Behaviour of high-strength concrete incorporating ground granulated blast furnace slag at high-temperature

Comportement à haute température du béton à haute résistance à base de laitier granulé de haut fourneau

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ملخص

تعرض هذه الورقة تأثير درجة الحرارة على السلوك الفيزيائي والميكانيكي لخرسانة عالية المقاومة باستخدام ألياف البولي بروبلين للحد من انفجار الخرسانة. و لهذاالغرض أجريت سلسلتين من الاختبارات على الخرسانة التي تحتوي على الخبث الحبيبي المنتج في مركب الحديد و الصلب عنابه الجزائر مع أو بدون إضافة الياف البولي بروبلين. أخضعت هده العينات لدرجات حرارة مختلفة (20°C, 100°C, 300°C , 500°C, 700°C), تم تطبيق استقرار لمدة ساعة واحدة ثم تأتي مرحلة التبريد حتى درجة حرارة الغرفة. ومن المؤكد أن ارتفاع درجة الحرارة قريبة من منحنى معياري ISO 834 (ما يعادل نار حقيقي). أظهرت النتائج أنه من الممكن تصنيع خرسانة عالية المقاومة مع خصائص فيزيائية وميكانيكية جيدة باستخدام المواد الموجودة في السوق المحلية الحالية. نتائج هذه الدراسة تشير إلى أن إضافة ألياف البولي بروبلين قد يقلل من مدى وشدة تفكك الخرسانة عالية المقاومة التي تحتوي على الخبث الحبيبي, مقارنة مع الخرسانة العادية, و الخرسانة عالية المقاومة التي تحتوي على غبار السيليكا.

الكلمات المفتاحية: *الخرسانة عالية المقاومة- الدقائق- الحرارة العالية- ألياف البولي بروبلين- الخبث الحبيبي.*

Summary

This paper presents the outcomes of a research investigating the effect of temperature on physical and mechanical behaviour of High Strength Concrete (HSC) to reduce the explosive spalling of concrete. Two series of tests were carried out on concrete incorporating Ground Granulated Blast Furnace Slag (GGBFS) of "Mittal steel Annaba" (Algeria) with and without polypropylene fibre additions were realized. Samples were subjected to various temperatures (20°C , 100°C, 300 °C, 500°C and 700°C), a stability of one hour was applied, then a cooling phase until ambient temperature. The heating rate used in this experimental work was close to the standard curve ISO 834. The obtained results show that it is possible to make a HSC with good physical and mechanical properties by using the existing materials on the local market and HSC incorporating polypropylene fibres behaves well towards high temperatures. Conclusions drawn from this study indicate that, HSC containing ground-granulated furnace slag can reduce the degree and severity of spalling as in the case of HSC containing polypropylene fibres or silica fume (SF).

Keywords: *High strength concrete- fillers- high-temperature- polypropylene fibres- Ground granulated Furnace Slag*

Résumé

Cet article présente l'effet de la température sur le comportement physique et mécanique du Béton à Haute Résistance (BHR), à base de fillers de laitier granulée en incorporant ou non des fibres de polypropylène pour réduire le comportement explosif de ce type de béton. À cet effet deux séries des bétons à base de laitier granulé de l'usine sidérurgique d'El-Hadjar (Algérie) avec ou sans ajouts de fibre polypropylène ont été réalisés. Les échantillons sont soumis à des températures différentes (20°C, 100°C, 300°C, 500°C, 700°C). Une stabilité d'une heure est appliquée, puis un refroidissement jusqu'à une température ambiante est subi. La montée en température est assurée de façon proche à la courbe normalisée ISO 834 (correspondant à un feu standard). Les résultats obtenus montrent qu'il est possible de fabriquer un BHR avec de bonnes propriétés physiques et mécaniques en utilisant les matériaux existants sur le marché local. Les conclusions tirées indiquent qu'un BHR contenant les fillers de laitier granulée peut réduire le degré et la sévérité de l'éclatement du béton, si l'on compare avec un BHR contenant de la fumée de silice ou encore contenant des fibres de polypropylène.

