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Research Article

The Application of Equivalent Age Concept to Sand Concrete Compared to Ordinary Concrete

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In this research the equivalent age concept was used, in order to simulate strength development of heat treated sand concrete compared with ordinary concrete at different temperature, 35, 55, and 70°C, and validate the simulation results with our experimental results. Sand concrete is a concrete with a lower or without coarse aggregate dosage; it is used to realize thin element as small precast prestressed beams, in injected concrete or in regions where sand is in extra quantity and the coarse aggregate in penury. This concrete is composed by principally sand, filler, superplasticizer, water, and cement. The results show that the simulation of ordinary concrete was acceptable with an error lower than 20%. But the error was considerable for the sand concrete. The error was due to large superplasticizer dosage, which modified the hardening of sand concrete; the most influent parameter in Arrhenius law is apparent energy activation, to search for the value of the activation energy which gives the best simulation; a superposition is used of two curves of different temperature and with superplasticizer dosage 4% and several values of activation energy, 15, 20, 25, and 30 × 10 kcal. The simulation becomes ameliorated with the adequate value of activation energy.

1. Introduction

It is known that there is a relationship between temperature and characteristics of concrete, that is why many researchers had studied strength development of concrete based on temperature history and then comes the maturity term [1] in the field of concrete industry. It has been shown that the development of cement hydration reactions as a function of time, expressed in produced heat quantity and for isothermal curing temperatures (of 20, 60, and 80°C), has refined curves [2], which confirm that heat emission phase has independent variables system behavior (temperature and time) [2].

On the basis of these results, in the short term, and assuming isothermal conditions, the curves of compressive strength development (f_c) are also refined curves. Then, to move from one curve to another just multiply the time by a constant; consequently

$$F_c(\theta_1, t_1) = f_c(\theta_2, t_2),$$
$$t_2 = K \cdot t_1,$$
$$F_c(\theta_1, t_1) = f_c(\theta_2, K \cdot t_1), \tag{1}$$

where θ_1 and θ_2 are isothermal temperature of curing, K is relative constant, and t_1 and t_2 are time.

If the strength development of concrete can be considered as independent variables system (time/temperature), maturity of concrete in real age (t) exposed to a temperature history $\theta(t)$ can be expressed by an equivalent age (t_e) determined at fixed reference temperature (θ_r):

$$F_c(\theta_r, t_r) = K(\theta(t), t). \tag{2}$$

Several functions have been proposed to express maturity of concrete; the most used function is Arrhenius law, which reflects thermal activation of chemical reactions of cement hydration as follows:

$$K = A \cdot \exp\left(-\frac{E}{R} \cdot T\right), \tag{3}$$

where K is constant for each state of reactions, A is equivalent age, R is constant of perfect gases, T is absolute temperature, and E is energy of activation.

And for state of reactions progress with two different temperatures T_1 and T_2,

$$\frac{K_1}{K_2} = \exp\left[\frac{E}{R}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right]. \quad (4)$$

If the curve of hydration degree development in isothermal conditions at 20°C (293 K) is known, the curve of hydration degree development may be calculated for any temperature using K_1/K_2 ratio in (4). And according to previous research [2], the relationship that links the relative strength (f_{cj}/f_{c28}: compressive strength at j day/compressive strength at 28 day) and the degree of hydration is the same for any temperature, where you can get the curve of strength development for any temperature.

Next, the problem is to calculate the equivalent age, which is the time required to cure at 20°C to produce the same strength (relation (5)); in this case, the curve of strength development function to equivalent age is independent of the temperature; then

$$t_e = \int_0^h \frac{K_1}{K_2} dt, \quad (5)$$

$$t_e = \int_0^h \exp\left[\frac{E}{R} \cdot \left(\frac{1}{293} - \frac{1}{(273+Q)}\right)\right] dt, \quad (6)$$

where Q is temperature [°C].

