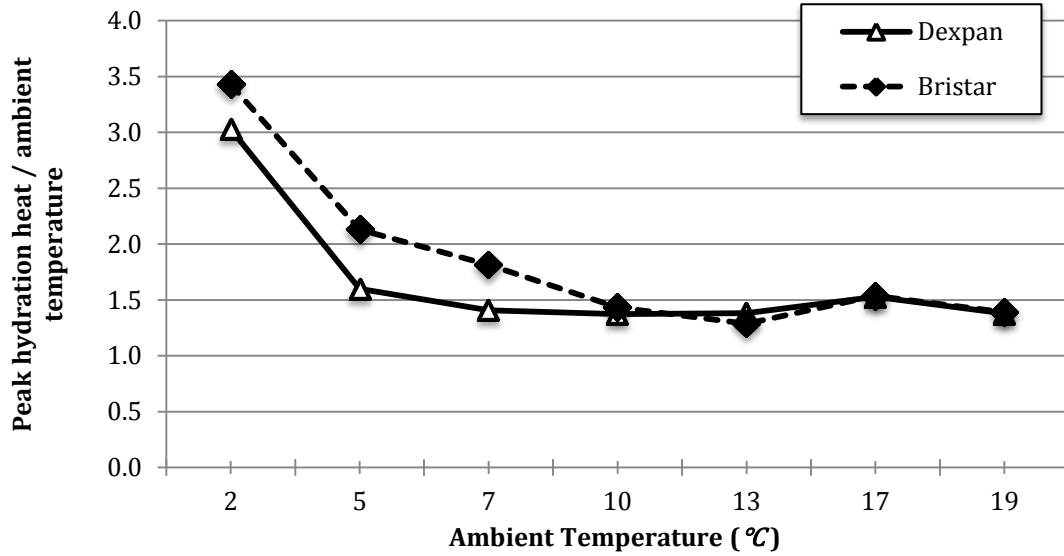| SCDA Brand	Ambient Temperature						
	2℃	5℃	7℃	10℃	13℃	17℃	19℃
Dexpan	6.06℃	7.99℃	9.85℃	13.74℃	17.94℃	25.95℃	26.19℃
Ratio	3.03	1.60	1.41	1.37	1.38	1.53	1.38
Bristar	6.86℃	10.65℃	12.7℃	14.33℃	16.73℃	26.11℃	26.42℃
Ratio	3.43	2.13	1.81	1.43	1.29	1.54	1.39

Figure 4: Peak hydration heat with respect to ambient temperature

4.2 Expansive Pressure

Experimental results generally showed that higher ambient temperatures resulted in larger expansive pressures (Figures. 5a and 6a), as well as a more rapid pressure gain. However, actual performance differed by product, and unlike peak hydration heat, the rate of SCDA expansive pressure development was not linear with ambient temperature. For example at just over 4 days (90 hours), the Dexpan exhibited a maximum expansion pressure of 28 MPa at the highest ambient temperature (19℃) and only 8 MPa at the lowest ambient temperature (2℃); a 350% increase over the 17℃ ambient temperature change. In contrast, in the same time frame, the Bristar exhibited an expansive pressure of 65 MPa at the highest ambient temperature (19℃) and 18.5 MPa at lowest ambient temperature (2℃). While this was accompanied by an expansive pressure rise of 350%, the difference in pressure increase between the 2 products was 3.7 times in favour of the Bristar.
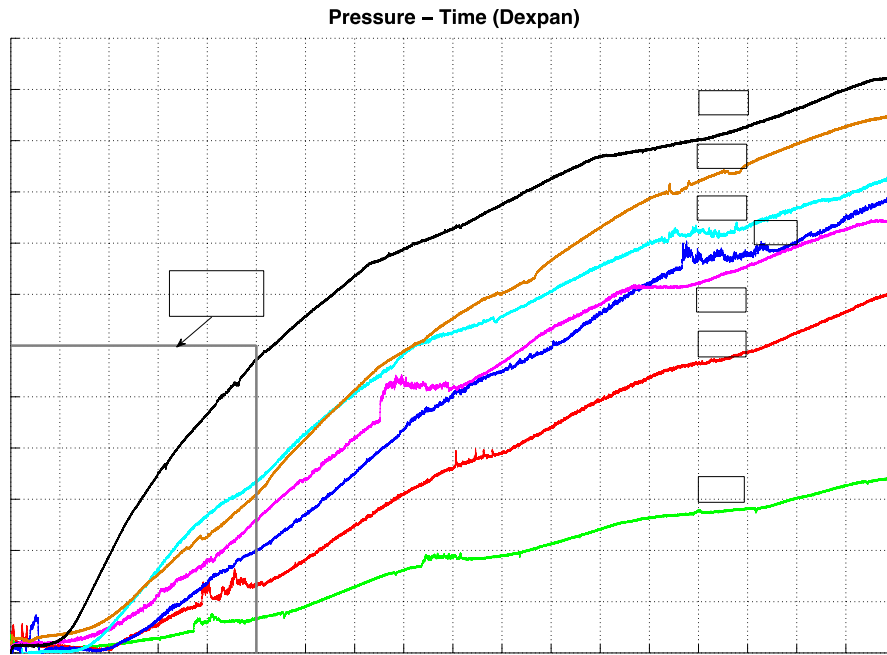
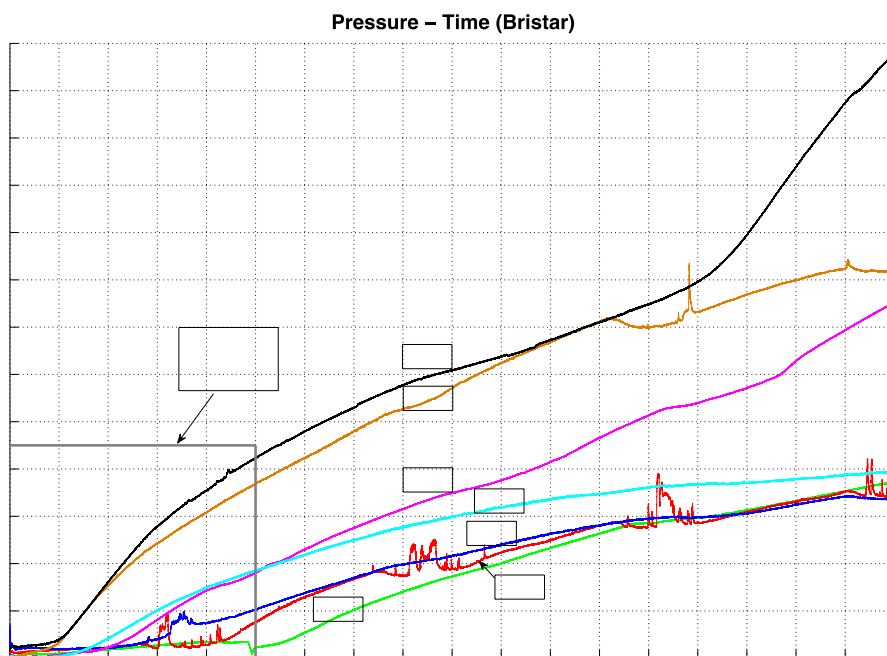**Pressure – Time (Dexpan)**

