Experimental study on the characterization of mechanical behavior of concrete under hot-arid climatic conditions

benoudjafer Imane [2][0000-1111-2222-3333], Benoudjafer ibtissam[1][0000-1111-2222-3333],

[1] Department of civil engineering, LMS laboratory, tahri Mohamed Béchar university, Béchar,

[2] Department of architecture, laboratory of LMS, tahri Mohamed university of Béchar, Béchar, Algeria

Algeria

banoudjafer.imane@univ-bechar.dz

ABSTRACT

Today, Concrete is the typical construction material. Every year, the number of cubic meters of concrete used in the world is equal to the population of the planet. Indeed, regulations for calculating concrete structures are evolving towards a probabilistic analysis of safety in all countries. As all structures may be subjected to significant thermal gradients for functional, accidental, or climatic reasons, it is now essential to know precisely the effect of temperature on the material's property variations. In this context, this article aims to study the mechanical behavior of concrete exposed to climatic thermal gradients. To highlight the experimental characterization, the residual measurement method was adopted. The mechanical characteristics of concrete were established in a reference state at 25°C and compared with those determined at temperatures of -25°C, -05°C, 45°C, and 65°C. The experimental results show that temperature is a significant parameter significantly influencing the mechanical properties (mechanical strength and Young's modulus) of concrete.

Keywords:

Concrete;
Temperature;
Young's Modulus;
Mechanical Strength; Arid.

1. INTRODUCTION

Today, Concrete is the quintessential construction material. Every year, the number of cubic meters of concrete used in the world is equal to the population of the planet. From the most modest construction to the most daring works of art, including tall buildings and public works (residential buildings, bridges, tunnels, airports, dams, ports, etc.), concrete is used on all continents and at all latitudes.

Certainly, laboratory tests on concrete materials are usually carried out at a controlled temperature, typically constant and usually chosen between 20 and 25°C, so most basic information on the properties of hardened concrete is based on the behavior of the material at these temperatures. However, in practice, concrete structures are always likely to be subject to a temperature gradient, for functional reasons (structures normally experiencing high gradients in service), climatic reasons (daily and seasonal variations), accidental reasons (fires, technical shocks), and finally, particular reasons (partial or local demolition by thermal processes).

Therefore, in practice, concrete remains at different temperature gradients in service, resulting in a wide temperature range in countries with hot climates, as well as in very cold regions. In fact, concrete can encounter situations in which it is exposed to low temperatures during the winter, even negative temperatures at night, and high temperatures during the summer, sometimes exceeding 50°C in Saharan climates.

Data on the behavior of concrete at service temperatures are necessary for predicting the safety of buildings and structures in response to certain accidents or particular states of service. However, the behavior of concrete at extreme service temperatures is currently not well understood. The evolution of mechanical characteristics as a function of temperature has not been taken into account in the design of structures. Consequently, temperature is an essential parameter to consider when studying the behavior of concrete structures.

This situation calls for a reflection on the condition of structures exposed to different climates and on the notion of risk associated with their maintenance in the functional conditions they encounter over time. In this context, the work we undertake is essentially experimental and is part of a research theme that aims to evaluate the mechanical behavior of hydraulic concrete in extreme service climates, taking into account certain composition parameters such as the effect of the nature of sand and weather conditions during exposure to different temperatures of ordinary concrete during the crushing of test specimens. In order to assess the effect of this parameter of the composite material that is concrete on its mechanical characteristics (compressive strength, tensile strength, and Young's modulus), three mixtures were made with the same constituents. All tests carried out in the recommended experimental program were performed according to recognized national and international standards in the field (NA,

AFNOR, and ASTM). The experimental work was carried out simultaneously in the Mechanics and Structures Research Laboratory (LMS), the civil engineering laboratory of the Tahri Mohamed University of Bechar, and in the Laboratory of Public Works of the West unit of Bechar (LTPO).

The materials that are the subject of this study are traditional concrete mixtures (C(C-S), C(C'-S), and C(SL-C)), composed of a granular skeleton made up of different types of sands (SL1-S, SL2-S, and SSC-C), two granular classes of gravel (GC1-C and GC1-C), and a single type of cement, CPA CEM I/A 42.5, specially designed for the study. The workability is normal and the concrete is placed in a conventional manner. In order to highlight the difference in properties of a sample when subjected to temperature, a measurement method was adopted that corresponds to residual measurements (after cooling). The characteristics of these concretes were established at the reference state of 25°C and compared with those determined at temperatures of -25°C, -05°C, 45°C, and 65°C. Such a comparison allowed us to evaluate the behavior of the concrete material during temperature variation.

