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Influence of environmental temperatures on the concrete compressive strength: Simulation of hot and cold weather conditions☆

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Abstract

The objective of this work is to study the influence of mixing hour on the properties of concrete, such as workability and compressive strength, under hot and cold weather conditions, with a view to industrial application. The variable focused on was the concrete mixing hour, and five different mixing hours were used for each type of weather condition. Three batches of concrete were prepared for each mixing hour, and the compressive strength of 15 cylindrical concrete specimens was measured after 7 and 28 days. In addition, the hydration kinetics of each batch of concrete was studied on the basis of the climatic conditions and the mixing hour. The results for compressive strength show that the concrete's best mechanical performance occurred when there was the least difference between ambient temperature and concrete temperature, that is, during the later hours of the day in hot weather conditions.

Keywords: Concrete (*E*); Compressive strength (*C*); Hot weather; Cold weather; Mixing hour

1. Introduction

The manufacture of concrete with Portland cement in adverse weather conditions involving high and low temperatures directly influences the performance of the concrete during mixing, transport, casting and curing, and its physical and mechanical properties. This is of concern to both concrete manufacturers and final users, as it affects a range of technical and economic aspects.

A high ambient temperature causes a higher water demand of the concrete and increases the temperature of the fresh concrete. This, results in an increased rate of loss of slump and in a more rapid hydration, which leads to accelerated setting and to a lower long-term strength of concrete [1]. Besides, an increased rate of evaporation from fresh concrete results in a lower effective water content and hence lower effective water–cement ratio per weight. Moreover, concrete workability is reduced. This implies either an addition of water in order to restore the workability or an insufficient compacting [2]. Likewise in hot climates, there is a tendency for plastic cracking and crazing. As a result, a high temperature can adversely affect the mechanical properties and serviceability of hardened concrete [3].

On the other hand, the chemical processes associated to the hardening of concrete in the first days after casting are accompanied by significant temperature changes, since cement hydration is a highly exothermic and thermally activated reaction [4]. The temperature variation caused by the heat of hydration or the change of external environment has a large influence on the mechanical properties of early-age concrete. Therefore, effects of temperature and aging on the mechanical properties must be studied and quantified [5].

The ultimate aim of the research initiated on this topic at UPC was "the optimization of the cement dosage in ready-mix concrete in adverse weather conditions, through the study of some properties of concrete manufactured at different temperatures". This paper presents the first stage of that research. Complementary research has been carried

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out on the microstructure of pastes and mortars in hot and cold weather conditions; the absorption rate of aggregates at different temperatures; the effect of temperature and admixture dosage on the properties of fresh cement paste; and the thermal properties of aggregates. In general, this project focuses on developing and defining industrial applications of ready-mix concrete.

2. Experimental program

Laboratory testing of concrete is usually performed at a controlled temperature, normally constant. As the early testing was done in temperature climates, the standardized temperature chosen was generally in the region of 18 to 21 °C so that much of the basic information about the properties of both fresh and hardened concrete is based on the behavior of concrete at these temperatures. In practice, however, concrete is mixed at a wide range of temperatures and also remains in service at different temperatures. In consequence, knowledge of the temperature effects in concrete is of great importance [1]. In our research, we simulated variable thermal cycles (temperature and relative humidity) as a function of time in order to ascertain and quantify the influence of temperature on the concrete's compressive strength.

2.1. Thermal cycles

The conditions defined by ACI Committees 305 and 306 for "Hot Weather Concreting" and "Cold Weather Concreting" were used as references in the determination of weather conditions [6,7]. Moreover, in order to simulate realistic climatic and industrial conditions, days of maximum and minimum temperatures were chosen for this study. Based on the records of the Pompeu Fabra Observatory in Barcelona, Spain [8], these days were 24 August 2000 for hot conditions and 23 December 2001 for cold conditions.

Fig. 1 (a) shows the temperature distribution for hot, cold and reference conditions. The relative humidity for the three conditions is shown in Fig. 1 (b).

In order to effectively simulate the weather conditions, we installed a climatic chamber whose temperature and relative humidity could be programmed. For the reference concrete, the temperature and relative humidity in the chamber over 24 h were 20 °C (constant) and about 95% (constant) respectively.

In order to obtain the temperature profiles of concrete, thermocouple wires were inserted into the concrete samples and were connected to a Squirrel data logger. One thermocouple measured the real ambient temperature. Temperature readings were taken every 15 min.

