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Effect of temperature on the strength development of mortar mixes with GGBS and fly ash.

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Notation

E_a	"apparent" activation energy (J/mol)
k	the rate constant (1/day)
M	Nurse-Saul maturity (°C·days)
R	universal gas constant (J/°K·mol)
S	compressive strength (MPa)
S_∞	limiting strength of the mortar (MPa)
T	average temperature (°C)
T_0	datum temperature (°C)
T_{abs}	absolute temperature (°K)
T_r	specified reference temperature (°K or °C)
t_0	age at which mortar strength development is assumed to begin (days)
t_e	equivalent age (days)
α	age conversion factor
Δt	time interval (days)

Abstract

The concrete mixes used were of 28-day mean strengths of 50 and 30 MPa and also had partial Portland cement (PC) replacement with ground granulated blast-furnace slag (GGBS) and fly ash (FA). These mixes were the ones used in a UK based project which involved casting of blocks, walls and slabs. The strength development of "equivalent" mortar mixes was determined in the laboratory for curing temperatures of 10, 20, 30, 40 and 50 °C. High curing temperatures have a beneficial effect on the early age strength but a detrimental effect on the long term strength. GGBS has been shown to be more sensitive to high curing temperatures than PC and FA and this is reflected in its higher "apparent" activation energy. The accuracy of strength estimates obtained from maturity functions was examined. The temperature dependence of the Nurse-Saul function, *i.e.* the concrete strength gain rate varies linearly with temperature, was not sufficient to account for the improvement in early age strengths resulting from high curing temperatures. The Arrhenius based function, on the other hand, overestimated them because of the detrimental effect of high curing temperature on strength starting from a very early age. Both functions overestimate long term strengths as neither accounts for the detrimental effect of high curing temperatures on the ultimate compressive strength.

Keywords

Compressive strength, Cement/cementitious materials, Temperature-related & thermal effects

1 Introduction

Portland cement in combination with ground granulated blast-furnace slag (GGBS) and fly ash (FA) is commonly used for many concretes (Bijen, 1996; ACI Committee 233, 2003; Ling *et al*., 2006; Won *et al*., 2015; Berndt, 2015; Golden and Wong, 2016). Use of GGBS and FA offers advantages like improved durability and workability and has even economic benefits (ACI 233R-03, 2003; Tang *et al*., 2013; Thomas, 2013). However, the strength development of concretes with partial cement replacement with GGBS and FA is considerably slower under standard 20 °C curing conditions than that of neat Portland cement concrete. This is despite that the ultimate strength is higher for the same water to binder (w/b) ratio (Roy and Idorn, 1982; Escalante-Garcia and Sharp, 2001; Escalante-Garcia *et al*., 2001; Barnett *et al*., 2007a; Barnett *et al*., 2007b). The use of GGBS and FA in applications where high early age strength is required tends to be avoided. However, the strength development of concretes with GGBS and FA is significantly enhanced at higher early age temperatures as the reactions of GGBS and FA is much more sensitive to temperature than Portland cement (Roy and Idorn, 1982; Escalante-Garcia *et al*., 2001). There can be a significant rise in temperature within the first few days after casting of large structural concrete elements where heat dissipation is slow and heat from the exothermic reaction of the binder cannot be dissipated quickly (Sanjayan and Sioulas, 2000; Yikici *et al.*, 2015; Soutsos *et al.*, 2016). Higher early age strengths are therefore expected and these can only be determined by temperature matched curing. Cubes or cylinders cured at 20 °C, or adjacent to the structure, would underestimate the strength in the structure.

Concrete mixture composition, including factors such as w/b ratio and the use of GGBS and FA affect the early age strength development of concrete as is the type of formwork and size of structural element, and the ambient temperature. All these factors formed part of a DTI Concrete Core Project (The Concrete Society, 2004), which involved casting concrete blocks, walls and slabs, see Figure 1, with neat Portland cement and partial cement replacement with GGBS and FA. The DTI project was designed to provide the information needed to enable the potential strength of concretes with GGBS and FA to be derived, taking into account age at test, thermal history, cement type and concrete strength. The data generated has been very extensive although aimed at long-term rather than early-age strength determination. The concrete mixes used in the DTI project, were replicated in the laboratory (Soutsos *et al.*, 2016) in order to determine the effect of temperature on their early-age strength development. Variables investigated were nominal concrete compressive strength (50 MPa and 30 MPa) and partial cement replacement with GGBS and FA. Results on the effect of *in situ* temperature history on the strength development were reported in Soutsos *et al.*, 2016. The work reported here formed the second phase of the project which investigated the effect of curing temperature, i.e. 10, 20, 30, 40 and 50 °C, on the strength development of equivalent mortars. Determination of the strength development of equivalent mortars enabled the initial "apparent" activation energies to be calculated.

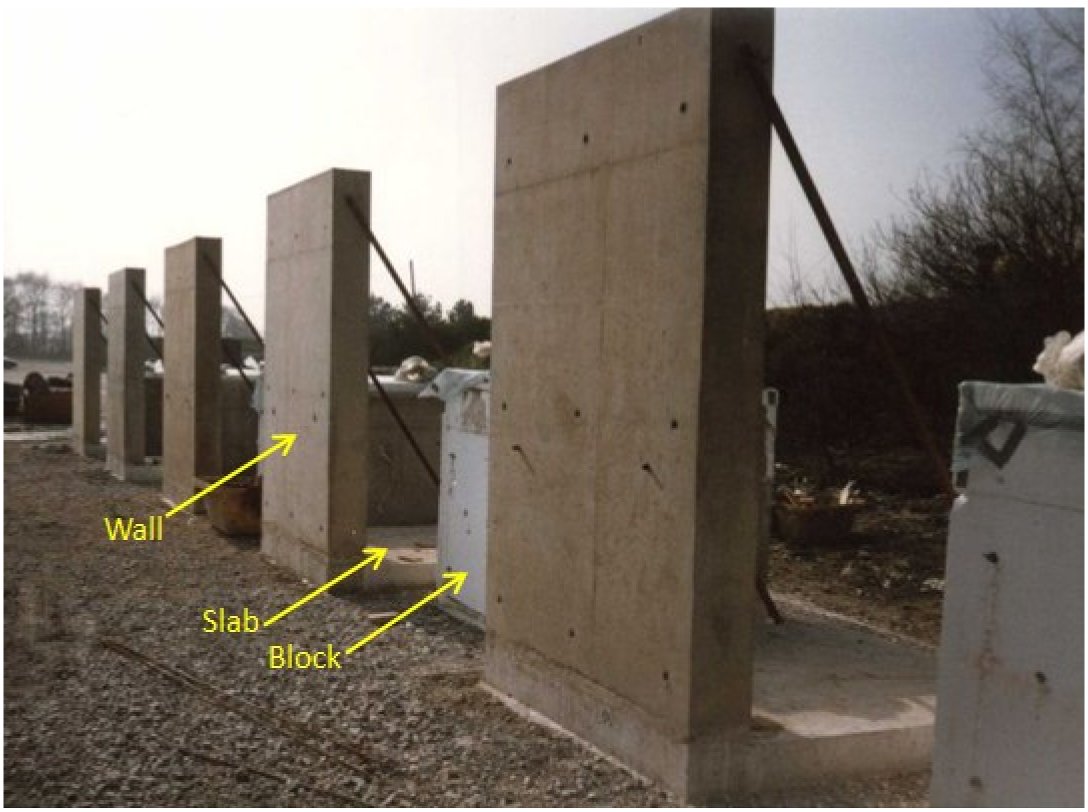

Figure 1: *Structural elements cast during the DTI project (The Concrete Society, 2004).*

The "apparent" activation energies determined were used in maturity functions, like the Arrhenius function, for estimating the *in situ* strength development of concrete and they have been reported in Soutsos *et al.*, 2016. These can also be used for estimating the strength development of mortars under isothermal curing regimes. The applicability/accuracy of the Nurse-Saul function for estimating the effect of curing temperatures on the strength development was also investigated despite that this does not require the determination of the "apparent" activation energies.

2 Materials and experimental procedures

Only equivalent mortars to concrete mixes used in DTI project (Hatzitheodorou, 2007; Soutsos *et al.*, 2016) have been investigated. The mix proportions of these mortars were determined according to ASTM C1074-11 (ASTM, 2011) based on the mix proportions of the corresponding concretes. The ASTM C1074-11 (ASTM, 2011) requirements were for the mortars to have the same water-binder (w/b) ratio as the concrete and the fine aggregate to binder ratio to be equal to the coarse aggregate to binder ratio of the concrete. The resulting mortar mixture proportions are shown in Table 1, alongside the concrete mixes.

Table 1: *Mix proportions of concrete of strength of 50 MPa and 30 MPa (Soutsos et al., 2016) and their equivalent mortars.*

Mix ID	*PC50*		*GGBS50*		*FA50*		*PC30*		*GGBS30*		*FA30*	
Material	**Concrete**	**Equivalent mortar**	**Concrete**	**Equivalent mortar**	**Concrete**	**Equivalent mortar**	**Concrete**	**Equivalent mortar**	**Concrete**	**Equivalent mortar**	**Concrete**	**Equivalent mortar**
PC [kg/m^3]	345	442	165	219	270	332	240	348	115	160	193	239
GGBS [kg/m^3]	-	-	165	219	-	-	-	-	115	160	-	-
FA [kg/m^3]	-	-	-	-	115	141	-	-	-	-	82	102
Gravel [kg/m^3]	1205	-	1151	-	1250	-	1102	-	1187	-	1319	-
Sand [kg/m^3]	615	1519	683	1588	533	1523	799	1583	721	1547	560	1633
Free water [kg/m^3]	160	204	165	200	135	166	158	229	150	208	144	180
Total water [kg/m^3]	197	244	203	241	171	207	198	271	190	252	181	224
Free w/b [-]	0.46	0.46	0.50	0.46	0.35	0.35	0.66	0.66	0.65	0.65	0.52	0.53
Total w/b [-]	0.57	0.55	0.62	0.55	0.44	0.44	0.83	0.78	0.83	0.79	0.66	0.66
Concrete slump [mm]	135	-	120	-	10	-	150	-	120	-	120	-

2.1 Materials

Portland cement (PC) CEMI 52.5N with standard strength of 57 MPa (determined based on BS EN 196-1:2005 (BSI, 2005)) and that conformed to BS EN 197-1:2011 (BSI, 2011) was supplied by British Lime Industries who were also the supplier of the PC for the DTI project. PC composition variations may have however existed since this research project started years after the DTI project had been completed. PC was partially replaced with GGBS and FA conforming to BS EN 15167-1:2006 (BSI, 2006) and BS EN 450-1:2012 (BSI, 2012), respectively. GGBS was supplied by Appleby Group whereas FA was supplied in by Fiddlers Ferry, a coal-fired electricity-generating station, in Warrington, UK. The chemical compositions of PC, GGBS and FA are shown in Table 2.

