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1 **Compressive strength estimates for adiabatically cured concretes**
2 **with the Modified Nurse-Saul (MNS) maturity function.**

3

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HIGHLIGHTS

- The effect of high early curing temperature is to accelerate the cement hydration, i.e. it starts earlier, and thus also accelerate the early age strength development.
- These enhanced strengths cannot be accurately predicted/estimated with current maturity functions like the Nurse-Saul and Arrhenius based maturity functions.
- The Modified Nurse-Saul maturity (MNS) function has been developed to account for the above deficiencies of current maturity functions. It relies on a relationship between concrete strength and the Nurse-Saul maturity index but incorporates an “acceleration” factor and a “temperature efficiency” factor.
- The Modified Nurse-Saul (MNS) function has been set up as an iterative procedure using a spreadsheet and the strength estimates have been shown to be more accurate than those from other maturity functions not only for the early age but also long term strengths.

1 **ABSTRACT**

2

3 The Modified Nurse-Saul function relies on (a) a relationship between concrete
4 compressive strength and the Nurse-Saul maturity index, (b) an “acceleration” factor
5 and (c) a “temperature efficiency” factor. The “acceleration” compresses a certain
6 percentage of hydration or strength development into a smaller time interval. The
7 strength development rate is therefore increased because of the “compression” of the
8 hydration interval. Had the hydration at higher curing temperatures been as efficient in
9 contributing to the compressive strength as at lower temperatures then the
10 “acceleration” factor would be equal to the “compression” factor. Procedures are
11 described to determine these factors from isothermally cured concretes. They are then
12 used in an iterative procedure to predict/estimate the strength development for
13 adiabatically cured concretes. The predictions/estimates are shown to be significantly
14 more accurate than those from the Nurse-Saul and Arrhenius maturity functions.

15

16 **KEYWORDS**

17 Curing Temperature, Compressive Strength, Maturity Function, Activation Energy

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1. INTRODUCTION

Two alternative functions for computing the maturity index from the measured temperature history of the concrete are described in ASTM C1074-11 Standard Practice for Estimating Concrete Strength by the Maturity Method [1]. The first is what has become known as the Nurse-Saul function [2,3] and the second was proposed by Freiesleben Hansen and Pedersen [4].

The Nurse-Saul function [2,3] computes the temperature-time factor as follows:

$$M(t) = \sum_0^t (T - T_0) \Delta t \quad \text{Equation 1}$$

where: $M(t)$ the temperature-time factor (the maturity index) at age t ,
°C·hours,
 Δt a time interval, days or hours,
 T average concrete temperature during the time interval Δt , °C
and it is 20 °C for standard curing,
 T_0 datum temperature, taken as -11 °C in this work.

Freiesleben Hansen and Pedersen's expression for equivalent age [4] is based on the Arrhenius equation and it is therefore referred to as the Arrhenius maturity function in this paper:

$$t_e = \sum_0^t e^{-Q \left[\frac{1}{273+T} - \frac{1}{273+T_r} \right]} \Delta t \quad \text{Equation 2}$$

where: t_e = equivalent age at a specified or "reference" temperature,
days or hours
 T = average temperature of concrete during time
interval Δt , °C,

1 Functions proposed to account for the long term detrimental effect are based on a
2 decreasing apparent activation energy with increasing relative strength, degree of
3 hydration or maturity [25,26]. They have been reported to “give some indication of the
4 retarding effect”. Whether the activation energy actually changes with degree of
5 hydration has been questioned [27] and it has been suggested that it might change as a
6 function of temperature only.

7

8 Recent work [8,28] indicated that the detrimental effect may become apparent as early
9 as three days which is much earlier than implied by the terms “later-age” or “long-term”
10 that are usually used to describe it. This is particularly the case for when high curing
11 temperatures are applied immediately after casting, i.e. steam curing in precast works,
12 or very early age such as the adiabatic temperature rises in large concrete pours [29,30].

13

14 Strength-time (age) and strength-maturity relationships need to be determined for the
15 particular concrete mix which can then be used in conjunction with the maturity
16 functions described above. The Three Parameter Equation (TPE) [31] is one of several
17 functions that have been proposed as strength-time (age) and strength-maturity
18 relationships:

19 Strength-time (age) relationship:

$$20 \quad S = S_{\infty} e^{-\left(\frac{\tau}{t}\right)^{\alpha}} \quad \text{Equation 3}$$

21 where: S = strength at time t, MPa,

22 S_∞ = limiting strength, MPa,

23 t = age or equivalent age of curing, hours,

24 τ = characteristic time constant, hours,

25 α = shape parameter.

1 Strength-maturity relationship:

$$2 \quad S = S_{\infty} e^{-\left(\frac{\tau}{M}\right)^a} \quad \text{Equation 4}$$

3 where: S = strength at maturity index M , MPa,

4 M = temperature-time factor or maturity index, °C·hours,

5 τ = characteristic time constant, °C·hours,

6

7 Changing the value of the time constant preserves the same general shape of the curve

8 while shifting it to the left or right [32]. Changing the value of the shape parameter

9 alters the shape of the curve in such a way that when α increases then the curve has a

10 more pronounced “S” shape. Combinations of τ (shifting of the curve to the left for

11 higher curing temperatures) and α (allowing for different ultimate strengths) can be

12 used to get a good fit of the regression curve for all curing temperatures. Whether α

13 should remain constant or it should change with temperature has been queried [10]. The

14 true potential of this equation is however in its differentiated form:

15

$$16 \quad \frac{dS}{dt} = \frac{a\tau^a(T-T_0)}{M^{a+1}} S_{\infty} e^{-\left(\frac{\tau}{M}\right)^a} \quad \text{Equation 5}$$

17

18 Where $M = t(T - T_0)$. Combining with Equation 4:

19

$$20 \quad \frac{1}{S} \frac{dS}{dt} = \frac{a\tau^a(T-T_0)}{M^{a+1}} \quad \text{Equation 6}$$

21

22 Differentiating Equation 4 with respect to “maturity” rather than “time” results in:

23

$$24 \quad \frac{1}{S} \frac{dS}{dM} = \frac{a\tau^a}{M^{a+1}} \quad \text{Equation 7}$$

1

2 If Saul's principle was valid then $\frac{1}{S_r} \left(\frac{dS}{dM} \right)_r$ at the reference temperature, e.g. 20 °C used
3 here, would be equal to $\frac{1}{S} \frac{dS}{dM}$ at any other temperature, whether isothermal or not. With
4 this not being the case, operations that transform $\frac{1}{S_r} \left(\frac{dS}{dM} \right)_r$ to $\frac{1}{S} \frac{dS}{dM}$ for curing
5 temperatures other than the reference are needed. These are:

- 6 • an acceleration factor to compensate for the inherent age conversion factor in
7 Nurse-Saul function which has been shown not to be sufficient, and,
- 8 • a temperature efficiency factor to compensate for the fact that the reaction at
9 the higher temperatures is not as efficient as at the lower temperature [33,34].

