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DROPS IN CONCRETE STRENGTH IN SUMMER RELATED TO THE AGGREGATE TEMPERATURE

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ABSTRACT

Drops in compressive strengths may occur for hot weather concreting. They are observed on specimens for manufacturing control tested in laboratory at 28 days. On the other hand, 7-day compressive strength seems not to be affected.

An experimental program was carried out. It constituted a quantitative approach to evaluate the effect of the aggregate temperature on the performances of plain concrete. So, this paper presents the results of tests for compressive and splitting tensile strengths conducted on normal strength concrete specimens. Cylinders (11 cm × 22 cm) were prepared with different aggregate temperatures ranging from 20-70°C and cured under either controlled laboratory conditions (20°C) or simulated conditions of hot weather (35°C). Results show that both the 28-day compressive strength and the splitting tensile strength of concrete are reduced with the increase in aggregate temperature by as much as 15% and 17% respectively. The aggregate temperature rise also implies an increase in the water demand of the concrete mixes which, in turn, cannot fully explain the drops in strength. © *1997 Elsevier Science Ltd*

Introduction

Cement-makers and ready-mixed concrete manufacturers are faced with drops in compressive strengths of concrete produced in summer. This problem may be related to concrete placing in hot weather.

Hot weather concreting induces well-known phenomenons. Particularly, hign ambient temperatures, low relative humidity and sometimes high wind velocity make possible an increased rate of evaporation from fresh concrete resulting in 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 [1], [2], [3], [4].

In fact reductions of compressive strengths are also observed on specimens for manufacturing control tested in laboratory at 28 days in order to verify the contractual compressive strength. In that case, other causes of strength degradation have to be investigated since particular attention has been given in order to avoid the adverse effects presented above.

Thus, elsewhere. 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 cement or/and aggregate, the greater the concentration of calcium hydroxide at the interface [5], [6]. This observation leads us to assume that the transition zone might be weakened by chemical phenomenons due to the rise of the constituent temperatures.

Further to these works, it was decided to study the influence of the aggregate temperature on concrete strength. This paper deals solely with the assumption that the rise of aggregate temperature induces lower concrete strengths. The cement temperature was maintained at 70°C whereas the aggregate temperature was increased from 20°C to 70°C.

In order to emphasize the influence of aggregate temperatures it was necessary to cure the specimens under controlled laboratory conditions according to standard specifications. Nevertheless, some specimens were placed and maintained at 35°C initial temperature to simulate non standard site conditions such as a time elapse between placing and transporting to laboratory. Hence the accuracy of the mechanical test results is impaired and the actual influence of the aggregate temperature can be hidden. Specimens at one day age were placed either in water as specified by the standard recommendations or in air for approximating to concrete structure conditions.

This paper presents the results of tests for compressive strength which is of course the studied mechanical parameter. In addition, splitting tests have been carried out. As in tensile conditions the strength of the cement-aggregate bond determines the global strength of concrete, these tests can allow us to verify if the rise of the aggregate temperature induces a weakening of the transition zone.

Experimental Program

Two series of normal strength concrete were performed.

Series A: 28-day nominal compressive strength of 35 MPa
Series B: 28-day nominal compressive strength of 22 MPa

For each series, three aggregate temperatures were chosen: 20°C, 35°C, 70°C. The cement temperature was kept constant (70°C: cement is often delivered on sites at this relatively high temperature in summer).

Materials and Mix Proportions. Following materials were used for concrete.

Cement. Ordinary Portland Cement (OPC) (CEM I 42.5)—Blended Portland cement with 20-25% of calcareous filler (CEM II/B 32.5 R). Both cements satisfied the requirements of revised NFP 15-301 (1994).

Fine aggregate. Siliceous sand 0/6 mm produced in Garonne Area, Specific gravity (S G): 2.68—Fineness modulus: 3.06—Absorption (ABS): 2.8%.

