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Mechanical characteristics of concrete under initial steam curing using solar energy

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Abstract - *In this article, the study is based on the effect of initial steam curing using solar energy on the mechanical characteristics of concrete for precast concrete production. During the early hours of heating, the concrete reaches the minimum strength considered essential for the rotation of the molds, with which he is able to support loads without deform or loss of bearing capacity. The curing period and temperature, is an important parameter in the steam curing process. An experimental program was conducted to investigate the effect of hardening time by steam curing on the mechanical characteristics of concrete. The concrete specimens were cast with a water/cement ratio of 0.40 and were subjected to steam hardening according to two cycles of covering steam curing of two periods of the year hot and cold at 45 and 29 °C for each one 8 hours, then they are left in the open air cured for 3 and 7 days. The results show that a gain of time and shorter manufacturing lead times to reach the mechanical strengths (compressive strength and flexural) at 28 days in the free air after a one day steam curing and 3 days of hardening in the free air.*

Résumé - *Dans cet article, l'étude est basée sur l'effet de durcissement à la vapeur initiale en utilisant l'énergie solaire sur les caractéristiques mécaniques du béton pour la production du béton préfabriqué. Pendant les premières heures de chauffage, le béton atteint la résistance minimum jugé indispensable à la rotation des moules, avec laquelle il est capable de supporter des charges sans se déformer ou de perte de capacité portante. La période de durcissement et de la température est un paramètre important dans le procédé de durcissement à la vapeur. Un programme expérimental a été réalisé pour étudier l'effet du temps de durcissement par durcissement à la vapeur sur les caractéristiques mécaniques du béton. Les échantillons du béton ont été coulés avec un rapport eau/ciment de 0.40 et ont été soumis au durcissement à la vapeur selon deux cycles d'étuvage couvrant deux périodes de l'année chaude et froide à 45 et 29 °C pour chaque un 8 heures, puis ils sont laissés durcir à l'air libre pendant 3 et 7 jours. Les résultats montrent qu'un gain de temps et plus courts délais de fabrication pour atteindre les résistances mécaniques (résistance à la compression et à la flexion) à 28 jours à l'air libre après un durcissement à la vapeur d'un jour et 3 jours de durcissement à l'air libre.*

Keywords: Concrete - Mechanical characteristics - Initial steam curing - Solar energy - Precast concrete.

1. INTRODUCTION

The needs of the modern world require producing more, faster and cheaper. The setting time and hardening of hydraulic concrete, building materials most used today, is incompatible with the requirements of industrial production. In order to accelerate the setting and hardening concrete heat treatments prominently among the different possible methods.

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An important benefit in terms of improving efficient use of resources such as electricity and combustibles, is harnessing renewable resources of energy, mainly solar energy. Solar energy can effectively be used in regions where solar radiation is very important either in intensity or over a long period yearly. Among these uses, thermal treatment of products like prefabricated concrete elements. Algeria is a region of high solar radiation with more than 220 equivalent days of sun shining a year. The use of heating by evaporation in climatic container having a polyethylene or metal covers permits to improve production capacity of prefabricated concrete elements. The use of solar energy can reduce remarkably the cost of production by reducing energy cost and hence improving the performance of enterprises [1].

The atmospheric steam curing is the way to thermo maturation most used. Atmospheric steam curing is a heat treatment which has been used for many years to accelerate the strength development of precast concrete products. Because of the hydration rate of cement increases with the increase in temperature, the gain of strength can be speeded up by curing concrete in steam. When steam is generated in atmospheric pressure, the temperature is below 100 °C; the process can be regarded as a special case of moist curing in which the vapour-saturated atmospheres ensures a supply of water [2, 3]. It is confirmed that the steam curing at low pressure could improve the quality of high performance concrete incorporating mineral admixtures, comparing with standard curing [4]. Maximum curing temperatures may be anywhere in the range of 40 to 100 °C. However, the optimum temperature has been found in the range of 65 to 85 °C. The curing temperature will be a compromise between rate of strength gain and ultimate strength, because of the higher, the curing temperature, the lower and the ultimate strength [5].