10

11 Determination of acceleration and temperature efficiency factors is described for three
12 concrete mixes with 28-day target mean compressive strengths of 37, 47 and 57 MPa.
13 How these can be programmed into a spreadsheet is also described. The procedure is
14 iterative and it can predict the detrimental effect of high early age curing temperature
15 on the ultimate/limiting compressive strength. This is demonstrated for isothermally
16 cured as well as adiabatically cured concretes.

17

18 **2. RESEARCH SIGNIFICANCE.**

19

20 The early-age strength development of concretes is greatly enhanced by high curing
21 temperatures, such as those used for steam curing of precast concrete elements, or in
22 structural elements as a result of the hydration being an exothermic reaction. In order
23 for contractors to be in a position to take advantage of these enhanced strengths, e.g.,
24 for increased production in precast concrete factories or for fast track construction for

in-situ concrete construction, there needs to be a method to predict relatively accurately the strength development for these high early age temperature curing regimes.

3. MATERIALS AND EXPERIMENTAL PROCEDURES.

The concrete mixtures investigated had target mean 28-day cube compressive strengths of 37, 47 and 57 MPa and thus they are referred to as PC37, PC47 and PC57. The strength classes, according to BS EN 206 [35], would be C25/30, C30/37, and C40/50, respectively, if a margin of approximately 7 to 10 MPa is allowed. “Equivalent” mortars were not used in this work for determination of the “apparent” activation energies [1]. Mortars that have the same water-cement ratio as well as coarse aggregate-binder ratio to concretes may be considered to be “equivalent” to the concretes under investigation. However, previous work has shown that the strength development of the “equivalent” mortars is not exactly the same as that of concretes [8,10]. These small differences may affect the maturity estimates and thus 100mm concrete cubes were used instead for this work. The mixture proportions for the concretes are shown in Table 1.

Table 1 – Concrete mix proportions.

Material	Mix ID		
	PC37	PC47	PC57
Portland cement (PC) [kg/m ³]	300	373	420
Gravel (4-10mm) [kg/m ³]	1107 ³	1241 ³	-
Gravel (6-14mm) [kg/m ³]	-	-	800 ⁴
Sand (0-4 mm) [kg/m ³]	817 ¹	612 ¹	580 ¹
Sand (0-2 mm) [kg/m ³]	-	-	300 ²
Limestone filler [kg/m ³]	-	-	120
Superplasticizer dosage [ltrs]	-	-	3
Free water [kg/m ³]	180	190	195
Total water [kg/m ³]	206	204	215
Free w/b	0.60	0.51	0.46
Concrete slump [mm]	135	120	700 mm (flow)
Compressive strength at standard curing temperature [MPa]			
Age [days]	PC37	PC47	PC57
0.5	2	8	11
1	7	14	16
2	12	19	24
3	15	26	33
7	24	37	42
14	31	43	47
28	37	48	57
56	-	54	-
91	-	59	-
182	-	60	-

1 - water absorption of 0-4mm sand was 1.02%

2 - water absorption of 0-2mm sand was 1.10%

3 - water absorption of 4-14mm gravel was 1.85%

4 - water absorption of 6-12mm gravel was 1.34%

3.1 Materials

Portland cement (CEM I 42.5N), conforming to requirements of BS EN 197-1:2011 [36], was supplied in bags by Quinn cement and had 60 MPa 28-day compressive strength (tested in accordance with BS EN 196-1:2016 [37]). Limestone filler (calcium carbonate) Eglinton GW1 – EG was only used for the flowable mix (designated as PC57) and was supplied in bags by Omya. The chemical compositions of Portland cement (PC) and limestone filler are shown in Tables 2 and 3, respectively.

Table 2: *Chemical composition of PC*

Chemical constituent	Cement (% by weight of dry mass)
SiO ₂	21.0
Al ₂ O ₃	5.5
Fe ₂ O ₃	3.0.
CaO	62.5
MgO	2.25
SO ₃	2.6
Equiv. Alks Na ₂ O _e	0.525
Chloride	0.045
Loss of ignition	2.0

Table 3: *Chemical composition of limestone filler*

Chemical constituent	Limestone filler
SiO ₂	4.3 % by weight of dry mass
Fe ₂ O ₃	0.1 % by weight of dry mass
CaCO ₃	95.0 % by weight of dry mass
Pb	1 ppm
As	0.3 ppm
F	200 ppm
Hg	<0.01 ppm
HCl insoluble content	4.5 % by weight of dry mass

The aggregates used in this study were sourced locally in Northern Ireland, supplied by the quarry of Creagh Concrete Products Ltd. The coarse aggregate used in the 37 and 47 MPa mixes was 4/10 mm crushed basalt whilst a 6/14 mm coarse

aggregate was used in the flowable PC57 mix. The fine aggregate used in all mixes was 0/4 mm Lough sand whilst a finer sand (0/2 mm) was also used in the flowable PC57 mix. The grading curves for the coarse and fine aggregates are shown in Fig. 1 alongside the grading limits described in BS EN 12620:2002+A1:2008 [38].

Fig. 1: Combined aggregate grading for the investigated mixes

3.2 Mixing, casting, curing and testing of mortar specimens

All concrete mixes were batched using a 0.1 m³ capacity horizontal pan mixer. Aggregates, which were oven-dried for at least 24-hours, were placed first together with the cement and filler in the mixing pan. Following dry-mixing for one minute, water was added and the mixing continued for another five minutes. The workability (consistence) of concrete was determined by carrying out the slump test, in accordance with BS EN 12350-2:2009 [39]. Concrete cube (100 mm) specimens conforming to BS EN 12390-1:2012 [40] were cast in two layers and each layer was compacted using a vibrating table.

