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Investigation of the Evolving Relationship Between the Properties of Ordinary Concrete and High Performance Concrete at High Temperatures

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Abstract

Elevated temperature can cause alterations in concrete materials by destroying the hydrated constituents of the cement paste. This destruction involves weakening by degradation of the material's mechanical properties such as stiffness and strength. As a result of this destruction, material weakening can occur. Higher temperature also generates significant fluid pressure which may lead to damage and cause concrete collapse characterized by the deterioration of the hydrated material. The main objective of this experimental study is to focus on the evolution of the residual properties of five ordinary concretes (OC) and three high performance concretes (HPC) and the evolution of the deterioration of hydrated material. The specimens were (15*15*15) cm^3 of ordinary concretes and (16*32) cm^2 of (HPC) and were subjected to temperatures of (200°C), (400°C), and (600°C) with a rate of (2°C/min) for three hours, followed by cooling at room temperature. The deterioration of various properties was evident compared with a room temperature of (20°C), with a maximum loss of compressive strength of (48%) for the ordinary concrete whereas (79%) for HPC. The loss of tensile strength was (65%) for OC (62%) for HPC**.** The loss in density and the dynamic modulus elastic were (5%) and (97%) respectively for (OC) and (6%) and (89%) respectively for (HPC). An explosive burst of one (HPC) between (400°C) and (600°C) was observed.

1. Introduction

Researchers have shown that concretes in general and high performance concrete (HPC) in particular have satisfactory intrinsic mechanical properties [1]. Indeed, (HPC) concretes are differentiated from ordinary concretes by their high density and low porosity, which provide good mechanical characteristics and better durability [1,2]. For this reason (HPC) is used for important structures such as bridges, tunnels, and nuclear establishments [1,3].

In spite of the good behaviour of (HPC) at room temperature and its significant economic and structural advantages compared with conventional concrete [4], several questions have been raised regarding its behaviour under extremely high temperature conditions such as fire [1,3]. For better understanding of the behaviour of concrete at elevated temperatures and to determine the main causes of thermal instability, much research has been performed [5]. Different experimental programmes have been carried out for better understanding of concrete's behaviour at high temperature [6]. A review of observations made and experiments conducted to quantify the effect of elevated temperature on concrete revealed that the increase in temperature of concrete results in a number of physico-chemical and micro-structural changes, leading to a change in mechanical properties [7-9], and even results in explosive bursts associated with higher temperatures for HPC [7,10,11]. The loss of mechanical strength of (OC) and (HPC) is owed on one hand to physico-chemical changes in the material and the effects of differential expansion of the aggregates and cement paste [6,12,13-15] and on the other hand to the development of high vapor pressure and high mechanical thermal stresses [16-19]. The concrete stiffness decreases also at high temperatures because of the degradation of the dynamic modulus. Destructive and non-destructive techniques were used to determine the evolution of the elastic properties of concrete with an increase in temperature [20]. Deterioration phenomena have been observed [21], and such spalling may manifest as simple scale detachment or an explosive burst [7,21,22].

Concrete composition and particularly its humidity both play an important role in spalling [23-25]. This experimental study compares the strength and residual elastic modulus of ordinary concrete (OC) and high performance concrete (HPC) and the relations between these properties at elevated temperature.

2. Experimental study

The materials used in this work for the preparation of the various concretes are of local origin whose chemical compositions and physical properties are shown in (Table 1) and (Table 2) reciprocally.

Five ordinary concretes and three high performance concrete mixes were compared (Table3). Compressive strength, tensile strength, ultrasonic velocity, the dynamic elastic modulus and the loss of mass were evaluated. All tests of (OC) were conducted on cubic specimens (15*15*15) cm^3 and those of HPC on cylindrical ones (16*32) cm^2. These residual properties were studied after exposure of the specimens to temperatures of (200°C), (400°C) and (600°C), and their cooling at ambient temperature. Temperature was increased at a rate of (2°C/min) to achieve the designated temperature at which the specimens were left for three hours.