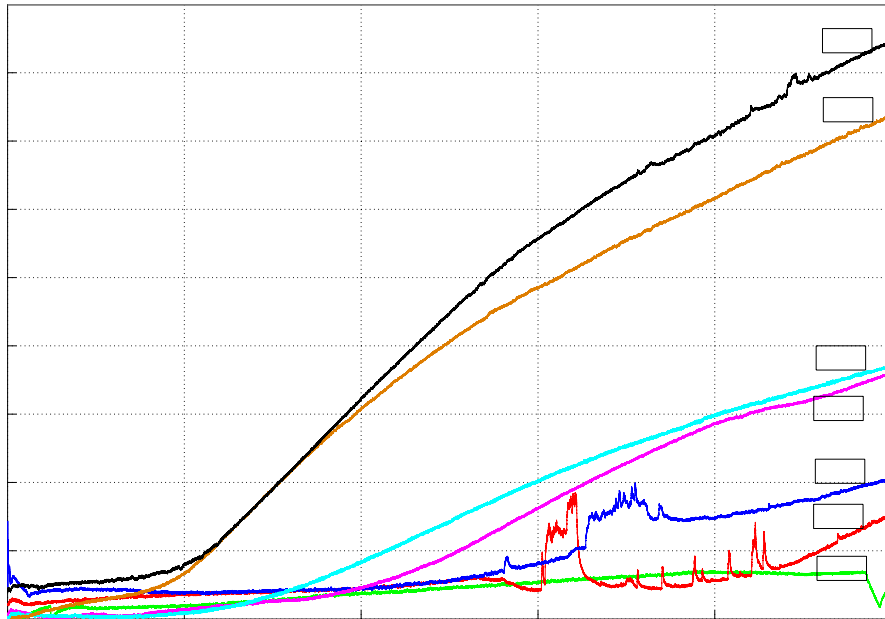a) Expansive pressure development over 4 days
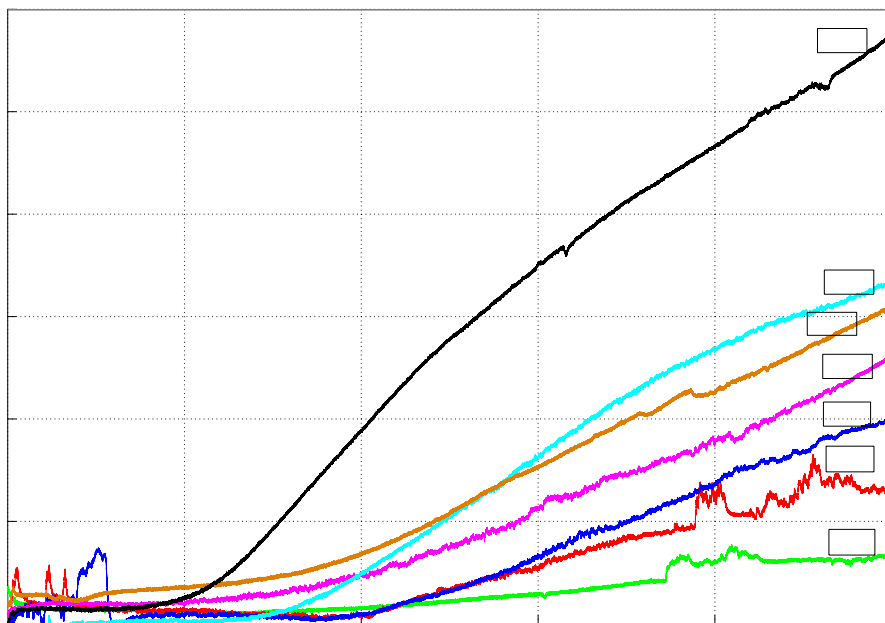
b) Expansive pressure development in first day