The curing procedures adopted were as follows:

- **Standard curing**, for which the concrete and mortar specimens inside the moulds were covered with damp hessian and polyethelene sheet and cured under

room temperature (approximately 20 °C). They were subsequently demoulded at 1 day after casting and placed into a water tank set at 20 °C.

- **Elevated isothermal curing**, for which the concrete specimens inside the moulds were wrapped using cling film and tape and were submerged in water tanks set at 30, 40 and 50 °C. They were demoulded at 1 day after casting (or prior to testing before that) and immediately placed back into the water tanks.
- **Adiabatic curing** – The adiabatic temperature rise is produced by the cement hydration and will occur if concrete is placed in a perfectly insulated environment, where there are no heat exchanges or losses, between concrete and surrounding environment. In order to achieve this in the current study, the surrounding temperature was set to be approximately the same as the concrete temperature. A 200 x 200 x 200 mm concrete cube was cast into a stainless steel box lined with 125mm Rockwool© thermal insulation and heavy duty polythene to prevent moisture loss. After casting, a stainless steel lid was bolted on top of the box and two copper/constantan thermocouples were inserted in it, through a hole in the lid, to monitor the temperature of the concrete. A PT100 probe was also inserted in the concrete through the top and was connected with the control box in order to match the temperature of the water in the tank with that of the concrete (a maximum of -1 °C difference between water and concrete temperature was maintained). Two more thermocouples were used to monitor the temperature of the water in the tank. It was assumed that once the peak temperature had been reached and there was no temperature drop, only very little heat losses occurred and therefore, relevant adjustments to the results obtained were not required. The adiabatic curing tank and test setup are shown in Fig. 2.

Fig. 2: *Adiabatic test setup*

The testing ages for all types of specimens and curing methods are shown in in Table 4. As an attempt to effectively quantify the effect of temperature on the early age compressive strength development, testing commenced as early as 3 hours (50 °C), 6 hours (30, 40 °C) and 12 hours (20 °C) after casting. At each testing age, 2 specimens were tested from each curing regime in term of compressive strength as described in BS EN 12390-3:2009 [41].

Table 4: *Testing ages for compressive strength*

<i>Curing regime</i>	<i>PC37</i>	<i>PC47</i>	<i>PC57</i>
Isothermal	6, 12 hours; 1, 2, 3, 7, 14, 28, 56, 91 and 182 days	3, 6, 12 hours; 1, 2, 3, 7, 14, 28, 56, 91 and 182 days	6, 12 hours; 1, 2, 4, 8, 16, and 32 days
Adiabatic	12 hours; 1, 2, 3, 7, 14 and 28 days	12 hours; 1, 2, 3, 7, 14 and 28 days	6, 12 hours; 1, 2, 4, 8, 16 and 32 days

4. RESULTS AND DISCUSSION

The data from isothermally cured specimens is first used to demonstrate the Modified Nurse-Saul procedure [34] and compare the strength estimates from this with those from the Nurse-Saul maturity function and the Arrhenius maturity method. Strength development data from adiabatically cured concrete specimens are then used to demonstrate the applicability of the procedure for non-isothermal curing regimes.

4.1 Strength estimates for isothermally cured specimens.

High curing temperatures result in higher early age compressive strengths, as shown in Fig. 3, but later or long-term compressive strengths are adversely affected. This phenomenon is what has been explained previously as the “cross-over” effect.

Regression curves were based on Equations 3 and 4 and the shape parameter α was set as 0.7 for all curing temperatures. Trial and error preceded the decision to use 0.7 which was made on the basis that it best fitted most of the results from the three mixes under investigation. No consistent relationship was found between the shape parameter α and curing temperature and thus its value was kept constant for all curing temperatures.

If Saul’s principle or “maturity rule” was true then the strength development versus time relationships would overlap if plotted against maturity, see Fig. 4. However, the “cross-over” effect is apparent in Fig. 4 indicating that Saul’s maturity rule is not valid, i.e. there is no single strength-maturity relationship. At the same value of low maturity,

- 1 a high curing temperature resulted in greater strength than a low curing temperature and
- 2 conversely at later maturities, resulted in lower strengths.

Fig. 3: *Compressive strength versus age (hours) after casting.*

Fig. 4: *Compressive strength versus maturity (°C·hours) after casting.*

1 The strength development was converted to rate of strength development with maturity
 2 (dS/dM) and it is shown in Fig. 5. A logarithmic scale for the maturity axis was used as
 3 it accentuates differences at early maturities and thus early ages. If Saul's principle or
 4 "maturity rule" were true then the rate of strength development with maturity (dS/dM)
 5 should have overlapped. They do not and this is as expected since the strength
 6 development versus maturity relationships did not either, see Fig 4. The maximum rates
 7 of strength development, i.e. the peak of the dS/dM curves shown in Fig. 5, did not only
 8 occur at earlier maturity values with higher curing temperature but they were also
 9 numerically higher. The effect of temperature on the reaction was to accelerate it and
 10 thus "compress" a certain maturity interval into a smaller one, e.g., the reaction up till
 11 the peak for PC37 takes place at maturities of 582.8 and 219.6 $^{\circ}\text{C}\cdot\text{hours}$, for 20 and 50
 12 $^{\circ}\text{C}$ curing temperatures respectively (see Table 5 for values of other mixes and curing
 13 temperatures).