2. Materials and Methods

2.1. Materials

2.2. Formulation and characterization of fresh concrete

In the context of this study, the concrete is formulated initially using the Dreux Gorisse method, and then optimized using the Baron-Lesage technique (Baron and olliveir, 1996), which determines the optimum gravel/sand (G/S) ratio. The study process consists of a logical sequence of progressive steps that take into account the characteristics of the materials used, as shown in Figure 1 The steps can be summarized as follows:

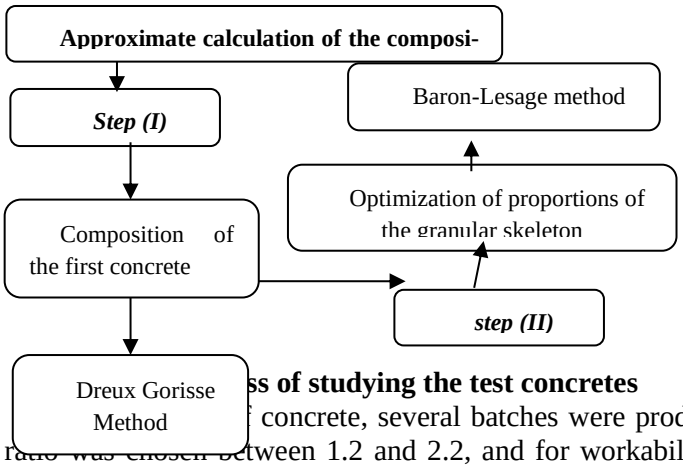
- **First step: composition of the first study concrete**

Initially, an arbitrary composition (water/cement ratio) and a volume of paste are set, usually resulting from a first composition determined by the Dreux Gorisse method, which is fundamentally empirical based on Caquot's granular optimum theory (Neville A.M., 1990). It is very simple to use since it only requires knowledge of the particle size distribution curves of the aggregates used [DUP 00].

- **Second step: Optimization of the mix skeleton**

With the parameters kept constant (water/cement ratio and a volume of paste), the skeleton is optimized by searching for the (gravel/sand) ratio that gives the best workability or slump. The optimal proportions of the aggregates are assumed to give the maximum slump, for a given amount of cement and water. Once the particle size proportions are identified, the water and cement dosages are experimentally adjusted so that the mix has the desired workability

and strength.



ss of studying the test concretes

concrete, several batches were produced where the G/S ratio was chosen between 1.2 and 2.2, and for workability reasons, it is not suitable to exceed a value of 2.2. Figure 2 shows that the optimal ratio (G/S), for which the slump is highest, is between 1.60 and 1.80 for the varieties of tested concrete.

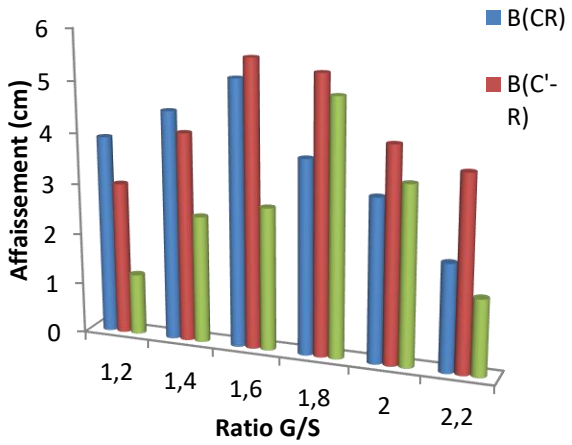


Figure 2: Optimization of the G/S ratio according to the measured slump

The results obtained are shown in Table 1, with the E/C and G/S ratios and the theoretical volumetric masses.

Table 1 Composition of the different concrete mixes (kg/m3)

Composition	Sand (Kg/m3)	gravillons (Kg/m3)	Concrete (Kg/m3)	Water (Kg/m3)	Ratios		Theoretical volumetric masse (Kg/m
					E/C	G/S	

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							3)
B (C-R)	642.00	1027.20	350.00	227.50	00.65	01.60	2246.70
B (C'-R)	698.00	1116.80	350.00	217.00	00.62	01.60	2381.80
B (SC-C)	610.00	1098.00	350.00	238.00	00.68	01.80	2296.00

Table 2: Composition of the different concrete mixes (kg/m3)

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For each batch of concrete, the following parameters were determined in each formulation: consistency or workability of the concrete, air content, and experimental density, as shown in Figure 3. The consistency of the concrete was determined by measuring the slump (or slump test) using an Abrams cone according to the [ENV 206-1] standard, which conditions the ease of placing the concrete in the formwork. The three concrete mixes prepared were plastic, with a slump between 5 and 5.6 cm and normal vibration. The air content was measured using a six-liter concrete air meter with an integrated pump and a pressure gauge for direct air percentage readings, in accordance with the [NF P 18-353] standard. The different formulations developed have an acceptable air content according to the current standard [NF EN 12350-7]. To determine the yield of fresh concrete and verify the validity of the theoretical formulation, we measured the experimental density of the different concrete compositions according to the [NF EN 12350-7] standard. To perform this measurement, we used the lower chamber of the concrete air meter. The results obtained show that the densities are acceptable.

2.3. Preparation of concrete

After the characterization tests at the fresh state, we proceeded to fill cylindrical molds (height 320 mm; diameter 160 mm). The protocol for mixing the different components of the concrete and placing the concrete in the molds complies with the standards [NF XP P 18-303], [NF P 18-400], [NF P 18-404], [NF P 18-421], and [NF P 18-422]. The [ASTM C 470-94] standard specifies the specifications for cylindrical molds. The method for making test cylinders is given in the standards [BS 1881-110] and [ASTM C 192-90a].