Compression and splitting tensile tests were performed using a machine of (2000KN) capacity at respective speeds of (0.5 MPa/s) and (0.05 MPa/s) [26,27]. The ultrasonic pulse velocity measurements were also taken in direct transmission mode [28]. They were conducted by an ultrasonic tester (mark controls) with a transmission head and receiving head of (54 KHz) [29].

Table 1: Chemical compositions of materials (%)

	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	K_2O	Na_2O	SO_3	Cl-	Loss on ignition
Cement	59-62	22-24	5.3-6.0	3-4	1.5-1.8	<0.9	<0.7	1.8-2.2	-	-
SF	0.2	93.7	0.6	0.3	0.2	0.5	0.2	< 2.5	< 0.2	2.9
$Sand_{sea}$	0.62	95.21	1.12	0.55	0.04	0.46	0.10	0.00	-	-
$Sand_{career}$	56.73	3.71	0.23	0.20	1.18	0.02	0.07	0.09	-	37.77
$Sand_{dune}$	1.63	90.46	1.38	1.92	0.39	0.22	0.00	0.2	-	2.56

Table 2: Physical characteristics of materials

	Unit	Sand sea	Sand career	Sand dune	Gravel (5 /12,5 ., 5/15)	Gravel (12,5/20 ., 15/25)	Cement	SF
Finess modulus	(%)	1.77	3.51	0.84	-	-	-	-
Sand equivalent (visual)	(%)	71.42	76.29	80.37	-	-	-	-
Sand equivalent (piston)	(%)	67.46	70.97	78.65	-	-	-	-
Apparent density	(g/cm^3)	1.70	1.49	1.63	1.58	1.58	1.12	0.5
Absolute density	(g/cm^3)	2.67	2.56	2.6	2.72	2.63	3.16	-
SSB	(cm^2/g)	-	-	-	-	-	3630	>15000

3. Evolution of concrete properties as a function of temperature

3.1. Compressive strength

In (Table 4) and (Figure 1) it was observed that at (200°C) the fall in compressive strength of (HPC) is more significant than that of (OC), ranging from a quarter to more than half of the initial value. These results are larger than those obtained by Kameche et al. [8], which indicated that the ratio of decrease is about a third of the initial strength. At (200°C), the decrease in (OC) strength is less important and varies from (6%) to (20%). Between (200°C) and (400°C), the compressive strength of (HPC) shows some stabilization or small variation (26%) to (58%) with a change of color [30] (Figure 2), whereas in the case of (OC) it decreases moderately (3%) to (30%). The difference between the two types of concrete at (600°C) was clearly observed: the loss in the strength reached (80%) for (HPC) whereas a slightly more than half of the initial rate for (OC). These results confirm the findings obtained by other studies [10, 31]. The presence of hairy cracks at (600°C) before loading explains the importance of this decrease for (HPC) (Figure 3).

The values of the ratios calculated for the three HPC are below those of the Unified Technical Document DTU (HPC) [32] and EUROCODE (EC2) [33] for the two types of granulates (siliceous or calcareous). For (OC), and below (400°C), the ratios determined are below those of the DTU (OC) and EC2, but above this temperature the ratios are greater than those of the DTU (OC) and EC2 remaining inside the DTU range. Therefore, at (600°C) the loss of strength for the three HPCs (80%) exceeds those given by regulatory codes by (50%).

Table 3: Compositions of concretes and properties at 28 days.