14 a) PC37 b) PC47 c) PC57
 15 **Fig. 5:** Rate of compressive strength gain with respect to maturity(dS/dM) versus
 16 maturity ($^{\circ}\text{C}\cdot\text{hours}$) - plotted on logarithmic x-axis.
 17

Table 5: Regression constants and other parameters required for the transformation of strength from the reference to other curing (isothermal and adiabatic) temperatures

Mix ID	Parameter	Curing Temperature (°C)			
		20	30	40	50
PC37	S _u (MPa)	44.29	37.72	34.62	30.66
	τ (hours)*	67.66	33.97	22.46	12.66
	τ (°C.hours) [#]	2097.4	1392.8	1145.5	772.0
	(dS/dM) _{max} (MPa per °C.hour)	0.011	0.014	0.016	0.021
	M at (dS/dM) _{max} (°C.hours)	582.8	393.6	323.85	219.6
	Ratio of (dS/dM) _{max}	1.000	1.264	1.411	1.853
	Ratio of Maturities at (dS/dM) _{max}	1.000	1.481	1.800	2.654
	Gradient C ₁ (Ratio of Maturities)	1.442			
	Gradient C ₂ (Ratio of (dS/dM) _{max})	0.911			
	Acceleration factor	1.000	1.497	2.050	2.654
	Compression factor	1.000	1.290	1.574	1.853
	Temperature efficiency (%)	100	86.2	76.8	69.8
PC47	S _u (MPa)	60.22	55.41	48.07	45.22
	τ (hours)*	50.88	33.46	21.12	15.26
	τ (°C.hours) [#]	1577.3	1371.7	1077.1	931.1
	(dS/dM) _{max} (MPa per °C.hour)	0.020	0.022	0.024	0.026
	M at (dS/dM) _{max} (°C.hours)	449.5	387.45	303.45	262.3
	Ratio of (dS/dM) _{max}	1.000	1.058	1.169	1.271
	Ratio of Maturities at (dS/dM) _{max}	1.000	1.160	1.481	1.714
	Gradient C ₁ (Ratio of Maturities)	0.795			
	Gradient C ₂ (Ratio of (dS/dM) _{max})	0.355			
	Acceleration factor	1	1.249	1.486	1.713
	Compression factor	1	1.104	1.193	1.272
	Temperature efficiency (%)	100	88.4	80.3	74.2
PC57	S _u (MPa)	62.73	58.79	55.32	52.18
	τ (hours)*	40.63	25.33	16.32	10.11
	τ (°C.hours) [#]	1259.6	1038.5	832.2	616.8
	(dS/dM) _{max} (MPa per °C.hour)	0.027	0.030	0.035	0.045
	M at (dS/dM) _{max} (°C.hours)	356.5	297.25	242.25	176.9
	Ratio of (dS/dM) _{max}	1.000	1.137	1.335	1.698
	Ratio of Maturities at (dS/dM) _{max}	1.000	1.199	1.472	2.015
	Gradient C ₁ (Ratio of Maturities)	1.035			
	Gradient C ₂ (Ratio of (dS/dM) _{max})	0.782			
	Acceleration factor	1.000	1.336	1.674	2.015
	Compression factor	1.000	1.244	1.476	1.698
	Temperature efficiency (%)	100	93.2	88.2	84.2

*Characteristic time constant for the strength-age relationship (Eq. 3)

[#]Characteristic time constant for the strength-maturity relationship (Eq. 4)

Taking logarithms of both sides of Equation 6 results in:

$$\log \left(\frac{1}{S} \frac{dS}{dM} \right) = \log(a\tau^a) - (a + 1) \log(M) \quad \text{Equation 8}$$

indicating that the plots should be straight lines with a gradient of $-(\alpha + 1)$, which therefore is minus 1.7, as shown in Fig. 6, since the shape parameter “ α ” used for the regression analysis of strength versus time as well as maturity was set as 0.7. All the lines in Fig. 6 would have overlapped had Saul’s maturity rule been valid.

Fig. 6: Relationship of $1/S \cdot dS/dM$ with maturity for curing at different temperatures.

The rate of the reaction (in terms of maturity index rather than time) is plotted against maturity in Fig. 7 for curing temperatures of 20 and 50°C . The two rate of hydration reaction curves do not coincide. An “acceleration” factor, in addition to the inherent age conversion factor in the Nurse-Saul maturity function, is therefore needed

Fig. 7: “Acceleration” and “temperature efficiency” factors used to transform the 20 °C rate of compressive strength gain (dS/dM) to that at 50 °C.

so that the 20 °C strength-maturity relationship can be applied for curing at 50 °C. The determination of the “acceleration” factor requires first the ratio of the maturity at the maximum dS/dM at 20 °C to the maturity at the maximum dS/dM at any other curing temperature, in this case 30, 40 and 50 °C:

$$\text{Ratio of Maturities at } \left(\frac{dS}{dM}\right)_{max} = \frac{M_r(20^\circ\text{C})}{M} \quad \text{Equation 9}$$

where:

- M_r = the maturity at peak dS/dM at the reference temperature of 20 °C, °C·hours,
- M = the maturity at peak dS/dM at any other curing temperature, °C·hours.

1

2 The “ratios of maturities at maximum dS/dM” are then plotted against $(T+11)/(T_{20}+11)$
3 on a log – log scale, as shown in Fig. 8. The gradient of the straight line C_I can then be
4 used in the following equation so that a relationship is obtained between the
5 “acceleration” factor and the age conversion factor, i.e. the ratio $(T+11)/(T_{20}+11)$,
6 inherent in the Nurse-Saul maturity function:

7

8
$$\text{Acceleration Factor (AF)} = \left(\frac{T+11}{T_{20}+11} \right)^{C_I} \quad \text{Equation 10}$$

9

10 where:

11 AF = “acceleration” factor

12 C_I = the gradient of the straight line relating the ratios

13 of maturities at peak dS/dM and age conversion factor

14

Fig. 8: Ratio of: (a) maturities at peak dS/dM , and, (b) $(dS/dM)_{max}$. versus $(T+11)/(T_{20}+11)$.

1 The effect of this “acceleration” is to compress a certain maturity interval into a smaller
2 one. As a result of the “compression” of the hydration the numerical value of dS/dM is
3 increased. If the reaction at the higher temperature was as efficient as at the lower
4 temperature, then the “acceleration” factor would be equal to the “compression” factor.
5 The Nurse-Saul function and indeed all other maturity functions consider that the
6 temperature efficiency is 100% irrespective of the curing temperature. The predicted
7 rates of strength development at the higher curing temperature of 50 °C and assuming
8 100% temperature efficiency (TEF) are shown as dashed lines in Figure 7(a), (b) and
9 (c) for PC37, PC47 and PC57 respectively. It was found that these were consistently
10 higher than those obtained from regression analysis of actual strength versus maturity
11 data. The actual “compression” factor (CF) therefore needed to be determined. The first
12 step was to determine the ratio of $\left(\frac{dS}{dM}\right)_{max}$ for each curing temperature with that at the
13 reference temperature of 20 °C. The ratio of $\left(\frac{dS}{dM}\right)_{max}$ is then plotted versus the age
14 conversion factor, i.e. the ratio $(T+11)/(T_{20}+11)$, on a log – log scale as shown in Figure
15 9. The gradient of the regression line C_2 is then used to express the “compression” factor
16 (CF) as a function of the age conversion factor:

