

Experimental Study on the Measurement of Some Physical Quantities for the Durability of Concrete under Hot-Arid Climatic Conditions

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Abstract

The synthesis of work carried out on the behavior of concrete subjected to temperature has allowed us to highlight certain physical phenomena, which can appear in particular during the degradation of the material. Among these phenomena are the evolution of porosity and apparent density during heating, which are two important physical quantities of cementitious materials, and they play a major role in the durability of concrete. In this context, the main objective of this experimental study is to improve the understanding of the behavior of tested concrete subjected to different temperature gradients, for hot and arid regions. To achieve this, some tests related to durability (open porosity and apparent density) were carried out in order to identify the origin of any disparities that were observed following the analysis of mechanical results.

Keywords: Physical characterization, durability, concrete, hot-arid, climatic.

1. Introduction

The detailed experimental study of concrete has always been a complex exercise. This complexity is linked to the material's variability, which depends on its composition, packaging, and the mechanical, thermal, or chemical stresses to which it is subjected. Therefore, it is necessary to specify, in addition to the nature of the experimental characterization, the composition and history of the material. Precision and rigor must always be two major characteristics of an experimental study on this type of material [3, 15]. This complexity in the characterization of concrete has amplified the need for experimental studies to understand and explain the material's behavior.

The synthesis of observations and experiments concerning the effect of temperature on concrete has shown that the evolution of mechanical properties is strongly linked to the evolution of microstructure, water loss, and dehydration reactions, which is reflected by the evolution of porosity and pore size. According to various authors such as [1, 6, 7, 8, 9, 10, 13 and 14], the total porosity of concrete increases with temperature due to the appearance of micro cracks.

These micro cracks can be caused by the dehydration of the cement paste [1] and the incompatibility of deformation between aggregates and the cement paste. On the other hand, [4, 5, 6, 13, 16, and 24] studies have shown that the evolution of porosity is mainly linked to the cement paste but also to the aggregate/paste interface, regardless of the type of concrete. Alarcon-Ruiz et al. (2002) [1] demonstrated that the porosity of a cement paste is strongly modified with temperature, increasing from 22% for an unheated sample to 40% for a sample heated to 600°C.

The porous structure of concrete is complex and there are several methods to characterize it. The voids in concrete are open and interconnected, and therefore porosity can be confused with "open porosity" and "open interconnected porosity." The most commonly used measurement method is that of the "porosity accessible to water," which involves saturating the material under vacuum, determining the apparent volume using hydrostatic weighing, and calculating the volume of the voids by difference between the mass of the saturated sample and that measured after drying [1, 5, 7, 19, 8, 17, and 20]. The method is subject to recommendations that set, among other things, the

minimum sample size and drying methods [17]. However, it is important to avoid counting chemically bound water as free water, as these can lead to inaccurate results [8, 12 and 17].

Determining the pore size is much more complex. The porous space is continuous and it is not easy to describe it by an assembly of pores having simple geometric shapes. In practice, the measurement methods use different principles and each of them responds to a convention for the definition of the pore and its size. Three methods are mainly used to characterize the porous structure of concretes. The first is based on the exploitation of "water sorption isotherms". It assumes that there is coexistence of liquid water condensed in the pores and water adsorbed on the walls of the pores. The pore size distribution is obtained from the desorption curve. The second method, which uses "image analysis" generally obtained by scanning electron microscopy. However, this method is not very suitable for the study of the porous structure of concrete because it requires considerable quantities of images to have a significant representation, and pore size is not uniform in the concrete. The third and most commonly used method is "mercury porosimeter". In this method, previously dried samples subjected to increasing pressures of mercury. The non-wetting liquid gradually penetrates the material and fills the pores. However, prior drying of the sample can alter its microstructure, making it difficult to compare at a obtained with different protocols. To facilitate comparisons, the AFGC has proposed a commendation for the preparation of samples [17].