The role of cement type as a binder has a great importance in heat treatment applications. The primary factors determining the behaviour of cements subjected to heat treatment are fineness and composition of cements, the type and amount of additives used in blended cements and curing cycle parameters. For compressive strength development of concrete, duration of steam curing is also an important parameter as well as temperature [6].

The treatment period and temperature is adjusted according to the targeted one day strength level. It is obvious that heat treatment application at a lower temperature is more economical and energy saving [7]. The length of the total curing period must allow for controlled heating application and cooling of the concrete [5]. Practical curing cycles are chosen as a compromise between the early and late strength requirements but are governed also by the time available. Economic considerations determine whether the curing should be suited to a given concrete mix or, alternatively, whether the mix ought to be chosen so as to fit a convenient cycle of steam curing.

Whereas, details of a satisfactory cycle would consist of the following: a preheating (delay) period of 2 to 5 h, heating at the rate of 22 to 44 °C/h up to a maximum temperature of 50 to 82 °C, then storage at maximum temperature, and finally a cooling period, the total cycle (exclusive of the delay period) should be completed preferably not more than 18 h [8].

Erdem *et al.*, [9] concluded that in the delay in the commencement of steam curing operation by a period equal to the initial setting time of cement, higher strengths were obtained when the delay period was equal to the setting time. The hydration rate of cement is greatly affected by a number of factors besides the temperature, so the gain in strength of concrete is also largely controlled by these factors. However, it is clear that the effect of the humidity during curing is a major consideration that cannot be ignored.

Steam curing by atmospheric vapour in concrete enclosures continues until the minimum is reached strength deemed essential to the performance of the element after demolding [10], this minimum would be difficult to determine a priori because it depends on the shape more or less massive parts, and depends on the nature of the stresses to which they submitted after release.

To fix ideas, we may admit that in the absence of any external load, the minimum strength to compressive should be located around 50 to 60% of the required strength (at 28 days under natural conditions) is 10 MPa [8], which can transport and store the parts in concrete rooms for a natural hardening to ambient air in the realization of business without breaking. For this purpose many studies have been conducted to study the influence of temperature on the various mechanisms involved during hydration [11-14].

A temperature raises during the early stages of hydration increases the development of strength but has adverse consequences on long-term properties [11]. This results in a faster hydration but promotes the development of a coarser porous network. Density and crown size of inner C-S-H are increased [12], portlandite crystallizes preferentially in massive clusters rather than as thin hexagonal platelets [14] and rates of sulfate measured in C-S-H are more important [13,15-17]). The effects of temperature on mechanical characteristics have been attributed to an increased polymerization of the chains of silicates [18] that dense and regidifient C-S-H [19,20].

The objective of this study is to evaluate through experiments the effect of initial steam curing by solar energy on the mechanical characteristics of concrete.

2. EXPERIMENTAL PROGRAM

Here is presented the materials used, study of the temperature in the steam curing chamber and at ambient air, formulation of concrete and the preparation of specimens

2.1 Materials

The cement that was used is composed Portland cement CPJ-CEM II/A 42.5 (Ain Touta (Batna)). Fineness = 3300 cm^2/g, apparent density = 1215 kg/m^3 and specific density = 3150 kg/m^3. The chemical analysis of cement shows that it is in conformity with NFP 15-301 standard. The potential mineralogical composition of the cement is calculated according to the empirical formula of Bogue [21]. Chemical and mineralogical compositions are presented in **Tables 1** and **2**, respectively.

Table 1: Chemical composition of cement (%)

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Free CaO	IR	LOI
20.34	5.37	3.00	61.69	1.80	1.20	0.97	1.12	4.51

IR- Insoluble residue , LOI- Loss on ignition

Table 2: Mineralogical composition of cement (%)

C_3S	C_2S	C_3A	C_4AF
56.10	16.30	9.20	9.10

The water is drinking water that contains little sulphate and having a temperature of 20 ± 1 °C. Its quality conforms to the requirements of NFP 18-404 standard.