Table 2: *Chemical composition of PC, GGBS and FA.*

Chemical composition (% by weight)			
Chemical constituent	**PC**	**GGBS**	**FA**
SiO_2	20.11	35.35	48
Al_2O_3	5.16	14	27
Fe_2O_3	3.14	0.36	9
CaO	65.49	41.41	3.3
MgO	0.8	7.45	2
SO_3	3.22	0.1	0.6
K_2O	0.59	-	3.8
Na_2O	0.13	-	1.2
$CaCO_3$	4.47	-	-
Equiv. Alks Na_2Oe	0.52	-	-
Free Lime	1.79	-	-
Chloride	71 ppm	-	-

The coarse aggregate used for the laboratory replicated concrete mixes (Soutsos *et al.*, 2016), shown in Table 1, was 5–20 mm uncrushed round gravel from the Fagl Lane quarry, which is located in Wales. Its specific gravity and water absorption were 2.6 and 1.7%, respectively. The fine aggregate used for the concrete mixes and the equivalent mortar mixes was fine sand obtained from the Fagl Lane quarry. It was considered to be fine according to BS 882:1992 (BSI, 1992) that was in use at the time of the DTI project. The sand would not comply with the new BS EN 12620:2002+A1:2008 (BSI, 2002). The sand had a specific gravity of 2.60 and water absorption of 2.6%. The grading for both coarse and fine aggregate is shown in Figure 2.

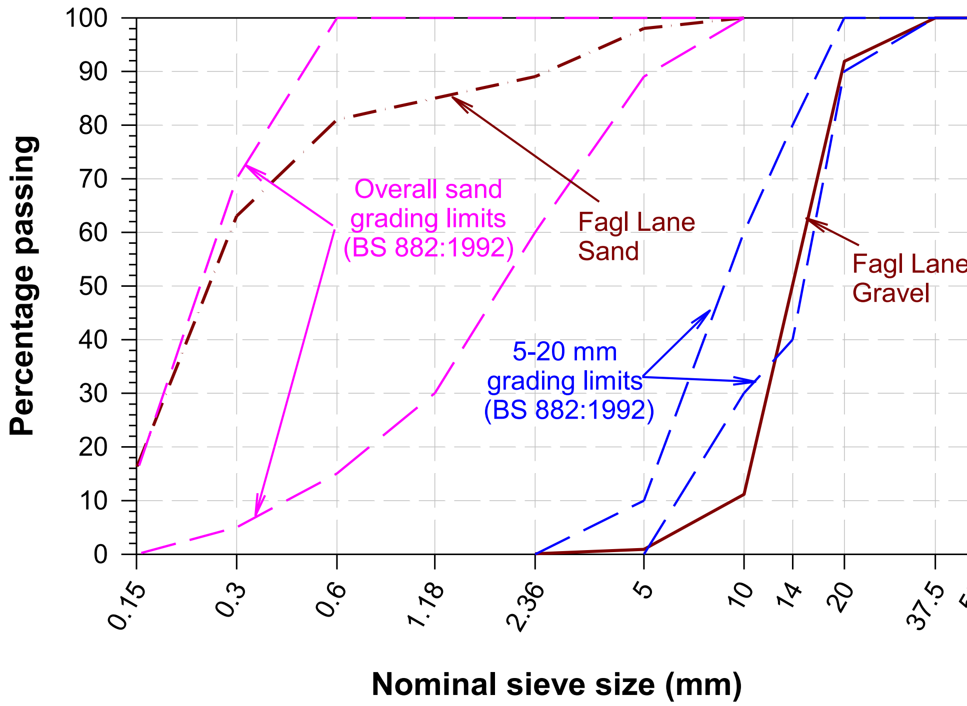

Figure 2: *Sieve analysis of coarse and fine aggregate used.*

2.2 Mixing, casting, curing and testing procedures

A horizontal pan mixer was used and the materials were added in the order: PC, GGBS or FA, sand and water. Quantities of mortar were 0.015 m^3 each time. Mixing was for 3 minutes after which the mortar was cast into steel 50 mm cube moulds consolidated on a vibrating table and wrapped in polyethylene film which ensured that they were sealed, to stop wash out when they were transferred to water tanks for curing at 20, 30, 40 and 50 °C. For curing at 10 °C, the specimens were wrapped in damp hessian and stored in an incubator. They were demoulded at the time of the first compressive strength test. Three cubes were tested at six to eight testing ages for each mixture/temperature combination. In each case, the first testing age corresponded to a compressive strength of approximately 4 MPa, achieved by trial and error and subsequent tests were carried out at twice the age of the previous test.

3 Results and discussion

The first part of the work involved "equivalent" mortars and their strength development is compared to the corresponding concretes. The second part was the investigation of the strength development at elevated curing temperatures. These were used in the third part for determining the "apparent" activation energies. The fourth part uses the Nurse-Saul and Arrhenius functions for estimating the strength development at elevated curing temperatures. The accuracy of these maturity functions was therefore investigated.

3.1 Strength development of concretes and their equivalent mortars

The determination of "apparent" activation energies, according to ASTM Standard C1074-11 (ASTM, 2011), requires monitoring of the strength development of "equivalent" mortars. These need to have the same w/b ratio as the concretes. The sand to binder ratios need to be equal to the coarse aggregate to binder ratios of the concretes. The mix proportions of the equivalent mortars, shown in Table 1, have been calculated from those of the corresponding concretes which are also shown in Table 1.

According to ASTM Standard C1074-11 (ASTM, 2011), tests can be performed on mortar specimens and the "apparent" activation energies applied to the concretes under investigation. The strength development at 20 °C of concretes and their equivalent mortars are shown in Figure 3 for both 50 MPa and 30 MPa. The strengths at very early ages are similar between concretes and mortars. However, there are differences in strengths at later ages and these increase with age. These are small for mortar and concretes of 50 MPa strength but considerable for those of 30 MPa. There is also no consistent trend as to which has the higher strength, *i.e.* concrete or mortar. GGBS and PC concrete strengths are lower for both 50 and 30 MPa compressive strengths. On the other hand, the FA concretes have higher compressive strengths than their equivalent mortars.

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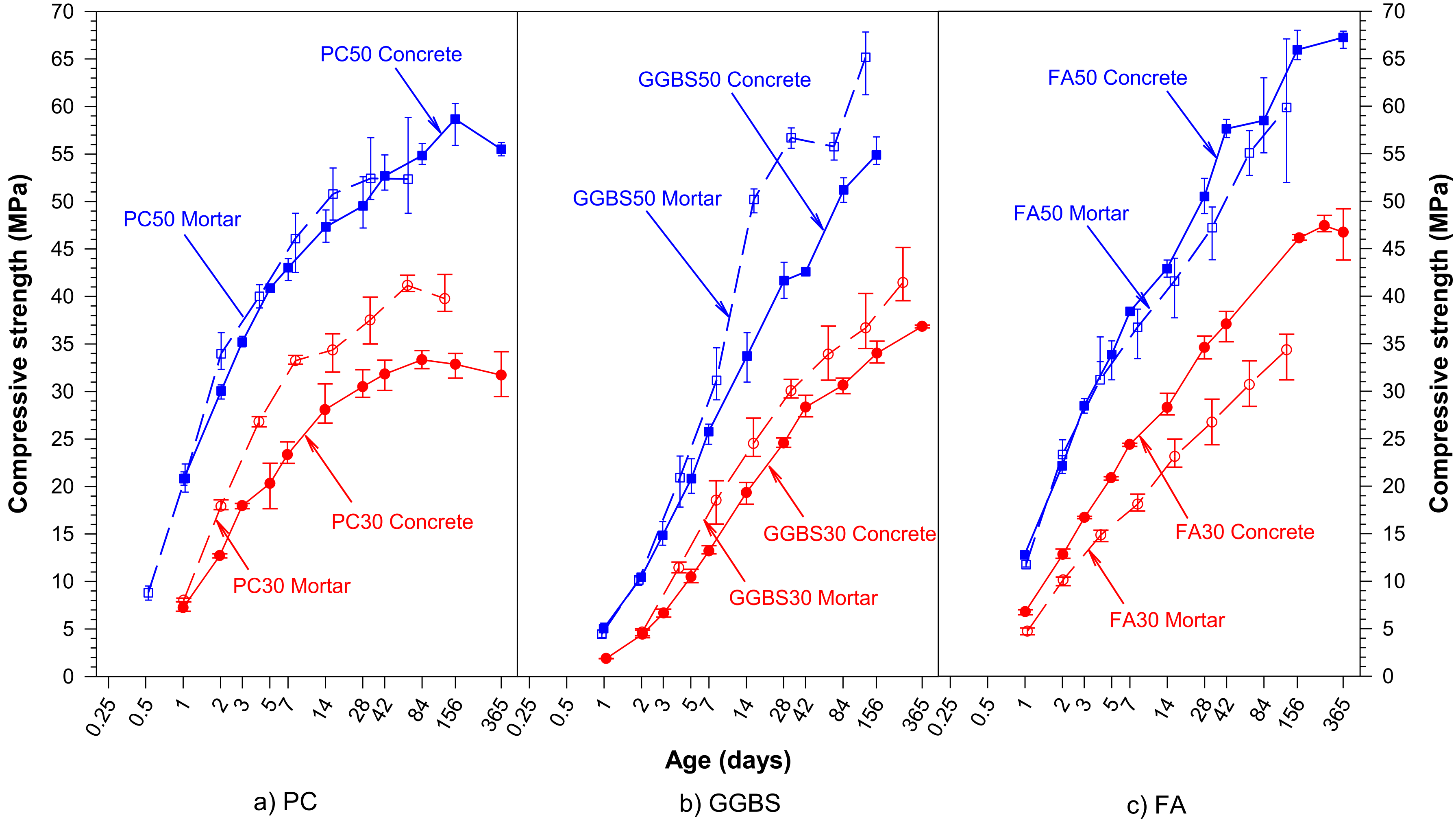

Figure 3: *Comparison of strength development of concretes of strength 50 and 30 MPa and their equivalent mortars.*

3.2 Effect of temperature on mortar strength development

The development of compressive strength, *S*, at a given curing temperature, can be described as a function of time, *t*, by the equation (Tank and Carino, 1991; Soutsos *et al.*, 2005):

$$S = \frac{S_\infty \cdot k \cdot (t - t_0)}{1 + k \cdot (t - t_0)} \qquad \textbf{Equation 1}$$

where:

	S_∞	is the limiting strength of the mortar (MPa),
	k	is the rate constant at temperature T (1/day),
	t	is the test age (days),
	t_0	is the age at which mortar strength development is assumed to begin at temperature T (days).