In this context, the aim of this experimental work is to contribute to the study of the influence of climatic thermal gradients on the evolution of two physical properties, namely porosity and apparent density, for different types of concrete. The study was conducted in a residual state, which involved observing the variation of the tested properties after a heating and cooling cycle to the test temperature and ambient temperature, respectively. The residual physical properties were monitored using three different types of concrete compositions.

2. Materials Used and Formulation Materials Used

The materials that are the subject of this study are concretes of composition setup especially for the needs of the study. The characteristics studied were established at the reference state and compared with

those determined at different thermal gradients. Two measurement methods have been adopted: measurements under thermal loading (cold and hot) and residual measurements (after cooling).

In addition, the aggregates used to make the material are of local origin, which implies great variability from one production site to another. You have to be aware that the result obtained, after experimentation on concrete, depends on all of this variability. The concretes studied here are classic, that is to say that their compositions, their implementation, their mode of production are common in civil engineering, which makes it possible to highlight the general features of their mechanical behavior. A single type of cement was used for the manufacture of all compositions. It is a sulphate-resistant Portland cement (CRS) of the CPACEMI/A42.5 type, and which meets the Algerian standard (NA443). Thielemans's essentially made up of clinker, more than 97%, and less than 3% of filler.

Formulation and characterization of concretes in the fresh state. As part of this study, the concrete formulations were first determined using the Dreux Gorisse method [11], and then optimized using the Baron-Lesage technique [4]. The optimum gravel/sand ratio (G/S) was determined to achieve the maximum slump for a given amount of cement and water [17]. Once the granular proportions were identified, the water and cement dosages were adjusted experimentally to achieve the desired workability and strength. For each concrete mix, the following properties were determined: consistency/workability, entrained air content, and experimental density. The three prepared concrete mixes were plastic, with a slump between 5 and 5.6 cm, and were placed with normal vibration (ENV 206-1). The air content in the mixtures was acceptable according to the relevant standard [NFEN12350-7]. The actual density was obtained by dividing the weight of the container (filled with concrete and weighed, minus the weight of the empty container) by the volume of the container.

The cylindrical specimens, with a height of 320 mm and a diameter of 160 mm, were prepared. The mixing and placing protocols of the different constituents of concrete in the molds followed the standards [NF XP P 18-303], [NF P 18-400], [NF P 18-404], [NFP18-421], and [NFP18-422]. According to [BS 188-1111], after smoothing the surface of the cylinder with a trowel, the cylinder was left in a temperature of $20 \pm 5^\circ\text{C}$ for

24±4hours. After this period, the cylinder was demolded and cured in water at room temperature [2].

The standard [ASTM C 470-94] specifies the specifications relating to cylindrical specimens. The method of making test cylinders is given in standards [BS1881-110] and [ASTMC192-90a]. The mixing of the concrete was carried out using a mobile mixer with a capacity of 50 liters, equipped with an emptying hatch and adjustable molds. The concrete was placed in the molds in two layers of equal importance, in accordance with standard [NF P 18-422], using a vibrating needle [9, 17]. The duration of vibration was sufficient to ensure the compactness of the concrete, but it must not be prolonged beyond the necessary time, otherwise segregation could occur [4]. Finally, the upper surface of the specimen was leveled using a leveling rule, in accordance with standard [NF P 18-404].

3. Measurement Procedure

Porosity and density are two important physical quantities of cementitious materials that play a major role in the durability of concretes. In this section, we will present the procedure for measuring the porosity accessible to water and the apparent density of concretes on samples previously brought to temperature. Before proceeding with the weighing of the test bodies, they were prepared beforehand. The samples are 1/4 of a cylinder with Adia meter of 160mmx 50mm, taken from cylinders (16x32 cm). Two control specimens of each concrete were prepared, as well as two per temperature.

All measurements were performed under transient conditions. For this type of heat treatment, four temperature cycles were applied with different stop temperatures: - 25°C, -5°C, -45°C, and 65°C (see Figure 1).