The concrete was mixed using a 50-liter mobile mixer equipped with an adjustable manual discharge door to recover the mixture in a tray or a wheelbarrow. The mixing time was sufficient to ensure good homogeneity of the concrete. Indeed, the quality of compaction has a major influence on the final quality

of the prepared specimens. In this case, the density measurement is an interesting indicator. Since the measured slump is less than 100 mm, we placed the concrete in the molds in two layers of equal importance, in accordance with the [NF P 18-422] standard, using a vibrating needle.



Figure 3: Placement and conservation of concrete test specimens

Finally, the process of leveling the upper surface of the test specimen was carried out using a leveling rule, in accordance with the standard [NF P 18-404]. Note that compaction continued as long as there was no segregation or appearance of laitance, as it is essential that the concrete in the cylinder be fully compacted so that the results are representative of the properties of perfectly compacted concrete. In accordance with the standard [BS 188-1111], once the surface of the cylinder was smoothed using a trowel, the cylinder was placed for 24 ± 4 hours at a temperature of 20 ± 5°C. At the end of this period, the

cylinder was demolded and cured in water at room temperature. In this experimental study, all specimens were kept in a water-filled basin until demolding for 28 days. Demolding was carried out 24 hours after placement. It was essential that the curing water contain no substances that could attack the hardened concrete, as shown in Figure 3.

2.4. Mechanical characterization procedure

The testing machine used for all mechanical tests is a CONTROL press with a capacity of 3000KN, in accordance with the requirements of standards [NF P 18-411] and [NF P 18-412]. It consists of three main parts: a frame, a hydraulic group, and a load measuring unit, as shown in Figure IV.2. Before each test, the ends of the cylindrical specimens were ground using a specimen grinder, according to standard [EN 12390-2], to ensure proper load distribution over the entire contact surface of the specimen during mechanical tests.



Figure 4: Overview of the compression press

The compression test was evaluated according to standard [NF EN 12390-3], using a hydraulic press, controlled by force, until the specimen ruptured. In order to obtain the maximum load "Fmax", the specimen was centered on the press with a tolerance of less than 1% of its diameter. It was then subjected to an increasing load, applied at a constant speed inducing a stress of 0.5 MPa/s, until failure.

The tensile strength of different concrete types subjected to temperature was obtained through the splitting (Brazilian) test; Figure IV.2. This was determined on cylindrical specimens of the same type used for the compression test (16Φ32 cm) at 28 days. The principle is to apply an induced compressive force along two opposite generatrices [NF P 18-408], creating tensile stresses in the plane passing through these two generatrices. The specimen was placed horizontally between the press plates, and the load was increased until indirect tensile failure occurred, which appears in the form of splitting along the vertical diameter of the cylinder, Figure IV.9.

The longitudinal elastic modulus in simple compression for the developed

concretes was measured on cylindrical specimens (Φ16×32 cm), during simple compression tests carried out with a compression press, Figure IV.10. The specimens were connected to an extensometric frame consisting of three metal rings spaced H/2 apart (H=32 cm: height of the specimen). These rings are arranged on the specimen using pointed screws. Between the two rings, three displacement sensors distributed at 120° allow, via an acquisition chain, to measure the specimen shortening in order to avoid friction when in contact with the press plates. The specimen fixing device is shown in Figure 5





Figure 5: Device for fixing test specimens

After determining the maximum loading "Fmax" for each composition and according to the measurement temperature, three loading-unloading cycles were performed at a loading rate of 0.5 MPa/s and a limit load of 0.3 Fmax, with unloads limited to σmin=0.05 fc (Figure 5). The stress-displacement curves were recorded for each specimen from the same formulation and subjected to the same temperature.

3. EXPERIMENTAL RESULTS AND ANALYSIS

3.1 Mechanical Resistances

The study of regular state mechanical behavior consists of observing the evolution of mechanical resistances (compression and tensile strength) during temperature variation. Therefore, mechanical properties are measured under thermal loading. This type of test allows for knowledge of mechanical behavior in Table IV.1, with the average value (05 samples), relative ratio, and percentage gap. These values are then illustrated in the graphs in Figures 6 and 7.

Table 3: Evolution of mechanical resistances of tested concrete with temperature (regular regime).

Con-	T (°C)	Age* (days)	Average strength (MPa)	Relative strength Cs(T)/Cs(T=20°C) (%)***	Gap (%)****

			Cs	Ts	Cs	Ts	Cs	Ts
C(C-S)	-25	28	40.72	07.63	160.63	161.18	+60.63	+61.18
	-05	28	34.07	05.30	134.39	112.02	+34.39	+12.02
	+25**	28	25.35	04.74	100.00	100.00	00.00	00.00
	+45	28	21.42	03.61	84.49	76.36	-15.51	-23.64
	+65	28	22.62	02.98	89.23	62.88	-10.77	-37.12
C(C' -S)	-25	28	44.25	08.57	154.45	148.36	+54.45	+48.36
	-05	28	41.34	07.62	144.29	132.00	+44.29	+32.00
	+25**	28	28.65	05.78	100.00	100.00	00.00	00.00
	+45	28	18.44	04.31	64.36	74.64	-35.64	-25.32
	+65	28	20.37	04.08	71.09	70.68	-28.91	-29.32
C(SL-C)	-25	28	56.16	08.14	263.41	176.23	163.41	+76.23
	-05	28	47.35	06.63	222.09	143.53	122.09	+40.53
	+25**	28	21.32	04.62	100.00	100.00	00.00	00.00
	+45	28	16.92	03.82	79.36	82.75	-20.64	-17.25
	+65	28	15.27	03.98	71.62	86.16	-28.38	-13.84

Note:

(*) A necessary regulatory deadline for which hydration reactions are considered complete.