This equation was used to obtain regression lines through the strength data and the regression constants for all the mixes are shown in Table 3.

Table 3: *Regression constants for strength-time relationship (Equation 1).*

	Mix ID	*PC50*			*GGBS50*			*FA50*			*PC30*			*GGBS30*			*FA30*		
Regression constants		S_u	k	t_0	S_u	k	t_0	S_u	k	t_0	S_u	k	t_0	S_u	k	t_0	S_u	k	t_0
Temperature [°C]	**10**	56.7	0.45	4.56E-01	66.4	0.08	6.73E-01	58.9	0.18	1.91E-01	45.1	0.28	8.02E-01	44.3	0.04	3.41E-01	31.3	0.15	1.99E-01
	20	53.6	0.89	3.03E-01	67.1	0.14	5.66E-01	56.8	0.26	4.44E-09	40.5	0.54	5.49E-01	40.8	0.10	4.09E-01	33.8	0.16	4.89E-09
	30	52.9	0.98	4.66E-02	62.4	0.35	4.18E-01	65.2	0.33	4.38E-09	38.1	0.80	2.22E-02	33.9	0.35	4.87E-01	37.0	0.17	1.52E-08
	40	44.4	1.67	5.18E-10	59.4	0.46	1.66E-01	54.6	0.52	2.71E-09	34.8	1.21	4.09E-02	33.1	0.41	1.36E-01	38.5	0.30	3.74E-09
	50	38.1	2.32	1.97E-09	51.1	0.72	1.24E-01	51.7	0.78	6.07E-10	27.7	2.22	4.47E-02	32.8	0.56	1.41E-01	32.4	0.48	6.94E-11
E_a [kJ/mol]		29.7			41.6			27.3			37.4			53.3			22.5		

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The compressive strength development with age at different curing temperatures is shown in Figures 4 and 5 for strengths of 50 and 30 MPa, respectively. As expected, the strength development of all the mortars depended on the curing temperature. At early ages, the strength was higher at higher temperatures since the rate of reaction is greater. At later ages, the strength was lower at high curing temperatures. This is believed to be due to the formation of dense hydrated phases around the unreacted cement particles, preventing further hydration (Escalante-Garcia and Sharp, 2001; Escalante-Garcia and Sharp, 1997). The non-uniform distribution of hydration products also leads to larger pores in the microstructure. The mortars containing GGBS were more sensitive on temperature, with the early age strengths showing a wider variation with temperature.

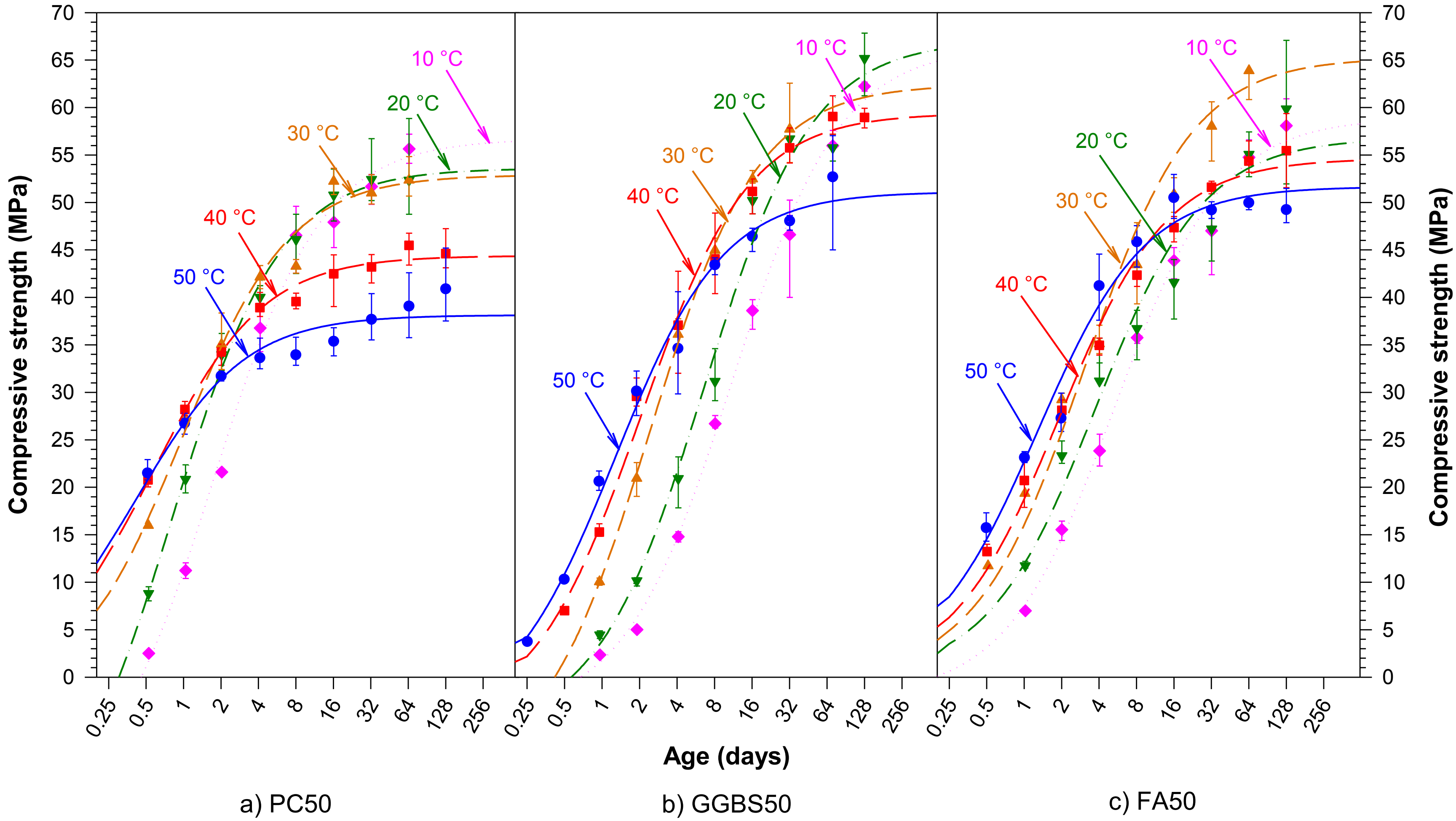

Figure 4: *Strength versus age for mortars with strength of 50 MPa.*

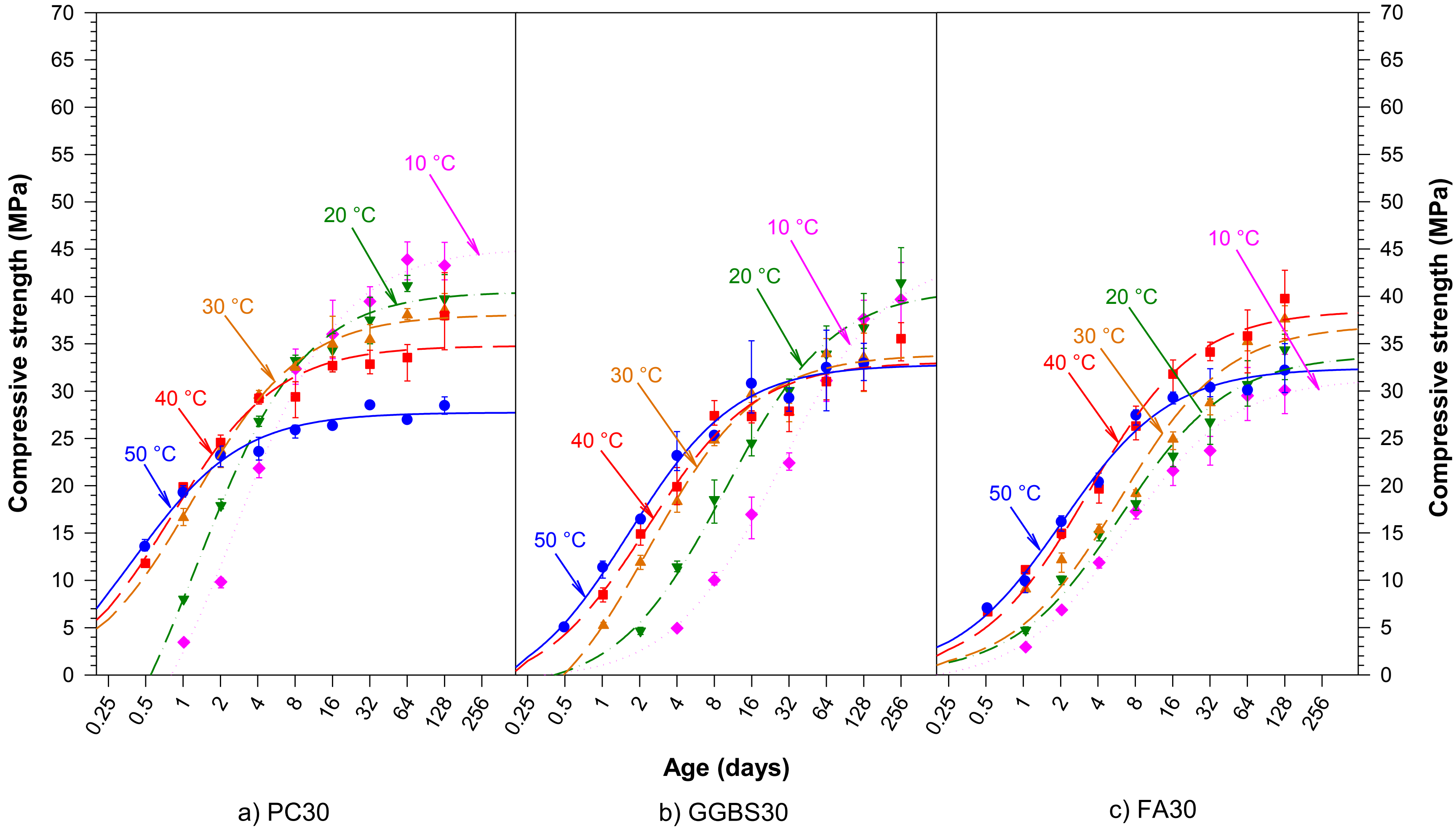

Figure 5: *Strength versus age for mortars with strength of 30 MPa.*

The relative strengths, *i.e.* the strength ratio of actual strength to that at 20 °C curing strength, are shown in Figures 6 and 7 for strengths of 50 and 30 MPa, respectively. These figures clearly show the benefit of higher curing temperatures on the early age strength development of mortars, especially those containing GGBS. Strength ratios of actual strengths with 20 °C curing strength for GGBS were as high as 4.63 at 1-day and 3.53 at 2-days for 50 and 30 MPa equivalent mortars respectively. These were much higher from the 1.28 and 1.29 for corresponding PC mortars.