Figure 5: Expansive pressure development of Dexpan at different temperatures

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At 19℃, the expansive peak pressure started to develop after 4 hours for both products (Table 2), and at 24 hours the Dexpan's expansive pressure was 13.73 MPa while the Bristar's was 20.6 MPa (Figures 5b and 6b). The onset of distinctive expansive pressure development was not identifiable until around 10 hours for most of the other ambient temperatures. At ambient temperatures less than 10℃, the onset of expansive pressure development for both products was identifiable, although slower and lower for the Bristar (e.g. at 2℃ the onset of peak pressure development for Dexpan occurred at 12.4 hours but not until 25.6 hours for Bristar (Table 2)).

a) Expansive pressure development over 4 days

b) Expansive pressure development in first day

Figure 6: Expansive pressure development of Bristar at different temperatures

Table 2: Time to onset of peak pressure development

SCDA Brand	Ambient Temperature						
	2℃	5℃	7℃	10℃	13℃	17℃	19℃
Dexpan	12.4 h	10.4 h	9.8 h	8.5 h	8.1 h	7 h	4.5 h
Bristar	25.6 h	15.2 h	13.4 h	8.5 h	6.5 h	4.3 h	4 h

At 19℃ the Bristar produced an expansive pressure almost 230% higher than the Dexpan over the first 4 days (Fig. 5a vs Fig. 6a). At the lowest temperature (2℃), Bristar produced an expansive pressure 370% more than Dexpan. Experimental results showed

that higher ambient temperatures resulted in greater hydration heat levels, which resulted in a more fierce chemical reaction and gave rise to greater expansive pressures.

Figures 7 and 8 are detailed examples of how peak hydration heat relates to the pressure development at the coolest and warmest temperatures tested for the two products. For Dexpan (Figure 7), the difference between peak hydration heat development at the extremes was almost 7 hours. At 19℃ the expansive pressure began to exhibit significant development after 4.5 hours, with continued, notable, rapid gain through the end of testing at 240 hours to a level of 68 MPa. For the 2℃ test a rough projection estimated continued pressure development until at least 240 hours to a level of 14 MPa. While long-term pressure development is interesting, its existence is not beneficial for most applications because of the time constraints on the majority of construction projects.
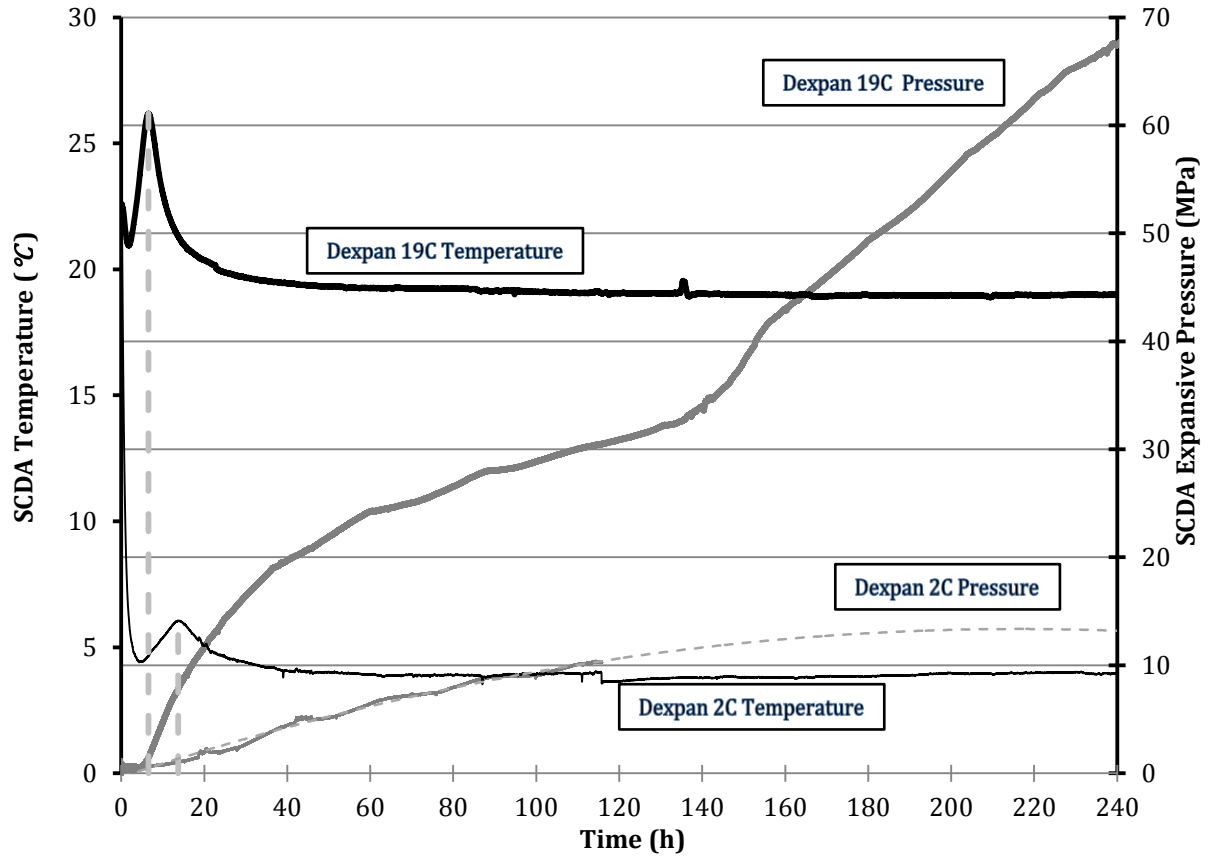
Figure 7: Dexpan behaviour at highest and lowest ambient testing temperatures

For the Bristar (Figure 8), the difference between peak hydration heat development be-
tween the highest and lowest ambient temperature tests was almost 22 hours. At an am-
bient temperature of 19℃, the expansive pressure began to increase notably after 4 hours
(Table 2). At 240 hours, the pressure reached 185 MPa and showed signs of further
growth. At 2℃ at 240 hours, the expansive pressure was only 33 MPa and with only
modest further growth predicted. Maximum expansive pressure of the Bristar was al-
most 270% higher than the Dexpan's at 19℃ after 240 hours, while at 2℃ maximum
expansive pressure was 240% higher.