2.2. Variables

The variable focused on was the concrete mixing hour; for this paper, five mixing hours were studied for each climatic condition. The mixing hours were as follows: 10:00, 11:30, 13:00, 14:30 and 17:30 for hot weather, and 8:15, 10:00, 12:00, 14:00 and 17:00 for cold weather. Furthermore, three series were prepared for each thermal cycle, so there were three sets of batches for each mixing hour and weather condition. Concrete demolding age was also studied in order to ascertain their influence on compressive strength, but in this specific case, it was found to have no influence. Each series relates to a demolding age.

2.3. Mix proportions and materials

The concrete mix used in this work corresponds to concrete with a nominal strength of 25 MPa that had a water–cement ratio of 0.55. For the experimental concrete mix, the aggregates were angular crushed limestone with a nominal maximum size of 20 mm. Four different sizes of aggregates were used: 12–20, 5–12, 0–5 and 0–2 mm. The specific gravity and absorption values for the aggregates were 2.72 and 0.37%, 2.67 and 0.45%, 2.60 and 1.60%, and 2.57 and 1.87% respectively. Ordinary Portland cement with a compressive strength of 42.5 MPa R (Type I) and a polyfunctional admixture with water reduction and setting retarding effects were used. The proportions of concrete are given in Table 1.

2.4. Preparation of specimens

Before the concrete was manufactured, all the materials were stored in the climatic chamber for 72 h, during which they were subjected to a given climatic cycle. Concrete mixing was accomplished in a 50-l capacity forced-mixing type mixer. The batches of concrete were prepared according to the following procedure: with the mixer running, the aggregates were added from largest to smallest particle size, followed by the water minus 300 ml that was used to dilute the admixture later on. The cement was added immediately afterwards and the concrete was mixed for 90 s; then the admixture and the reserved water were added and the entire batch was mixed for other 120 s. The slump was measured for each batch of concrete and five cylindrical concrete specimens were made in order to obtain compressive strength values after 7 days (2 specimens) and 28 days (3 specimens).

2.5. Curing process

Immediately after the concrete had been cast and compacted, the thermocouples were introduced into fresh concrete samples and thereafter the specimens were covered with plastic bags to prevent excessive water evaporation. When the concrete specimens had remained in the climatic chamber for 24 h (Series 1), 48 h (Series 2) and 72 h (Series 3), they were demolded and stored in the curing chamber at a constant temperature of 20 °C and a relative humidity of 95% for 7 or 28 days, at the end of which the compressive strength was tested.