Composition (kg/m^3)	Concrete							
	HPC 1	HPC 2	HPC 3	OC 1	OC 2	OC 3	OC 4	OC 5
$Sand_{sea}$	575.12	/	243	607.31	602.54	596.92	582.77	586.13
$Sand_{career}$	/	492	492	/	/	/	/	/
$Sand_{dune}$	/	243	/	/	/	/	/	/
$Gravel_{5/12,5}$	/	461	/	/	/	/	/	/
$Gravel_{5/15}$	630.76	/	461	589.58	584.97	579.52	565.79	569.04
$Gravel_{12,5/20}$	/	448	/	/	/	/	/	/
$Gravel_{15/25}$	649.32	/	448	626.44	621.52	615.72	601.13	604.50
Cement	500	500	500	300	345	398	450	500
Water	172.5	173	173	208.33	206.60	208.38	209.30	210.08
SF	75	/	75	/	/	/	/	/
Sup	10	3,4	3,4	/	/	/	/	/
W/B	0.495	0,346	0.496	0.69	0.59	0.52	0.46	0.42
Slump	18	14	08	16	14	11	09	06
f_c (MPa)	54.60	65.80	69.73	20.28	22.3	27.76	39.42	44.43
f_t (MPa)	2.99	3.59	3.86	1.10	1.25	1.62	1.75	1.68
V (m/s)	5127	4639	4781	3945	3978	4109	4225	4216
E_{dyn} (MPa)	54770	43078	46531	33616	34538	37635	40116	39900

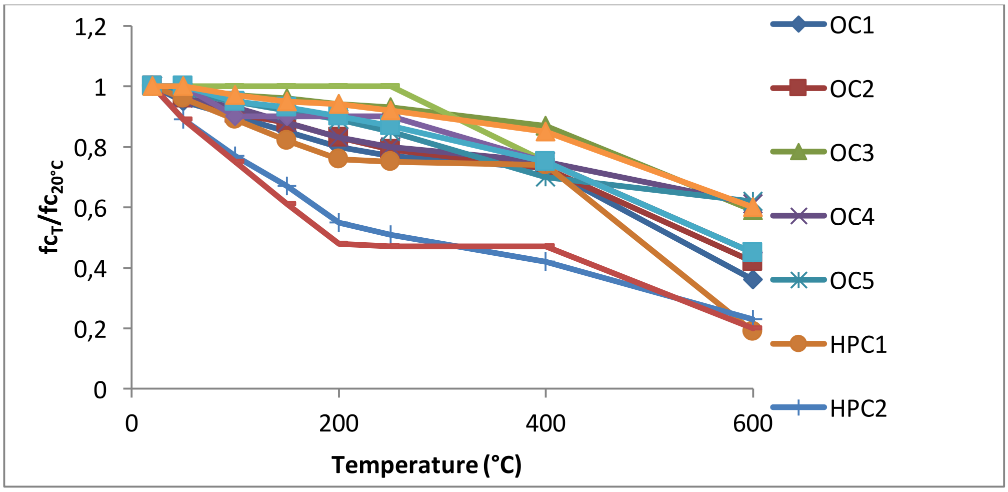

Figure 1: Evolution of compressive strength ratio (fc_T / $fc_{20°C}$) with temperature

Table 4: Relationship between compressive strength ratio (fc_T / $fc_{20°C}$) and temperature.

Temperature (°C)	OC 1	OC 2	OC 3	OC 4	OC 5	HPC 1	HPC 2	HPC 3
200	0.80±0.03	0.83±0.06	0.94±0.004	0.83±0.03	0.89±0.05	0.76±0.139	0.55±0.03	0.48±0.011
400	0.73±0.13	0.73±0.07	0.87±0.11	0.75±0.03	0.70±0.04	0.74±0.06	0.42±0.203	0.47±0.011
600	0.36±0.08	0.42±0.08	0.59±0.03	0.61±0.08	0.62±0.03	0.19±0.021	0.23*	0.20±0.002

(*) Explosive bursting of the tests specimens.