In attempting to test Bristar at 21℃, a peak hydration heat of 156.1℃ was recorded at 3.2 hours, which provided sufficient pressure to expel some of the SCDA mixture from the drillhole. The performance of the strain gauges, which measured the expansive pressure, was compromised by the SCDA blowout. The last recorded measurement was 19 MPa at 3 hours, which was not achieved at 19℃ for more than 20 hours. At the 19℃ ambient temperature, the pressure development was only 0.44 MPa with an accompanying heat of hydration of 22.7℃. Thus, this relatively small increase in the ambient temperature had a radical impact on the hydration heat development and expansive pressure formation. Based on the experimental results, the rate of SCDA expansive pressure development is not linear with ambient temperature. This is crucial, as the required demolition time is an important factor in SCDA usage with respect to construction scheduling.
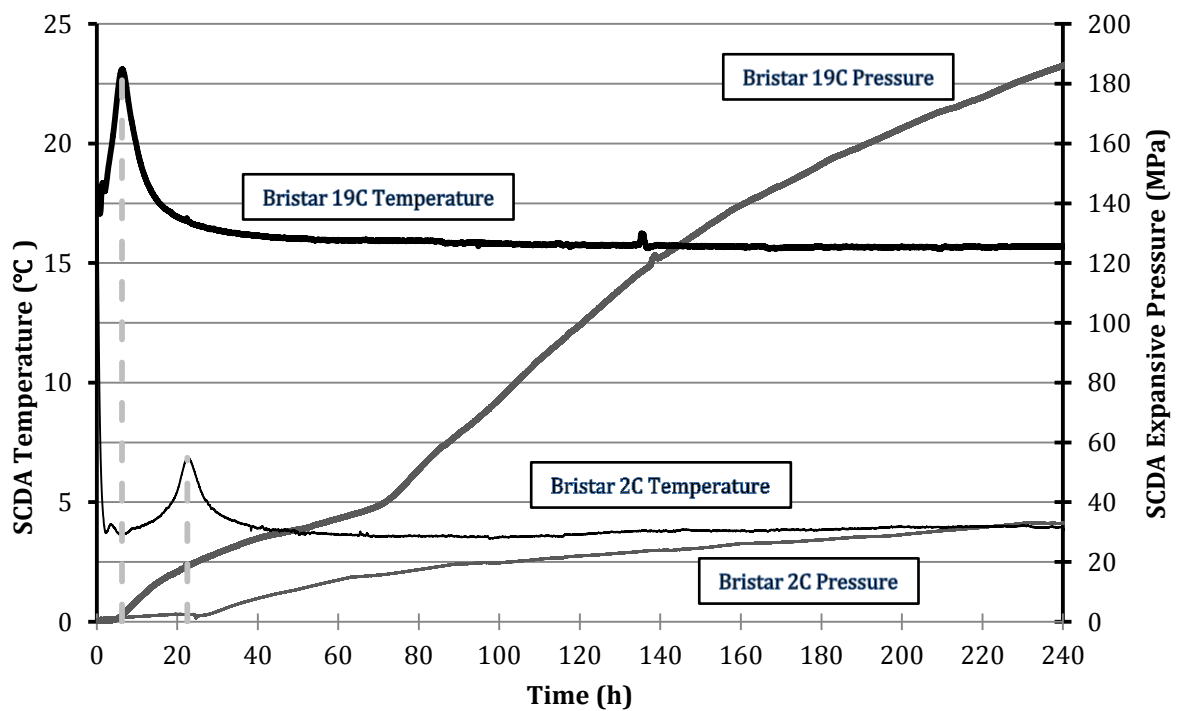

Figure 8: Bristar behaviour at highest and lowest ambient testing temperatures

There is a marked increase in pressure development just after the peak hydration (Figures 7 and 8) and is largely linear for both products across the tested temperature range (Figure 9). The data also showed that apart from the main hydration heat peak there were other small hydration heat peaks that resulted in further contemporaneous expansive pressure peaks (Figure 10).

The chart shows two data series:
- $\triangle$ Dexpan
- $\blacksquare$ Bristar

X-axis: Time to onset of peak pressure development (hours), ranging 0 to 30.
Y-axis: Peak hydration heat time (hours), ranging 0 to 30.

$$t_{\text{Peak hydration heat}} = 0.769 t_{\text{Onset of peak pressure}} + 4.5584$$
$$R^2 = 0.94011$$