Therefore, equivalent age concept makes the estimation of strength development of concrete for any temperature history possible, if strength development at 20°C is known. In this research, equivalent age concept was applied to calculate the strength development of sand concrete compared to ordinary concrete, with different curing temperature, 35, 55, and 70°C.

Sand concrete is considered as fine concrete, micro concrete, or special concrete, with a granular distribution different from normal concrete [3], and they often consist of a large amount of sand (river, sea, crushed, or dune sand), fine additions, admixtures (superplasticizer) and cement, and if necessary small amount of gravel. Sand concrete is used in case of penury of coarse aggregate or, when sand is in extra quantity.

2. Materials and Methods

2.1. Materials and Concrete Mixtures. In this paper, sand concrete was made from crushed limestone sand (often not used in reinforced concrete, due to the high proportion of fine particles), small amount of coarse aggregate (coarse aggregate to sand ratio less than 0.7), and superplasticizer (SFR® GRANITEX). Ordinary concrete was made from sea sand and coarse aggregate. In both types of concrete, used cement was CEM-II A 42.5.

Grading of used sands and coarse aggregate are summarized in Table 1.

Table 1: Grading of used sands and aggregate.

Sieves (mm)	Crushed sand (%)	Sea sand (%)	Coarse aggregate (%)
0.08	8.5	0.20	
0.125	13.33	0.60	
0.25	15.53	15.90	
0.5	28.80	94.80	
1	52.60	99.40	
1.6	75.40	99.80	
2	84.00		13.36
3.15	98.53		26.86
4	99.13		45.63
5			72.83
6.3			86.60
8			99.86

Figure 1: Photo of specimens inside the oven and thermocouples.

Mixes of sand concrete and ordinary concrete are summarized in Table 2. Appropriate methods for mixes formulation were used for each type of concrete [2, 3], concrete was prepared, poured, cured, and conserved and its characteristics were measured according to NFP18-403 (concrete properties determination for scientific research) [4]. Concretes of both mixes give plastic concrete, with values of flow test between 50 and 90%, with water/cement ratio of about 0.5 and 25 MPa minimum compressive strength at 28 days.

Cubic metallic molds 7 × 7 × 7 cm^3 were used to investigate strength development of both concretes. In the day of the test, 24 specimens (7 × 7 × 7 cm^3) were prepared per mix (according to Table 2) and heat treated in the oven (Figure 1); to draw strength development curve at least three specimens were tested per point, three or four points at early age before one day (which depend on temperature of treatment), and two points at 7 and 28 days age. Specimens were covered by plastic sheet (in order to prevent excessive water evaporation). Before heat treatment, concrete must be pretreated at ambient temperature in one and half hours (to avoid thermal shock), an oven and thermocouple has been used for heat treatment and monitoring temperature of concrete, as shown in Figure 1. In the end time of heat treatment, the oven was switched off, and the specimens lived inside, in order to have slow cooling to avoid thermal shock,

Table 2: Mixes of sand and ordinary concrete.

Type of concrete	Components (kg/m^3)						
	Coarse aggregate	Crushed sand	Sea sand	Addition	Cement	Superplasticizer (% of C)	Water
Sand concrete	377	1000	—	128	400	4%	220
Ordinary concrete	1032	—	1000	—	400	—	232

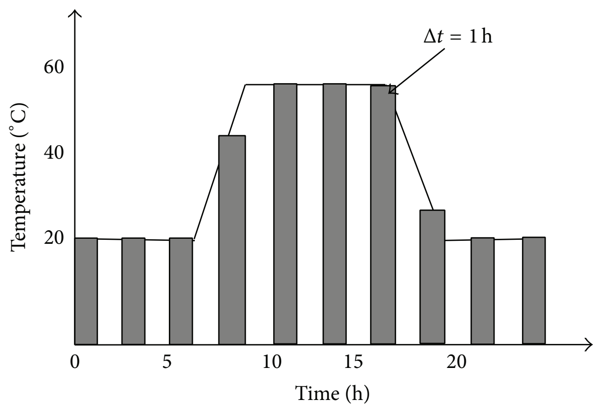

Figure 2: History of the temperature.