Coarse aggregate. Siliceous fine gravel 6/10 mm (Garonne Area): SG = 2.69 - ABS = 0.70; Siliceous gravel 10/ 20 mm (Garonne Area): SG = 2.66 - ABS = 0.70.

Aggregates were selected according to the specifications of NFP 18-541 (1994).

TABLE 1

Denomination of the Mixes

CEMENT		AGGREGATE					
	temperature	20°C		35°C		70°C	
		series A	series B	series A	series B	series A	series B
CEM I	70°C	A1	B1	A2	B2	A3	B3
CEM II/B	70°C	A4	B4	A5	B5	A6	B6

Admixture. Plasticizer based on naphthalene (series B only).

The denomination of all the mixes is presented in Table 1. Mix proportions are shown in Table 2.

Mix Procedure. Each concrete was constituted of two 50-litre successive batches. The time elapsed between the manufacturing of both batches never exceeded 45 minutes.

Materials preparation. As the case may be, the aggregates were heated in an oven till casting for at least 2 days. The cement was prepared in the same manner but was always heated for a 24 hour period before casting. One hour before mixing, the water content of aggregates was measured so that the required amount of water in the concrete might be adapted.

Mixing. Mixing sequence was:

1) 10/20 mm and 6/10 mm gravels, cement and sand 0/6 mm added at the selected temperature in a vertical axis mixer - 2) 30-second mixing - 3) water added at 20°C (in the case of series B, the plasticizer was introduced directly in water before mixing) - 4) 3-minute mixing - 5) mix temperature measured - 6) slump measured.

TABLE 2

Mix Proportions (kg/m^3)

	CEMI 42.5		CEM II/B 32.5 R	
	series A	series B	series A	series B
0/6 mm	730	810	690	780
6/10 mm	300	340	300	340
10/20 mm	820	820	820	820
cement	350	240	400	270
water	180[1]	170[1]	180[1]	170[1]
plasticizer	/	0.3% [2]	/	0.3% [2]

[1]Theoretical amount of water in the mix corresponding to 80 mm slump (series A) and 90 mm slump series B).

Percent by weight of cement.

Sufficient extra quantities of water were added to the mixes for high aggregate temperature (35°C and 70°C) to compensate for the evaporation of water (this latter was more visible at 70°C) so as to get the mixes of approximately the same workability at all the temperatures (80 mm slump for series A, 90 mm slump for series B). So, the mixing was continued till 5 minutes.

The record of the electric power of the mixer made possible the control of the concrete consistency.

Measure of fresh concrete characteristics. Density and air content with airmeter (NFP 18-353 (1985)) were performed on fresh concrete.

Specimens preparation. At the same time, the concrete was placed in PVC molds (11 cm × 22 cm cylinders) in two approximately equal-layers and each layer was compacted by vibrating with a vibrating needle. Thermocouples were introduced into the core of some specimens in order to monitor the temperature evolution for a 24 hour period (series A) and a 30 hour period (series B). After finishing, the specimens were rapidly covered with a polyethylene sheet to minimize evaporation. The time elapsed between casting and finishing never exceeded 30 minutes.

<u>Curing Procedure</u>.

<u>Series A</u>: all the specimens were cured in an air room (20°C ± 2°C-60 ± 5% HR) for a 24 hour

<u>Series B</u>: half of the specimens from a batch was transferred to an air room (20°C ± 2°C-60 ± 5% HR) for a 24-hour period (cure1: C1).

The other half was kept in simulated conditions of hot weather: 35°C during the first five hours after casting, next progressive decrease in temperature down to about 25°C till 24 hours after mixing (cure2: C2). The cure of the second batch was carried out in the same manner than the first one.

24 hours after casting, the specimens were removed from the molds. Each specimen was then weighed and its volume was also measured so as to calculate its apparent specific gravity. After stripping and weighing, the following conservation modes were used up to the time of tests:

<u>series A</u>: half of the specimens was immersed in a water tank under the temperature of 20°C. The other half was transferred to an air room (20°C ± 2°C-60 ± 5% HR).