The sand used (0/5 mm) is from the Biskra region (River Oued-Djedi). It with is noted that the grading curve of our sand fits in the spindle recommended by the current concrete.

The grading curve of sand is given in figure 1. Apparent density = 1630 kg/m^3, Specific density = 2650 kg/m^3, Fineness modulus = 2.82 (sand is suitable for a satisfactory workability and strength with limited risk of segregation) and sand equivalent (sight) = 80.10 (argillaceous sand of acceptable cleanliness for concretes of current quality).

Fractions of crushed stone was used (7/15 and 15/25 mm) the Ain-Touta (Batna) region. The grading curves of gravels are given in figure 1. Apparent density = 1410 kg/m^3, Specific density = 2600 kg/m^3 and coefficient of Los Angeles = 21% (hard).

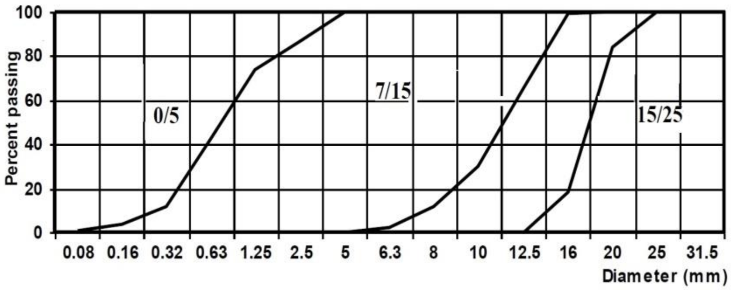

Fig. 1: Grading curves of sand and gravels

2.2 Study of the temperature in the steam curing chamber and at ambient air

Our study is to first identify the temperatures in the free air using a thermometer and within the steam curing chamber exposed to solar radiation (figure 2) for 12 months of the year (from 01 January to 31 December 2012), the average of these monthly recordings are illustrated in figure 3.

Fig. 2: Steam curing chamber exposed to solar radiation

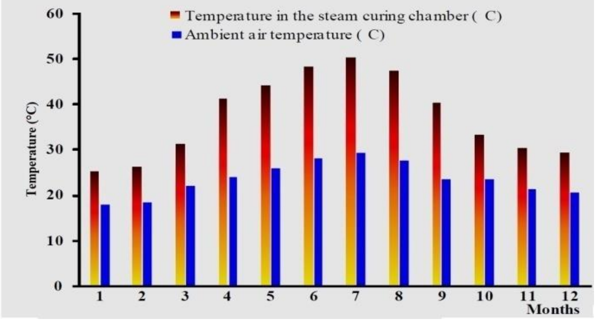

Fig. 3: Monthly exchange in ambient air temperatures and the steam curing chamber

2.3 Formulation of concrete

The optimizing the formulation of concrete-based on several criteria that are often a compromise between them: consistency, strength, durability and economy. Multiplicity of used methods to determine the concretes compositions was used that gives accurate results and seems to be the least known. This is the method of B. Scramtaiv. This method relies on the fact that the sum of the absolute volumes of original material in a cubic meter is equal to the volume of the composition of tamped concrete [22].

Whose consistency is such that its cone slump of 7 cm. In all tests the $\omega/c = 0.4$, $A=0.6$, $D_m=25\text{mm}$ and $S/CS=0.33$. The composition of concrete is reported in **Table 3**.

Table 3: Composition of concrete (kg/m^3)

Cement	Sand	Crushed stone (7/15)	Crushed stone (7/15	Water (1)
512.50	407	432	802	205

From the graphs of the temperature variation with time of 12 months of the year, we can say that for six months from April to September the average temperature coefficient ($K_1=1.70$), and October to March the average temperature coefficient ($K_2=1.40$).

$$T_{\text{in steam curing chamber}} = K \times T_{\text{air temperature}}$$

With: T is the temperature in °C and K: the average temperature coefficient.