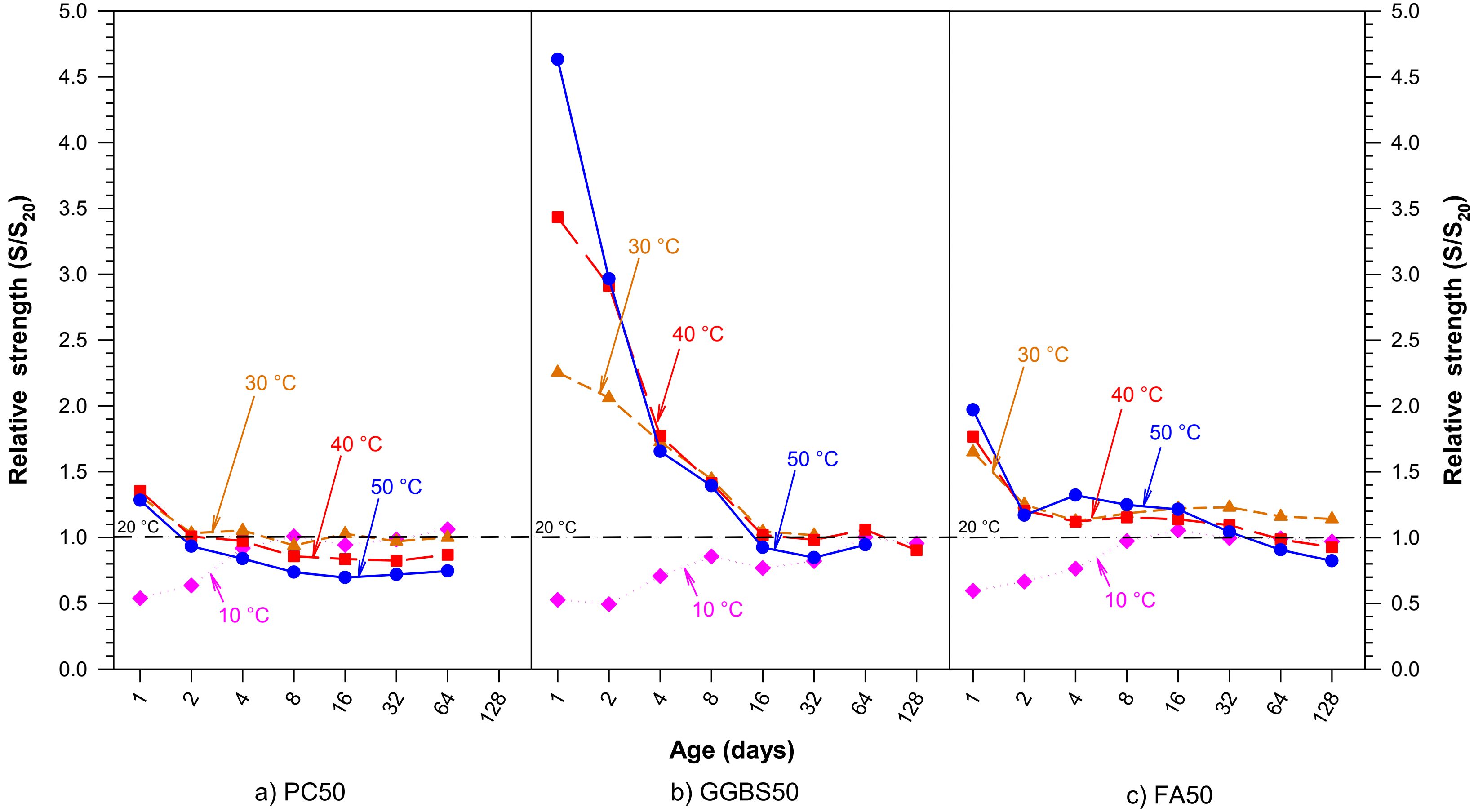

Figure 6: *Relative strengths, i.e. strength ratio of actual strengths (S) with 20 °C curing strengths (S_{20}), for mortars with strength of 50 MPa.*

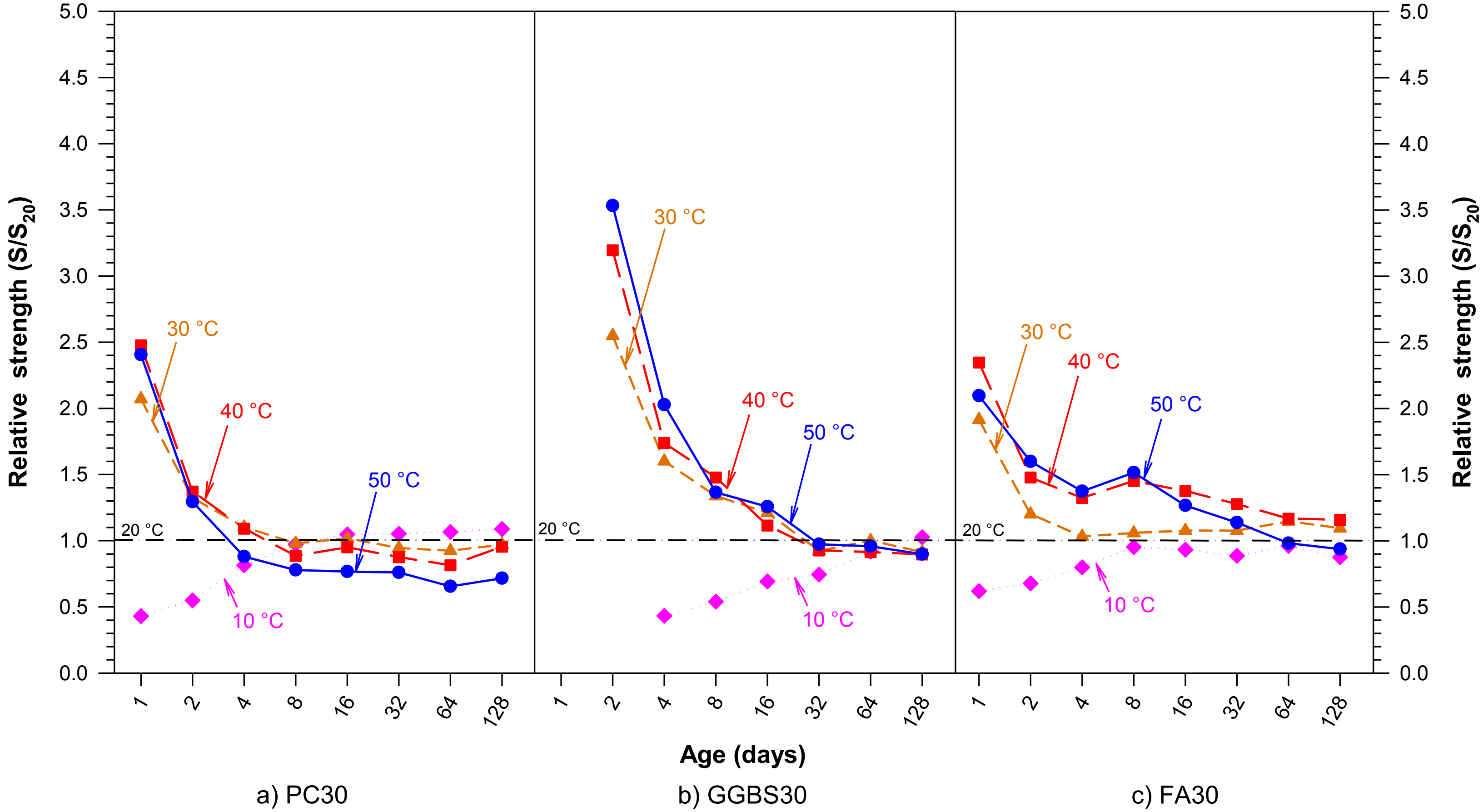

Figure 7: *Relative strengths, i.e. strength ratio of actual strengths (S) with 20 °C curing strengths (S_{20}), for mortars with strength of 30 MPa.*

3.3 Determination of "apparent" activation energies

There are a number of functions available to describe the variation of the rate constant *k* with temperature. The Nurse-Saul maturity model (Nurse, 1949; Saul, 1951):

$$M = \sum_{t} (T - T_0) \cdot \Delta t \qquad \textbf{Equation 2}$$

assumes a linear relationship:

$$k_{NS} = a \cdot (T - T_0) \qquad \textbf{Equation 3}$$

where:
- M is the Nurse-Saul maturity (°C·days),
- T is the average temperature (20 °C for standard curing) over the time interval Δt (°C),
- T_0 is the datum temperature (°C),
- Δt is the time interval (days),
- k_{NS} is the rate constant,
- a is a constant (1/°C).