<u>series B</u>: specimens cured at 20°C were kept immersed in water at 20°C. Specimens cured at 35°C for a five hour period were kept in an air room (20°C ± 2°C-60 ± 5% HR).

Testing of specimens. All the specimens were tested at 1, 7 and 28 days age in accordance with NFP 18-406 (1981) for the compressive strength and, at 7 and 28 days age in accordance with NFP 18-408 (1981) for the splitting tensile strength.

Each test result is a mean of three values for compressive strength and splitting tensile strength. These three values are representative of the two successive batches which constituted a concrete mix prepared with an aggregate temperature.

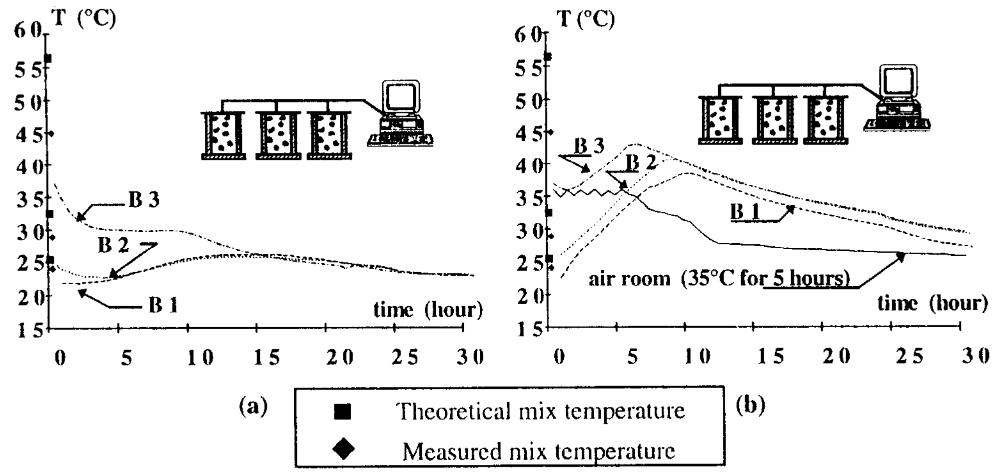

FIG. 1.
(a), (b). Temperature evolution in concrete specimens—series B.

Measurement of Specimen Temperature

Examples of temperature-time curves are shown in Figs. 1a & 1b; these curves derived from series B are representative of the two curing procedures performed in this program. Whatever the cement was employed, the following discussion applies as well to series A as to series B.

Initial mix temperatures are also plotted in Fig. 1: the measured ones as well as the theoretical temperatures calculated from the relation (1), [1]:

$$T = \frac{0.22(Ta.Wa + Tc.Wc) + Tw.Ww + Ta.Wwa}{0.22(Wa + Wc) + Ww + Wwa} \tag{1}$$

where,

Ta, *Tc*, *Tw* = temperatures (°C) of aggregate, cement and batched mixing water respectively.
Wa, *Wc*, *Ww*, *Wwa* = weights (kg) of aggregate, cement, batched mixing water and, free and absorbed moisture in aggregate at *Ta*.
0.22 = specific heat of the solids in the mix (kcal/kg K).

The measured mix temperature (about 3 to 5 minutes after mixing) was always lower than the calculated mix temperature. The difference is explained by the fact that the mixer was at ambient temperature of the laboratory casting area (18°C ± 2°C). Similarly, the concrete temperature at time of monitoring (about half an hour to an hour after casting) was lower than the measured mix temperature because of the cooling effect due to the heat conduction to the ambiance.

Controlled Laboratory Conditions (Fig. 1a). During a period of about 4 hours after casting the temperature in specimens falls (B2, B3) or is quite constant (B1). This time section represents the dormant period for hydration and the temperature changes are dominated by thermal exchanges with the ambiance in the air-room (20°C). However, the heat generation due to hydration may be obscured by the thermal gradient between concrete specimens and the surroundings. This is mainly the case for B3 (70°C aggregate temperature).