Mots-clés: B*éton à haute résistance- fillers- haute température- fibre polypropylène- laitier granulée.*

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1. INTRODUCTION

The use High Strength Concrete (HSC) has been on the increase, particularly in the developed countries. However, the use of HSC is still very limited in many countries. This limitation is related to the special conditions and additives needed for its production. Producing HSC requires more care in preparing, mixing, compacting, and placing than normal concrete, Ali et al. [1]. The main benefit of using HSC stems from the reduction in element's cross sections, thinner floor slabs and consequently their self-weight. This is particularly useful in high-rise buildings. Using some additives and fine particles can be improve the mechanical properties of concrete. The main characteristic of high strength concrete is their dense internal microstructure which ensures a very low permeability. Recent fires in buildings, laboratory tests and in tunnels showed that, when concrete is exposed to high temperature resulting, sometimes, in an explosive spalling [2–11]. According to Arup Fire [12], they are many types of spalling, explosive spalling, surface spalling, aggregate splitting, corner separation, sloughing and post cooling spalling. The causes and factors influencing explosive spalling are somewhat inconsistent and unquantifiable. Some influencing factors on the spalling phenomena have been identified such as, w/c ratio, heating rate, strength of concrete matrix, concrete microstructures with low permeability, moisture content and imposed loading [13–16].

According to these studies, concrete spalling occurs due to the development of thermal stresses and pore pressure within the concrete microstructure. The pressure development is caused by the transformation of the residing free water within the concrete pores together with the chemically bound moisture into the gaseous phase. High strength concrete is believed to be more susceptible to the pressure build up because of its low permeability, compared to that of normal strength concrete. The dense microstructure of high strength concrete reduces the migration of liquid and vapour water. Ultimately the development of pore pressure can be alleviated through the use of various fibres within the concrete matrix.

According to some authors [17–23], concrete thermal stability is improved by incorporating polypropylene fibres to the mix. Since the fibres melt at 160-165°C, which produces expansion channels. The additional porosity and small channels created by polypropylene fibres melting may lower internal vapour pressure in the concrete and reduce the likelihood of spalling, but the additional porosity due to the melting of polypropylene fibres can lead to a decrease of the residual mechanical performances of concretes. Several studies carried out by different authors [22, 24, and 25] show a decrease of residual strength in agreement with the additional porosity while other authors [20, 23, and 26] showed that, there was an improvement of the residual strength. These results are contradictory, but, fundamentally, the inclusion of polypropylene fibre (PP-F) has proved to be one of the most advantageous techniques employed to reduce the spalling phenomenon. Moreover experimental studies have indicated that the practical inclusion of PP is the most effective method of passive fire protection [26-28]. It is worth to pointing out that, according to Chen and Liu [26], the inclusion of steel fibre along with PP fibre reduced the occurrence of spalling.

Several studies have been made on the effect of spalling of high-strength concrete, some other on mechanical properties and fire performance of high-strength concrete, incorporating silica fume. However, very little has been done on the effect of the occurrence of spalling of HSC incorporating Ground-Granulated Blast Furnace Slag (GGBFS). This has motivated the authors to perform the present research work, taking into account the effect of temperature on physical and mechanical behaviour using polypropylene fibres to reduce explosive spalling of concrete. The objective of this paper is to report the main outcomes of a parametric experimental study on the occurrence of spalling of HSC incorporating GGBFS. The research program included the testing of more than 60 high-strength concrete specimens subjected to two different heating rates, incorporating GGBFS or not. The detailed fabrication and testing program at Annaba University, Materials Laboratory are reported herein.

2. EXPERIMENTAL DETAILS

2.1. Materials and design mix proportions

2.1.1. Cement

The cement used in this study was CEMII 42.5 R PM CP2 NF, which comes from H'djar

Essoud plant (North Algeria). The chemical composition and physical properties of cement and GGBFS are given in table 1 and table 2 respectively.

Tab.1 Chemical composition of cement and Ground Blast furnace Slag (GGBFS)

Chemical composition	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	MnO	Na_2O	K_2O	Cl^-	CaOL
Cement	23.45	4.86	3.2	60.8	1	2.2	-	0.1	0.45	0.05	0.9
GGBFS	39.11	8.76	1.08	39.26	5.64	0.71	1.64	-	-	-	-

Tab.2 Physical properties of cement and GGBFS

Physical properties	Blaine specific surface (cm^2/g)	Absolute volumetric mass (kg/m^3)	Bulk density (kg/m^3)	Compressive strength at 28days (Standard mortar) (MPa)
Cement	3480	3100	1120	42.5
GGBFS	3650	2860	880	-

2.1.2. Aggregates

Aggregates are alluvial calcareous composed of 53% of calcium carbonate. The aggregates fractions were 0/5 mm (sand) and 5/12.5 mm (gravel).