Figure 2: Change in color after 400 ° C (HPC)

The results showed that the strength loss is influenced by the (W/C) ratio. An increase of this ratio of (60%) (OC5 to OC1) causes a strength loss of (16%) at(400°C) and (600°C). This decrease is caused by the excessive amount of water because the cement content does not affect this decrease, as pointed out by Ergun [14]. For (HPC), the largest loss is observed for the highest (W/B) ratio (HPC1, HPC3), but the explosive burst is formed in the lowest (W/B) ratio composition of the three HPCs (Figure 4). This HPC does not contain silica fume, which makes it less compact and thus more porous, which can cause more moisture, leading to significant pressure and causing the concrete to failure on heating.

Figure 3: Appearance of significant cracks after 600 ° C (HPC)

Figure 4: Explosive Burst of HPC2 at 544 ° C

3.2. Tensile strength

*Tensile strength r*esults are presented in (Table 5) and in (Figure 5). At (200°C) the loss of tensile strength is relatively similar to that of compressive strength for all the concretes except for (OC5) and (HPC3), which have a significant decrease in compressive strength compared with tensile strength. The tensile strength decrease at (200°C) varies between (5%) and (19%) for (OC) and from (5%) to (25%) for (HPC). At (400°C), the decrease is more significant for (OC) than (HPC); it reaches (42%) for the (OC) and just (33%) for HPC (HPC2), whereas at (600°C) the decrease values are close and vary from half to one-third of initial resistance. A burst of (HPC2) was seen at a temperature of (544°C), which is in agreement with previous studies where the burst occurs above (300°C) but higher than the interval indicated by Menou [13], after a drop of (25%) at (200°C) and (33%) at (400°C).

All tested concretes showed drops below those of the DTU and above those of the EC2.

Table 5: Relationship between tensile strength ratio (ft_T / $ft_{20°C}$) and temperature

Temperature (°C)	**OC 1**	**OC 2**	**OC 3**	**OC 4**	**OC 5**	**HPC 1**	**HPC 2**	**HPC 3**
200	0.85± 0.20	0.95± 0.17	0.93± 0.14	0.81± 0.25	0.95± 0.23	0.95± 0.063	0.75± 0.031	0.93± 0.094
400	0.70± 0.05	0.52± 0.08	0.52± 0.05	0.70± 0.08	0.83± 0.13	0.90± 0.023	0.67± 0.045	0.86± 0.015
600	0.33± 0.04	0.34± 0.08	0.27± 0.04	0.39± 0.06	0.43± 0.1	0.45± 0.005	*	0.31± 0.011

(*) Explosive spalling of the tested specimens (figure 4)

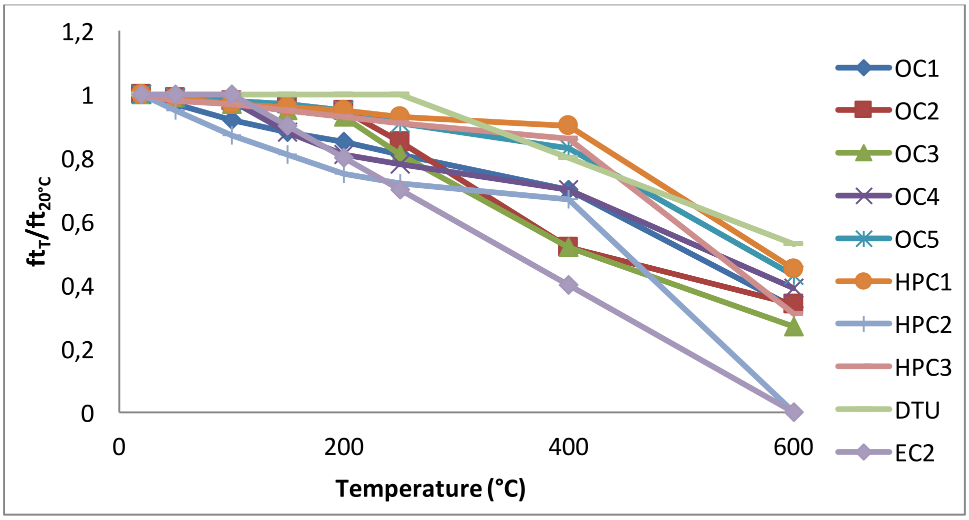

Figure 5: Evolution of tensile strength ratio (ft_T / $ft_{20°C}$) with temperature