$$t_{\text{Peak hydration heat}} = 0.9089 t_{\text{Onset of peak pressure}} + 2.1545$$
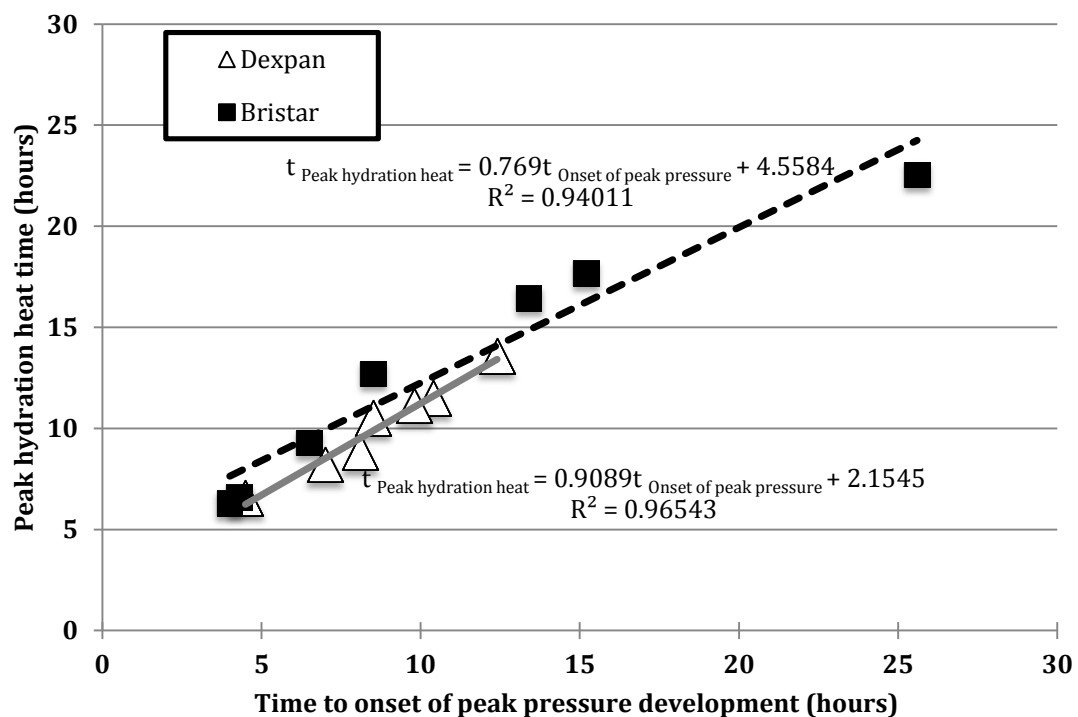$$R^2 = 0.96543$$

Figure 9: Relationship between time of peak hydration heat and onset of expansive pressure development
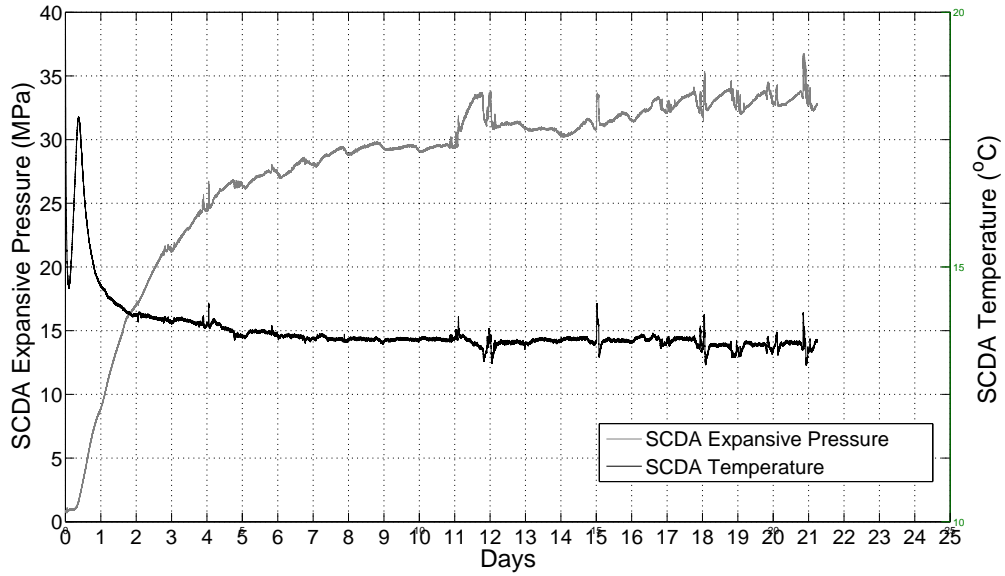
Figure 10: Expansive pressure development and the same reaction influence respond on temperature for Dexpan at 13℃