Based on the results deduced from the variation of temperature versus time inside the chamber (figure 3), we select the six months which corresponds to the seasons: (spring and summer) as shown in **Table 4**. We choose for steam curing a cycle 1: (3×8×3) with a maximum temperature bearing 45 °C as shown in figure 4.

Table 4: Cycles of steam curing and maximum temperature (Spring – Summer)

Months	April	May	June	July	Aug.	Sep.
Cycles (**h×h×h**)	**3×8×3**	**3×8×3**	**3×8×3**	**3×9×3**	**3×9×3**	**3×8×3**
Temp. max in The chamber	41	44	48	50	47	40

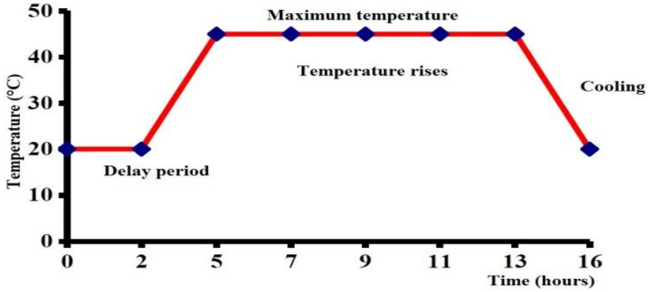

Fig. 4: Schematic representation of steam curing (1 cycle)

We do the same for the other six (06) months representing (autumn and winter) as shown in **Table 5**. We choose for steam curing a cycle 2: (3×7×3) with a maximum temperature bearing 29 °C as shown in Fig.5.

Table 5: Cycles of steam curing and maximum temperature (Autumn - Winter)

Months	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.
Cycles (**h×h×h**)	**3×8×3**	**3×7×3**	**3×7×3**	**3×7×3**	**3×7×3**	**3×8×3**
Temp. max in The chamber	33	30	29	25	26	31

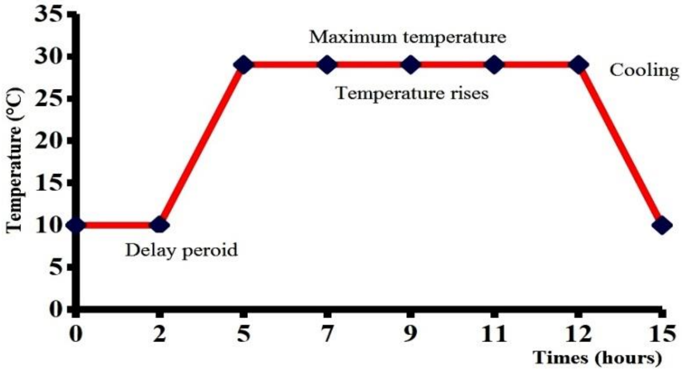

Fig. 5: Schematic representation of steam curing (2 cycle)

2.4 Preparation of specimens

(100×100×100 mm) cubic samples were used for compressive strength tests and (100×100×400 mm) prismatic specimens were used for flexural strength tests. For both compressive and flexural strength, three samples were tested and then their values averaged [22].

The concretes studied: a control concrete stored in water at an ambient temperature of 20 ± 1 °C, concrete cured outdoors without irrigation, and concretes subjected to two cycles of steam curing. The steam curing cycle must include four phases: delay period; temperature rises; maximum temperature and cooling.

After mixing the concrete, the specimens are preserved in plastic to prevent evaporation of water from the concrete, after demolding, the specimens are introduced into the steam curing chamber by solar energy with the rise of the temperature in the chamber, the thermometer was placed outside of the chamber can adjust the temperature level selected at 45 °C in the chamber for the warm period of the year (6 months from October to March) and 29 °C for the cold period (6 months from April to September), for durations of steam curing 1, 2, 3 and 7 days hardening in open air without spraying of 3 and 7 days.