(**) A temperature of 25°C is considered the reference temperature (room temperature).

(***) Relative strength represents the percentage ratio between the recorded strength at a given temperature (S(T)) and the reference strength (S(T=25°C)).

(****) Gap represents the percentage increase or decrease in strength recorded at a temperature compared to the reference strength (S(T=25°C)).

3.2. Compressive Strength

Compressive strength is a fundamental property of concrete and one of the essential parameters of our study. In a regular regime, the determination of this characteristic and its evolution with temperature have been followed for all the concrete compositions studied. The values of compressive strength and the curves of the variation of the gap of the relative compressive strength are shown on Figures 6 and 7, respectively.

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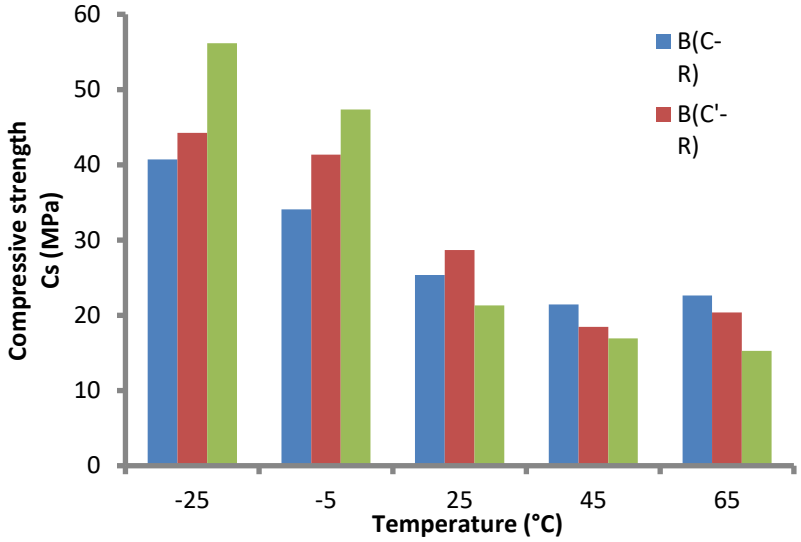


Fig 6: Evolution of compressive strength of tested concrete as a function of temperature (regular regime)

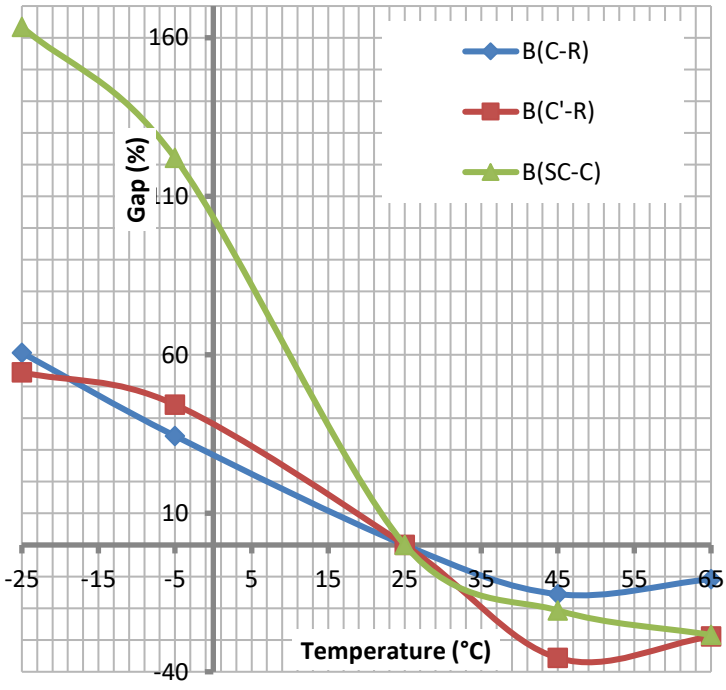


Figure 7: Evolution of the gap of relative compressive strength of tested

concrete as a function of temperature (regular regime).

From these figures, we mainly notice that the compressive strength of all tested types of concrete varies with temperature. We can distinguish two consecutive phases in the evolution of compressive strength with temperature:

Phase (I) (ranging from -25°C to 25°C): In this first phase, the compressive strength of different concrete mixtures is significantly higher than that recorded at room temperature (S(T=25°C)). Between -25°C and -05°C, the C(SC-C) composition exhibits better strength than the C(C'R) and C(CR) concrete mixtures, respectively. Its strength reaches values higher than 55MPa when cooled to -25°C. At this temperature, its strength is more than twice that measured at room temperature. For temperatures between -05°C and 25°C, we observe that the position of the compressive stress evolution values begins to show deviating lines, meaning that the three categories of concrete formulated based on different aggregate types do not maintain the same ranking of compressive strength evolution with respect to temperature. We observe that the concrete based on silico-limestone aggregates C(SL-C), which gave the best results in the previous phase (-25°C to -15°C), records lower stresses compared to the two concrete mixtures.