Whatever the aggregate temperatures may be, a change exists at about 4 hours after casting: i) a more important growth rate of the temperature (B1), ii) a subsequent increase in the temperature (B2), iii) a stabilization of the temperature (B3).

The heat generation due to hydration and setting of cement is followed by a cooling which appears to approximately the same time for B1 and B2 (15 hours and 16.5 hours after mixing respectively). But, this cooling is more advanced for B3 (10 hours after mixing), thus traducing a more rapid hydration kinetics for B3 than B1 and B2.

During the 15-hour period after casting, the higher the aggregate temperature, the higher the maturing temperature of the concrete specimens: the gap is very pronounced between B3 and {B1, B2}. Beyond 15 hours after mixing, the temperatures tend towards the same values.

Simulated Conditions of Hot Weather (Fig. 1b). A significant increase in temperature appears for B1 and B2 at the beginning of the monitoring. In the case of B3, a cooling of concrete specimens exists and when the temperature gradient is vanished between these latter and the ambiance, the temperature increases in specimens. High aggregate temperature reduces the setting time which results in reaching peak temperatures earlier. This clearly underlines the distinction between the effect of the aggregate temperature on the specimen temperatures and the effects due to the immediate transfer of specimens at curing temperature of 35°C, after placing. In other words, the compensating effect of the greatest maturity at 35°C do not hide the influence of the aggregate temperature on time-temperature relationships of the specimens. This will be discussed below.

Mechanical Test Results

Compressive Strength.

Compressive strength correction. For every composition (Ai or Bi), it was difficult to obtain first the required slump value, second the very same slump between both batches. Fig. 2 shows the experimental scatter in slump values and the confidence interval.

In order to eliminate the influence of the slump variation, compressive strengths were corrected according to the following method:

- fit the water content in concrete to the theoretical slump by means of DREUX abacus[3] [7].
- correction of the compressive strength using FERET's relation modified by J. Baron [8] and expressed by equation (2):

$$fc_{st} = R^{2.2} \cdot fc_{sm} \quad \text{with} \quad R = \left(\frac{1 + F_{sm}}{1 + F_{st}} \right) \qquad (2)$$

[3]This abacus is used to assess the cement content in connection with C/W ratio and the workabilities which have to be obtained.

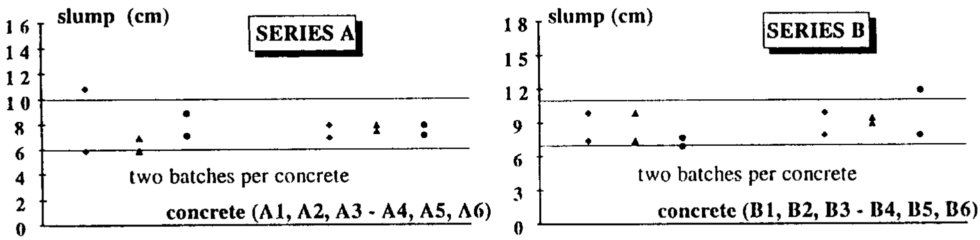

FIG. 2.
Measured slump for each batch.

where fc_{st} is the compressive strength value adjusted to the required slump *st*. fc_{sm} is the effective compressive strength corresponding to the measured slump *sm*.

$F_{st} = \frac{W_{st} + V}{C}$; $F_{sm} = \frac{W_{sm} + V}{C}$ where W, V, C = water, void and cement volumes per m^3 of concrete. Baron raised the coefficient R to the power of 2.2 instead of 2 (classical exponent value of FERET's relation). This results from independent experiments on mortar [8]. It is not possible to know the void volume of concrete corresponding to the corrected water content. So, calculations are realized assuming the same void volume before and after corrections. Indeed, random values of air content are measured even if the measured slump is equal to the reference value.