17

$$18 \quad \text{Compression Factor (CF)} = \left(\frac{T+11}{T_{20}+11}\right)^{C_2} \quad \text{Equation 11}$$

19 where:

20 CF = “compression” factor

21 C_2 = the gradient of the straight line relating the ratios of maximum
22 dS/dM and age conversion factor

23

24

The temperature efficiency (η) factor is then the ratio of the “compression”/“acceleration” factors and it varies with curing temperature. As an example, the temperature efficiency (η) factor for these concrete mixes cured isothermally at 50 °C, are:

a) PC37 has a *Temperature efficiency factor* $= \eta = 1.853/2.654 = 69.81\%$,

b) PC47 has a *Temperature efficiency factor* $= \eta = 1.272/1.714 = 74.24\%$,

and,

c) PC57 has a *Temperature efficiency factor* $= \eta = 1.698/2.015 = 84.26\%$,

Fig. 9: “Acceleration” and “temperature efficiency” factors used to transform the 20 °C relationship between $1/S.dS/dM$ and maturity to that of specimens cured at 50 °C.

Fig. 9 shows how the relationship of the $1/S.dS/dM$ with maturity is first accelerated and then with the use of the temperature efficiency (η) factor is shifted upwards to overlap the actual/experimentally determined relationship. If one were to plot the 100%

1 temperature efficiency of the predicted dS/dM at 50 °C then it would again overlap the
 2 actual/experimentally determined relationship. It may at first appear surprising that
 3 when the predicted dS/dM at 50 °C and for 100% temperature efficiency for all three
 4 concretes are converted to $1/S.dS/dM$ they again overlap the 69.81%, 74.24% and
 5 84.26% temperature efficiencies for PC37, PC47 and PC57 respectively and their actual
 6 relationships. This is because strength and rate of strength development are interrelated,
 7 see Equation 8, and they are both needed for the relationship with maturity.

8

9 The strength development for elevated curing temperatures and for non-isothermal
 10 curing conditions can be estimated/predicted with the use of the compression factor
 11 (CF) and temperature efficiency (η) factor. An iterative procedure can be programmed
 12 in a spreadsheet; this is required in order to account for the effect of temperature on the
 13 compression factor (CF) and temperature efficiency (η) factor at different maturities.
 14 Figure 10 shows the spreadsheet that has been developed for this purpose. The first
 15 column (A) requires the temperature history of the concretes/mortars (in this case it is
 16 the adiabatic temperature history), the second (B) and third (C) is the time (in hours and
 17 days). The maturity increment is then calculated in the fourth column (D) and the
 18 maturity is shown in the fifth column (E). The “accelerated” maturity makes use of the
 19 acceleration factor (AF) previously determined. The maturity increment is multiplied
 20 by the acceleration factor (AF), calculated in column (F), and then the maturity
 21 calculated in the previous cell is added to it. The “stretch factor” is obtained by dividing
 22 the “accelerated maturity” (column F) with maturity (column E). The compression
 23 factor (column H) is calculated from Equation 11. The temperature efficiency factor
 24 (column I) is the (Compression Factor)/(Stretch Factor) ratio. Strength at the
 25 accelerated maturity is then calculated in column (J) using Equation 3 with constants

1 for 20 °C shown in Table 5. The maturity M used is the accelerated maturity in column
 2 F. The accelerated $\left(\frac{1}{S} \frac{dS}{dM}\right)_{accelerated}$ is then calculated (column K) based on Equation
 3 7 noting that the accelerated maturity needs to be used:

$$4 \quad \left(\frac{1}{S} \frac{dS}{dM}\right)_{accelerated} = \frac{a\tau^a}{M_{accelerated}^{a+1}} \quad \text{Equation 12}$$

6 The above has been calculated based on a temperature efficiency of 100% but the
 7 strength increment for a certain maturity increment, i.e. $\left(\frac{dS}{dM}\right)$, is affected by both the
 8 acceleration factor as well as the temperature efficiency factor (η). Thus:

$$10 \quad \frac{1}{S_{accelerated}} \left(\frac{dS}{dM}\right)_{shifted} = \left(\frac{1}{S} \frac{dS}{dM}\right)_{accelerated} \times \left(\frac{\Delta M_{accelerated}}{\Delta M}\right) \times Temp\ Eff\ (\eta)$$

$$12 \quad \text{Equation 13}$$

13 The above calculation results in a shift upwards of the accelerated $\left(\frac{1}{S} \frac{dS}{dM}\right)_{accelerated}$
 14 to that of the $\frac{1}{S_{accelerated}} \left(\frac{dS}{dM}\right)_{shifted}$. The shifted relationship is shown in column L.

15
 16 The $\left(\frac{dS}{dM}\right)_{modified}$ is shown in column M and the cumulative strength, i.e. the strength
 17 development, is shown in column L.

Fig. 10: Spreadsheet developed for the transformation of strength based on the Modified Nurse-Saul (MNS) maturity method (PC47 used as example)

1 The 20 °C strength development versus age relationship has been used with the above
2 procedure to estimate the strength development at curing temperatures of 30, 40 and 50
3 °C and these are shown in Fig. 11. Also shown for comparison are the strength estimates
4 for 50 °C obtained from the Nurse-Saul and Arrhenius maturity functions.

5 a) PC37 b) PC47 c) PC57
6 **Fig. 11:** Strength development estimates obtained from the Modified Nurse-Saul (MNS)
7 function. Estimates from the Nurse-Saul and Arrhenius functions for 50 °C are also
8 shown for comparison.

10 The only requirement of the Nurse-Saul function, in order to calculate the maturity
11 index according to Equation 1, is the temperature history of the concrete. Conversely,
12 in addition to the temperature history, the Arrhenius function also required the
13 “apparent” activation energies, E_a , of concretes under investigation. These were
14 previously determined [10] and they were 31.7, 33.1 and 41.1 kJ/mol for PC37, PC47
15 and PC57, respectively. These E_a values are in good agreement with those found in
16 other literature [8,42-45]. Equation 2 was used to calculate the Arrhenius equivalent
17 age t_e at time t . The specified reference temperature, T_s , used was 293 °K (20 °C). T_a

1 (in °K) was the average concrete temperature during time interval Δt , i.e. the recorded
2 adiabatic temperature histories. The calculated equivalent age, t_e , from Equation 2 was
3 then substituted for t in Equation 3 with regression constants S_∞ , τ , α , as previously
4 determined for the strength results obtained for the concrete cured at the reference
5 temperature (20 °C), see Table 5.