3.3. Dynamic modulus

In (Table 6) and (Figure 6) significant falls in the dynamic modulus of elasticity at (200°C) were noticed. They varied from (31%) for (OC) and (21%) for (HPC). At (400°C), the falls accelerates to reach (74%) OC and (57%) for (HPC) with a linear increase, as reported by Noumowe [34]. Results show also that the falls of dynamic modulus of elasticity are more significant for (OC) than for (HPC) despite the similarity of their evolution. This difference is owed to the high compactness of (HPC). At (600°C), concretes exhibit nearly zero value of the modulus. This involves a significant micro-cracking that may be observed beyond heating of the specimens. Most of the values of determined ratios for concretes are below those of EC2 and above of the DTU as shown in (Figure 6).

Table 6: Relationship between dynamic modulus ratios (E_{dT} /$E_{d20°C}$) and temperature

Temperature (°C)	OC 1	OC 2	OC 3	OC 4	OC 5	HPC 1	HPC 2	HPC 3
200	0.71± 0.06	0.75± 0.06	0.69± 0.05	0.79± 0.07	0.79± 0.087	0.82± 0.035	0.79± 0.045	0.79± 0.024
400	0.28± 0.08	0.27± 0.04	0.26± 0.02	0.35± 0.06	0.38± 0.06	0.43± 0.047	0.66± 0.118	0.48± 0.042
600	0.01± 0.008	0.02± 0.006	0.02± 0.006	0.07± 0.004	0.06± 0.02	0.01± 0.004	*	0.03± 0.03

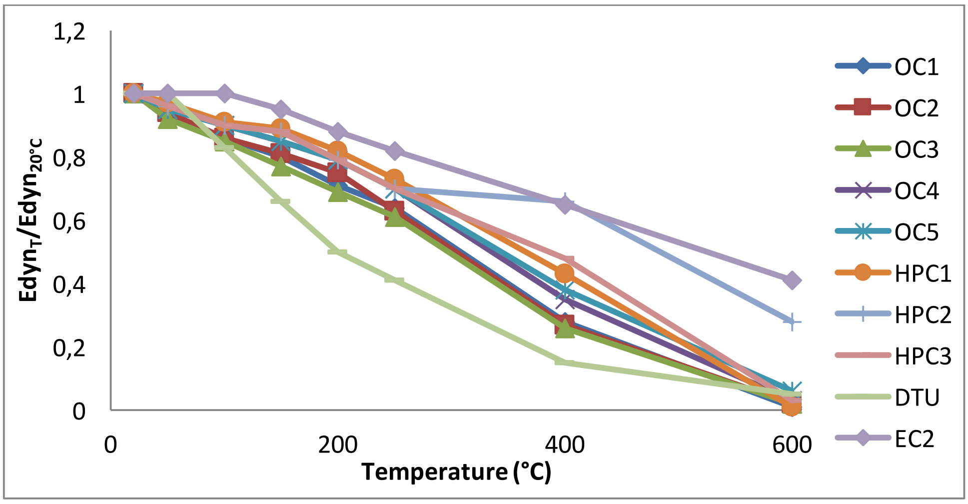

Figure 6: Evolution of the dynamic elastic modulus ratio (E_{dT} /$E_{d20°C}$) with temperature

4. Relationships between the properties of concrete as a function of temperature

4.1. Temperature effect

Generally for all considered temperatures, the relationship between the compressive strength and the tensile on one hand and between the compressive strength and the dynamic elastic modulus on the other hand, showed great dispersions (Figures 7 and 8) and involved that it depends on several factors including the type and the composition. Based on the evolution of ratios $f_t(T)/f_t(20°C)$ and $E_d(T)/E_d(20°C)$, according to $f_c(T)/f_c(20°C)$, these relationships have less accurate correlations with OC (R_t^2=0.63 and R_E^2=0.68) and with HPC (R_t^2=0.68 and R_E^2=0.54) considering all compositions and temperatures (Figure 9).