4.3 Volumetric Expansion

During testing, the SCDA volumetrically expanded beyond the geometry of the testing cylinder. The extent of this expansion was measured at the end of testing, prior to the sample's removal from the cylinder. A vertical expansion of 62 mm and 65 mm was measured for Dexpan and Bristar, respectively at 19℃, while at 2℃, vertical expansion was only 18 mm for Dexpan and 33 mm for Bristar; as radial expansion of the pipe was negligible it was not considered. The higher ambient temperature clearly resulted in greater vertical expansion (Figure 11), with the Bristar expanding 4.6% more than the Dexpan at 19℃, and 45% more at 2℃, which coincided with the Bristar's overall higher peak of hydration heat. Little correlation was found however between the volumetric expansion and the level of peak hydration heat.
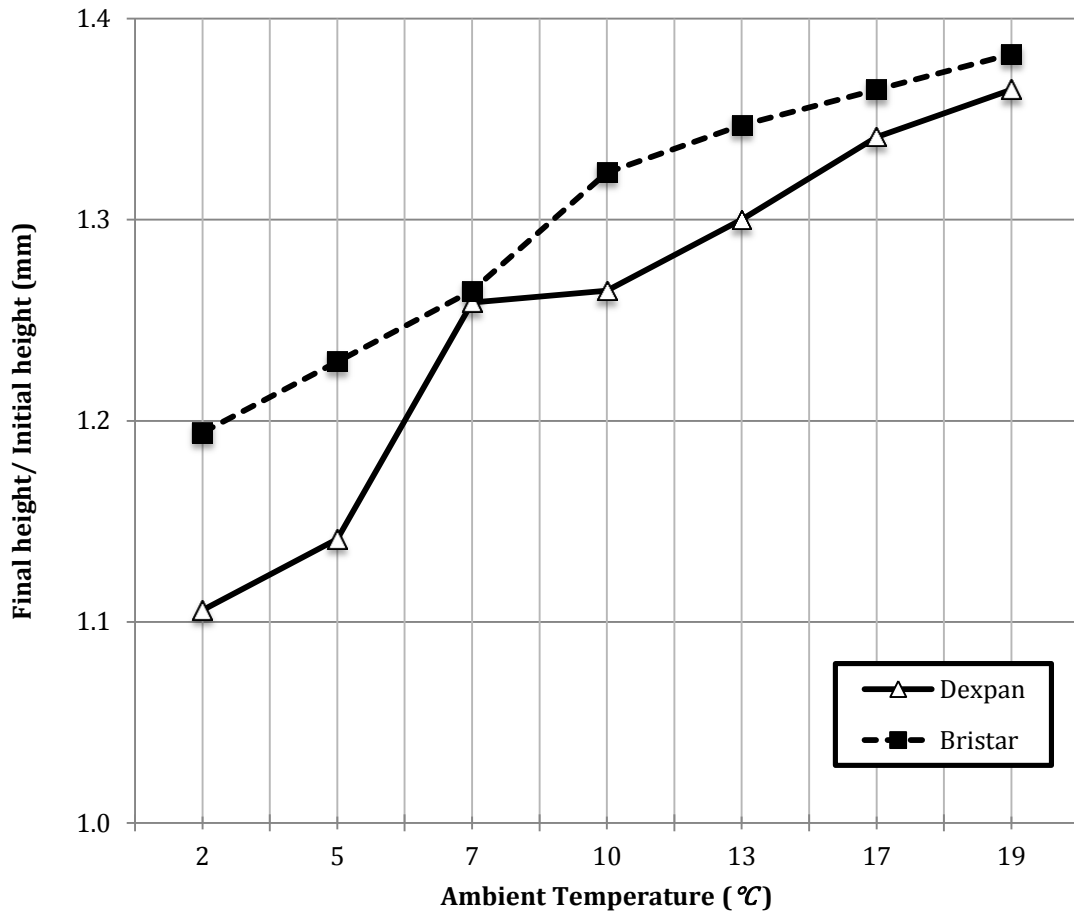
Figure 11: SCDA volumetric expansion

5. DISCUSSION

Similar hydration heat development curves to those reported herein (Figures 7 and 8) were shown with individual tests by Harada et al. (1993) in a 33mm diameter pipe in the ambient temperature range of 20℃ to 30˚ (Figure 12) and by Nocun-Wczelik et al. (2010) using cement with a different expansive mixture under a temperature of 25℃, although those by Nocun-Wczelik et al. (2010) were slower and generated less pronounced peaks (Figure 13).

The research undertaken herein and that done by others showed a linear relationship between the ambient temperature and the time to peak hydration heat, with the proportionality being product specific (Figure 14). Connolly (2013) was also working with Dexpan in a steel pipe of the same size, but reported higher peak hydration heats at 10℃ and 5℃ possibly due to a different version of the product than used here, while Yamazaki (1988) tested an SCDA described as "High Calmmite 30" under ambient temperatures of 0℃ to 20℃ in a 44 mm diameter steel pipe as (Figure 14), where at 20℃, the time to peak hydration heat was 200% faster than at 0℃. Despite clear differences in peak hydration heat development time, the overall, behaviour in each data grouping of accelerated hydration heat development and its general linearity was clear within a product class and testing configuration.
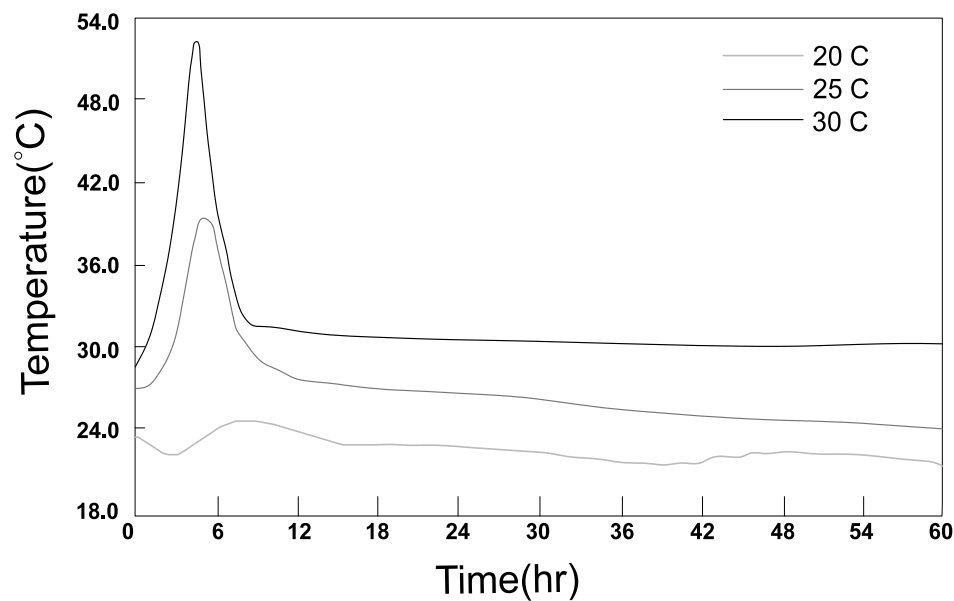
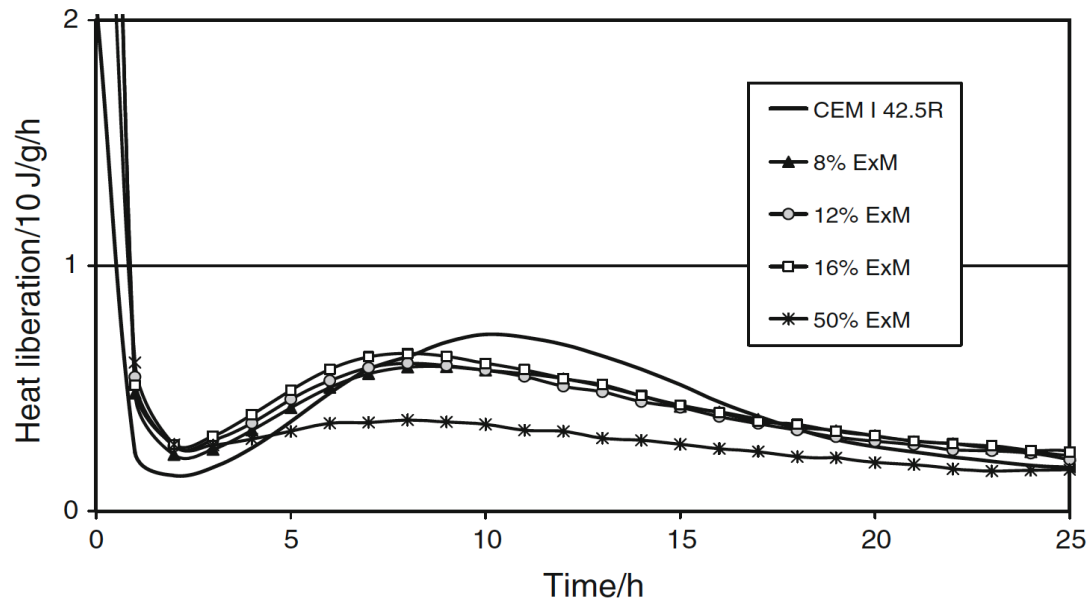Figure 12: Influence of ambient temperature on peak hydration heat (Harada et al. 1993)