Results and analysis. Table 3 presents all the data concerning the compressive strength (1, 7 and 28 days age). Each average value is determined with a 0.75 MPa standard deviation. This was evaluated, for one composition and for each conservation mode, by tests conducted on 12 concrete cylinders at 7 and 28 days age. The characteristic evolution of the average 28-day compressive strength according to the aggregate temperatures for series A & B is shown in Figs. 3 and Figs. 4 respectively.

Influence of the curing and conservation modes. For each series and whatever the type of cement and the aggregate temperature are, the 28-day compressive strength is greater for specimens stored in water at 20°C than for the ones stored in an air-room (20°C-60% RH). In air, the desiccation is preponderant and involves the stopping of the hydration process as soon as the relative humidity in capillaries becomes lower than 80% [9], and even less than this latter value (75% RH) [10].

As far as 7-day compressive strengths are concerned, this trend remains true for series A (see Table 3). However, in the case of series B, there is no evident difference between 7-day values for water-cured and air-cured specimens. Such an effect may be attributed to the well-known accelerating rate of hydration reactions due to higher initial temperatures after placing (cure C2). This results in higher compressive strengths at 1-day age and lower ones at 28-day age as shown in Table 3. This adverse effect of high curing temperatures on compressive strengths of concrete was studied by Verbeck and Helmuth who proposed also the same conclusions[11]. So, the 7-day strengths seem not to be adversely affected by initial elevated temperatures. This phenomenon is worthy of confirming with series A for which only specimens were cured at 20°C (conservation in water or in air).

TABLE 3

Summary of Average Compressive Test Results (MPa)

composition	1 day		7 days		28 days	
	C1	C2	air 20°C	water 20°C	air 20°C	water 20°C
A1	15.3		28.4	30.5	34.5	41.5
A2	15.7		28.1	30.8	35.3	37.8
A3	16.2		25.6	27.3	30.9	35.3
A4	15.8		28.2	30.6	34.4	38.2
A5	15.8		27.6	31.3	34	39.7
A6	16.7		26.2	28.4	32.3	38.4
B1	6.9	8.8	15.8	16.6	20.3	24.4
B2	6.4	9.1	16.8	16.8	20.1	24.7
B3	7.6	9.2	16.9	16.9	19.6	22.5
B4	7.6	10.6	17.9	19.1	22.1	25.7
B5	7.9	10.9	17.7	17.3	21.8	24.3
B6	6.8	8.7	14.9	16.9	19.1	23.4

Influence of aggregate temperature. The difficulty to draw a general trend shows that the compressive strength evolution is not only governed by the aggregate temperature, but also by underlying parameters such as cement type, curing procedures and concrete class. But, in any case, as plotted in Figs. 3 & 4, the drops in 28-day values occur when the aggregate temperature increases from 20°C to 70°C. Strengths can be reduced by as much as 15% (relative variation of the mean value $\left\{1-\frac{A3}{A1}\right\}$ for water curing), but are similar between 20°C and 35°C in most cases. This adverse effect of elevated aggregate temperature on concrete strength do not clearly appear at 7 day-age. On the contrary, at 1 day-age, strengths