The analysis by diffraction of the X-rays of the gravel is presented on figure 1 which was made in LMDC UPS Laboratory / INSA of Toulouse. The diffractogramme of the gravel shows that it essentially consists of calcite ($CaCO_3$).The physical characteristics of aggregates are given in table 3.

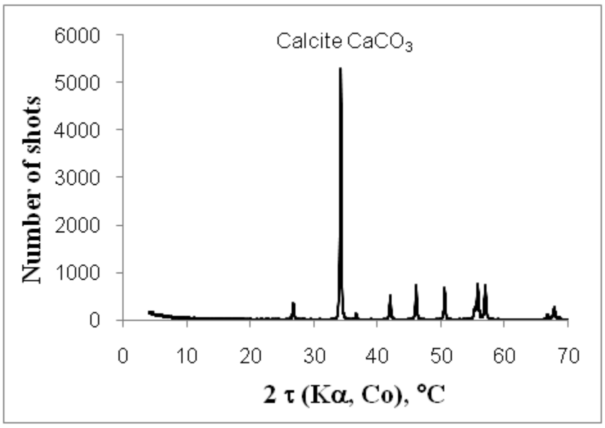

Figure.1. Diffractogram for limestone

Tab. 3 Physical characteristics of aggregates

Characteristics		Units	Fine sand	Crushed sand	gravel
True density		(g/cm^3)	2.67	2.54	2.73
Bulk density		(g/cm^3)	1.48	1.40	1.38
Porosity		(%)	44.48	44.87	49.25
Sand Equivalent	Esv	(%)	86.54	83.69	-
	Esp	(%)	79.35	82.62	-
Fineness Modulus		-	2.31	3.59	-
Los-Angeles test		(%)	-	-	28.08

2.1.3. Superplasticizer

The used additive was a superplasticizer VISCOCRETE TEMPO 12 in accordance with EN9342 [29].The superplasticizer density was 1.06 g/cm^3 and the dry extract was 30.2%.

2.1.4. Polypropylene fibres (PP-F)

The fibers used were fine polypropylene monofilaments. They were cylindrical of 12 mm length with a nominal diameter of 30 µm. The PP-F density was 0.9 g/cm^3 and the melting temperature was 160-165°C. The tensile strength was 300 MPa. The modulus of elasticity of polypropylene fibres was 3 GPa.

2.2. Cure condition

The samples were covered with plastic sheet and wet hessian to prevent evaporation for the first 24 hours, then demoulded and sealed in plastic bags. The samples were left to cure for 28 or 90 days at 20°C. After the designated curing period, the samples were unwrapped to be used for testing.

3. EXPERIMENTAL PROCEDURE

3.1. Heating–cooling cycles

The fire curve used in this test is represented in Figure2 which is a low rate of heating resulting in lower thermal gradients within the element. Four heating–cooling cycles were carried out in a muffle furnace (Fig. 3) from the room temperature up to 100°C, 300°C, 500°C and 700°C. The cycles included a phase of rise in temperature, a phase of temperature dwell and a phase of cooling. The heating rate was 10°C/min and the dwell duration was for one hour. The specimens were then left in the furnace to cool down at room temperature.