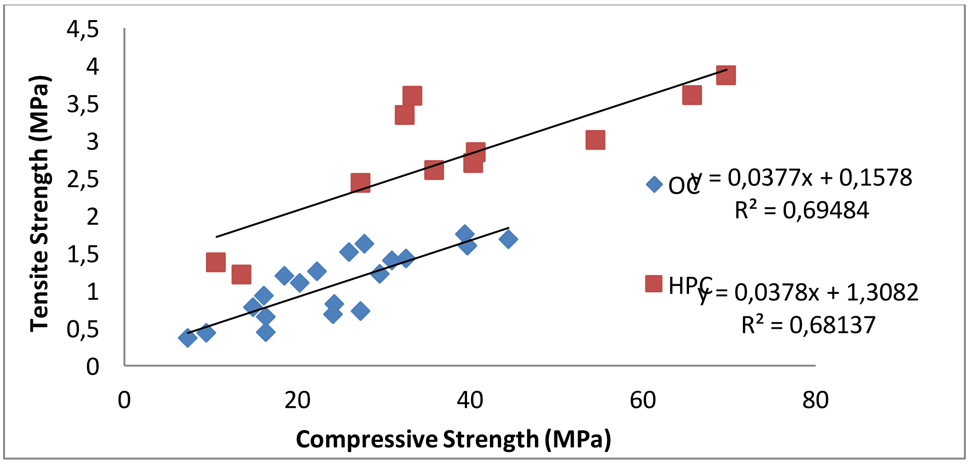

Figure 7: Relationship between compressive strength and tensile strength

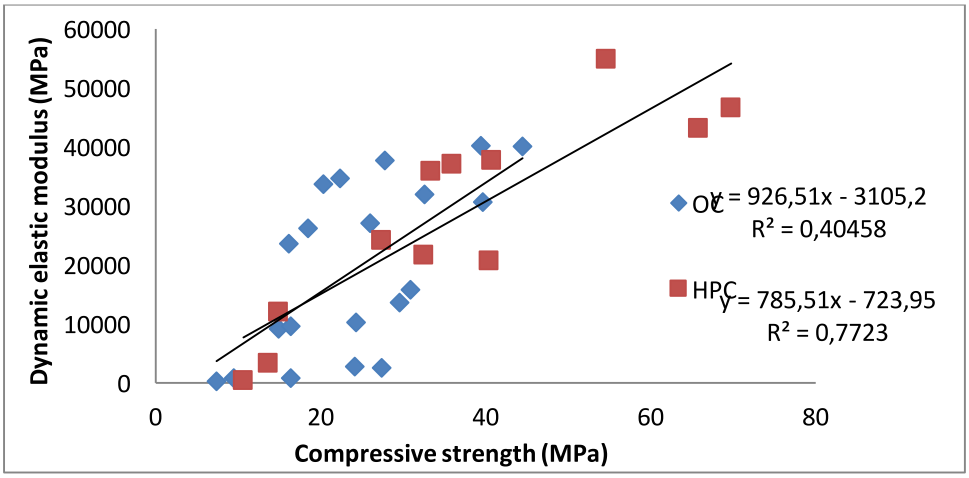

Figure 8: Relationship between compressive strength and dynamic elastic modulus

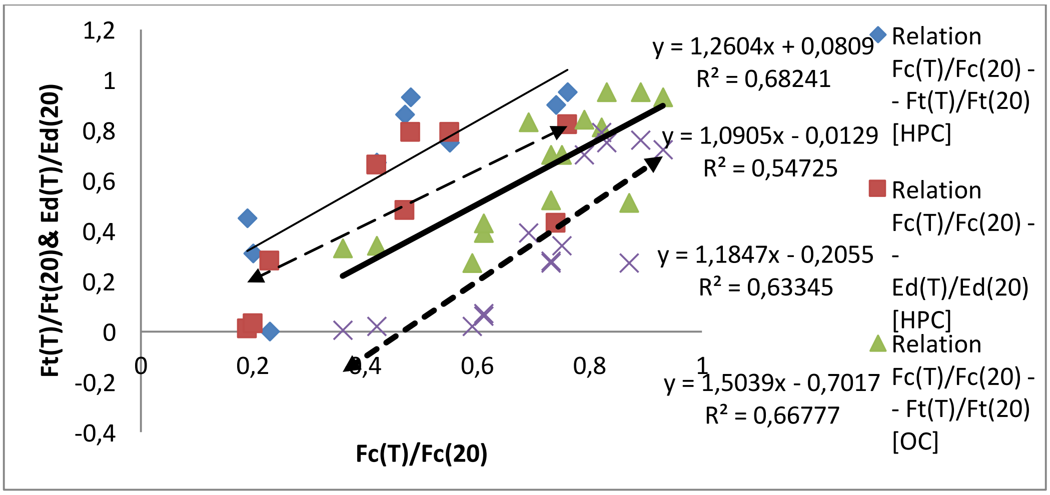

Figure 9: Relationships between the ratios in compression and tensile