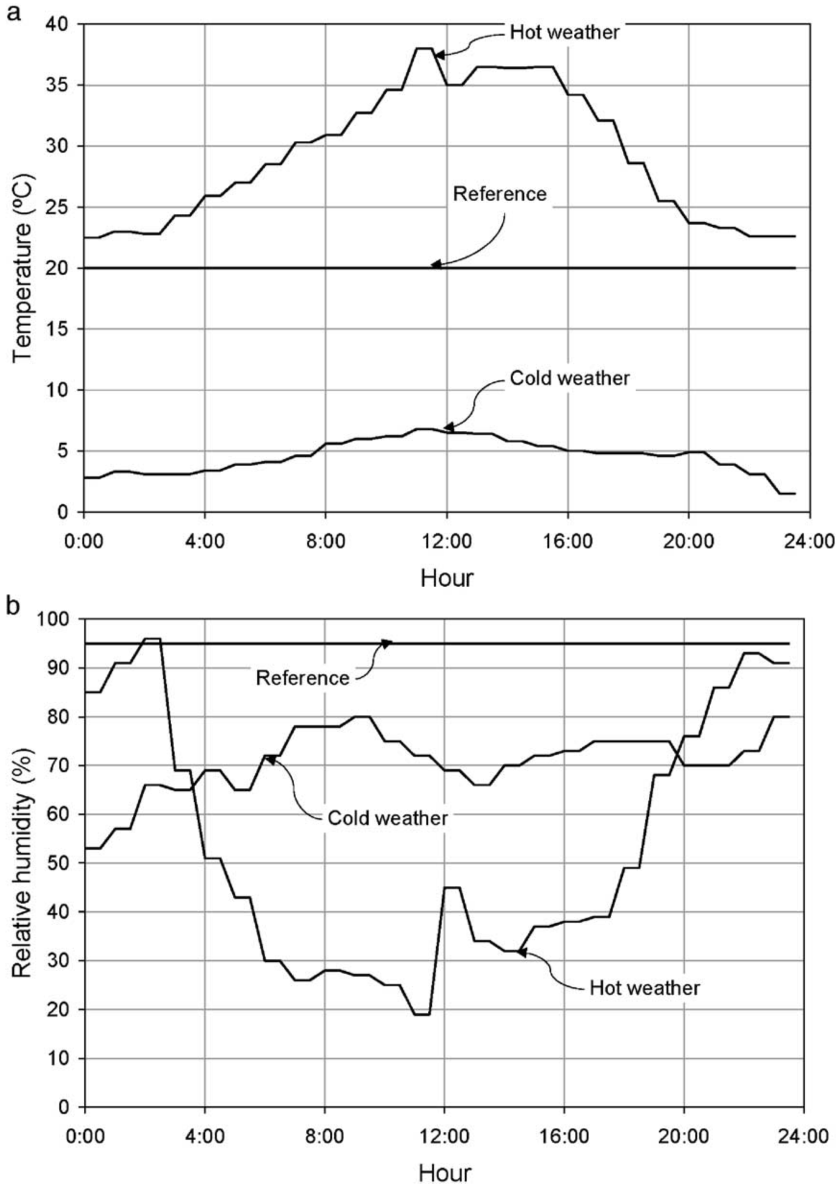

Fig. 1. Thermal cycles (hot, cold and reference conditions). (a) Temperature profiles, (b) relative humidity profiles.

2.6. Compressive strength testing

The specimens of each concrete batch were removed from the curing chamber at the ages of 7 and 28 days; thereafter, compressive tests were performed using a hydraulic, servo-controlled compressive testing machine. Before the tests, the top surfaces were capped with sulfur mortar. The compressive strength results were taken as the average values of the three series for each mixing hour, that is to say, six specimens for 7 days and nine specimens for 28 days.

Table 1
Concrete mix proportions

Material	Unit weight (per m^3)
Cement	292 kg
Water	162 l
Gravel 12–20	830 kg
Gravel 5–12	85 kg
Sand 0–5	860 kg
Sand 0–2	205 kg
Admixture (0.70%)	2.044 kg

3. Test results

3.1. Thermal profiles

Fig. 2 shows the concrete thermal profile for 72 h in hot weather conditions. Only one concrete batch has been plotted in order to facilitate the visualization of the curves.

In the above figure, we can see that, in the first 24 h, the concrete's thermal evolution is affected by exothermic reactions of cement, which show a rising stage and a

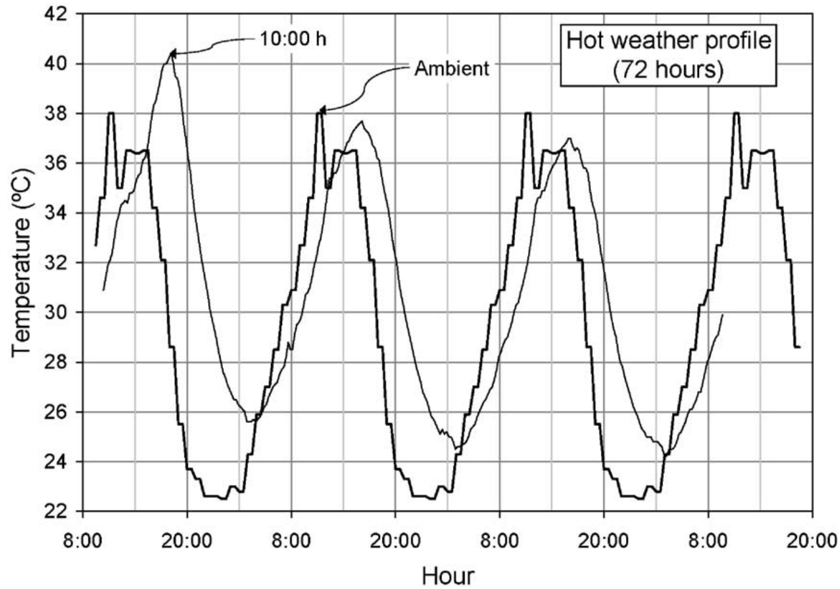

Fig. 2. Concrete thermal profile for 72 h (hot weather).

maximum peak temperature. Subsequently, the temperature of the concrete follows the ambient temperature profile except for a negligible difference in time and temperature due to the concrete's thermal inertia. For the thermal results, the stages to be studied were those that corresponded to the first 24 h for all climatic conditions.

The concrete thermal profiles obtained after the first 24 h for reference, hot and cold weather conditions are shown in Fig. 3 (a, b and c respectively). Since for every series, in hot and cold weather conditions, the thermal profiles were practically the same, only one representative profile is shown for each climate. The temperature variation (ΔT) between the initial temperature (T_i) and the maximum temperature (T_{max}) resulting from the exothermic reactions of the cement in the concrete and the time increase (Δt) between the initial temperature moment (t_i) and the maximum temperature moment (t_{max}) are plotted in Fig. 3 (a), which corresponds to the reference profile.