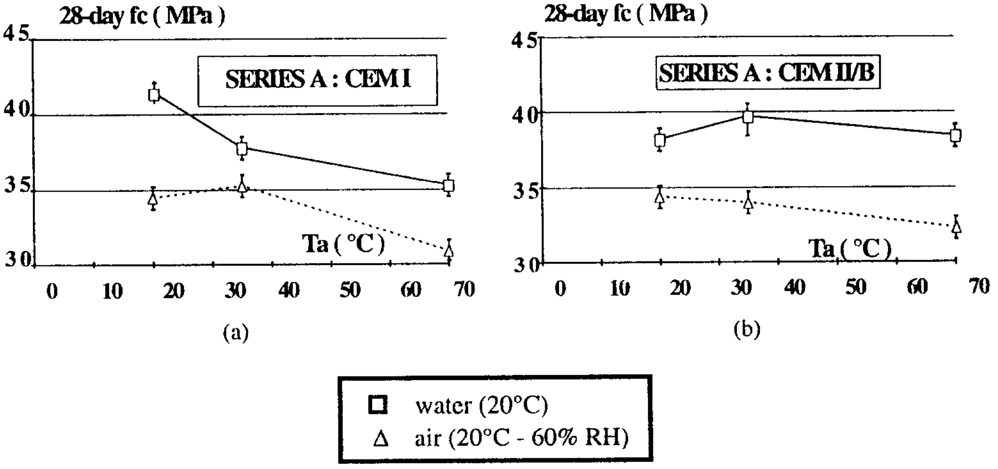

FIG. 3.
(a), (b). 28-day compressive strength average—aggregate temperatures relationships.

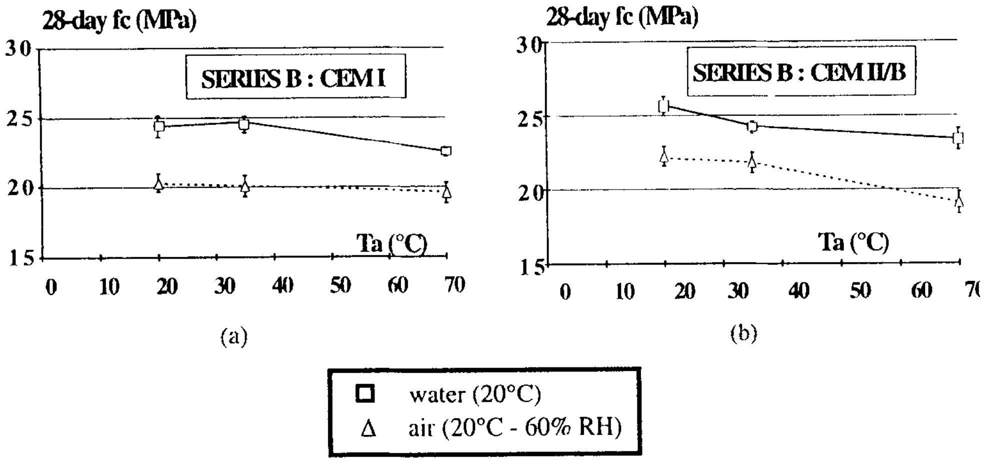

FIG. 4.
(a), (b). 28-day compressive strength average-aggregate temperatures relationships.

tend to increase (series A) or to be equivalent (series B) with the rise of the aggregate temperature.

So, elevated aggregate temperatures have the same effect as high curing temperature on the strength development of concrete. Furthermore, the 70°C aggregate temperature might be an aggravating factor for the strength of a concrete cured at initial elevated temperatures, like series B concrete cured in an air room (see Fig. 4b). This is a somewhat unexpected observation because the initial curing temperature at 35°C, inducing a more important maturity than the one involved by cure 1, should have hidden the aggregate temperature contribution.

Splitting Tensile Strength. All the results concerning the splitting tensile strengths are presented in Table 4. The values globally follow the same trend as those of compressive

TABLE 4

Summary of Average Tensile Splitting Test Results: ft (MPa)

composition	7 days		28 days	
	air 20°C	water 20°C	air 20°C	water 20°C
A1	2.58	3.20	2.95	3.85
A2	2.80	2.87	3.35	3.72
A3	2.42	2.81	2.92	3.24
A4	2.60	3.22	2.96	3.40
A5	2.80	3.07	2.85	3.86
A6	2.62	2.87	3.08	3.36
B1	1.87	1.99	2.30	2.98
B2	1.91	1.98	2.27	2.47
B3	1.88	1.91	2.22	2.47
B4	2.06	2.20	2.46	2.93
B5	2.23	2.25	2.28	2.60
B6	1.71	2.11	2.08	2.57