The datum temperature is the temperature below which it is assumed that no strength gain will occur, taken as -11 °C in this work which is the average of what is recommended in the literature, i.e. between -10 °C and -12 °C (Han, 2005; Malhotra, 2006; Gambhir, 2013). The relationship between strength and maturity is assumed to be independent of temperature history, and can therefore be determined at a reference temperature. An equivalent age, t_e, can be defined as the age at the reference temperature at which the concrete has the same strength as at a time *t*:

$$t_e = \frac{\sum (T - T_0)}{(T_r - T_0)} \cdot \Delta t \qquad \textbf{Equation 4}$$

where:
- t_e is the equivalent age at the reference temperature (days),

T_r is the reference temperature (°C).

Equation 4 can be written as follows (Carino, 2004):

$$t_e = \sum \alpha \cdot \Delta t$$ **Equation 5**

and the age conversion factor, *α*, is:

$$\alpha = \frac{T - T_0}{T_r - T_0}$$ **Equation 6**

where:
- t_e is the equivalent age at the reference temperature (days),
- T_r is the reference temperature (°C),
- T is the average temperature (20 °C for standard curing) over the time interval Δt (°C),
- T_0 is the datum temperature (°C),
- α is the age conversion factor.

The ratio *α*, which is called the "age conversion factor", has a simple interpretation: it converts a curing interval *Δt* to the equivalent curing interval at the reference temperature (Carino, 2004).

The assumption that the rate of strength development obeys the Arrhenius equation leads to the maturity function (referred to as Arrhenius function in this paper):

$$t_e = \sum e^{-\frac{E_a}{R}\cdot\left(\frac{1}{T_a} - \frac{1}{T_s}\right)} \cdot \Delta t$$ **Equation 7**

where:
- t_e is the equivalent age (days),
- T_a is the average temperature of concrete during time interval Δt (K),
- T_s is the specified reference temperature (K),

E_a is the "apparent" activation energy (J/mol),

R is the universal gas constant (J/K·mol).

In this case the age conversion factor is:

$$\alpha = e^{-\frac{E_a}{R}\cdot\left(\frac{1}{T_r}-\frac{1}{T}\right)}. \qquad \textbf{Equation 8}$$

In order to calculate the "apparent" activation energy, E_a, the ASTM C1074-11 recommendation (ASTM, 2011) is to plot *ln(k)*, obtained from Equation 1 and shown in Table 3, against $1/T_{abs}$ (given in 1/Kelvin), where T_{abs} is the absolute curing temperature. The negative of the slope of the line, $-Q$, is the "apparent" activation energy, E_a, divided by the universal gas constant, R (equal to 8.31 J/K·mol gas), *i.e.* $-Q = E_a/R$ or $E_a = -Q \cdot R$. The plots of *ln(k)* versus $1/T_{abs}$ are shown in Figure 8 and E_a, obtained are shown in Figure 9. GGBS mixes appear to have higher "apparent" activation energies than PC mixes. FA mixes on the other hand appear to be slightly lower than PC mixes. The effect of temperature on the strength gain rate becomes more apparent when the age conversion factor is plotted against temperature, see Figure 10.