strengths, modulus of elasticity at each temperature

4.2. Composition effect

The correlations for each concrete composition are better than the previous results as shown in (Figures 10 and 11).

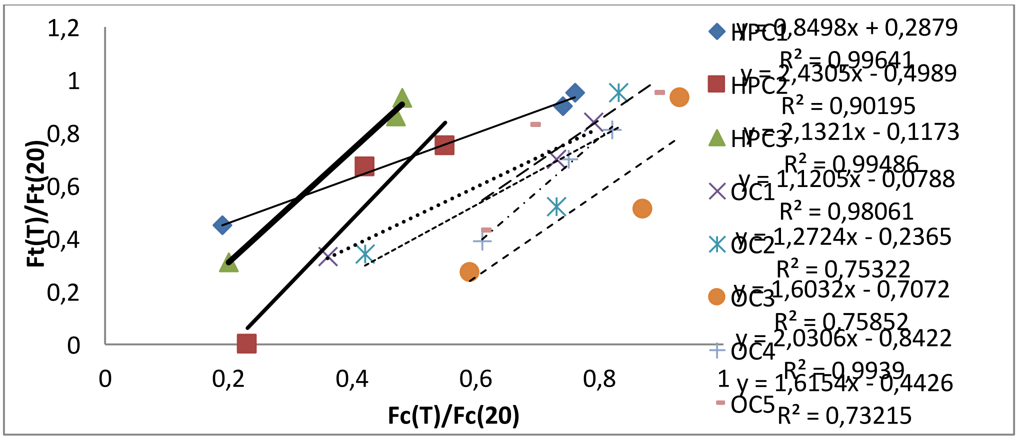

Figure 10: Relationship between compressive strength ratios and tensile strength ratios for each concrete