In the case of the hot weather profile, Δt is higher in the later hours of the day and lower in the early hours of the day. Therefore, when the variations in temperature (ΔT) as a result of both ambient temperature and exothermic reactions show the same positive slope, the kinetics is faster and consequently Δt is lower. Moreover, in the later hours of the day, ΔT decreases, and vice versa. These minor variations in temperature could have a positive effect on mechanical strength.

For the cold weather profile, the thermal evolution of concrete always follows the same trend, which is close to that of the temperature ambient profile. Nevertheless, the time increases are longer than in hot weather conditions. In contrast, the maximum temperatures (T_{max}) reached by the concrete are lower than those attained in hot weather conditions. In addition, from the point of view of mechanical strength, these minor concrete temperatures could have positive effects.

3.2. Summary of thermal results

The values for thermal variations ($\Delta T = T_{max} - T_i$) and time increases ($\Delta t = t_{max} - t_i$) for all the climatic conditions studied are presented in Table 2.

The data corresponding to thermal variations and time increases are shown graphically in Figs. 4 and 5 respectively.

In the above figure, we can see that, for hot weather conditions, the thermal variations show a downward tendency during the day; the maximum variation occurs during the first hours of the day and the minimum value is obtained in the later hours. In the case of cold weather, the behavior remains stable throughout the day and no significant trend can be observed.

On the other hand, it is evident that time increases for the two weather conditions display opposite tendencies, so, in cold weather conditions, the tendency is for the time to decrease and, in hot weather conditions, the tendency is for it to increase as mixing hour increases.

All the facts mentioned above regarding thermal variations and time increases can be explained by the fact that a rise in the curing temperature speeds up the chemical reaction of hydration and a higher temperature during and following the initial contact between cement and water reduces the length of the dormant period so that the overall structure of the hydrated cement paste becomes established very early [1]. We might remember the well-known axiom from physical chemistry which states: the reaction velocity is doubled if the temperature at which the process is taking place is increased by 10 °C [9].