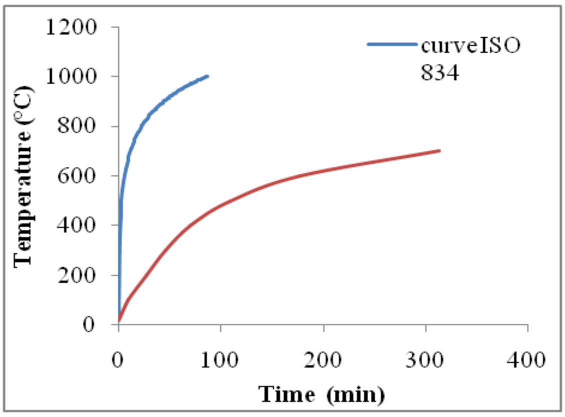

Fig.2. The used curve in

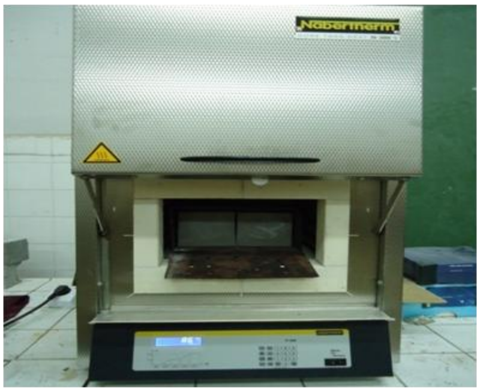

Fig.3. Muffle furnace

3.2. Mass loss

The specimens were weighed before and after each heating–cooling cycle in order to determine the mass loss during heating. The concrete mass loss was obtained on three cubic specimens (100x100x100) mm.

3.3. Compressive strength

Compressive strength was carried out at 28 and 90 days on three cubic specimens (100x100x100) mm in accordance with NF EN 12390-3 [30]. The loading rate was 0.5 MPa/s, until failure.

3.4. Flexural tensile strength

This test was carried out on three prismatic specimens (70x70x280) mm, in accordance with NF EN P-407[31]. The loading in three points was carried out at a speed of 0.25 mm/min, until failure.

3.5. Modulus of elasticity

Three cylindrical specimens (110x220) mm, were used in order to determine the modulus of elasticity which is obtained by a non-destructive test, in accordance to NF standard P 18-418 [32].

3.6. Design mixes proportions

Two groups of high strength concrete mixes were studied: one group of HSC mixes without PP designated as (HSC), the second group of HSC mixes containing PP fibres (HSC PP-F). All mixes have the same water/cement (W/C) ratio of 0.3 and the same paste volume. One part of the specimens was tested without thermal load (20°C) and the second part was subjected to heating–cooling cycles before the mechanical load. The heating rate was relatively close to the standardized curve ISO 834 (corresponding to a standard fire). The mix proportions are summarized in table 4.

Tab. 4 High strength concrete mix proportions

Ingredients	Quantity kg/m^3		
	HSC	HSCPP-F	HSC-SF
Water	155	155	155
Cement	459.26	459.26	516.67
Ground-Granulated Blast Furnace Slag	114.81	114.81	-
Silica fume	-	-	57.41
Gravel 5/12.5	1050	1050	1050
Natural sand	498.68	498.68	491.2
Rolled sand	203.31	203.31	200.26
Super plasticizer	11.48	11.48	11.48
Polypropylene fibre (PP-F)	-	1.80	-
W/C	0.3	0.3	0.3
Slump test (cm)	18	12.5	9
Concrete Density (g/cm^3)	2.53	2.47	2.48
Occluded Air (%)	2.1	2.4	1.9

4. RESULTS AND DISCUSSION

Compressive strength, flexural tensile strength and modulus of elasticity and mass loss were studied as function of the surface, temperature of the heated specimens are shown in Figures 5-8 respectively.

4.1. Spalling phenomenon

Fifteen cubic specimens 100x100x100 mm and 15 prismatic specimens 70x70x 280 mm were heated for each group. For all groups of concretes, no explosive spalling was observed. The only spalling phenomena observed after the various heating–cooling cycles was some hairy fractures on prismatic specimens as shown in figure 4. Many authors [2-11, 25-26], have shown some explosive spalling of concretes with PP-F, S-F and fibres cocktail. All specimens cited in the above references, were almost in the same conditions. The results showed a significant explosive spalling with S-F concretes between 200°C and 400°C. The initial moisture condition of specimens and the higher heating rate can explain the thermal instability of concretes studied by Peng et al. [33]. As it was pointed out by P-Pliya [34], the amount of PP-F or S-F in concrete can have an important effect on the concrete thermal stability, moreover, the type of filler has played an important role in the spalling phenomenon of HSC in this case.

	Heating temperature		
	300°C	500°C	700°C
HSC			
HSC PP-F			

Figure.4. Heating temperature for different specimens

4.2. Concrete mass loss

Figure 5 shows the addition effect of PP-F on concrete mass loss as a function of the heating temperature. The addition of PP-F did not affect the concrete mass loss evolution, as reported by Pliya [25] where FS was used instead of PP-F. At 300°C, the average mass loss was 4% for all specimens' concretes and 6 % at 700°C, regardless the age of the specimen. After the heating–cooling cycle of 300°C, the mass loss of the two groups of concretes are similar to Bidossessi [35], except in the case of Zhi Xing [36], where there was a slight difference of mass loss of 4%.