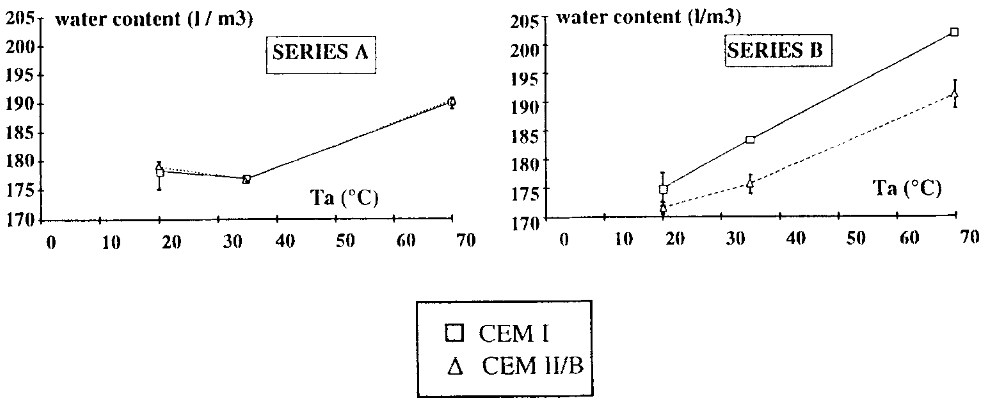

FIG. 5.
Corrected water content in concrete—aggregate temperature.

strengths (they can be reduced by as much as 17% (relative variation of the mean value $\left\{1-\frac{B2}{B1}\right\}$ or $\left\{1-\frac{B3}{B1}\right\}$ for water curing), but the dispersions are greater under tensile conditions than under compressive conditions. However, drops in 28-day splitting tensile strengths can be more important than the corresponding ones dealing with 28-day compressive strengths (series B). This is a phenomenon previously observed [2]: even if the required compressive strength is obtained, the splitting tensile strength could be reduced.

For normal strength concrete, fracture under tensile condition generally results from crack growth initiating at the transition zone. So, drops in 28-day splitting tensile strengths generally encountered with the rise of the aggregate temperature from 20°C to 35°C and 70°C may be attributed to a more pronounced weakness of the transition zone. That is why the previous investigations [5], [6] about the microstructure change in the paste-aggregate interface for summer concrete specimens are worthy of deepening.

Discussion

Compressive Strength/Temperature Evolution Relationships. Since the greatest portion of concrete is aggregate, an increase in aggregate temperature brings about the greatest increase in concrete temperature. Problems occur if this latter exceeds 32°C [1], [4]. This is the case in this study when the aggregate temperature reaches 70°C, involving drops in concrete strength. Thus, in a some extent, the higher the temperature during first ages in concrete specimens, the lower the later age compressive strength of these specimens are.

Increased Water Demand. Fig. 5 show that the amount of water required to produce a given consistency is generally increased with the rise of the aggregate temperature. Particularly, it is indicated in Fig. 5 that the water demand is systematically more important when aggregates are brought to 70°C. At this temperature an evaporation of some amount of mixing water was observed during casting and placing.

The extra water effect on the increase in the water-cement ratio and the decrease in long term concrete strength is well-known [1]. Nevertheless, do these additional quantities of water fully explain the drops in 28-day compressive strength observed when the aggregate

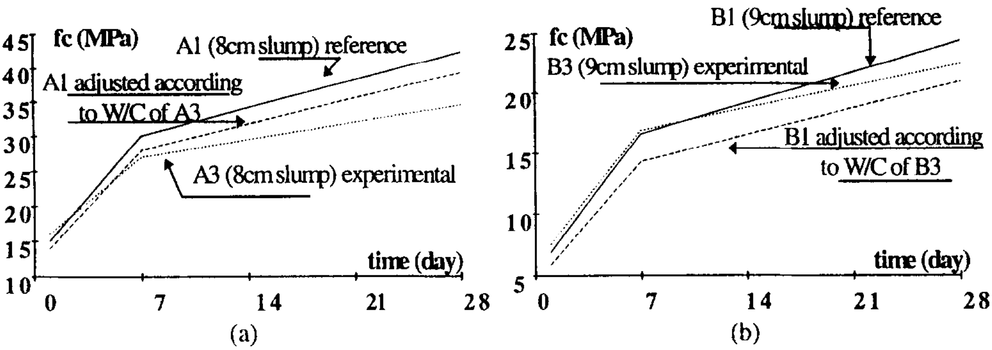

FIG. 6.