6 a) PC37
7 b) PC47
8 c) PC57
9 **Fig. 12:** Ratios of estimated/actual strengths of isothermally cured specimens using
10 the Modified Nurse Saul (MNS) for 30, 40 and 50°C. The Nurse-Saul and Arrhenius
11 estimates for 50°C are also shown for comparison.

12 Fig. 12 uses the strength development data from Fig. 9 but converted to ratios of the
13 estimated/actual strengths. The Modified Nurse Saul (MNS) method results in
14 compressive strength estimates that are within $\pm 20\%$ of the actual and only rarely
15 exceed $\pm 10\%$. The Nurse-Saul and Arrhenius methods not only under- or over-
16 estimated the compressive strengths at early ages but they notably overestimated the
17 28-day compressive strength by up to 40% in some cases. The incorporation of the

detrimental effect of high early age temperatures on the long-term strengths in the Modified Nurse-Saul (MNS) function resulted in not only improved early age strength estimates but also improved strength estimates for later ages.

4.2 Strength estimates for adiabatically cured specimens.

The temperature histories of the adiabatically cured PC37, PC47 and PC57 concretes are shown in Fig. 13. The PC37 having the lowest cement content of 300 kg/m³ had the lowest peak temperature equating to 259 kJ heat output per kg of cement. The PC57 seems to have reached a peak temperature much earlier than the PC47. However, the PC47's temperature continued to rise beyond 40 hours after casting and exceeded that of the PC57 after 67 hours since casting. The heat outputs per kg of cement were 284 kJ and 223 kJ for the PC47 and PC57 respectively. It is known that heat outputs are slightly reduced at lower water-cement ratios.

Fig. 13: Adiabatic temperature histories of PC37, PC47 and PC57 concretes.

Fig. 14 shows the strength development of these adiabatically cured specimens. High curing temperatures resulted in higher early age compressive strengths but later or long-term compressive strengths were adversely affected as they were for isothermally cured specimens at elevated temperatures. The “cross-over” effect, previously described for isothermally cured specimens, is also apparent in Fig. 14, for the adiabatically cured specimens.

Fig. 14: Strength development of adiabatically cured specimens. Estimates obtained from the Modified Nurse-Saul (MNS) function are compared to those from the Nurse-Saul and Arrhenius functions.

Strength estimates for the adiabatically cured specimens were obtained from the Modified Nurse-Saul procedure previously described and which is shown in Fig. 10 as a spreadsheet. These strength estimates were used to determine the rate of compressive strength gain with respect to maturity (dS/dM) which is plotted versus maturity ($^{\circ}C \cdot \text{hours}$), on logarithmic x-axis, in Fig. 15. Also plotted is the dS/dM for 20 and 50 $^{\circ}C$ for comparison purposes. The “accelerated” adiabatic dS/dM curve is shown before the temperature efficiency factor (η) is applied to it. The adiabatic dS/dM is not a parabola, i.e. it is not mirror-symmetrical and it is not U-shaped, as are the ones for 20 and 50 $^{\circ}C$. The reason for this is the non-isothermal curing temperature that results in a non-constant “acceleration” factor and thus a “distorted” parabola. It is because of this that it is not correct to carry out a regression analysis of the adiabatic strength development curve using Equation 3; the regression “constants” do not remain constant

1 but should vary with curing temperature. This can also be seen from Fig 16 which
2 shows the $1/S.dS/dM$ versus maturity relationship. The estimated $1/S.dS/dM$
3 relationship is not a simple shift to the left of the 20 °C relationship; it is not even a
4 straight line! The gradient of the estimated $1/S.dS/dM$ relationship continuously
5 changes as does the curing temperature. This is not however because the α in Equation
6 4 changes with temperature. We have shown that the α remains constant with
7 temperature; what changes is the “acceleration” factor and this is what is again causing
8 the straight line to be “distorted”. The line has highest gradient when the temperature
9 is changing, in this case rising, rapidly. Once the peak temperature in the adiabatic test
10 is reached then it remains almost constant and thus the gradient of the $1/S.dS/dM$ line
11 remains constant.

12

Fig. 15: Rate of compressive strength gain with respect to maturity(dS/dM) versus maturity ($^{\circ}C \cdot hours$) - plotted on logarithmic x-axis for adiabatically cured specimens.

Fig. 16: Accelerated and estimated $1/S.dS/dM$ for adiabatic cured concrete specimens. The $1/S.dS/dM$ for $50^{\circ}C$ curing regime is also shown for comparison purposes.

1 The 20 °C strength development versus age relationship has been used with the
2 Modified Nurse Saul (MNS) procedure to estimate the strength development of
3 adiabatically cured specimens; in the same way as it was used for estimating the
4 strength development of isothermally cured specimens at 30, 40 and 50 °C. The
5 estimates from the Modified Nurse Saul (MNS) are shown in Fig. 14. Also shown for
6 comparison are the strength estimates obtained from the Nurse-Saul and Arrhenius
7 maturity functions. Fig. 17 uses the strength development data from Fig. 14 but
8 converted to ratios of the estimated/actual strengths. The Modified Nurse Saul (MNS)
9 method results in compressive strength estimates that are within $\pm 20\%$ of the actual,
10 with the exception of PC37 at 12 hours and of PC47 at 24 hours. The estimates improve
11 to below $\pm 10\%$ for later ages. The Nurse-Saul and Arrhenius methods not only under-
12 or over-estimate the compressive strengths at early ages but they notably overestimated
13 the 28-day compressive strength by up to 40% in some cases. The incorporation of the
14 detrimental effect of high early age temperatures on the long-term strengths in the
15 Modified Nurse-Saul (MNS) function resulted in not only improved strength estimates
16 for later ages but also improved early age strength estimates.
17

Fig. 17: Ratios of estimated/actual strengths of isothermally cured specimens.