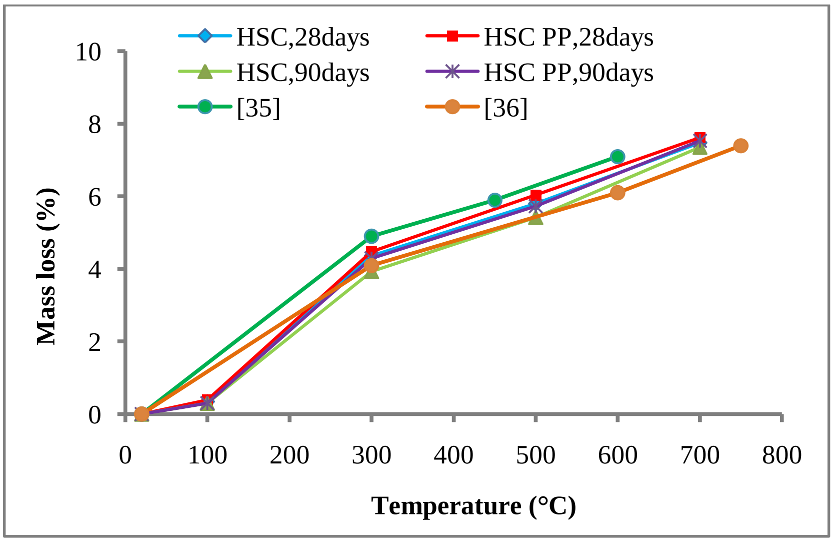

Figure.5. Mass loss as a function of temperature

4.3. Residual compressive strength

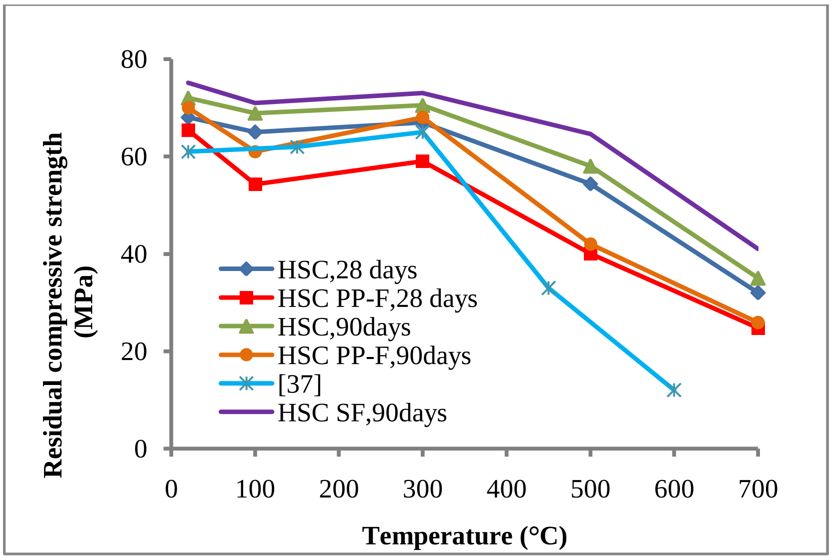

Figure.6. Relative residual compressive strength against temperature

Figure 6 shows the evolution of relative residual compressive strength of HSC and HSC PP-F at 28 days and 90 days as a function of heating temperature. As it can be seen from this figure that, for all specimens, residual compressive strength decreases with the temperature. Adding PP-F did not influence the general shape of the curves whether at 28 days or 90 days. According to many authors like Ali et al. [1], adding Silica Fume (SF) increases the residual strength. It is worth to point out that, the relative residual compressive strength of HSC PP-F concretes is lower than that of HSC

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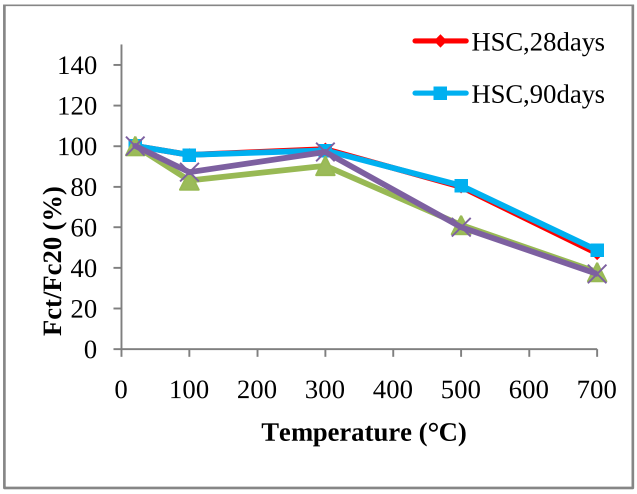