The first phase (I) consisted of keeping the samples at room temperature ($T=25^{\circ}\text{C}$) for one hour. The second phase consisted of a temperature ramp, followed by a ten-hours well time at the measurement temperature (phase III). In this case, the tests were conducted after the thermal cycle, when the sample was at the test temperature, and after cooling down to ambient temperature.

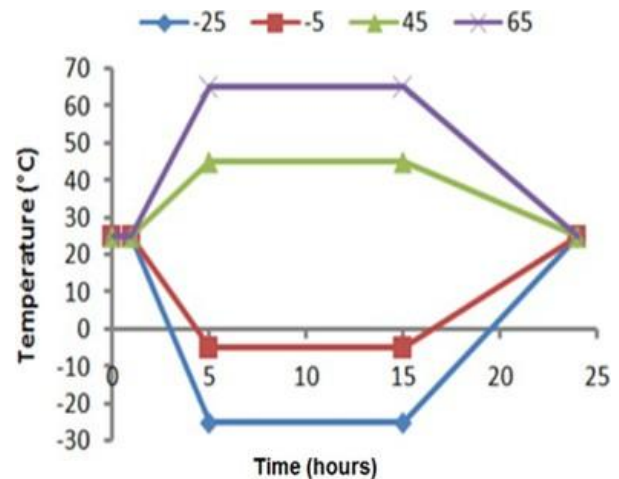


Figure. 1: The real cycle in transient state

4. Porosity Accessible to Water Densities of Concretes

The procedure described here follows the recommendations of the AFPC AFREM [17], which allows for estimating the overall or open porosity. The method is based on hydrostatic mass measurements of the samples. First, the dry mass of the specimen is taken. Then, the specimens are placed in a sealed container in which a vacuum of 25 m bar is applied. After 24 hours, water is gradually introduced until the specimens are completely submerged. Initially, the immersion is carried out on half the height to the samples for 15 minutes, followed by total immersion. This process reduces air entrapment in the heart of the samples. The vacuum is maintained for the next 24 hours.

After this cycle, the saturated mass of the sample immersed in water is weighed on a hydrostatic balance, followed by the saturated mass of water. Before weighing, each specimen is wiped with a damp cloth to remove excess water from the surface. The measurement of Densities of concretes was carried out by taking the results obtained during the determination of the porosities with water.

5. Experimental Results and Discussion

The results of the variation of the porosity accessible to water and the apparent density of the different concrete in the hardened state, according to the temperature ranging from -25°C to 65°C , are summarized in Table 1.

Table 1: Water accessible porosity and apparent density of tested concretes

Concrete	T (°C)	Average Value		Relative Value (%)	
		Porosity (%)	Apparent density (g/cm ³)	Porosity	Apparent density
C(C-S)	-25	10.81	02.49	105.36	105.95
	-05	10.85	02.48	101.64	105.53
	+25	10.87	02.35	100.00	100.00
	+45	11.34	02.31	105.47	98.29
	+65	11.94	02.25	110.54	95.74
C(C'-S)	-25	09.50	02.58	103.85	107.05
	-05	09.52	02.44	103.17	101.24
	+25	09.54	02.41	100.00	100.00
	+45	10.23	02.30	106.84	95.43
	+65	10.50	02.26	109.34	93.77
C(SL-C)	-25	11.87	02.49	114.35	108.73
	-05	11.95	02.46	106.98	107.42
	+25	12.02	02.29	100.00	100.00
	+45	12.84	02.24	112.84	97.81
	+65	17.22	02.16	117.22	94.32

5.1. Porosity Accessible to Water

Figure 2 shows the evolution of porosity as a function of temperature for the different concrete mixes tested. The values obtained are residual values obtained after the cycle of heating up and cooling down to ambient temperature. Thus, the results of the variation of deviation as a function of temperature are presented graphically in Figure 3. as a function of temperature