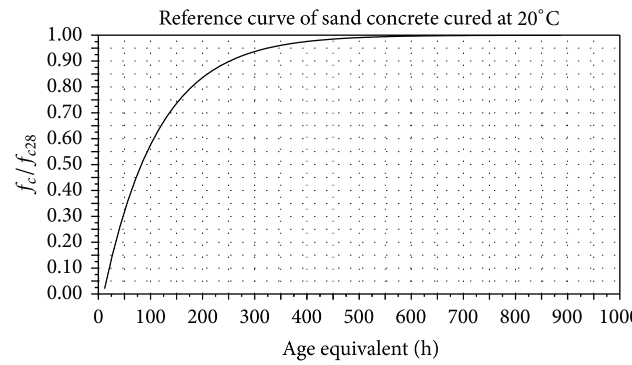

Figure 3: Reference curve of sand concrete.

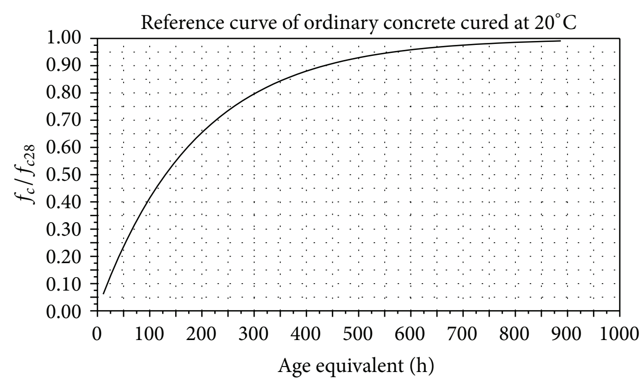

Figure 4: Reference curve of ordinary concrete.

which reduces the mechanical properties of the concrete in the long term, finally specimens were kept in a pool of water at 25°C after the end of heat treatment.

3. Numerical Simulation

The simulation of compressive strength development of heat treated concrete was programmed using MS Excel software, using CERIB model [5], which requires the following steps.

3.1. Equivalent Ages Calculation. To calculate equivalent age the following steps are necessary.

(1) Division of Real Age of Concrete. Division of real age of concrete at time intervals of one hour ($\Delta t = 1$ h) is shown in Figure 2.

(2) Division of K Values. Using CERIB model [5] and depending on the temperature and strength of the used cement as follows:

$$K = \mathrm{EXP}\left(\left(10300 - 1800 * LN\left(f_{c2\,\mathrm{d}}\right)\right) * \left(\frac{1}{293} - \frac{1}{(273+Q)}\right)\right), \tag{7}$$

where $f_{c2\,\mathrm{d}}$ is concrete strength (MPa) at 2 days. Q is concrete temperature (°C).

(3) Calculation of Equivalent Age. Calculation of equivalent age uses the following:

$$A_e = \Delta K_i * \Delta t. \tag{8}$$

3.2. Reference Curve. Basing on laboratory test, the reference curve is constructed which describes the strength development of the concrete at 20°C.

3.3. Strength Calculation. The relative strength is calculated by the projection of the equivalent age in the reference curve. For this, the followed functions are used (which are affinity of curves in Figures 3 and 4).