(a), (b). Average reference strength, average corrected reference strength at the same W/C as strength of other compositions.

temperature reaches 70°C ? FERET's rule could give an answer to this question by applying to compressive strength references (i.e. series A1, A4; B1, B4) according to relation (3):

$$fc_i = R'^{2.2}\, fc_{ref} \quad \text{with } R' = \frac{1+Fi}{1+Fref} \tag{3}$$

where fc_{ref} is the compressive strength reference and fc_i the adjusted value according to the water-cement ratio of mixes Ai or Bi. Only the values of reference specimens cured in water can be corrected. The conservation in air involves a desiccation of the concrete which is expected to modify the water-cement ratios and hence eq. (3) would have no sense. If the reduction of 28-day strengths solely depend upon the extra water demand, fc_i value should be fitted in the experimental strength ones.

Fig. 6 gives 2 examples. In Fig. 6a, the corrected values A1 adjusted according to W/C of A3 come closer to the experimental ones of A3 but stay greater. Then it could be thought that the differences between A1 and A3 strengths are partially due to the extra water-effect. On the contrary, Fig. 6b shows that the corrected values are moved away from the experimental ones B3 and are always lower. In that case Feret's relation appears absolutely inadequate.

One can propose an explanation of these scatters by coming back to the basic form of Feret's relation which has to be written like:

$$fc = K\left(\frac{1}{1+F}\right)^{2.2} \quad \text{with} \quad F = \frac{W+V}{C} \tag{4}$$

where K is a function of various parameters such as cement type, aggregate nature, time placing, ... and temperature.

When applying equation (3), the ratio R' implicitly involves that the coefficient K is the same for the two concretes of a given series with different initial aggregate temperatures. So, the conflicting results derived from relation (3) show clearly that the influence of concrete temperature cannot be neglected in the K factor through either an effect of the initial mix temperature solely or in addition a specific effect of the aggregate temperature.

So, all these considerations lead us to think that the extra-water due to higher aggregate temperatures is not the main reason of the drops in concrete strengths. An other explanation has to be investigated 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 the 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.

Conclusions and Prospects

In this investigation, the effect of elevated aggregate temperatures (35°C and 70°C) on the compressive and splitting tensile strengths of plain concrete specimens cured under either controlled laboratory conditions or simulated conditions of hot weather were studied. Following conclusions were obtained:

(1) Drops in 28-day compressive and splitting tensile strengths were observed with the increase in the aggregate temperature, mainly from 20°C to 70°C, while 7-day strengths seem not to be affected.

(2) Drops in 28-day strengths occured as well in controlled laboratory conditions as in initial simulated conditions of hot weather. The 28-day strength of concrete specimens cured in water was greater than the 28-day strength cured in an air room (20°C ± 2°C-60 ± 5% RH).

Furthermore, initial elevated curing temperatures did not hide the effect of elevated aggregate temperatures. These latters might rather be an aggravating factor for the drops in strength of concrete.

(3) The application of FERET's relation did not explain drops in the compressive strengths of concrete by the mere effect of the increased water demand due to the increased aggregate temperatures. So, the initial observations (i.e., studies about the transition zone of summer concrete specimens and the paste-aggregate models) which led to this investigation have to be taken up again. Simultaneously, a microstructural study on concretes made up at the laboratory has also to be carried out.

This experimental program was performed using only siliceous aggregates. Consequently, the same investigation is to undertake with another mineralogical nature of the aggregate.

Acknowledgements

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