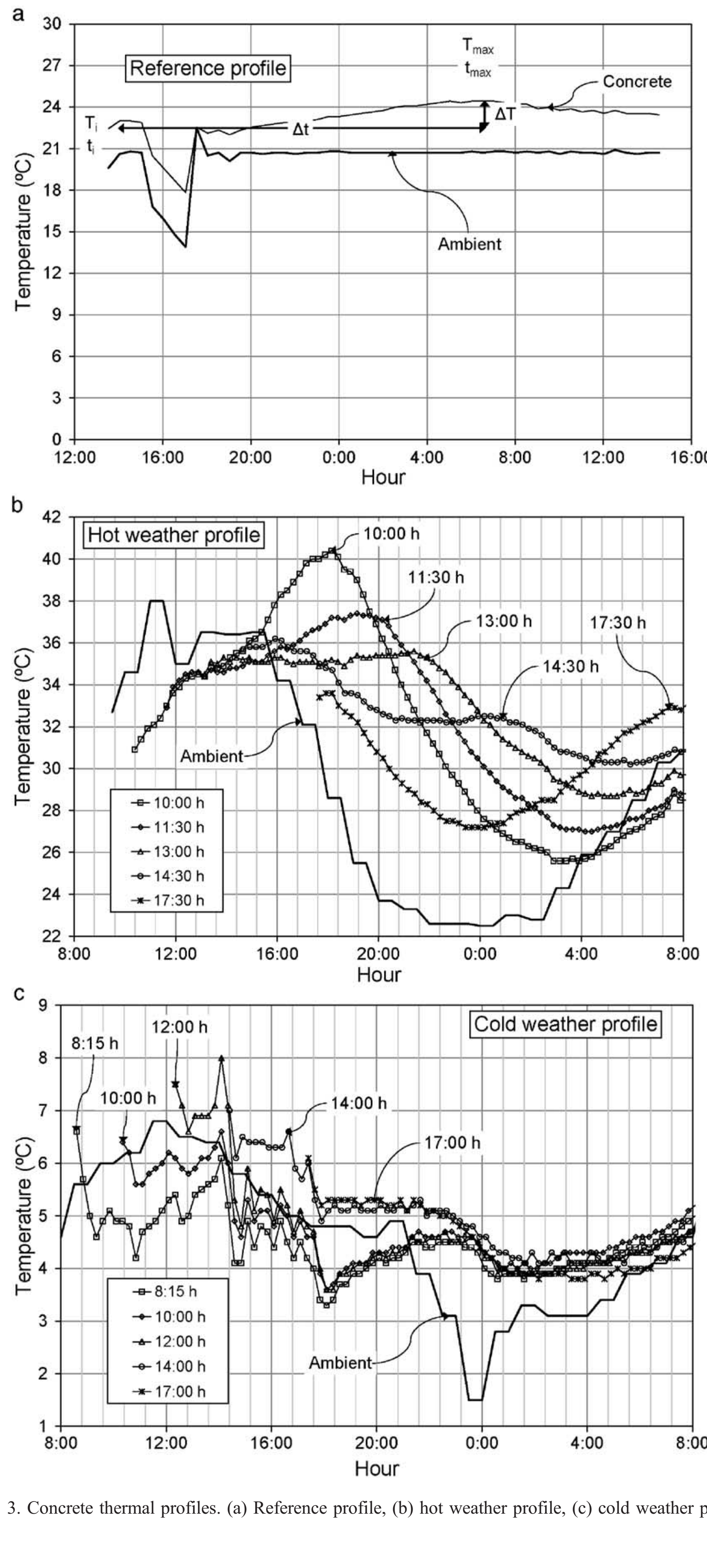

Fig. 3. Concrete thermal profiles. (a) Reference profile, (b) hot weather profile, (c) cold weather profile.

Table 2
Thermal variation (ΔT) and time increase (Δt)

Hour	T_i (°C)	T_{max} (°C)	ΔT (°C)	Δt (h)
Hot weather conditions				
Reference	22.4	24.5	2.1	17.00
10:00	31.1	40.3	9.2	7.65
11:30	33.5	36.8	3.3	7.65
13:00	34.2	35.5	1.3	8.22
14:30	33.6	32.4	−1.2	9.83
17:30	34.1	33.5	−0.6	13.58
Cold weather conditions				
Reference	22.4	24.5	2.1	17.00
8:15	6.6	4.5	−2.1	14.17
10:00	6.4	4.7	−1.7	12.33
12:00	7.5	4.7	−2.8	10.42
14:00	8.4	4.8	−3.6	8.17
17:00	6.4	4.8	−1.6	5.25

With reference to the type of cement used in this work, it is important to note that there is an optimum temperature during the early life of concrete that leads to the highest strength at a desired age. For laboratory-made concrete, using ordinary or modified Portland cement, the optimum temperature is approximately 13 °C; for rapid-hardening Portland cement it is about 4 °C. It must not be forgotten, however, that beyond the initial period of setting and hardening the influence of temperature (within limits) accords with the maturity rule: a higher temperature accelerates the development of strength [1].

3.3. Compressive strength results

The compressive strength results were obtained by calculating the mean of all the concrete specimens for the three series for each mixing hour; i.e. for each mixing hour, the average values used were from six specimens for 7 days and from nine specimens for 28 days.

In order to provide a statistical approach and visualize the inner dispersion of each series of data, the calculation of the single population variance through the pondered mean of all the sample variances is included. In this approach, the standard deviation of a single population is calculated by means of the following equation [10]:

$$S = \sqrt{\frac{\sum_{i=1}^{k}(n_i - 1)\cdot s_i^2}{\sum_{i=1}^{k}(n_i - 1)}} = \sqrt{\frac{\sum_{i=1}^{k}(n_i - 1)\cdot s_i^2}{N - k}}$$

where: s standard deviation of a single population; k number of treatments to be compared; n_i number of data available for treatment i; s_i^2 variance of data corresponding to treatment i; N number of data in the k treatments.

The sample size was not large enough to use normal distribution, so we used Student's t-distribution to calculate the scale factor according to the total degrees of freedom, with a statistical confidence interval of 90%. The standard deviation values of a single population calculated for each weather condition for 7 and 28 days respectively, are the next (in MPa): 1.001 and 0.970 for reference concrete; 0.869 and 1.044 for hot weather conditions; 1.175 and 0.847 for cold weather conditions.

The slump and compressive strength values for each test age and mixing hour and for each climatic condition are presented in Table 3 below. The coefficients of variation (expressed as percentages in parenthesis) of average strength are shown for each mixing hour.