Figure.7. Residual compressive strength as a function of temperature

However, the relative residual compressive strengths of concretes with and without PP-F are similar for a heating at 600 °C as shown in figure 7. Some authors like Behnood et al. [23] and Chen et al. [26] have obtained an increase or a slightly increase of residual compressive strength of the concretes with PP-F. It is not consistent with our observations. The difference between the studies can be related to the experimental conditions. Specimens were cured in water [23, 26]. In the present study, specimens were not cured in water but were covered with plastic sheet and wet hessian to prevent evaporation. A loss of 14% of relative residual compressive strength of HSC, where as in the case of HSC PP-F there was 23% at a heating temperature 500°C. This compressive strength loss is related to the melting of the polypropylene fibres which generates channels in the concrete. No significant influence of different fraction volumes of the two types of fibres on the residual compressive strength was noticed. When comparing the rate of strength loss for the two groups of concretes, it is observed that the higher rate of compressive strength loss after 300 °C can be related to the cracks generated by the vaporisation of the PP-F and to the loss of adherence between the paste and the S-F. The addition of S-F delays the damage evolution with the increase of the temperature. The tensile strength of S-F restricts the initiation and development of cracking in the concrete.

4.4. Residual flexural tensile strength

Figure 8 shows the evolution of relative residual flexural tensile strength of the concretes with or without polypropylene fibres. The flexural tensile strength decreases gradually with the rise in temperature for all concretes groups. The addition of S-F or PP-F did not influence the shape of the curve. As for the residual compressive strength, the addition of polypropylene fibres involves a reduction of the residual flexural tensile strength, in particular at 500 °C. The general trend of the residual flexural strength is that, between 300°C and 500°C, the reduction is 40%, whereas between 500°C and 700°C, it is about 20%.

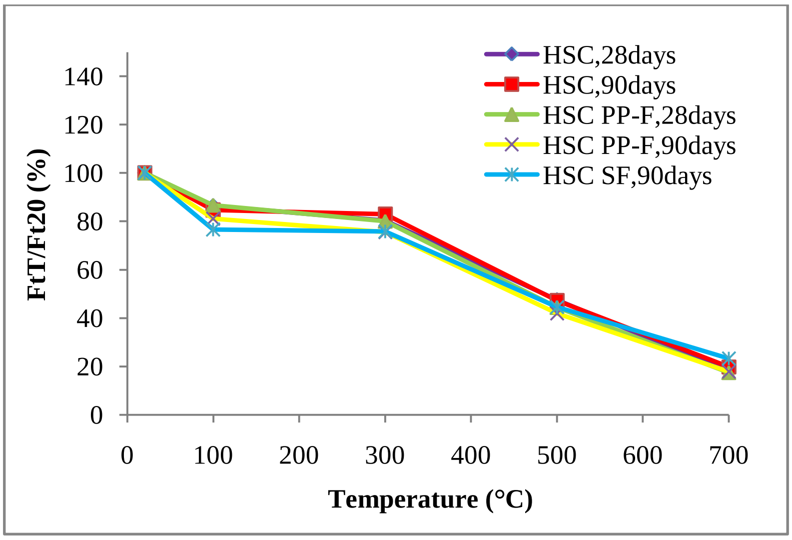

Figure.8. Residual flexural tensile strength as a function of temperature

It can be seen from this figure, that no improvement of the tensile strength, for a concrete whether containing or not PP-F. The loss of residual flexural tensile strength can be explained by the presence of PP-F. The flexural tensile strength decreases gradually with the rise in temperature for all specimens. As for the residual compressive strength, the addition of polypropylene fibres involves a reduction of the residual flexural tensile strength, particularly at 500°C. At 700 °C, all specimens have relative flexural tensile strength around20%. The works of Pliya [25] showed a little higher improvement of the tensile strength, around30% at 600 °C, for a concrete containing silica fume, and PP-F.