Phase II (ranging from 25°C to 65°C): In this temperature range, various evolutions of compressive strength are observed with respect to temperature. The two concrete mixtures C(CS) and C(C'S) show a small decrease in strength from 25°C to 45°C and then an equivalent increase from 45°C to 65°C. On the other hand, the concrete C(SL-C) exhibits a significant decrease in strength, reaching values lower than 16 MPa when heated to 65°C.

The analysis of these experimental results allows us to make the following interpretations:

The increase in compressive strength at low temperatures for the different concrete mixtures tested can be explained by the formation of ice in the hydrated cement paste. Knowing that the freezing point of gel water is lower, the smaller the pore size, so that absorbed water freezes at low temperatures (MIU et al 1989). As ice can resist stresses, unlike the water it replaces, frozen concrete has an extremely low effective porosity and therefore high strength. In addition, the strength of ice and its coefficient of thermal expansion vary with temperature (Bernier et al., 1993), so that the changes occurring in the hydrated cement paste are complex. If the concrete is not exposed to low temperatures, the pores remain empty, so the increase in strength is low.

On the other hand, the decrease in compressive strength of the tested

concrete mixtures for temperatures between 25°C and 65°C is mainly related to the evaporation of free water. According to several authors (Harada et al., 1972), (Noumowe A., 1995), and (Alarcon R. l. et al., 2002), this evaporation has been observed when concrete is exposed to temperatures between 30°C and 90°C. According to various studies (Verbeck G. and Copeland G., 1972) , (Schneider U AND Scheneider P., 1990) , (Sullivan P.J.E, Sharchar R., 1992), the presence of water in the form of steam at high temperature can also modify the physical and chemical structure of the cement paste. According to Verbeck & al. (1972), the combination of hygrothermal conditions can cause changes in the nature of hydrates . These changes mainly depend on the C/S (CaO/SiO2) ratio, temperature, and pressure in the material (Benoudjafer I. et al., 2020). The value of this report affects the formation of various hydrate forms, leading to the creation of hydrate forms with different mechanical properties [CAM 04]. It is necessary to mention that the properties of the material will also depend on the interaction between the paste and aggregates and the behavior of the transition zone (Barron J., Lesage R., 1976) .

Furthermore, the remarkable variation in the gap observed in the evolution of compressive strength from one concrete to another, during temperature variation, can be explained by the effect of the mineralogical nature of the aggregates in these concretes on the evolution of compressive strength with temperature. According to several authors (Elsharierf A., et al., 2003), (Basheer L.P. and A. LONG, 2005), and (Akçaoglu et al. 2004), the behavior of aggregates at high temperatures is completely different. Similarly, Campbell & al. (1967) showed that limestone aggregates exhibit good thermal behavior at high temperatures (Campbell et al., 1967), and Felicetti & al. (1999) also confirmed that the type of aggregate influences the durability of concrete at high temperatures (Felicetti et al., .1995). The loss of strength is considerably lower when the aggregate does not contain silica (certain forms of silica undergo dimensional changes); this is the case with limestone aggregates (Felicetti et al., l999).

Furthermore, studies explain the microcracks generated during the heating of concrete due to the effect of the incompatibility of the behavior of the components of the concrete (Venecanin S.D. 1978) , (Venecanin S.D. 1983), (Venecanin S.D. 1984), (Baker et al., 1989). This effect, which has been named "Thermal Incompatibility of Concrete Components" or TICC, finds its explanation in the creation of internal stresses in the concrete during the temperature variation caused by the incompatibility of the thermal characteristics of the concrete components, and more specifically the coefficient of thermal expansion.

These explanations can justify the shape of the curves at high temperatures, which we present in Figure 7 and IV.20, and thus limestone aggregates exhibit good behavior at high temperatures, as is the case with two compositions C(C-

S) and C(C'S) which are based on limestone sands. On the other hand, the composition C(SL-C) based on silico-limestone sand has lower strengths than those recorded by the two previous compositions based on limestone sands.

3.3. Tensile Strength

In this type of experimental characterization, the tensile strength was determined by the splitting (Brazilian) test during thermomechanical loading at 28 days, and corresponds to the average of the strengths of a series of five rectified cylindrical samples measuring 16x32 cm. The evolution of the tensile strength by splitting and their gap are presented in Figures 8 and 9.

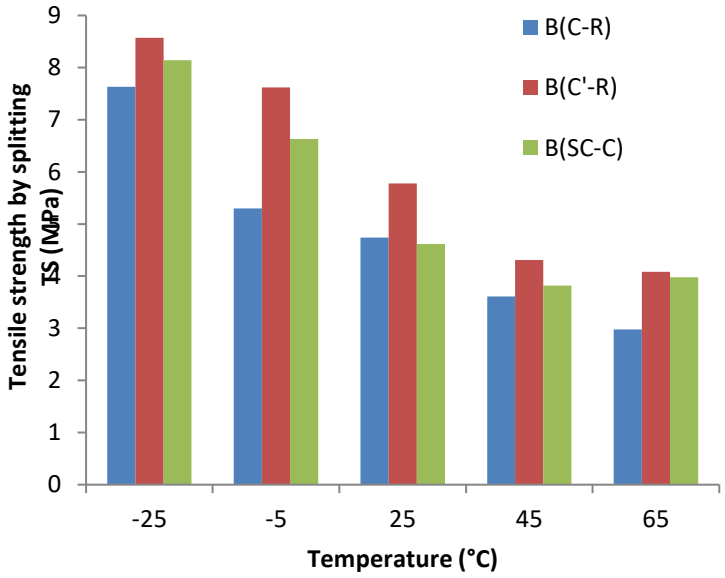


Figure 8: Evolution of the tensile strength by splitting of the tested concrete as a function of temperature (regular regime)