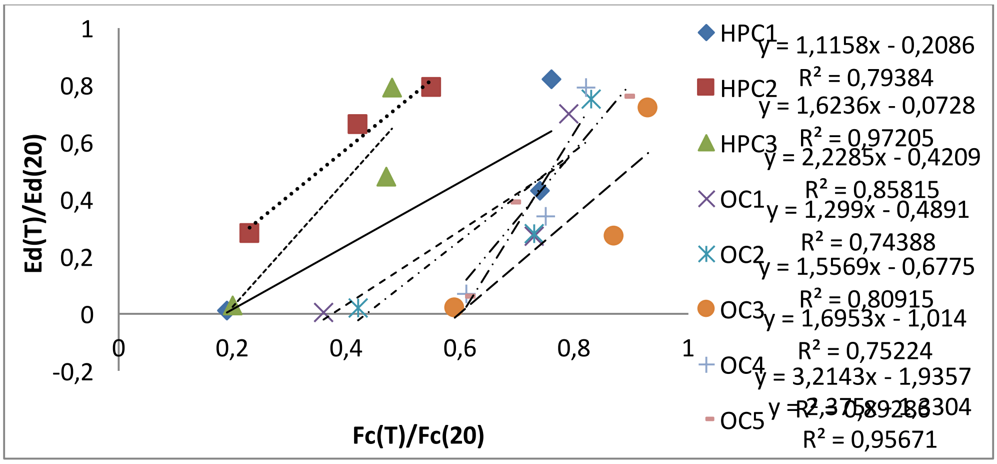

Figure 11: Relationship between compressive strength ratios and elastic dynamic modulus ratios for each concrete

The evolution of curve slopes connecting $f_t(T)/f_t(20°C)$ ratios and $E_d(T)/E_d(20°C)$ ratios is proportional to the dynamic modulus of elasticity for the two types of concrete (OC) and (HPC). However, (OC4) has the greatest curve slope and the highest dynamic modulus (E_d=40116 MPa). As regards (HPC), the curves connecting the $f_t(T)/f_t(20°C)$ to $f_c(T)/f_c(20°C)$ ratios a similar evolution and the slope is less significant. The loss of tensile strength ratios (HPC2, HPC3) is less significant than that of compressive strength (bursting of HPC2).

Conclusion

This experimental study emphasized the difference in terms of behaviour at high temperatures between (OC) and (HPC). The maximum loss of the tensile strength exceeded (50%) for (OC) at (600°C) and (80%) for the (HPC). In tension, it reaches for the OC (20%) at (200°C), (50%) at (400°C) and (67%) at (600°C) compared to the initial value whereas for the (HPC), it does not exceed 15% (HPC1, HPC3) at (400°C) but it reaches (65%) at (600°C) for (HPC3). (HPC2) presented an explosive burst at (544°C). This means that the adverse effect of temperature on tensile strength has more effect than that of the compressive strength for (OC).

It is differently influenced by the temperature increase from one (HPC) to another compared with compressive strength. The falls in dynamic modulus of elasticity are between (31%) OC and (21%) HPC at (200°C) and between 74% (OC) and 57% (HPC) at 400°C. Thus, on this level, the dynamic modulus of OC is more influenced by the rise in temperature than that of (HPC), tending to be cancelled at 600°C (loss of 99% for both concretes). The (HPC) which suffered an explosive burst showed the least significant fall in the various properties and it also presented less cracking before spalling, which favoured an increase in pressure.

The relationships between (f_c) and (f_t) for (OC) exhibit similar evolutions below (200°C) while at (400°C) the relation has a greater slope. This temperature causes major changes in the material. The loss in tensile strength is less significant than in compressive strength. At (600°C), the trend is reversed whereby excessive cracking of the material leads to a greater reduction in f_t compared with f_c.

The relationships between (f_c) and (E_d) for (OC) and below 400°C exhibit similarities to previous relations. At (600°C), the f_c-E_d has a low slope reflecting a quasi total loss of material stiffness. This difference with the measured resistances reflects a diffused state of cracking that influences the ultrasonic wave propagation determining the dynamic modulus of elasticity. Unlike (HPC), the f_c-E_d relationship exhibits different evolutions at each temperature with smooth slopes except at (600°C). The slope evolution of the curves connecting $f_t(T)/f_t(20)$ and $E_d(T)/E_d(20)$ ratios to $f_c(T)/f_c$ (20) is proportional to the dynamic modulus for both types of concrete.

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