(1) Ordinary Concrete. Consider

$$\frac{F_c}{f_{c28\,\mathrm{d}}} = 1 - 0.99518 * e1\left(-\frac{A_e}{189.00374}\right), \quad \mathrm{Chi}^2 = 0.0053. \tag{9}$$

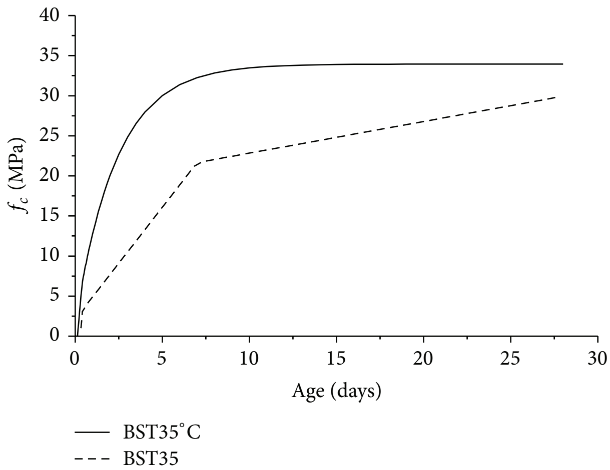

FIGURE 5: Simulated and experimental strength development curves of heat treated sand concrete at 35°C.

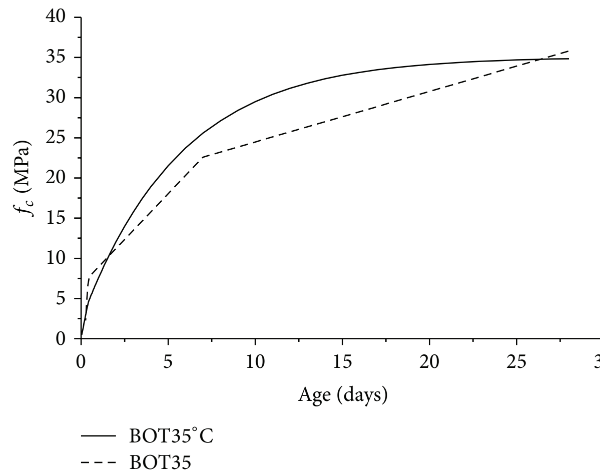

FIGURE 6: Simulated and experimental strength development curves of heat treated ordinary concrete at 35°C.

(2) Sand Concrete. Consider

$$\frac{F_c}{f_{c28\,\mathrm{d}}} = 1 - 1.09828e1\left(-\frac{A_e}{105.025}\right),$$
$$\mathrm{Chi}^2 = 0.0014. \tag{10}$$

Finally, concrete strength equals the multiplication of the relative strength by the concrete strength at 28 days.

4. Discussion

4.1. Ordinary Concrete. Several researchers have confirmed the applicability of the Arrhenius law for the simulation of strength concrete development, with acceptable results for different temperatures and an average error less than 20% [6], 7% [7], and 27% [8], as confirmed in this study (Table 3, Figures 6, 8, and 10) for ordinary concrete, especially in the short and long term; there is a slight difference in the medium term, which may be due to the projection of the equivalent age on the curve reference, by using a negative exponential function (which is beyond the scope of the simulation).

4.2. Sand Concrete. Contrary to ordinary concrete simulation results, as shown in Figures 5, 7, and 9 and Table 3, sand concrete results are not at the same precision; the error between simulation and experiment results is over 100% (Table 3). This significant error is probably due to the high dosage of superplasticizer (which act as retarder) and/or lime stone addition [9]; both components affect the hydration heat; therefore the development of strength [10], previous researches [11, 12], and modeling by the concept of equivalent age, in the case of special concrete (HPC) superplasticizer and SCMs, have modified the modelisation by changing the value of apparent energy of activation in order to minimize error of the simulation. In this study also, it is necessary to adjust the simulation for sand concrete.