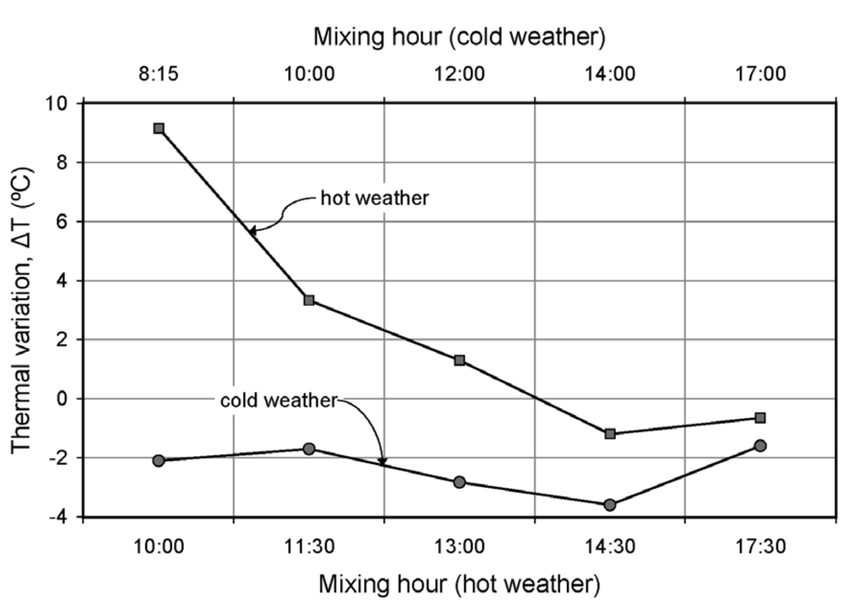

Fig. 4. Thermal variation for hot and cold weather.

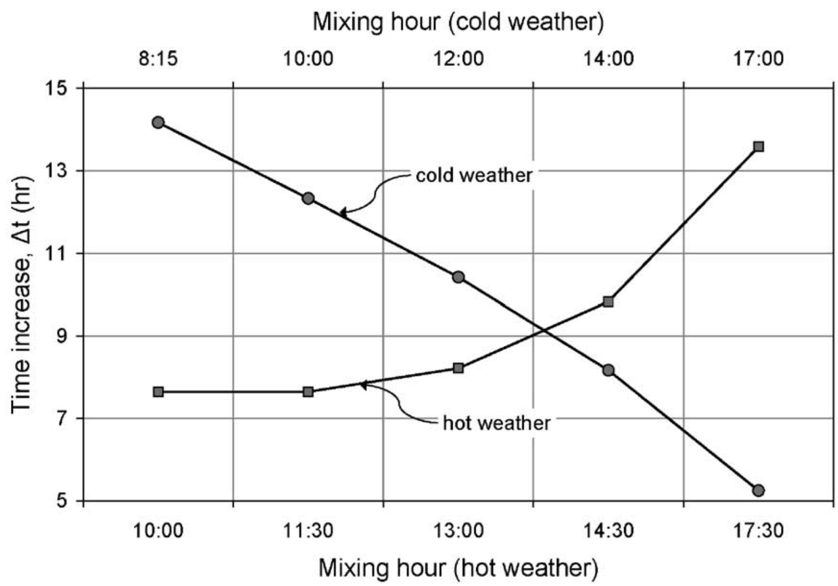

Fig. 5. Time increases for hot and cold weather.

As shown in the previous table, the influence of the ambient temperature on the workability of the fresh concrete is most unfavorable in hot weather conditions, in which the slump values were very low. In the case of cold weather conditions, the slump values were somewhat higher but were in any case close to the reference values##. In addition, we can see that, under given weather conditions, the slump does not have a significant effect on compressive strength.

In order to visualize the tendencies followed by the concrete for each mixing hour, the compressive strength values for 7 days (a) and 28 days (b) are plotted in Fig. 6 for all the weather conditions. Standard deviations are included.

It is evident that the compressive strength values are higher in cold than in hot weather; the compressive strength after 7 days in cold weather is in fact comparable to the compressive strength after 28 days in hot weather. If we consider the standard deviation bars plotted in the compressive strength results, we can see that some overlapping occurs at certain points, mainly in cold weather conditions. One of our main goals was to develop an industrial application for ready-mix concrete production, so the results obtained will be of great value in this endeavor.

