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Influence of atmospheric steam curing by solar energy on the compressive and flexural strength of concretes

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HIGHLIGHTS

- Accelerated hardening of the steam curing by solar energy of concretes.
- A good strength and high electrical energy saving for precast concretes production.
- A gain of time and shorter manufacturing lead times.
- Beneficial effect of a steam curing to achieve high strength especially in the earlier ages of curing.

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ABSTRACT

In this paper, influence of atmospheric steam curing by solar energy on the compressive and flexural strength of concretes for precast elements was investigated. An experimental program was carried out to studying in parallel the effect of water/cement ratio (0.4, 0.5 and 0.6), the influence of cement type and the influence of curing methods (four methods of curing were used: water curing, air curing, steam curing at 29 °C and steam curing at 45 °C) on the compressive and flexural strength of concretes. Six formulations of similar workability made from ordinary Portland cement (CEM I 42.5) and a composite cement (CEM II/B 42.5) three of each type are studied. The results allow us to highlight the beneficial effect of a steam curing procedure to achieve high compressive and flexural strength, especially in the earlier ages of curing. However, after 28 days of steam curing, a strength reduction was observed in all samples. The technique of steam curing by solar energy is an effective technique for accelerated hardening of concretes, for a good strength and high electrical energy saving for precast concretes production. We can say that the increased compressive strength during the progress of the reaction of hydration is accompanied by an increase in flexural strength. Through the results obtained a gain of time and shorter manufacturing lead times to reach the compressive strength at 28 days in the free air after a one day steam curing and 3 days of hardening in the free air for the two types cement and the different *w/c* ratios.

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1. Introduction

Development of conventional forms of energy for meeting the growing energy needs of society at a reasonable cost. In recent years, public and political sensitivities to environmental issues and energy security have led to the promotion of renewable energy resources (such as solar energy) [1]. It is very important to apply solar energy for a wide variety of applications and provide energy solutions by modifying the energy proportion, improving energy stability, increasing energy sustainability, conversion reduction and hence enhance the system efficiency [2]. 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 [3]. The curing method used for precast concrete products differs from the normal curing method where steam curing is usually employed because it accelerates the rate of strength development. However, this curing method alters the properties of the resulting concrete [4,5]. For the production of

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concrete and reinforced concrete prefabricated structural elements, and for increasing the reuse of formworks and the performance of climatic containers, it is sufficient to maintain heating by evaporation until the strength at 28 days is reached which will help in transporting these prefabricated structural elements without damaging them. After that, the final strength will be reached in the normal storage areas. Steam curing at atmospheric pressure is an important technique for obtaining high early strength values in precast concrete production. Cement type, as well as curing period and temperature, are the important parameters in the steam-curing process [6]. It has been generally accepted that the performance of hardened cementitious composites is greatly dependent on the curing temperature and duration as well as environmental conditions. In particular, steam curing with heat treatment at high temperature is commonly used in the production of precast concrete elements to increase the rate of hydration and accelerate early-age strength development. It was reported that the optimum maximum temperature of steam curing was near 60 °C considering strength and the increase of procuring time increased the strength of concrete [7]. 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 vapor-saturated atmospheres ensures a supply of water [8,9]. 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 [10]. Maximum curing temperatures may be anywhere in the range of 40–100 °C. However, the optimum temperature has been found in the range of 65–85 °C. The curing temperature will be a compromise between rate of strength gain and the ultimate strength, because of the higher, the curing temperature, the lower and the ultimate strength [11]. The role of cement type as a binder has a great importance in heat treatment applications. The primary factors determining the behavior of cements subjected to heat treatment are fineness and composition of cements, the type and quantity of mineral additions used in blended cements and the curing cycle parameters. For compressive strength development of concrete, duration of steam curing is also an important parameter as well as temperature [12]. The treatment period and temperature is adjusted according to the targeted 1 day strength level. It is obvious that heat treatment application at a lower temperature is more economical and energy saving [13]. A temperature raises during the early stages of hydration increases the strength development [9,14,15]. The steam curing enhanced the 1-day compressive strength and ultrasonic pulse velocity while causing loss of long term strength. Indeed, an initial rapid hydration can lead to the formation of hydration products have a physical structure less compact, this will lead to a lower strength compared to less porous concrete, hydrated slowly with a water curing [9,15–17]. The length of the total curing period must allow for controlled heating application and cooling of the concrete [11]. 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 2–5 h, heating at the rate of 22–44 °C/h up to a maximum temperature of 50–82 °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 [18]. Erdem et al. [4] 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 vapor in concrete enclosures continues until the minimum is reached strength deemed essential to the performance of the element after demolding [19], 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 [18], 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 [14–16,20–23]. The required objective is to evaluate through experiments the influence of atmospheric steam curing by solar energy on the compressive and flexural strength of concretes.

2. Experimental program

Here is presented the materials used, study of the temperature in the steam curing chamber and at ambient air, testing method and concretes compositions, samples preparation and tests conducted.

2.1. Materials

2.1.1. Cement

Two cements from the same clinker are used: an ordinary Portland cement (CEM I) class 42.5 MPA and a composite cement (CEM II/B) class 42.5 MPA with 35% to limestone fillers. The clinker is from the cement factory of M'sila. The chemical and mineralogical compositions of cements are presented in Tables 1 and 2, respectively. The potential mineralogical composition of the cements is calculated according to the empirical formula of Bogue [24]. The physical properties of cements are shown in Table 3.

2.1.2. Water

The water is drinking water that contains little sulfate and having a temperature of 20 ± 2 °C. Its quality conforms to the requirements of NFP 18-404 standard.

2.1.3. Sand

The sand used (0/5 mm) is from the Biskra region (River Oued-Djedi). Apparent density = 1697 kg/m^3, specific density = 2600 kg/m^3, fineness modulus = 2.82 (sand is suitable for a satisfactory workability and strength with limited risk of segregation), sand equivalent (sight) = 80.10 (argillaceous sand of acceptable cleanliness for concretes of current quality). The grading curve of sand is given in Fig. 1.

2.1.4. Crushed stone

Fractions of crushed stone was used (3/8, 8/15 and 15/25 mm) the Ain-Touta (Batna) region. Apparent density = 1340 kg/m^3, specific density = 2610 kg/m^3 and coefficient of Los Angeles = 20% (hard). The grading curves of gravels are given in Fig. 1.

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 (Fig. 2) for 12 months of the year (from 01 January to 31 December 2012), the average of these monthly recordings are illustrated in Fig. 3.

2.3. Testing method and concretes compositions

An experimental program was carried out to studying in parallel the effect of water/cement ratio (0.4, 0.5 and 0.6), the influence of cement type and the influence of curing methods (four methods of curing were used: water curing, air curing, steam curing at 29 °C and steam curing at 45 °C) on the compressive and flexural strength of concretes. Concrete samples were manufactured from six mixes of similar workability made from ordinary Portland cement (CEM I 42.5) and a composite cement (CEM II/B 42.5). The optimizing the formulation of concrete-based on