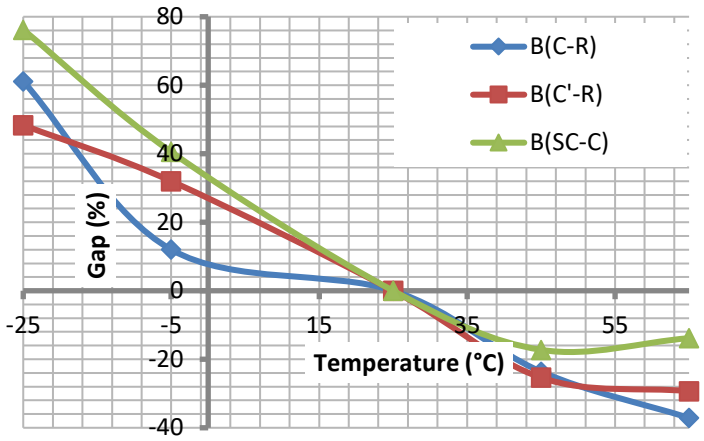


Figure 9: Evolution of the gap of the tensile strength by splitting of the tested concrete as a function of temperature (transient regime)

For the three types of tested concrete, it is possible to note that the evolution of the tensile strength by splitting, in the steady-state regime, generally presents a similar trend to that of the compressive strength. We can distinguish two consecutive phases of evolution:

Phase (I): (ranging from -25°C to 25°C):

In this temperature range, we observe that the tensile strengths behave in the same way for all the studied concretes. In this domain, the B(C'-S) concrete exhibits a strong resistance reaching values higher than 8 MPa when cooled to -25°C, with a phase shift that can reach a maximum difference in stresses equal to 1 MPa.

Phase (II): (ranging from 25°C to 65°C):

On the other hand, for temperatures between 25°C and 45°C, different behaviors of the tensile stress can be observed. A confusing curve shape is observed from 25°C to 45°C for both B(C-S) and B(SC-C) compositions, but it can be deduced that their behavior is almost identical in this range. However, the C(C-S) composition exhibits a marked decrease in resistance. In the high-temperature range, ranging from 45°C to 65°C, we observe various evolutions of tensile strength. A severe and progressive drop in tensile stress is reported for the C(C-S) composition, reaching values higher than 35%, where the measured tensile stress is lower than 3 MPa, which is relatively low.

Few studies have been conducted in this area; however, as with compressive strength, tensile strength decreases with increasing temperature. Recent studies (Schneider U., 1982), (Mori T., Tanaka K., 1973), (Noumowe A.,

1995), and (Felicetti R., Gambarova P.G., 1999) have indicated the existence of a strong sensitivity of tensile strength to temperature, which exceeds even that of compressive strength. Using an analogous reasoning as the following:

The bond between the aggregates and the cement paste is an important factor in the strength of concrete, especially in tensile strength. However, the nature of the bond is poorly understood. It is generated by the interlocking of the aggregates and the hydrated cement paste due to the roughness of the surface of the aggregates (Reynouard J.M., Pijaudier C..G., 2005) . At high temperatures, a rougher surface, such as that of crushed aggregates, generates a better bond due to mechanical interlocking, i.e., the bond between the paste and crushed aggregates is stronger than with rolled aggregates at high temperatures (Benoudjafer I. et al., 2011). Moreover, the bonds are not affected by other physical and chemical properties and the electrostatic condition of their surface. For example, chemical bonds may exist in the case of limestones, dolomites, and possibly siliceous aggregates (Venecanin S.D. 1983) At high temperatures, the bond between silico-calcareous aggregates and cement paste is better than that obtained with silicas (Benoudjafer I. et al., 2019).

On the one hand, in ordinary concrete, the interface between paste and aggregates, also called the transition zone, is more porous and better crystallized than the matrix (TOR et al., 1996). This zone is the weak point of concrete subjected to mechanical stress, and the first cracks bypass the aggregates and pass through the matrix. Piasta & al. (1994) were able to show that the quality of the transition zone depends strongly on the nature of the aggregates (Piasta et al., 1994).

3.4. Compressive elastic modulus

The residual elastic moduli in compression are the slopes of stress-strain (σ-ε) curves calculated within the elastic range (0 to 25% of the breaking strength). We have chosen this interval because concrete exhibits linear elastic behavior whose limit is around 30% of its compressive strength (Akçaoglu et al. 2004).

The stress/strain curves were used to determine the elastic moduli. Apparent elastic moduli are determined by calculating the slopes between the origin and points located on the abscissa. The variation of the residual compressive elastic moduli, the relative moduli, and their gap, for different concrete formulations developed at temperatures ranging from -25°C to 65°C are summarized in Table 4.