Figure 13: Heat evaluation of cement with different expansive mixture (Nocun-Wczelik et al. 2010)
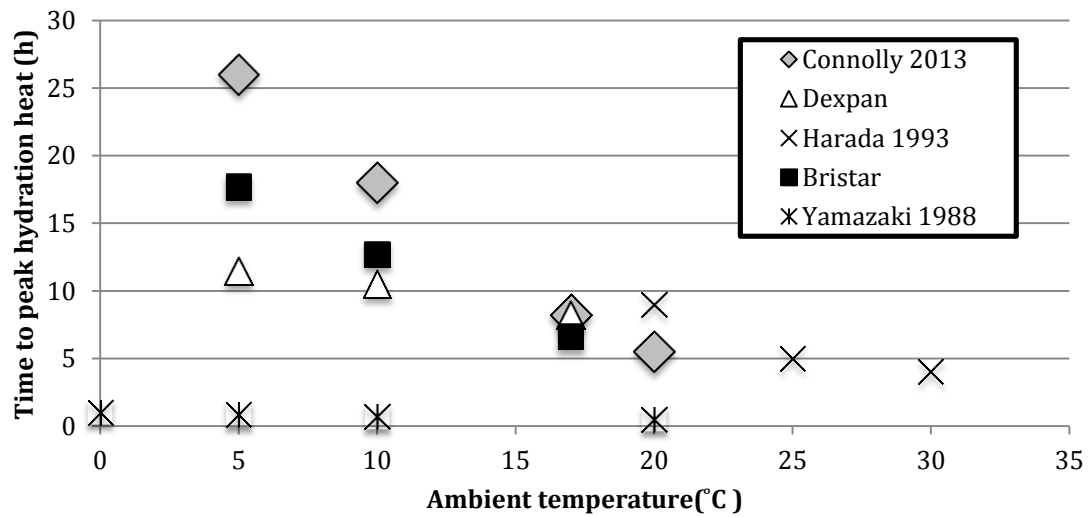

Figure 14: Verification of the linear relationship between ambient temperature and time to peak hydration heat

In the research undertaken herein, at temperatures of at least 10℃ and less than 21℃, the peak hydration heat was consistently 1.5 times that of the ambient temperature (Figure

4). At the lowest ambient temperature (2℃), the peak hydration heat was more than 3 times greater than the ambient temperature. In research by Harada et al. (1993), the peak hydration heat was also higher than the ambient temperature (1.2 times at 20℃ and almost 1.6 times at 25℃ and 30℃). In attempting to test Bristar at 21℃, the peak hydration heat reached at least 7.4 times higher than the ambient temperature. Thus, the work presented represents only part of the story.

The research herein demonstrated a linear relationship between peak hydration heat time and the onset of expansive pressure development. While ambient temperature directly influences $Ca(OH)_2$ generation which, in turn, impacts expansive pressure generation, as previously noted by Soeda and Harada (1993). Based on available experimental results, predicting the exact time at which peak pressure begins to develop under specific ambient temperatures is not wholly possible (Figure 15) using only these two factors. This contrasts to the highly linear relationship between that and time of peak hydration heat, which if monitored in the field, a highly reliable prediction of the onset of pressure development should be achievable. The former is more difficult, as it must also consider thermal transfer issues from the SCDA to the surrounding material. Peak hydration heat also has the advantage of being easy to measure, which is not the case with expansive pressure development in the field.

In order to develop usage guidelines, a linear correlation between time to peak hydration heat and the onset of peak pressure development is recommended. As this correlation was only developed with two products, the exact relationships should be applied to other products with care. While previous researchers have claimed that the ambient temperature impacted the SCDA expansive pressure, the more accurate way to convey this is its

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influence over the peak hydration heat, as this also considers thermal transfer issues (Figures 5 and 6).