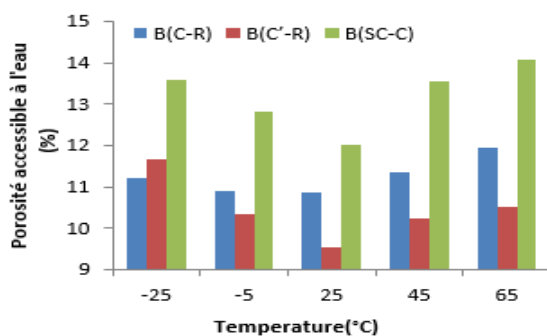


Figure.2: Evolution of the porosity accessible to water as a function of temperature

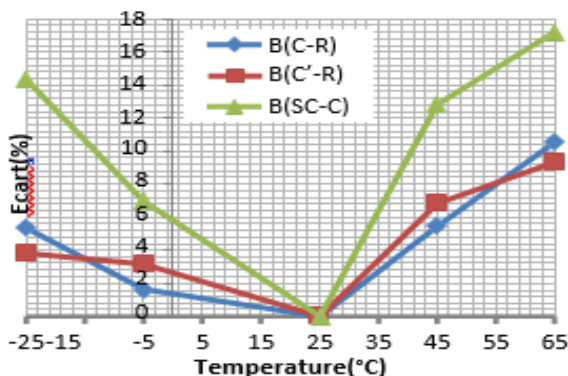


Figure. 3: Variation of porosity accessible to water as a function of temperature

From these figures, we observe an increase in total porosity with rising temperature for the different types of concrete studied. However, this increase varies according to the temperature range in which the concrete is subjected. It is more significant in the range between 25°C and 65°C than that between -25°C and 25°C, as shown in Figure 3.

In this last phase, the total porosity increases very little for all the compositions prepared, compared to that recorded at high temperatures. At a temperature of -25°C, there is a slight increase of 3.85% and 5.36% compared to the reference state for C(C'-S) and C(C-S), respectively, but that of C(SL-C) increased by 14.35%. On the other hand, at a temperature of 65°C, the total porosity of the concretes studied increases compared to the reference state by 10.54% for C(C-S), 9.34% for C(C'-S), and 17.22% for C(SL-C).

Heating to 65°C, linked to the evaporation of free water, leads to a slight increase in the porosity of the solid skeleton. This confirms the fact that at this temperature, part of the free water has escaped but the microstructure of the concrete is not modified. Thus, we notice that the porosities of the two concretes C(C-S) and C(C'-S) increase in a substantially equal way. This is explained by the very similar composition of the two concretes (limestone aggregates).

Heat treatment leads to an increase in total porosity and pore size, regardless of the concrete type. The impact of heating is more significant for concrete made with sand-limestone aggregates, resulting in increased porosity caused primarily by the transformation of small pores into large pores, probably due to the rupture of capillary wall under the effect of water vapor pressure generated by the temperature rise [18, 19, and 20]. Another cause of increased large pores is likely to be microcracking due to thermal stress [21].

5.2. Densities of Concretes

The measurements of the apparent density for the three prepared concretes C(C-S), C(C'-S), and C(SL-C) in the hardened state, as a function of temperature ranging from -25°C to 65°C, are shown in Figures 4 and 5. According to the latter, we observe a decrease in density with an increase in temperature. The increase in temperature up to 45°C does not have a significant influence on the apparent density. The decrease in density, compared to that measured at room temperature, is 1.71% for concrete C(C-S), 2.19% for C(SL-C), while that of concrete C(C'-S) is 4.57%.

Figure 4 shows that after drying at 65°C, a more remarkable decrease in the density of concrete C(C'-S) is observed compared to those of C(SL-C) and C(C-S), respectively. The decrease is 6.23% for C(C'-S), 5.68% for C(SL-C), and 4.26% for C(C-S).

Additionally, the nature of the aggregates appears to have an influence on the evolution of the apparent density as a function of temperature. Therefore, this variation in apparent density is probably associated with various parameters, such as their loss of free water, the composition of the concrete, the nature of the aggregates, and the appearance of microcracking.