3. RESULTS AND DISCUSSIONS

3.1 Consistency

It is important to know the properties of concrete in fresh state before setting and hardening. Among these properties, consistency can be defined as the ease of implementation of concrete. The slump test to Abrams cone NF P18-451 is currently in use worldwide, it provides reliable measurements of small variability. Depending slump obtained, class consistency of different concrete is plastic (slump varies from 6 to 8 cm).

3.2 Mechanical characteristics

The strengths are estimated at 1, 2, 3 and 7 days of steam curing, 28 days in wet and dry. The compressive tests were performed on a hydraulic press with a measuring range of 3000 kN. The results of compressive and flexural strength of concrete in the open air, in water and concretes having undergone, a steam curing are given in **Tables 6**, **7** and **8**.

- 1, 2, 3 and 7 days of the steam curing chamber: the results of the steam curing chamber are presented in **Table 6**.

Table 6: Compressive and flexural strength of concrete
(1, 2, 3 and 7 days of the steam curing chamber)

Concrete	Hardening in the open air without watering	Hardening (in water)	Steam curing at 45 °C				Steam curing at 29 °C			
Age (days)	28	28	1	2	3	7	1	2	3	7
Cycles (h×h×h)	/	/	3×8×3	3×8×3	3×8×3	3×8×3	3×7×3	3×7×3	3×7×3	3×7×3
Compressive strength (MPa)	40.70	43.00	30.70	33.70	35.50	37.00	23.60	26.40	30.30	33.20
Percentage of hardening (%)	100	/	75	83	87	91	58	65	74.40	81.60
Flexural strength (MPa)	2.21	3.60	1.35	1.55	1.83	1.90	1.35	1.45	1.61	1.79
Percentage of hardening (%)	100	/	61	70	83	86	61.10	65.60	72.90	81.10

- 1 day of steam curing at 45 °C and hardening of 3 and 7 days : the strengths estimated from (1 day of steam curing and hardening of 3 days) and (1 day of steam curing and hardening of 7 days), for steam curing at 45 °C are shown in **Table 7**.

Table 7: Compressive and flexural strength of concrete
(1 day of steam curing at 45 °C + hardening of 3 and 7 days)

Strength (MPa)	1 day of steam curing at 45 °C + hardening in the open air at 3 days	Percentage of Hardening (%)	1 day of steam curing at 45 °C + hardening in the open air at 7 days	Percentage of hardening (%)
Compressive	40	99	43	105
Flexural	1.80	82	2.00	90

- 1 day of steam curing at 29 °C and hardening of 3 and 7 days: the strengths estimated after (1 day of steam curing and hardening of 3 days) and (1 day of steam curing and hardening of 7 days), for steam curing at 29 °C are shown in **Table 8**.

Table 8: Compressive and flexural strength of concrete
(1 day of steam curing at 29 °C + hardening of 3 and 7 days)

Strength (MPa)	1 day of steam curing at 29 °C + hardening in the open air at 3 days	Percentage of Hardening (%)	1 day of steam curing at 29 °C + hardening in the open air at 7 days	Percentage of hardening (%)
Compressive	39.30	96.50	41.00	100
Flexural	1.43	64.70	1.62	73.30

3.2.1 Period (spring - summer) at 45 °C

The months of April-September the results show that treatment with steam curing in the chamber ensures a rapid increase in compressive strength for: 1, 2, 3 and 7 days of steam curing at 45 °C, are: 30.7, 33.7, 35.5 and 37.0 MPa, which are: 75, 83, 87 and 91 % of the strength of hardened concrete even under natural conditions to 28 days respectively.

Compressive strength of one day steam curing at 45 °C (08 h of oven) and hardening of 3 and 7 days under natural conditions, which are: 40.3 and 43 MPa, are: 99 and 105%

of the strength of the hardened concrete even under ambient conditions at 28 days respectively.