Table 3
Slump and compressive strength values for 7 and 28 days

Mixing hour	Slump (cm)	Compressive strength (MPa) (coefficient of variation, %)	
		7 days	28 days
Hot weather conditions			
Reference	9.0	37.9 (0.2)	43.3 (4.6)
10:00	4.5	34.3 (2.5)	40.9 (5.2)
11:30	3.5	34.4 (3.2)	41.1 (2.9)
13:00	3.5	35.2 (4.6)	41.9 (2.8)
14:30	4.0	36.8 (3.6)	41.5 (3.5)
17:30	3.2	37.3 (3.2)	42.5 (6.6)
Cold weather conditions			
Reference	9.0	37.9 (0.2)	43.3 (4.6)
8:15	7.0	41.7 (2.2)	45.8 (2.8)
10:00	7.5	41.7 (4.4)	45.7 (1.5)
12:00	7.0	41.6 (3.1)	45.5 (3.7)
14:00	6.5	40.4 (4.3)	46.7 (3.5)
17:00	7.5	40.6 (5.4)	46.0 (4.2)

In these results, the most influential factors are the temperature of the concrete and the ambient temperature, and also the difference between these two temperatures, mainly in the first hours of the concrete. One must stress the reverted tendency between hot and cold weather conditions in the sense that the higher values of compressive strength in hot weather conditions correspond to those of the later mixing hours. In cold weather conditions, however, this tendency is inverted, i.e. the higher values of compressive strength are obtained in the first mixing hours. This tendency is more pronounced at 7 days. In comparison to the reference values for concrete strength, all the strength values are lower in hot weather conditions and higher in cold weather conditions. These effects can be related to the "crossover effect", as Alexander and Taplin called the phenomenon whereby concrete subjected to a high temperature at an early age attains higher early-age compressive strength but lower later-age compressive strength [11].

4. Discussion of results

Mouret et al. (1997) found that the amount of water required to produce a given consistency generally increased with an increase in the temperature of the aggregate. The evaporation of a certain amount of mixing

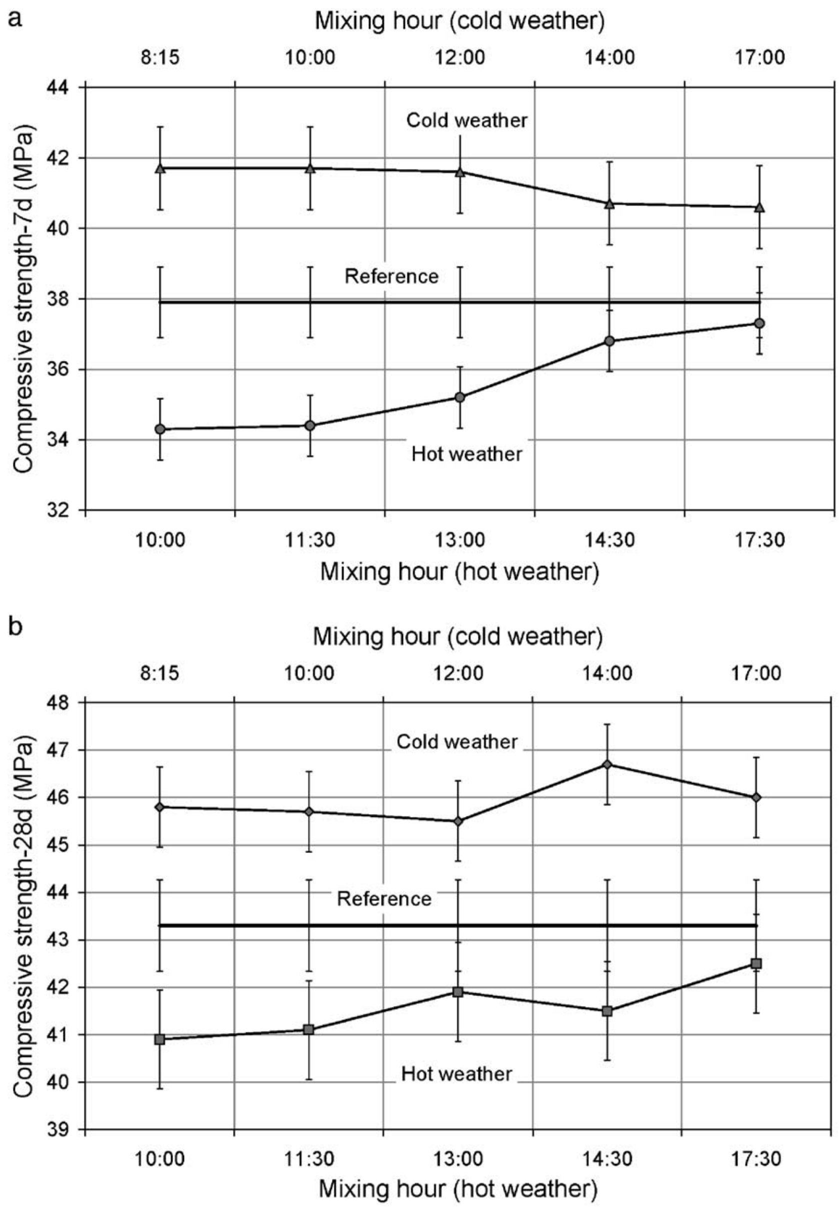

Fig. 6. Compressive strength results. (a) 7 days, (b) 28 days.