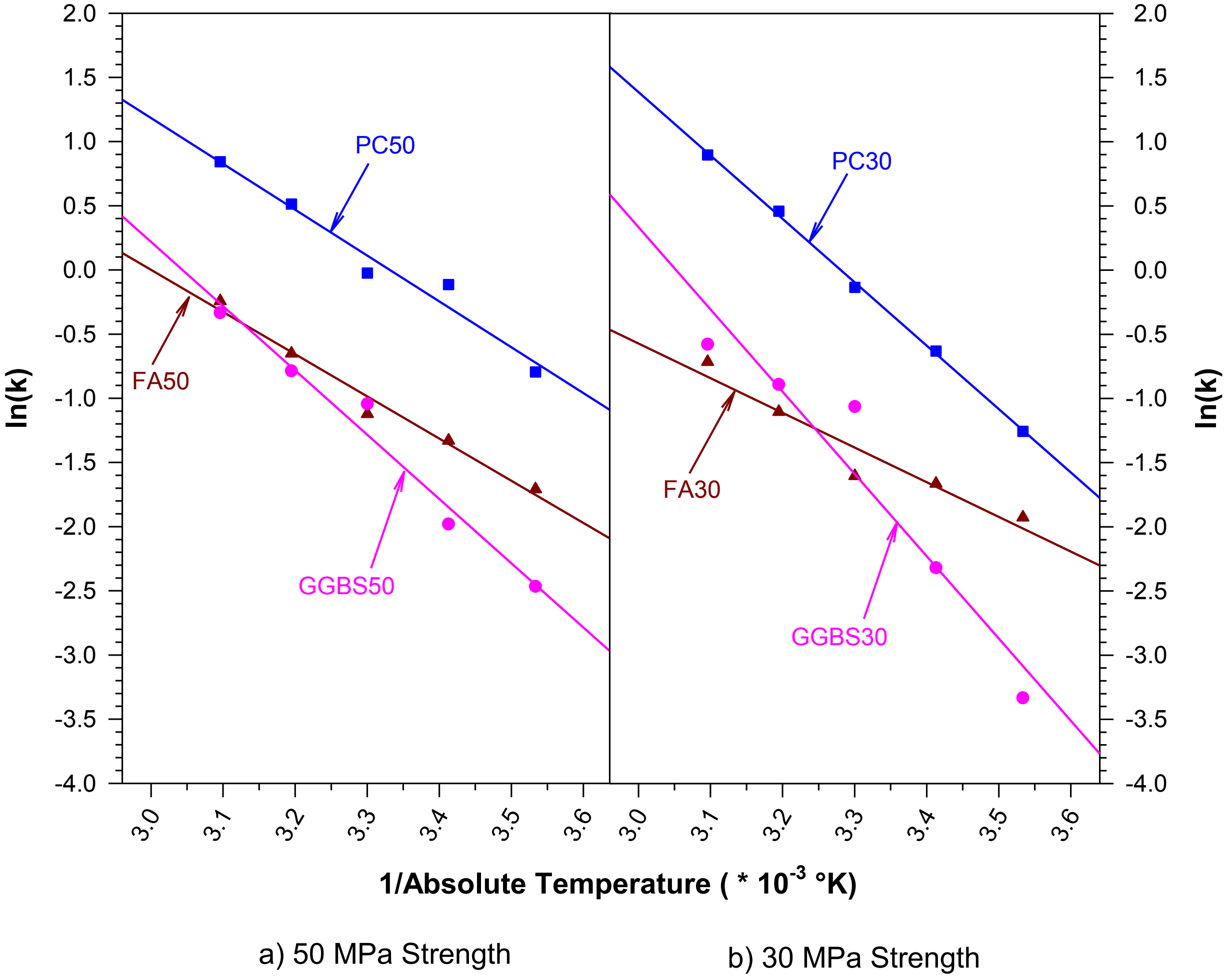

Figure 8: *ln(k) against 1/T_{abs} for mortars.*

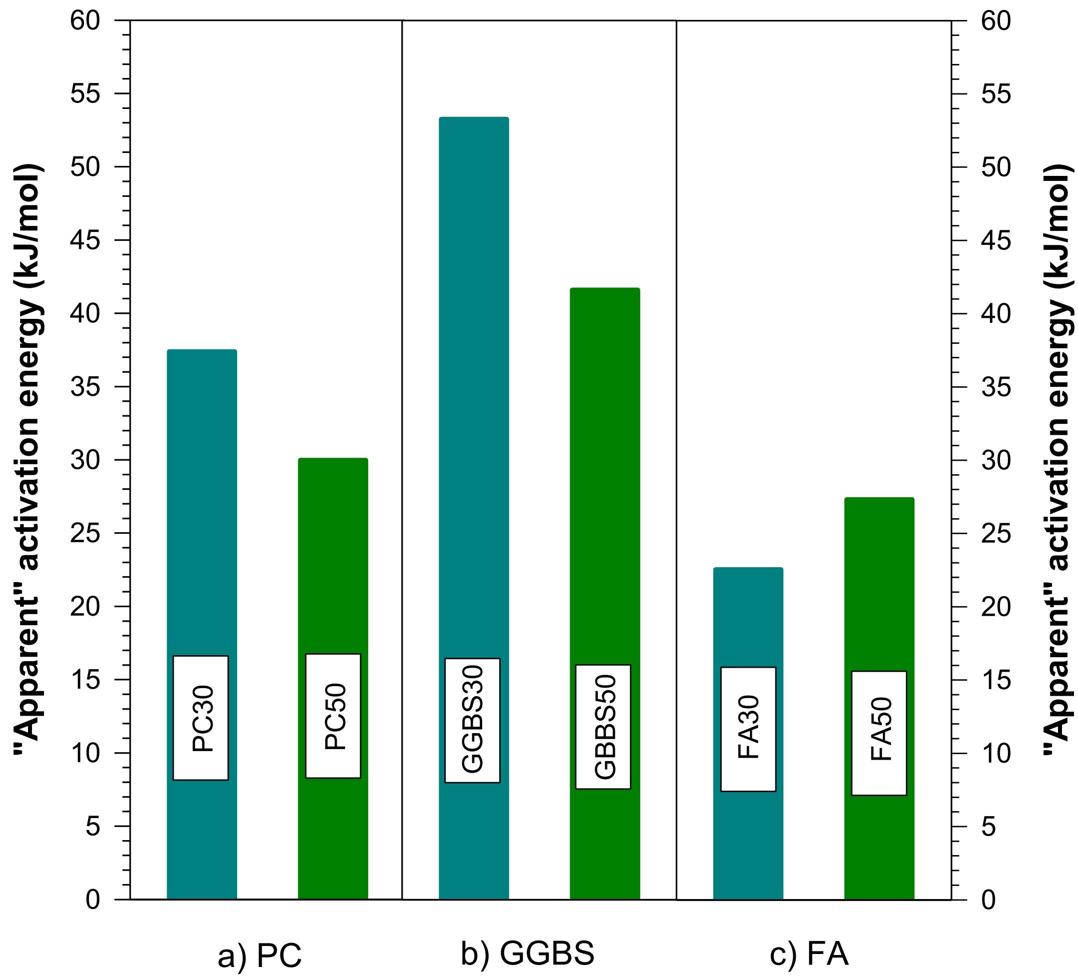

Figure 9: *"Apparent" activation energies for PC, GGBS and FA mortar mixes.*

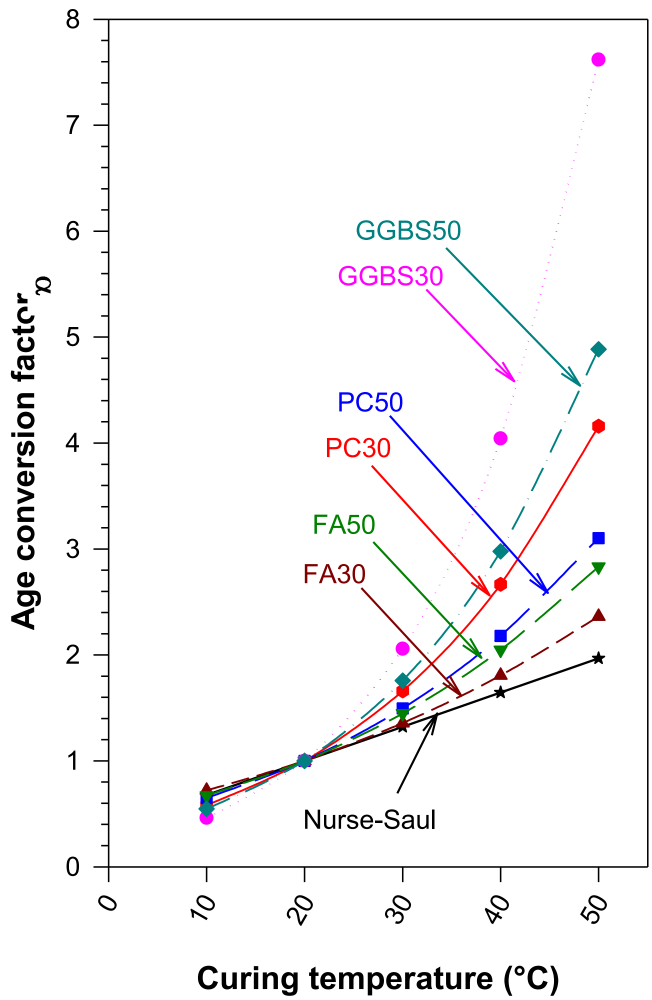

Figure 10: *Effect of curing temperature on age conversion factor.*

The age conversion factors for different curing temperatures were calculated from Equation 6 and the rate constant values shown in Table 3 were used with Equation 8. The reference temperature was taken to be 20 °C. The age conversion factors increase exponentially with temperature. The linear relationship for the variation of *k* with temperature assumed by the Nurse-Saul model is inadequate to describe the temperature sensitivity of particularly GGBS. The deviation from linear relationship of the age conversion factor with temperature is greater for GGBS followed by PC and FA. This indicates that the sensitivity of GGBS to temperature is higher than PC which in turn is higher than FA.

Table 4 shows “apparent” activation energy values found in the literature and these have been plotted in Figure 11. “Apparent” activation energy values for neat Portland cement (CEM I or Type I) seem to be in the range from 30 to 50 kJ/mol, but there are some exceptionally high values above 60 kJ/mol. Partial cement replacement with GGBS seems to increase the “apparent” activation energy as the replacement level increases. There is only a limited number of values for “apparent” activation energies for FA mixes in the literature. The ones obtained from this work appear to indicate that partial cement replacement with FA will decrease the “apparent” activation energy.

Table 4: *"Apparent" activation energies from literature based on compressive tests on concretes/mortars.*

Cement type	GGBS/FA level	w/b	"Apparent" activation energy [kJ/mol]	Source	Year
CEM I	Neat Portland cement [100% PC]	**0.66**	**37.4#**	**Results from current study**	**2016**
Type I		0.6	48.0+ and 43.6#	Carino & Tank (1992)	1992
CEM I		**0.46**	**29.7#**	**Results from current study**	**2016**
CEM I		0.45	39.3#	Hatzitheodorou (2007)	2007
Type I		-	42.0#	Carino (1981)	1981
Type I		-	41.0+ and 44.0#	Carino (1984)	1984
CEM I		0.6	34.8#	Barnett *et al*. (2006)	2006
CEM I		0.4	35.1#	Barnett *et al*. (2006)	2006
CEM I		0.26	32.9#	Barnett *et al*. (2006)	2006
CEM I		0.51	36.2#	Turru'allo (2013)	2013
CEM I		0.33	28.9#	Turru'allo (2013)	2013
Type I		0.45	61.1# and 63.6+	Carino & Tank (1992)	1992
Type I	20% FA	0.45	33.1# and 30.0+	Carino & Tank (1992)	1992
Type I		0.6	36.6# and 31.2+	Carino & Tank (1992)	1992
CEM I	30% FA	**0.35**	**27.3#**	**Results from current study**	**2016**
CEM I		**0.53**	**22.5#**	**Results from current study**	**2016**
CEM I	20% GGBS	0.25	36.8#	Barnett *et al*. (2006)	2006
CEM I		0.32	43.5#	Turru'allo (2013)	2013
CEM I		0.39	35.2#	Barnett *et al*. (2006)	2006
CEM I		0.48	39.4#	Turru'allo (2013)	2013
CEM I		0.62	36.6#	Barnett *et al*. (2006)	2006
CEM I	35% GGBS	0.25	46.8#	Barnett *et al*. (2006)	2006
CEM I		0.33	44.0#	Turru'allo (2013)	2013
CEM I		0.36	47.0#	Barnett *et al*. (2006)	2006
CEM I		0.47	42.3#	Turru'allo (2013)	2013
CEM I		0.58	47.1#	Barnett *et al*. (2006)	2006
CEM I	50% GGBS	0.25	52.6#	Barnett *et al*. (2006)	2006
CEM I		0.32	53.9#	Turru'allo (2013)	2013
CEM I		0.38	48.0#	Barnett *et al*. (2006)	2006
CEM I		0.44	44.1#	Turru'allo (2013)	2013
Type I		0.45	42.7# and 44.5+	Carino & Tank (1992)	1992
CEM I		**0.46**	**41.6#**	**Results from current study**	**2016**
Type I		0.6	51.3# and 56.0+	Carino & Tank (1992)	1992
CEM I		0.61	54.6#	Barnett *et al*. (2006)	2006
CEM I		**0.65**	**53.3#**	**Results from current study**	**2016**
CEM I	70% GGBS	0.25	57.9#	Barnett *et al*. (2006)	2006
CEM I		0.30	54.7#	Turru'allo (2013)	2013
CEM I		0.39	62.1#	Barnett *et al*. (2006)	2006
CEM I		0.44	48.2#	Turru'allo (2013)	2013
CEM I		0.52	58.8#	Barnett *et al*. (2006)	2006

+ – concrete, # – mortar

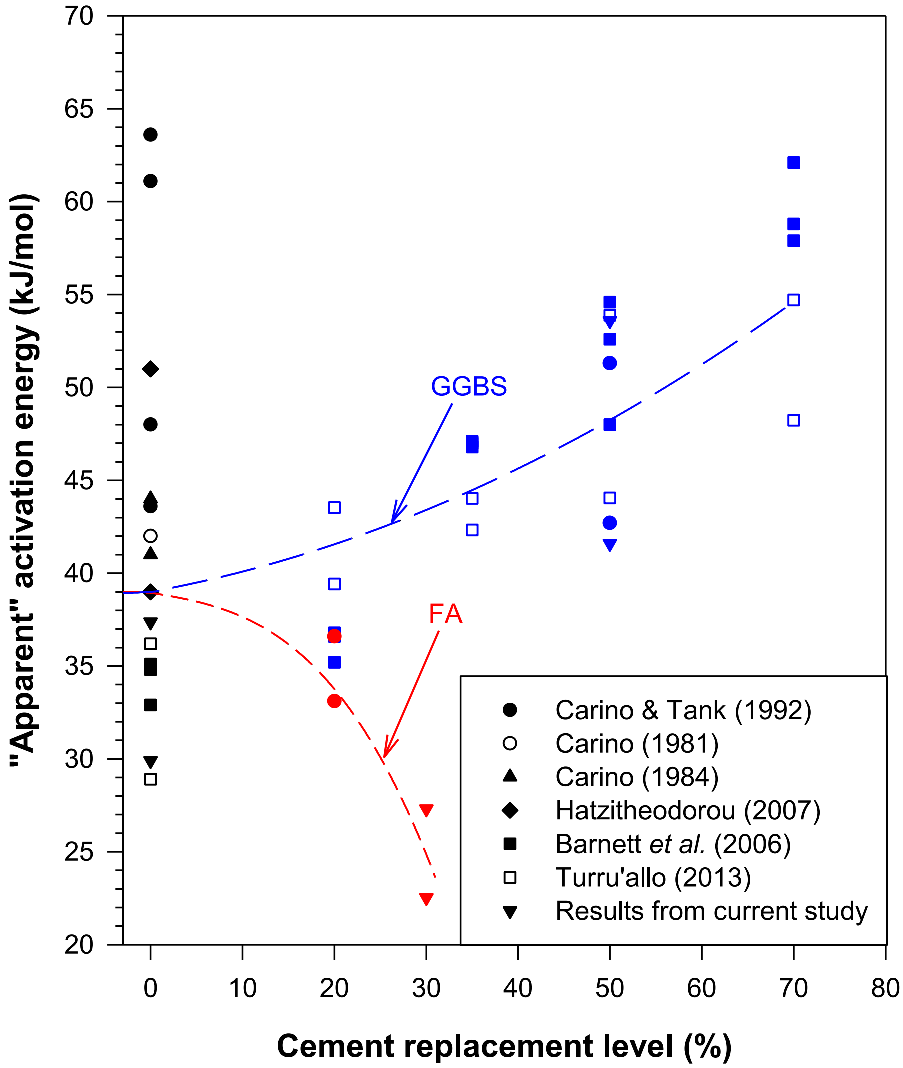

Figure 11: *"Apparent" activation energies obtained from literature and current study.*

3.4 Applicability/accuracy of maturity functions for estimating the effect of elevated curing temperature on the strength development

Several maturity functions exist in the literature (Saul, 1951; Parsons and Naik, 1985; Kjellsen and Detwiler, 1993; Babu and Rao, 1994; Chanvillard and D'Aloia, 1997; Adbel-Jawad, 2006; Liao *et al.*, 2008; Galobardes *et. al.*, 2015), which estimate the strength development of concrete under elevated and variable temperature conditions from its temperature history. These models use the experimentally determined strength-age relationship at a reference temperature (usually at 20 °C) to estimate the strength at any other temperature. These models, however, were developed for Portland cement concrete. The temperature sensitivity GGBS and FA has been shown to be different from that of Portland cement (Soutsos *et al.*, 2016; Soutsos *et al.*, 2009; Boubekeur *et al.*, 2014; Soutsos *et al.*, 2013). It is therefore necessary to examine the applicability/accuracy of these maturity functions for concretes with GGBS and FA.