A gain of time and shorter manufacturing lead times to reach the compressive strength at 28 days in the free air after a day steam curing at 45 °C and 3 days of hardening in the free air.

An increase in flexural strength as a function of time for 1, 2 and 3 days and hardening of 3 and 7 days under natural conditions.

3.2.2 Period (autumn - winter) at 29 °C

For the months of October to March:

1 day of steam curing at 29 °C: 23.6 MPa, which shows: 58% of the strength of hardened concrete even under natural conditions to 28 days.

1 day steam curing concrete at 29 °C (08 h of steam curing) and hardening of three days under natural conditions, which presents: 39.3 MPa, or 96.5% of the strength of hardened concrete even under natural conditions to 28 days.

1 day steam curing concrete at 29 °C and 7 days of hardening under natural conditions, which presents: 41.0 MPa, 100% of the strength of hardened concrete even under natural conditions to 28 days.

An increase in compressive strength and flexural as a function of time which also ensures demolding of the molds only after a one day steam curing and 3 days of hardening in the free air.

3.3 Mass loss in the steam curing chamber at 45 °C and 29 °C

The quantification of water lost between the demolding and the release of specimens of the steam curing chamber was done through a balance has a capacity of 10 kg and an accuracy of 0.01 g. It has been used for the determination of the mass of the specimens before and after two cycles of steam curing and hardening to the ambient air.

Table 9: Mass loss in (g) of the cubes and prisms at 45 °C

Specimens	Hardening in the open air without watering at 28 days	Steam curing				1 day of steam curing chamber + hardening in the open air at 3 days	1 day of steam curing chamber + hardening in the open air at 7 days
		1 day	2 days	3 days	7 days		
Cubes	35	24	46	68	149	30	45
Prisms	110	90	130	185	240	102	120

Table 10: Mass loss in (g) of the cubes and prisms at 29 °C

Specimens	Hardening in the open air without watering at 28 days	Steam curing				1 day of steam curing chamber + hardening in the open air at 3 days	1 day of steam curing chamber + hardening in the open air at 7 days
		1 day	2 days	3 days	7 days		
Cubes	35	20	40	60	128	27	40
Prisms	110	80	120	175	220	93	111

The results presented in **Tables 9** and **10**. The mass losses for both steam curing at 45 °C and 29 °C between the demolding castings of concrete and time of the test for different ages of 3 and 7 of hardening caused by the creation of very fine cracks caused by the expansion of air bubbles in the cement paste and the evaporation of the capillaries water of concretes.

4. CONCLUSION

In light of the tests carried, the following conclusions could be drawn:

These results well justify interest that present the hardening technique to the initial steam by the solar energy for allows rapid formwork removal a short-term resulting in an accelerated gain of mechanical characteristics and a great economy of electrical energy, accelerating the cement hydration reactions, acceleration cadences by reducing the taking time, so a faster advancement of construction workshop and accelerated rotation especially in precast plants.

The demolding of the molds is assured after all steam curing (by solar energy at 45 °C or 29 °C), since we met and it exceeds the minimum strength to compressive which is approximately 10 MPa after one day of steam curing, which ensures high productivity molds.

We reached the 28 days strength after a day and 3 days of hardening in open air, for 02 types of steam curing, which has a gain of time and shorter manufacturing lead times.

The plastic concrete works to heat treatment, for a temperature of 45 °C in steam with 8 hours of heat treatment with a pre made, the strength reach 75% of the control concrete strength of 28 days of normal hardening, also the fall of mechanical characteristics at the age of 28 days of a concrete treated compared to concrete o f control is around 10%.

In the absence of solar energy (solar radiation insufficient) electrical energy is used to a temperature of 45 °C.

The technique of atmospheric steam curing in Algeria which is rich in solar energy, and use of this renewable energy in the heat treatment of parts of reinforced and prestressed concrete in areas with high solar radiation concentrated and long periods of time, this reduces the cost of concrete parts, leading to a remarkable saving of costs for production companies, as well as changes in productivity to the concrete industry.

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