Experimental results also showed that the two SCDA products were most effective in the temperature range for which they were configured but notable pressure development was later and longer than indicated by the manufacturers.
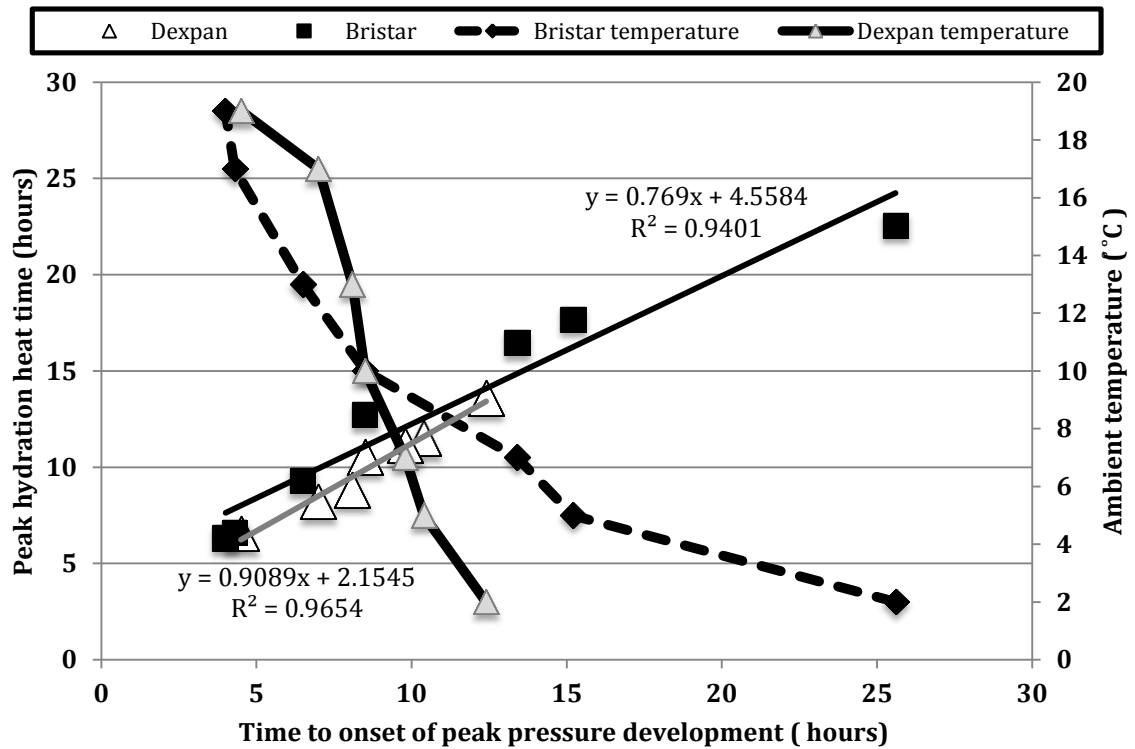

Figure 15: relationship between peak hydration heat time, time to onset of peak pressure development and ambient temperature

Another notable effect of temperature is the SCDA's volumetric expansion caused by the chemical reaction between water and calcium oxide (Harada et al. 1993). Ambient temperature has a direct influence on the rate and magnitude of expansion due its impact

on ettringite formation during hydration (Polivka 1973). Connolly (2013) noted this but did not quantify it. In the research undertaken herein, at 19℃ the volumetric expansion for both products was almost 1.4 times, while at 2℃ only 1.1-1.2 times. Fukui (1996) recorded a 1.96 times increase when measuring the expansion of raw calcium oxide (CaO) hydration at 25℃. The results show a pronounced upward trend with higher temperatures. As a final observation, while manufacturers claim expansive pressure development in the first few days, expansive pressure development was shown herein to continue for at least 21 days (Figure 10).

6. CONCLUSIONS

In this paper, a series of experimental tests explored the impact of cool and moderate temperatures (2°C to 19°C) on two SCDAs (Dexpan and Bristar). The relationships between ambient temperature, peak hydration heat, and expansive pressure development were investigated in a section of steel pipe. Expansive pressure was measured by strain gauges, while heat of hydration was monitored with thermocouples.

Experimental results showed faster exothermic reactions between the SCDA and the mixing water at higher ambient temperatures, which accelerated and heightened peak hydration heats, which lead to greater and earlier expansive pressures, as well as more volumetric expansion. Results showed a linear relationship between ambient temperature and time to peak hydration heat, with an amplifier of at least 1.5. Below 10℃ and above 19℃, this factor was higher. A linear relationship was also definitively demonstrated between the time to peak hydration heat and the onset of significant pressure development. When the ambient temperature was raised from 2℃ to 19℃, the experi-

mental work showed a 350% pressure increase for 2 prominent SCDA brands. Products were most effective in the temperature range for which they were configured but notable pressure development was later and longer than indicated by the manufacturers. Furthermore, although most of the hydration reaction happened within the first few days, mini-hydration heat peaks occurred for several weeks, which can in part account for the continuing pressure development over the same period. Finally, volumetric expansion was also shown as a function of temperature with an expansion factor of 1.1-1.2 at 2℃ ranging up to 1.5 at 19℃.

While previous researchers have claimed that the ambient temperature impacted the SCDA expansive pressure, the more accurate way to consider this is directly with the peak hydration heat, as this avoids thermal transfer issues. Thus, to develop usage guidelines, a linear correlation between time to peak hydration heat and onset of peak pressure development is recommended as its starting point. As this correlation was only developed with two products, the exact relationships should be cross-applied to other products with care and further research is needed to quantify the rate of thermal loss.

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