Table 4: Evolution of compressive elastic moduli of tested concretes with temperature (transient regime)

Concrete	T (°C)	Compressive elastic modulus CE (GPa)	Relative modulus (%)	Gap (%)
C(C-S)	-25	21.41	90.03	-09.97
	-05	23.53	98.94	-01.06
	+25*	23.78	100.00	00.00
	+45	19.85	83.47	-16.53
	+65	19.25	80.95	-19.05
C(C' -S)	-25	23.41	92.35	-07.35
	-05	23.88	94.74	-05.26
	+25*	25.31	100.00	00.00
	+45	21.92	86.66	-11.34
	+65	19.58	77.36	-22.64
C(SL-C)	-25	18.11	83.11	-16.89
	-05	18.86	86.55	-13.45
	+25*	21.79	100.00	00.00
	+45	21.14	97.01	-02.99
	+65	13.07	59.98	-39.98

We distinguish reactive and neutral aggregates in contact with the cement paste. Limestone aggregates have the strongest bond with the cement paste due to the chemical reactions that occur over time, increasing the adhesive forces (Pliskin L., 1993). The reaction between the CaCO3 from the limestone aggregates and the tricalcium aluminates and tetra calcium luminometries generates the formation of calcium monocarboaluminate C3ACaCO3H11. Thus, the transition zone between the limestone aggregates and the cement paste is more resistant and less permeable (Diamond S., 2003). The increase in the strength of the concrete material achieved with aggregates of this nature has been observed, unlike quartz-type aggregates, which are neutral with respect to the cement paste. We present the paste-aggregate interface of the different tested concretes.

These explanations can justify the shape of the curves at high temperatures (ranging from 45 to 65°C) that we present in

Figures 10 and 11, where the composition made with crushed silico-limestone sand decreases slightly compared to the two concretes containing rolled limestone sands. It is important to note that the slopes recorded for the different concretes elaborated in traction are stronger than those given in compression. This can confirm the existence of a strong sensitivity of the tensile strength to temperature, which even exceeds that of the compressive strength.

The measurement of residual compressive elastic moduli was carried out simultaneously with the determination of residual compressive strengths. The values of elastic moduli in compression for the three types of tested concretes, in the transient regime, are illustrated in the graphs of Figure 10. The relative values compared to the value obtained at 25°C are represented as graphs as a function of temperature in Figure 10.

For temperatures between 25°C and 65°C, we can observe a gradual decrease in the residual elastic modulus during heating, which is reflected in a decrease in the slope of the stress/strain curves with temperature. The relative residual elastic moduli decrease progressively over the entire high temperature range (45-65°C). At 45°C, we observe a reduction in the modulus of 02% to 17%. The modulus continues to decrease, reaching about 40% at 65°C. It appears that the mineralogical nature influences the evolution of the relative elastic modulus. The three curves are indistinguishable and decrease with approximately the same intensity with temperature. We do not observe on these curves a sequential character, characteristic of the evolution of strength. In other words, water during temperature variation does not influence the modulus, or this influence is negligible.

In accordance with mechanical strengths, the elastic modulus of concrete is regularly deteriorated by heating to 65°C. The variations in the elastic modulus are comparable for C(SL-C) and C(CS), although the decrease in the elastic modulus is more pronounced for the latter between 45°C and 65°C. This deterioration is quasi-linear up to 65°C. After heating to 65°C, the concrete samples exhibit very low rigidities.

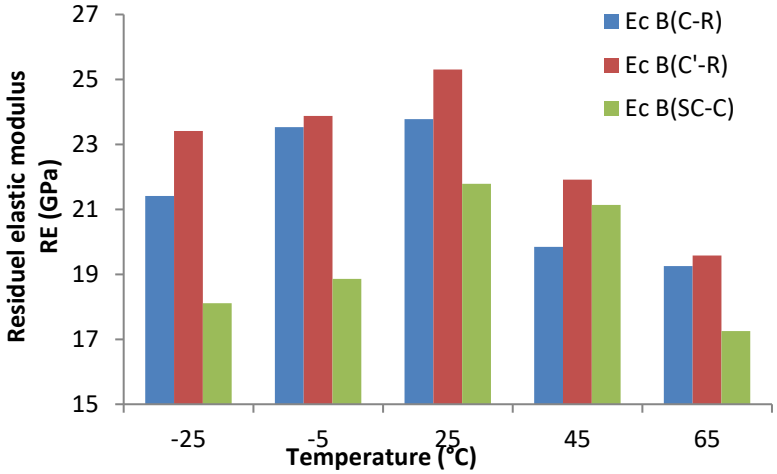


Figure 10: Evolution of the compressive elastic modulus of tested concrete as a function of temperature (in transient regime).