The Nurse-Saul function requires the temperature history, in this case the curing temperature, of the concrete in order to calculate the maturity index according to Equation 2. The equivalent age t_e at time t was calculated using Equation 4. The value of equivalent age obtained, t_e, was then substituted for t in Equation 1 with constants S_u, k and t_0, as previously determined for the strength data obtained for the mortar cured at 20 °C (see Table 3) and the estimated strength was thus obtained.

The Arrhenius function required the “apparent” activation energies which are shown in Figure 9. The equivalent age t_e at time t was calculated using Equation 7. The specified reference temperature, T_s, used was 293 °K (20 °C). T_a being the average temperature, in Kelvin, of mortar during time interval Δt was none other than the curing temperature. The value of equivalent age obtained, t_e, was then substituted for t in Equation 1 with constants S_u, k and t_0, as previously determined for the strength data obtained for the mortar cured at 20 °C (see Table 3). The estimated strength was thus obtained.

The Nurse-Saul function estimated the early age strengths of PC and FA mortars, even at the high curing temperature of 50 °C, much better than for GGBS, see Figure 12. However, it overestimated strengths beyond two days for PC and this increased with increasing age. This appears to be due to the inability of this function to account for the detrimental effect high early age temperatures have on later age strength. The estimates for the strength of FA mortars continue to be relatively accurate for longer ages as the “cross-over” effect (first reported by McIntosh (McIntosh, 1956)) is not as pronounced as for PC mortars and it does occur much later. The Nurse-Saul function underestimated the strength development of GGBS mortars even at early ages. This is because the Nurse-Saul function assumes that the concrete or mortar strength gain rate varies linearly with temperature irrespective of whether GGBS or FA is used or not. GGBS has been shown, see Figure 10, to be more temperature sensitive than PC and FA. This is also indicated by its higher "apparent" activation energy as compared to PC and FA – see Figure 9. The cross-over effect affects later age predictions, but these are much later than for PC mortars.

The strength estimates from the Arrhenius function, see Figure 13, appear to be affected very early-on by the cross-over effect of PC mortars. This is more than the Nurse-Saul function and this is because the Arrhenius function considers that the strength gain rate varies exponentially with temperature, as shown in Figure 10. If the strength estimates of the Arrhenius function are correct then the detrimental effect of high curing temperature starts from early age and is simply more pronounced in long term. The strength estimates are more accurate for FA mortars since the cross-over effect occurs at much later ages. The strength estimates for GGBS mortars are more accurate than those of the Nurse-Saul function because of the use of the "apparent" activation energies which account for the higher temperature sensitivity of GGBS than PC and FA.

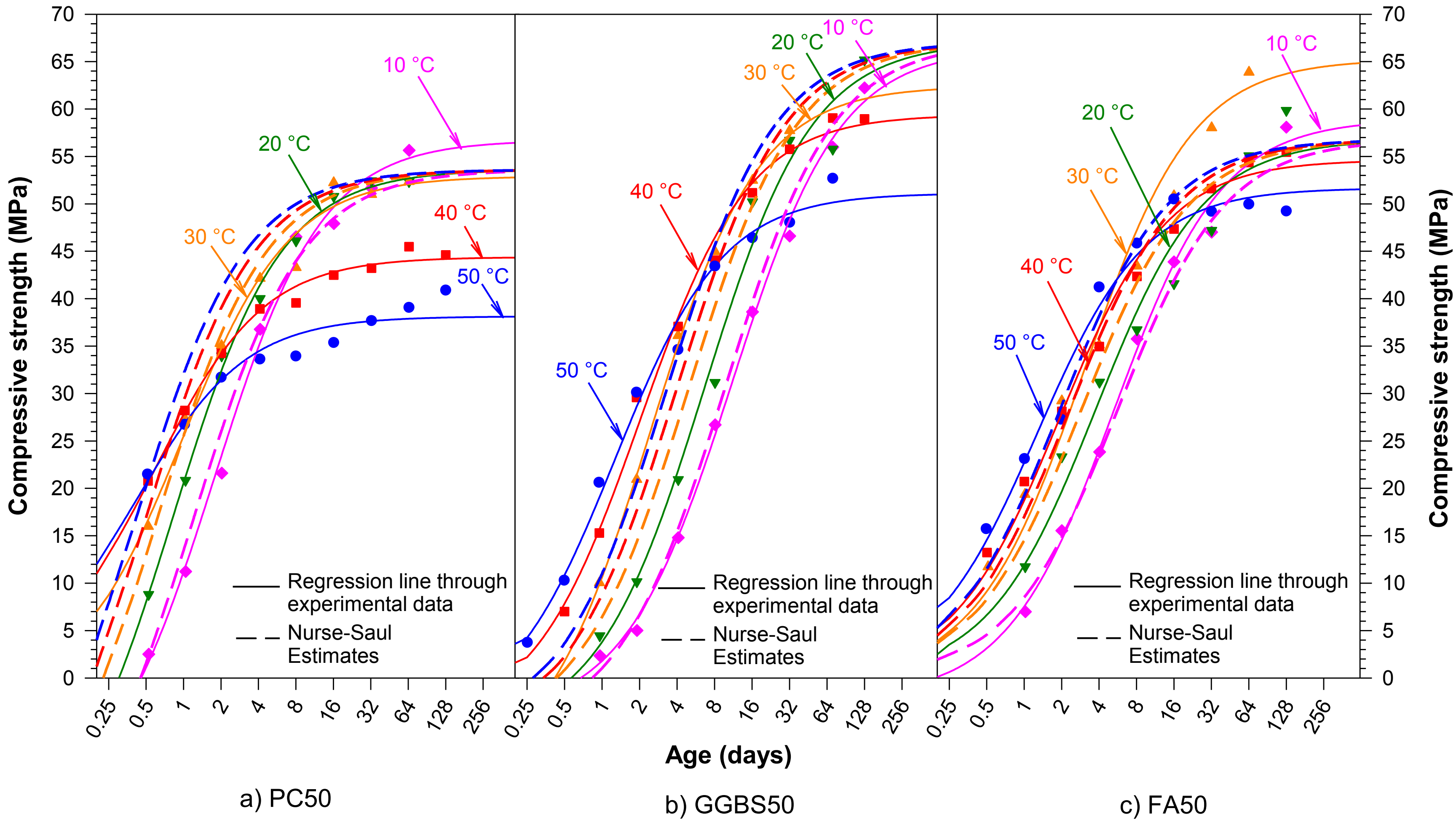

Figure 12: *Nurse-Saul compressive strength estimates for 50 MPa compressive strength mortars.*

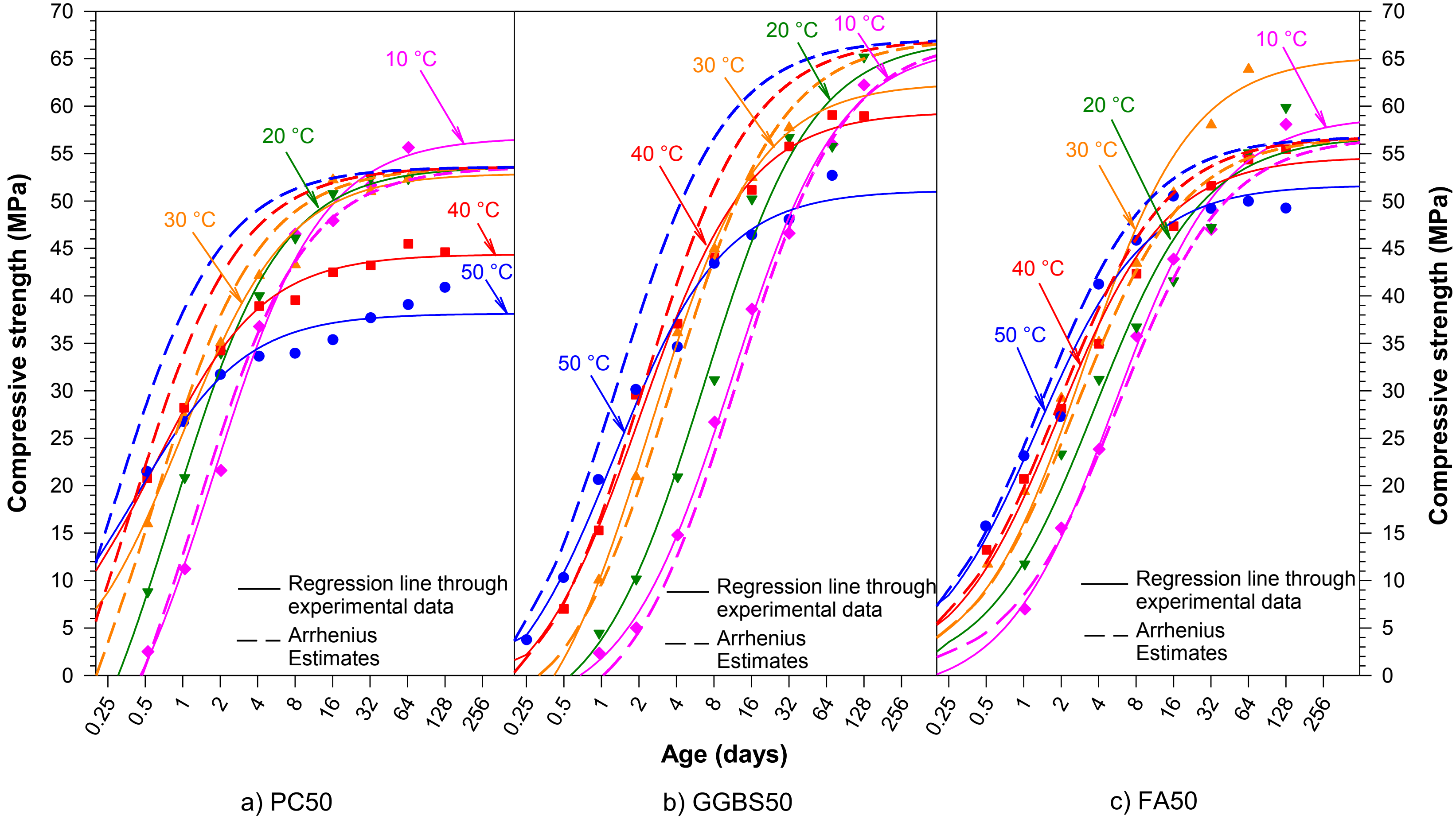

Figure 13: *Arrhenius compressive strength estimates for 50 MPa compressive strength mortars.*

The ratios of estimates to actual strength are shown in Figures 14 and 15. These confirm that the Nurse-Saul function underestimates the effect of high early age curing temperatures on the early age strength and this is most noticeable for the GGBS mixes. Strengths are overestimated at later ages because the Nurse-Saul function does not account for the long-term detrimental effect of high early age curing temperatures. The Arrhenius function on the other hand, overestimates even early age strength especially at the higher curing temperatures. This may be due to the detrimental effect starting from very early age at particularly the high curing temperatures. The Arrhenius function, similarly to the Nurse-Saul function, overestimates strengths at later ages.