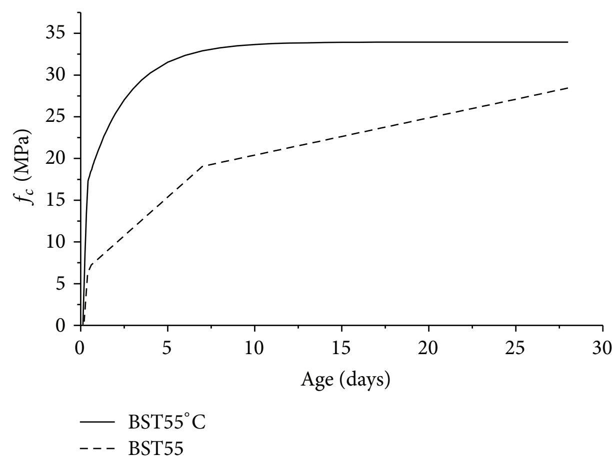

FIGURE 7: Simulated and experimental strength development curves of heat treated sand concrete at 55°C.

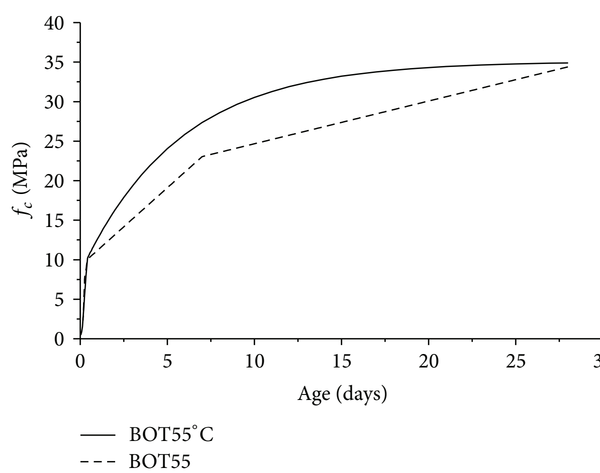

FIGURE 8: Simulated and experimental strength development curves of heat treated ordinary concrete at 55°C.

Table 3: Relative error of strength simulation of sand concrete and ordinary concrete.

Ordinary concrete in 35°C (BOT35)	Sand concrete in 35°C (BST35)	Ordinary concrete in 55°C (BOT55)	Sand concrete in 55°C (BST55)	Ordinary concrete in 70°C (BOT70)	Sand concrete in 70°C (BST70)	Concrete type, temperature of treatment code in figures
20.74	238.38	11.42	108.53	25.43	203.04	Relative error (%)

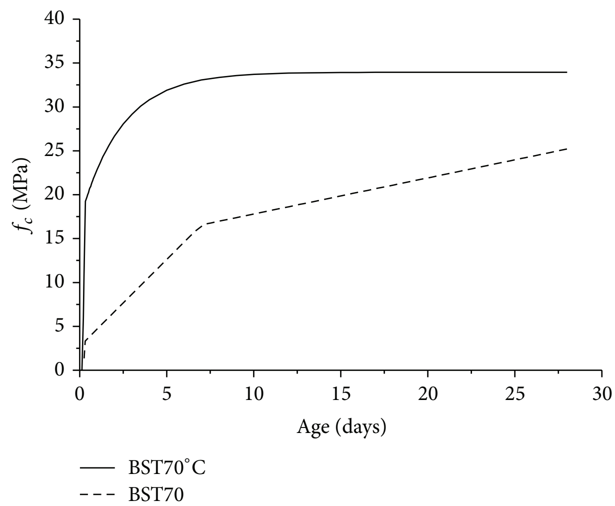

Figure 9: Simulated and experimental strength development curves of heat treated sand concrete at 70°C.

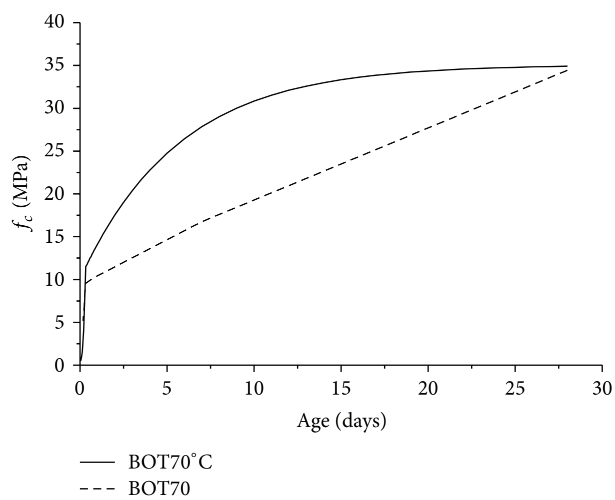

Figure 10: Simulated and experimental strength development curves of heat treated ordinary concrete at 70°C.