water during casting and placing was also observed. The extra water resulting from a higher aggregate temperature was not deemed to be the main reason for the decrease in concrete strength. In their research, however, no extra water was added, just the amount used in the reference concrete, which meant that the losses of workability were observed. The authors proposed that another explanation must lie in the microstructure of concrete, i.e. the effect of aggregate temperature on the nature, the morphology and the distribution of hydration products in the internal space between cement grains. In this respect, the counting of the unhydrated cement grains should provide more information about the hydration state of concrete as well as the evaluation of the combined water. Previous studies have shown a microstructure change in the paste–aggregate interface for both summer concrete specimens and aggregate–paste models. Particularly, the higher the temperature of the cement and/or aggregate, the greater the concentration of calcium hydroxide (CH) at the interface. This observation leads them to surmise that the transition zone might be weakened by a chemical phenomenon, due to a rise in the constituent temperature. The authors found that high aggregate temperatures have the same effect as high curing temperatures on the development of the concrete's strength. Since the greater portion of concrete is aggregate, an increase in aggregate temperature brings about the greatest increase in concrete temperature [2].

The effects of temperature on hydration and strength development are still not well known. Rapid hydration due to elevated temperatures is thought to act as a "shell" that eventually hinders the diffusion of hydration products into the bulk cement paste matrix. The porosity of the bulk paste is also reported to increase as a result of the non-uniform diffusion of the hydration products. Furthermore, if the temperature increases rapidly during the early age, this may cause internal stresses that exceed the tensile strength of the immature concrete, which will in turn lead to increased porosity, cracking and a reduction in strength potential. An increase in the early curing temperature makes the hydration rate and concrete strength increase rapidly, but due to the non-homogeneous diffusion of the hydration products and the difference in the thermal expansion coefficients of the concrete's constituents, the porosity of the cement paste increases and microcracks develop, which finally leads to decreased strength at a later time [12].

Although a higher temperature during placing and setting increases strength in the very early stages, it may adversely affect the strength from about 7 days onwards. The explanation for this is that rapid initial hydration appears to form products of a poorer physical structure, which are probably more porous, so a proportion of the pores always remain unfilled. It follows from the gel/space ratio rule that this would lead to a lower strength than that of a less porous but slowly hydrating cement paste, in which a high gel/space ratio would eventually be reached.

This explanation of the adverse effects of a high early temperature on later strengths has been extended by Verbeck and Helmuth, who suggest that a rapid initial rate of hydration at higher temperatures slows hydration down and produces a non-uniform distribution of the products of hydration within the paste. The reason for this is that, at the high initial rate of hydration, there is insufficient time for the diffusion of the products of hydration away from the cement particles and for a uniform precipitation in the interstitial space (as is the case at lower temperatures).

As a result, a high concentration of the products of hydration builds up in the vicinity of the hydrating particles, and this subsequently slows hydration down and has an adverse effect on long-term strength. In addition, the non-uniform distribution of the products of hydration adversely affects the strength per se, because the gel/space ratio in the interstices is lower than would otherwise be the case for an equal degree of hydration, and the weaker local areas lower the overall strength of the hydrated cement paste. The quality of the concrete also depends on its temperature and not that of the surrounding atmosphere, so the size of the structural member also affects the rise in temperature caused by hydration [1].

By way of summary, a faster and non-uniform precipitation of the products of hydration, as a consequence of a curing process at a higher temperature, makes the structure more disordered and the microstructural development is consequently more heterogeneous and less compact; this effect is eventually reflected in minor increases in mechanical strength over time.

5. Conclusions

The results obtained regarding concreting in extreme weather conditions serve to underline the well-known fact that in cold weather compressive strength is higher than it is in hot weather. Similarly, in relation to workability, the best results were obtained under reference conditions and the worst under hot weather conditions.

Several other specific conclusions concerning the mixing hour, hydration kinetics and compressive strength results are presented:

- In hot weather conditions, it is advisable to place concrete in the later hours of the day when the ambient temperature decreases, in order to make the setting and hardening of the concrete coincide with this decrease.
- In cold weather conditions, it is advisable to place concrete in the early hours of the day when the ambient temperature rises, in order to make the setting and hardening of concrete coincide with this increase.

Finally, on the subject of compressive strength, the main conclusion, from an industrial point of view, is that it is advisable to place concrete in hot weather in the afternoon and in cold weather in the morning. This statement has been proved in realistic conditions at a ready-mix concrete plant.

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