5. CONCLUSIONS

The effect of high early curing temperature is to accelerate the cement hydration, i.e. it starts earlier, and thus also accelerate the early age strength development. It is important that these strengths are accurately predicted/estimated if they will be of benefit to contractors and precast concrete suppliers.

- The Nurse-Saul function appears to underestimate the concrete strength at early ages because this function assumes that the concrete strength gain rate varies linearly with temperature.
- The Arrhenius maturity function tends to over-estimate the compressive strengths especially from one day onwards because of the detrimental effect higher early age curing temperatures have on later age strengths. This detrimental effect seems to be affecting strength predictions/estimates from an earlier age than expected.
- The strength predictions/estimates from both the Nurse-Saul and Arrhenius functions converge to a single value at 28 or 32 days which was the latest testing age used for determining the strength-time relationship at 20 °C. The detrimental effect of high early age curing temperatures on the long-term strengths is not accounted for.

The Modified Nurse-Saul maturity (MNS) function has been developed to account for the above deficiencies of current maturity functions. It relies on a relationship between concrete strength and the Nurse-Saul maturity index but incorporates an “acceleration” factor and a “temperature efficiency” factor.

- The “acceleration” factor can be obtained by plotting the ratio of maturities at peak dS/dM versus the ratio of relative “temperatures + datum”, i.e. $(T+11)/(T_{20}+11)$.

- The “temperature efficiency” factor can be obtained by plotting dS/dM at maximum values versus the ratio of relative “temperatures + datum”, i.e. $(T+11)/(T_{20}+11)$.

The “acceleration” factor is used to modify the maturity, i.e. to accelerate it to compensate for the inherent age conversion factor (which has been shown not be sufficient), and this is subsequently used to determine $(1/S.dS/dM)_{\text{accelerated}}$. This is then modified with the use of the “temperature efficiency” factor to compensate for the reaction at the higher temperature not being as efficient as at the lower temperature. Is is subsequently multiplied by the strength at the accelerated maturity to obtain the strength increase over the maturity increment. The procedure is incremental in that it considers the effect of temperature on the strength development over the particular maturity increment considered.

The “acceleration” and “temperature efficiency” factors are both mixture specific and they therefore need to be determined from isothermally cured specimens before they can be used to predict/estimate strength development for non-isothermal curing regimes, e.g., adiabatically cured concretes.

The Modified Nurse-Saul (MNS) function, which incorporates “acceleration” and “temperature efficiency” factors, has been set up as an iterative procedure using a spreadsheet and the strength estimates have been shown to be more accurate than those from other maturity functions not only for the early age but also long-term strengths.

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REFERENCES

1. ASTM C918 / C918M-13, Standard Test Method for Measuring Early-Age Compressive Strength and Projecting Later-Age Strength, ASTM International, West Conshohocken, PA, 2013.
2. Saul, A.G.A. "Principles underlying the steam curing of concrete at atmospheric pressure," *Magazine of Concrete Research*, Vol. 2, No. 6, 1951, pp. 127-140.
3. Nurse, R.W. "Steam curing of concrete", *Magazine of Concrete Research*, Vol. 1, No. 2, 1949, pp. 79-88.
4. Freiesleben, H. P., and Pedersen, E. J. (1977) "Maturity computer for controlled curing and hardening of concrete," *J. Nordic Conc. Fed*, Vol. 1, pp. 21-25.
5. Soutsos, M., Hatzitheodorou, A., Kwasny, J. and Kanavaris, F. "Effect of *in situ* temperature on the early age strength development of concretes with supplementary cementitious materials," *Construction and Building Materials*, Vol. 103, 2016, pp. 105-116.

6. Vollpracht, A., Soutsos, M. and Kanavaris, F. “Strength development of GGBS and fly ash concretes and applicability of fib model code’s maturity function – A critical review”, *Construction and Building Materials*, Vol. 162, 2018, pp. 830-846.
7. Carino, N. J., and Tank, R. C. “Maturity functions for concretes made with various cements and admixtures,” *ACI Materials Journal*, Vol. 89, No. 2, 1992, pp. 188-196.
8. Soutsos, M., Hatzitheodorou, A., Kanavaris, F. and Kwasny, J. “Effect of temperature on the strength development of mortar mixes with GGBS and fly ash,” *Magazine of Concrete Research*, Vol. 69, No. 15, 2017, pp. 787-801.
9. Yikici, T. A. and Chen, H.-L. “Use of maturity method to estimate compressive strength of mass concrete”, *Construction and Building Materials*, Vol. 95, 2015, pp. 802-812.
10. Kanavaris, F. “Early age behaviour and cracking risk of concretes containing GGBS”, *PhD Thesis*, Queen’s University of Belfast, UK, 2017.
11. Soutsos, M., Turu’allo, G., Owens, K., Kwasny, J., Barnett, S. J. and Basheer, P. A. M. “Maturity testing of lightweight self-compacting and vibrated concretes,” *Construction and Building Materials*, Vol. 47, 2013, pp. 118-125.
12. Sofi, M., Mendis, P. A. and Baweja, D. “Estimating early-age in situ strength development of concrete slabs”, *Construction and Building Materials*, Vol. 29, 2012, pp. 659-666.
13. Barnett, S. J., Soutsos, M. N., Millard, S. G. and Bungey, J. H. “Strength development of mortars containing ground granulated blast-furnace slag: Effect of curing temperature and determination of apparent activation energies”, *Cement and Concrete Research*, Vol. 36, No. 3, 2006, pp. 434-440.

14. Verbeck, G. J. and Helmuth, R. H. "Structure and physical properties of cement paste," Proc. Fifth Int. Symp. On the Chemistry of Cement, Part III, Tokyo, 1968, pp. 1-32.
15. Soutsos, M., Kanavaris, F. and Hatzitheodorou, A. "Critical analysis of strength estimates from maturity functions", *Case Studies in Construction Materials*, Vol. 9, 2018, e0018, pp. 1-19.
- 16.
17. Turkel, S. and Alabas, V. "The effect of excessive steam curing on Portland composite cement concrete", *Cement and Concrete Research*, Vol. 35, No. 2, 2005, pp. 405-411.
18. McIntosh, J. D. "The effects of low-temperature curing on the compressive strength of concrete," Proc. RILEM Symp. On Winter Concreting, Session BII, Copenhagen, Danish Institute for Building Research, Copenhagen, 1956, p. 17.
19. Copeland, L., E., Kantro, D., L. and Verbeck, G. (1962), "Chemistry of hydration of Portland cement: Energetics of the hydration of Portland cement", In: Proceedings of the 4th International Symposium on Chemistry of Cement, NBS Monograph 453, Washington D.C., pp. 453-462.
20. Gallucci, E., Zhang, X. and Scrivener, K. L. (2013), "Effect of temperature on the microstructure of calcium silicate hydrate (C-S-H)", *Cement and Concrete Research*, 53, pp. 185-195.
21. Roy, D., M. and Idorn, G., M. (1982), "Hydration, structure and properties of blast furnace slag cements, mortars and concrete", *ACI Journal*, pp. 444-457.
22. Ezziane, K., Bougara, A., Kadri, A., Khelafi, H. and Kadri, E. (2007), "Compressive strength of mortar containing natural pozzolan under various temperatures", *Cement and Concrete Composites*, 29(8), pp. 587-593.