4.3. Adjustment of the Simulation for Strength Development of Sand Concrete. As noted above, the error was significant on the simulation of the strength development of the sand concrete using equivalent age concept; this is due to the superplasticizer and mineral addition that change the hardening of the concrete, which is not reflected in the coefficient K calculated by the formula (5) and based only on the cement strength at two days ($f_{c2\,\mathrm{d}}$). The value of apparent activation energy in this model was on the basis of ordinary concrete, without chemical or mineral admixtures.

Table 4: Relative error of simulation of strength development of heat treated (at different temperature) sand concrete using several values of apparent energy of activation.

E_a (10^4 cal)	BST35	BST55	BST70	Average
	Relative error: $E = (f_c.\exp/f_c.\mathrm{cal}) * 100$			
12	33.77	48.34	51.92	44.67
16	22.50	42.75	44.63	37.62
25	33.09	28.04	53.86	38.33
30	45.11	21.85	69.77	45.57
35	61.44	33.61	90.18	61.74

In the simulation the K value was calculated function of cement strength at 2 days and temperature history (equation (7)), which is a modification of Arrhenius law without using the value of apparent activation energy; this is true for ordinary concrete. In the adjustment of the simulation for the case of sand, the value of K was recalculated using initial Arrhenius law (equation (3)).

4.4. Calculation of Equivalent Age. Consider the following:

(i) division of the real concrete age by intervals of one hour (Figure 1),

(ii) calculation of the coefficient K, depending on the history of temperature and apparent activation energy, according to the Arrhenius law, as follows:

$$K(\theta) = \mathrm{EXP}\frac{E_a}{R} * \left(\frac{1}{293} - \frac{1}{(273+Q)}\right), \tag{11}$$

where E_a is apparent activation energy (J·mol^{-1}). R is constant of perfect gases, equal to 8.314 (J·mol^{-1}·K^{-1}). Q is concrete temperature in (°C).

Different values of apparent activation energy were used (12×10^4, 16×10^4, 25×10^4, 30×10^4, and 35×10^4 cal). For the next steps, they are unchanged.

Figures 11, 12, and 13 and Table 4 show that simulation of compressive strength development is ameliorated compared with the first simulation, with the adjustment of the simulation relatives errors being reduced to near 20%, when the apparent energy of activation was equal to $16{\cdot}10^4$ cal and $30{\cdot}10^4$ cal at heat treatment temperature, respectively, 35 and 55°C.

A paper [13] using maturity method to estimate concrete strength including admixtures (specially superplasticizers) and SCMs (Fly ash, blast furnace, pozzolan, . . .) has proposed constant values of energy of activation to adjust the model.

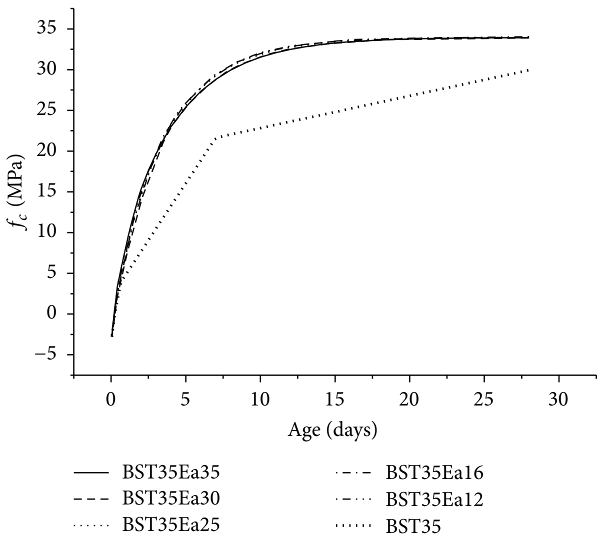

Figure 11: Simulation development of compressive strength with variation of energy of activation and experimental curves of sand concrete heat treated at 35°C.