4.5. Residual modulus of elasticity

The modulus of elasticity of the concretes with or without PP-F decreases gradually with the rise of temperature as shown in Figure 9. The general behaviour of the concrete does not vary with or without PP-F. The relative residual modulus of elasticity is almost the same for all the concretes groups at the temperature up to300 °C, a decrease of 30%. Minor variations are to be noted with the presence of PP-F between the temperatures 500°C and 700°C. The relative modulus of elasticity of HSC and HSC PP-F decreases up to70% and 74%, respectively. An explanation to this, is that, since the water within the concrete was expelled at this temperature, the mass loss is very important, the mechanical properties at this stage have changed including the modulus of elasticity.

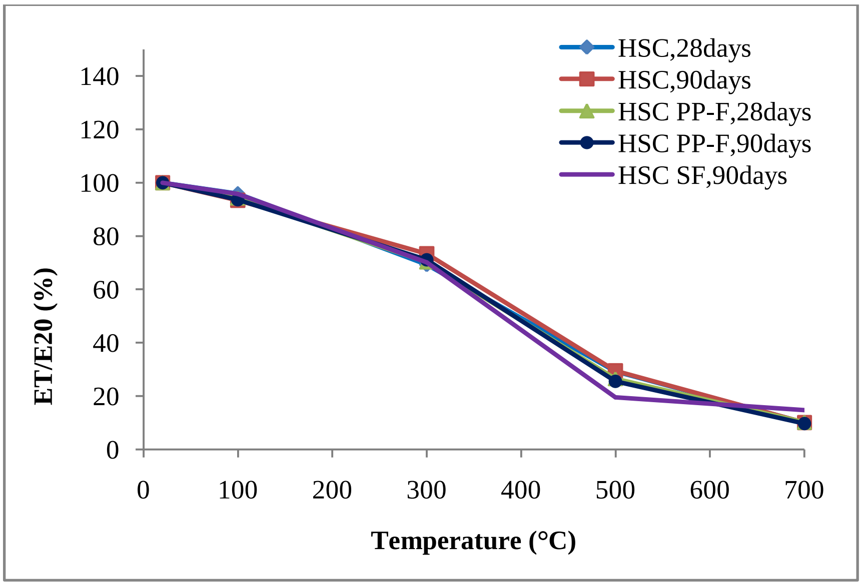

Fig.9. Residual modulus of elasticity as a function of temperature

5. CONCLUSION

In this study, specimens of various concretes compositions were made and subjected to different heating–cooling cycles. Two concretes groups containing ground-granulated furnace slag were formulated with or without PP-F. Concrete mass loss and residual mechanical properties were studied. Some conclusions can be drawn from the experimental results:

- The mass loss of the different groups of concretes decreases as the temperature increases. The addition of PP-F did not affect the concrete mass loss evolution At 300 °C; the average mass loss was 4% for all specimens and 6 % at 700°C, regardless the age of the specimen.
- Residual compressive strength decreases with the temperature. Adding PP-F did not influence the general shape of the curves whether at 28 days or 90 days. It is worth to point out that, the residual compressive strength of HSC PP-F concretes is lower than that of HSC. A loss of 14% of relative residual compressive strength of HSC, where as in the case of HSC PP-F there was 23% at a heating temperature 500°C. It can be related to the melting of the polypropylene fibres which generates channels in the concrete. When comparing the rate of strength loss for the two groups of concretes, it is observed that the higher rate of compressive strength loss after 300°C can be related to the cracks generated by the vaporisation of the PP-F
- The flexural tensile strength decreases gradually with the rise in temperature for all concretes groups. The addition PP-F did not influence the shape of the curve. As for the residual compressive strength, the addition of polypropylene fibres involves a reduction of the residual flexural tensile strength, in particular at 500°C. Between 300°C and 500°C, the reduction is 40%, whereas between 500°C and 700°C, it is about 20%.
- At a heating temperature of 300 °C, the relative residual modulus of elasticity is almost the same for all the concretes groups, where a decrease of 30% was noticed. Between 500 and 700°C, there has been a decrease of up to 70% of the relative elasticity for specimen containing PP-F.

This study shows that HSC made with ground-granulated furnace slag can have the same residual mechanical properties of concretes incorporating PP-F. Two heating–cooling cycles were tested at a heating rate of 10 °C/min. It would be necessary to test other heating–cooling cycles and heating rates in order to have completed understanding of the influence of the fibres.

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