23. Escalante-Garcia, J., I. and Sharp, J., H. (1998), “Effect of temperature on the hydration of the main clinker phases in Portland cement: Part I, neat cements”, *Cement and Concrete Research*, 28(9), pp. 1245-1257.
24. Escalante-Garcia, J., L. and Sharp, J., H. (2001), “The microstructure and mechanical properties of blended cements hydrated at various temperatures”, *Cement and Concrete Research*, 31(5), pp. 695-702.
25. Chanvillard, G. and D’Aloia, L. “Concrete strength estimation at early ages: modification of the method of equivalent age”, *ACI Materials Journal*, Vol. 94, No. 6, 1997, pp. 520-530.
26. Kjellsen, K.O. and Detwiler, R.J. “Later-age strength prediction by a modified maturity model”, *ACI Materials Journal*, Vol. 90, No. 3, 1993, pp. 220-227.
27. Schindler, A. “Effect of temperature on hydration of cementitious systems”, *ACI Materials Journal*, Vol. 101, No. 1, 2004, pp. 72-81.
28. Soutsos, M., Hatzitheodorou, A., Kanavaris, F. and Kwasny, J. “Compressive Strength Estimates of Adiabatically Cured Concretes Using Maturity Methods”, *Journal of Materials in Civil Engineering*, Vol. 31, No. 7, 2019.
29. Kanavaris, F., Soutsos, M., Chen, J-F. and Nanukuttan, S. “An investigation on appropriate curing regimes for precast concrete structural elements with GGBS using maturity functions”, International RILEM/COST Conference on Interdisciplinary Approaches for Cement-based Materials and Structures - SynerCrete18’, (Azenha, M., Schlicke, D., Bendoudjema, F. and Jędrzejewska, A. (eds.)), October 2018, Funchal, Madeira, Portugal.
30. D. Schlicke, F. Kanavaris, R. Lameiras and M. Azenha, “On-site monitoring”, Book chapter in: RILEM State-of-the-art report in cracking mitigation in

- 1 massive concrete structures (Fairbairn, E. and Azenha, M. (eds)), Springer,
2 2019.
- 3 31. Freiesleben Hansen, P., and Pedersen, E.J. “Curing of concrete structures,” CEB
4 Inf. Bull., 166, May, 1985.
- 5 32. Carino, N. J. “The Maturity Method,” in Handbook on Nondestructive Testing
6 of Concrete, Editors: Malhotra, V. M. and Carino, N. J., 2nd Edition, *CRC Press*,
7 2004, pp. 5.1- 5.47.
- 8 33. Soutsos, M., N. “Effect of temperature on the rate of strength development of
9 mortar mixes”, in: 13th International Conference on Structural Faults and
10 Repair – 2010 (Forde, M., C. (ed)), Engineering Technics Press, Edinburgh,
11 UK.
- 12 34. Soutsos, M. and Kanavaris, F. “The modified nurse-saul (MNS) maturity
13 function for improved strength estimates at elevated curing temperatures”, *Case*
14 *Studies in Construction Materials*, Vol. 9, 2018, e00206, p. 14.
- 15 35. British Standards Institution, “BS EN 206:2013+A1:2016, Concrete.
16 Specification, performance, production and conformity”, *BSI*, London, UK,
17 2013.
- 18 36. British Standards Institution, “BS EN 197-1:2011 – Cement. Composition,
19 specifications and conformity criteria for common cements”, *BSI*, London, UK,
20 2011.
- 21 37. British Standards Institution, “BS EN 196-1-2005 – Methods of testing cement.
22 Determination of strength”, *BSI*, London, UK, 2005.
- 23 38. British Standards Institution, “BS EN 12620:2002+A1:2008, Aggregates for
24 concrete”, *BSI*, London, UK, 2002.

- 1 39. British Standards Institution, “BS EN 12350-2:2009, Testing fresh concrete.
2 Slump-test”, *BSI*, London, UK, 2009.
- 3 40. British Standards Institution, “BS EN 12390-1:2012, Testing hardened concrete
4 Part 1: Shape, dimensions and other requirements for specimens and moulds”,
5 *BSI*, London, 2012.
- 6 41. British Standard Institution, “BS EN 12390-3:2019 Testing hardened concrete.
7 Compressive strength of test specimens”, *BSI* , London, 2019.
- 8 42. Barnett, S. J., Soutsos, M. N., Bungey, J. H., and Millard, S. G. “Fast-track
9 construction with slag cement concrete: Adiabatic strength development and
10 strength prediction,” *ACI Materials Journal*, Vol. 104, No. 4, 2007, pp. 388-
11 396.
- 12 43. Brooks, A.G., Schindler A.K. and Barnes R.W., “Maturity method evaluated
13 for various cementitious materials”, *J. Mater. Civ. Eng.* Vol. 19, Issue 12, 2007,
14 pp. 1017–1025.
- 15 44. J.L. Poole, K.A. Riding, M.C.G. Juenger, K.J. Folliard, A.K. “Schindler Effects
16 of supplementary cementitious materials on apparent activation energy”, *J.*
17 *ASTM Int.*, Vol. 7, 2010.
- 18 45. J.L. Poole, K.A. Riding, K.J. Folliard, M.C.G. Juenger, A.K. Schindler
19 “Methods for calculating apparent activation energy for Portland cement”, *ACI*
20 *Mater. J.*, Vol. 104, No. 1, 2007, pp. 303-311.