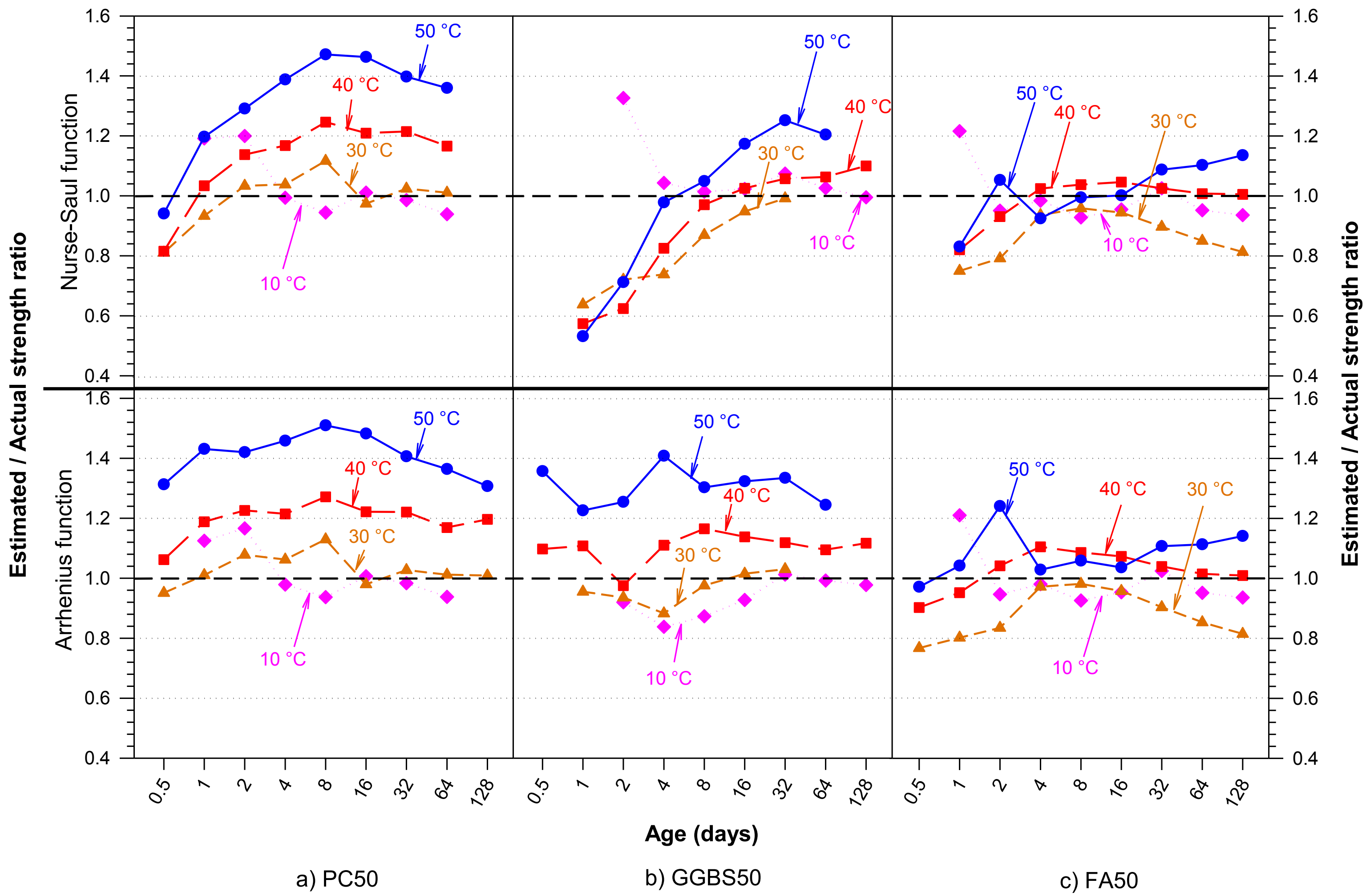

Figure 14: *Estimated and actual strength ratios for 50 MPa mortars based on the Nurse-Saul and Arrhenius functions.*

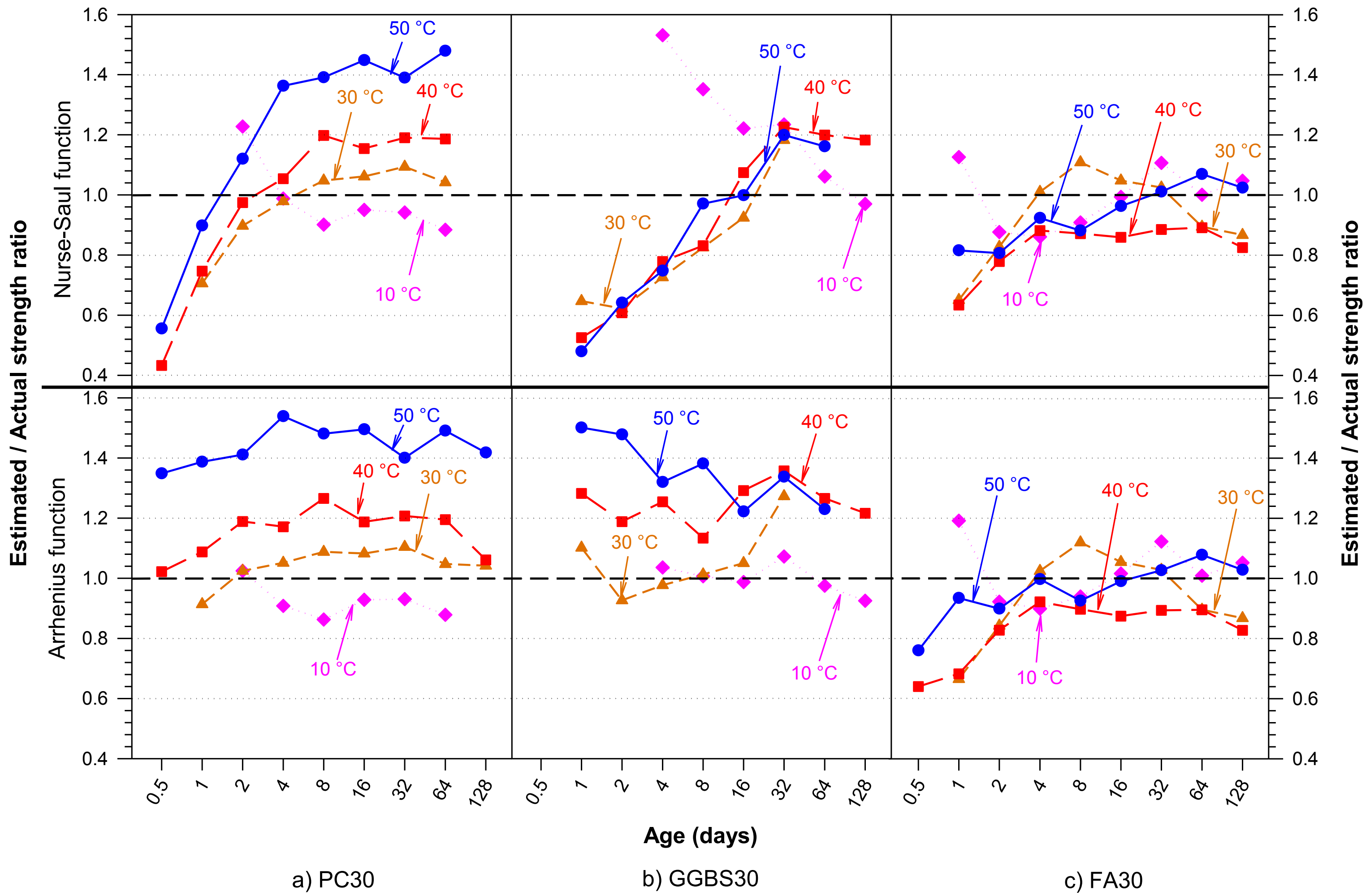

Figure 15: *Estimated and actual strength ratios for 30 MPa mortars based on the Nurse-Saul and Arrhenius functions.*

4 Conclusions

The effect of temperature on the strength development of mixes with GGBS and FA has been investigated. The conclusions are:

- Strength development of “equivalent” mortars appears to be similar but not exactly the same as for the corresponding concretes. Nonetheless they can be used for determining the “apparent” activation energies for concrete mixes.
- High curing temperatures have a beneficial effect on the early age strength but a detrimental effect on the long term strength development. This confirmed previously reported findings.
- GGBS has been shown to be more sensitive to curing at high temperatures than PC and FA and this is reflected in its higher “apparent” activation energy.
- The Nurse-Saul function underestimates the early age strength development at higher curing temperatures whilst the Arrhenius function overestimates them. The reason for the latter appears to be the detrimental effect starting from a very early age. Both functions overestimate long term strengths as neither accounts for the detrimental effect of high curing temperatures on the ultimate compressive strength.

Work is continuing aiming to determine modification to the maturity functions in order to improve estimates of both early age and long term strength development with and without GGBS and FA.

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