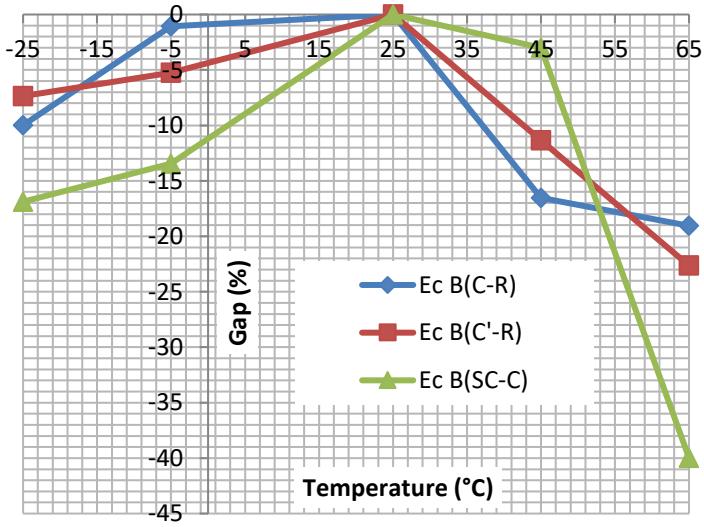


Figure 11: Evolution of the gap in compressive elastic modulus of tested concrete as a function of temperature (in transient regime).

4. CONCLUSION

All structures, for climatic, functional or accidental reasons, are likely to be subjected to significant thermal gradients. While, in all countries, regulations for calculating concrete constructions are evolving towards a probabilistic

analysis of safety (ACKER et al. 2005), it now seems essential to know precisely the effect of temperature on the variations in material properties.

The objective of this experimental work is to contribute, to the numerous researches undertaken, in order to understand the evolution of the mechanical behavior of concrete with temperature during its service. The study of the mechanical properties of the concrete studied provides the evolution of compressive strength, tensile strength, and compressive modulus of elasticity, during temperature variation. Based on the experimental results obtained, we can draw the following conclusions:

The thermal gradients in service have a significant influence on the evolution of mechanical properties; it varies depending on the mineralogical nature of the aggregates used for making the concrete, and according to the thermal cycle used and the temperature to which the concrete was exposed. The loss of strength varies depending on the temperature reached and the type of concrete. A progressive drop in tensile strength was observed, exceeding that of compressive strength, reaching values close to 60% at 65°C. This shows the existence of a strong sensitivity of tensile strength to temperature that exceeds compressive strength. In addition, the stress phase shift observed is considerable and more remarkable in the high-temperature phase (45°C up to 65°C). This can be explained by the variation of the properties of the aggregates during heating, resulting in a strong degradation of the concrete microstructure.

A gradual decrease in compressive modulus of elasticity was observed following exposure to temperature. Its evolution occurs in two distinct phases. In phase I, between -25°C and 25°C, the material loses 7-17% of its initial modulus. This modulus decreases gradually during phase II, which is in the temperature range of 25-65°C, reaching values close to 40% at 65°C."

Looking ahead, it is possible in the short term to extend the experimental program to involve:

considering all parameters that provide necessary information during the experimental study about the location of damage during temperature variation. Notable sensitivity of the studied mechanical characteristic was observed depending on the type of concrete studied and the temperature to which it was subjected. Therefore, it is necessary to accurately identify the location of the damage. To achieve this, it would be very interesting and useful to identify specific locations associated with the mechanical characteristics of the concrete in order to track and detect damage caused during temperature exposure. (Rangappa & Siengchin, 2023)

And on the other hand, other parameters related to the aggregates (shape and texture of the aggregates, bond, strength and resistivity, porosity and absorption of the aggregates), the composition of a concrete (cement dosage, overall grain size distribution of the aggregates, compaction method, maximum

aggregate size, age at which strength is specified, nature of hydraulic components), the strength of the concrete (water/cement ratio, effective water content in concrete, freeze/thaw ratio, porosity, aggregate/cement ratio, maturity and age of the concrete). Additionally, some aspects of hardened concrete (concrete curing, variation in cement strength, modification of cement properties, electrical and acoustic properties of concrete), and some durability factors (influence of the pore network, permeability, diffusion, resistance to aggressive agents, severe climate conditions, and fatigue).

Finally, we believe that this study only represents a part of the overall picture and would benefit from further investigation in order to achieve a study that takes into account all parameters involved in understanding the mechanical behavior of concrete. Therefore, we list below some elements concerning the effect of temperature as well as directions to further deepen this study:

The matrix-aggregate interface must be taken into account, and in particular the compatibility and adhesion between them. These parameters influence the rigidity or fragility of the samples as well as their sensitivity to cracking.

The incompatibility of thermal deformations (the deformation of the constituents of the concrete, the cement pastes and the aggregates) must be taken into account during exposure to temperature, particularly with regard to the evolution of its mechanical properties. This type of deformation represents a superposition of the deformations of the matrix and the aggregates during heating (Benoudjafer I. et al., 2013). It strongly depends on the properties of these constituents, especially their nature and quantity.

The hydric movements due to temperature variation are necessary to predict the behavior of concrete subjected to temperature. Temperature variation in concrete can produce temperature gradients within the material, causing hydric imbalances due to drying and wetting, and damage to the microstructure (Barker et al., 1992).

Knowledge of the thermal properties of concrete is essential for estimating thermal gradients in the concrete. Thermal conductivity and diffusivity come into play during the development of temperature gradients, thermal deformations, warping, and cracking at a very young age of the concrete, as well as during the thermal insulation of concrete (ACK et al., 2005).

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CONFLICT OF INTEREST

The authors haven't any financial interests in this part., the authors have no conflicts to disclose.

AUTHORS CONTRIBUTION

Specify the contribution role of each author within this section. For more details, please refer to CRediT taxonomy (Contributor Roles Taxonomy).

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