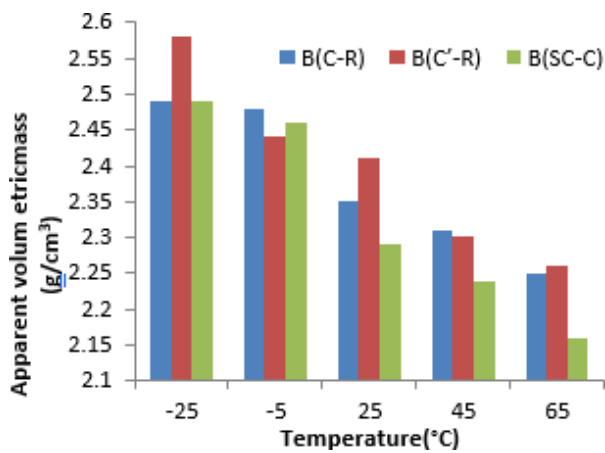


Figure 4: Apparent density of concretes as a function of temperature

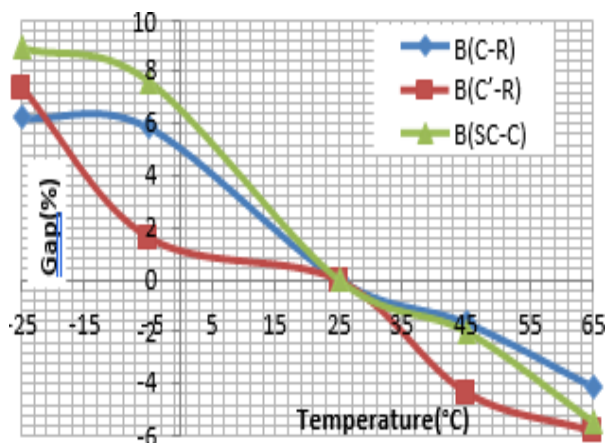


Figure 5: Evolution of the difference in the apparent density of concretes as a function of temperature

6. Conclusion

Concrete is a heterogeneous material that inevitably contains air, which has rather harmful consequences on the mechanical characteristics of concrete. Consequently, porosity and apparent density represent two important physical parameters of cementitious materials, which play a major role with regard to the durability of concrete.

The synthesis of the observations and experiments carried out under transient conditions showed that the evolution of the physical properties is strongly related to the departure of free water and the evolution of the concrete microstructure. This is reflected in the evolution of porosity and, consequently, in the loss of mass. Among the parameters significantly influencing the behavior of concrete at high temperatures is the presence of water in the material.

An increase in total porosity was observed with the increase in temperature, for the different types of concrete studied. However, it varies according to the temperature range to which the concrete is subjected. Heating to 65°C, linked to the evaporation of free water, leads to a slight increase in the porosity of the solid skeleton. This confirms the fact that at this temperature, part of the free water has escaped but the micro structure of the concrete is not modified. Regarding the apparent density, we observed that it is slightly low for all types of concrete. An inversely proportional relationship is shown between temperature and density, where an increase in temperature causes a decrease in the material's density. This variation in apparent density is most likely associated with various parameters such as the departure of free water, the composition of the concrete, the nature of the aggregates, and the appearance of microcracks.

7. Acknowledgements

This work is part of a research axis of the "Study and Use of Innovative Materials in Civil and Mechanical Construction" team of the laboratory to which it belongs. This axis aims to contribute to the improvement of the performance/cost ratio of materials used in the general field of construction. The team's work will cover a wide range of studies on the use of materials ranging from traditional materials to innovative materials. Therefore, the envisaged research aims to improve the properties of materials through the use and valorization of local materials (e.g., materials based on plant particles). The research will also focus on the thermo-mechanical and mechanical behavior of various materials, including complex composite materials (stitched composites). This development requires a very fine understanding and knowledge of the characteristics of the components of a material based on experimental, numerical and analytical approaches.

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