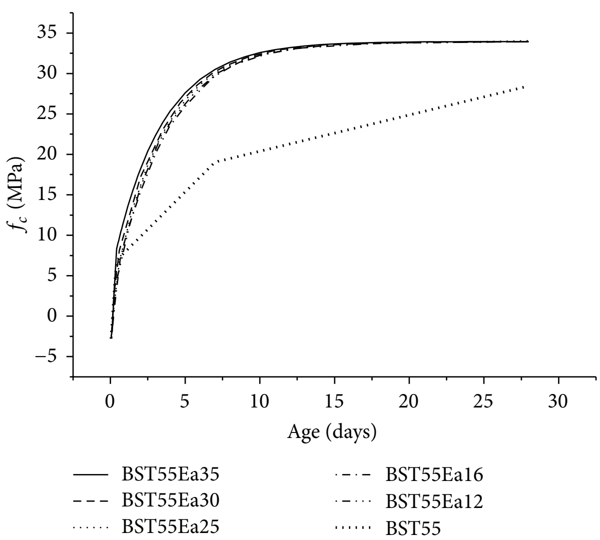

Figure 12: Simulation development of compressive strength with variation of energy of activation and experimental curves of sand concrete heat treated at 55°C.

Other authors [14] find that the apparent activation energies were determined according to ASTM C1074, which were found to vary approximately linearly. Other authors [15] have proposed a model, with the apparent activation energy as a nonlinear function of temperature and age. Further studies are necessity to clear the conflict.

5. Conclusion

The concept of equivalent age using the Arrhenius law gives acceptable results for ordinary concrete, where the error is about 20%, but requires model modification in the case of sand concrete where the error was very considerable, caused particularly by using a high dosage of superplasticizer and

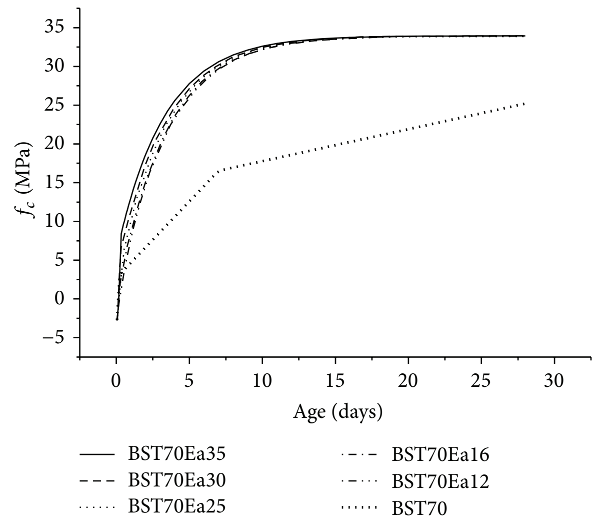

Figure 13: Simulation development of compressive strength with variation of energy of activation and experimental curves of sand concrete heat treated at 70°C.

lime addition, which modify the concrete characteristics. The simulation was repeated with several values of the activation energy; the values of the activation energy which give the best results are between 16 and $25 \cdot 10^4$ cal. In the estimation of the values of activation energy of concrete using admixtures and/or SCMs, authors are in conflict, some find it constant, while others find it to vary linearly and others nonlinearly. Further investigation researches are necessary to clear this point.

Competing Interests

The authors declare that they have no competing interests.

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