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Impact of Aggregate Properties on the Microstructural Performance of Concrete Exposed to High Temperatures: An Analytical Review

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Abstract – Exposure of concrete to high temperatures affects its mechanical properties by reducing the compressive strength, bending… etc. Factors reducing these properties have been focused on by several studies over the years, producing conflicting results. This article interested an important factor, that is the type of aggregates. For this, an experimental study on the behavior of concrete based on different types of aggregates: calcareous, siliceous and silico-calcareous subjected to high temperatures. In addition, the particle size distribution of the aggregates was chosen to be almost identical so that the latter does not affect the behavior of the concrete. Aggregates and concrete samples were subjected to a heating/cooling cycle of 300, 600 and 800 ° C at a speed of 1 °C/ min. The mechanical and physical properties of concrete before and after exposure to high temperatures were studied. Thus, a comparative study between various researches on the mechanical properties of concrete exposed to high temperatures containing different types of aggregates was carried out.
The compressive strength test results showed that the concrete based on siliceous aggregates (C-S) has better mechanical performance up to 300 ° C. However, above 300°C, the compressive strength decreases faster compared to calcareous-based concrete (C-C).
This study reinforces the importance of standardizing test procedures related to the properties of concrete in a fire situation so that all the results obtained are reproducible and applicable in other research.

Keywords – Types of Aggregates, High Temperature, Compressive Strength, Review

I. Introduction

This Fire is one of the most severe accidents to which structures can be subjected [1, 2]. Thus, when designing concrete structures, it is necessary that engineers take into consideration the consequences associated with high temperatures, such as explosive spalling [3] [2]. This phenomenon observed by many research hers often results in a serious deterioration of concrete [4], [5].

Fire resistance of concrete is mainly influenced by the temperature and fire duration, the type of aggregate and the cement used in its composition as well as porosity and moisture content of concrete [6].

The aggregates occupy 70 to 80% of concrete volume which strongly influences its thermal behavior [7]. Researchers Fares, H., et al [8] Xing, Z., et al [9] have shown that there is an accumulation of water at the paste-aggregate interface. This high amount of water creates a more porous area and initiates cracking of concrete. In addition, the quality of the paste-aggregate bond strongly depends on the geometry of aggregates and their mineralogical nature (calcareous, siliceous, etc.). Damage in concrete subjected to temperature rise is mainly caused by cracking, which occurs due to the variation in temperature between the aggregates and the paste [10]. Consequently, the paste-aggregate bond plays a very important role in the resistance of concrete subjected to high temperature [7].

Several studies have shown that concrete with siliceous aggregates has a low fire resistance than that with calcareous aggregates [11]. This is mainly due to the decomposition of calcareous aggregates at a higher temperature than siliceous aggregates [11]. In addition, at 573° C, the thermal expansion of siliceous aggregates due to the transformation of α quartz to β quartz causes an expansion of concrete [10]. However,

Robert, F et al [10] showed that concretes prepared with siliceous aggregates can have better residual mechanical behavior than those prepared with calcareous aggregates. The decomposed carbonates release carbon dioxide during heating. This carbon dioxide rehydrates during cooling. This re-hydration reaction causes an increase in the volume of 44% which is the cause of spalling after cooling of calcareous concrete [12].

Hager, I et al [7] studied an ordinary concrete based on silica-calcareous aggregates heated up to 600 °C. They showed, using SEM, that the cracks pass through the cement paste and the interfacial transition zone and reach the siliceous aggregates. This phenomenon indicates that certain siliceous aggregates have low resistance at a temperature of 350 °C. Jean-Christophe Mindeguia et al [13] have shown that concrete made with silica-calcareous aggregates exhibits considerable cracks at the cement paste/aggregate interface (especially around gravel), due to the high thermal deformation mismatch.

In addition, in their study Masood, A., et al [14] cited that after heating to 800 °C, the calcareous aggregate concrete retained 40% of its resistance. Thus, crystallization and microstructure play an important role in the thermal stability of concrete based on the different types of aggregates subjected to heating-cooling cycles at high temperatures up to 750 °C.

Over the past 30 years, the study of concrete mechanical properties on a macroscopic scale has gradually reached maturity. Besides, the strength and durability of concrete depends strongly on the pore structures [15]. So, microscopic studies seem necessary to deepen our knowledge the behavior of concrete subjected to high temperature [16]. In addition, a recent study in 2021 by Sollero et al [17] that analyzed studies on the evaluation of the mechanical properties of concrete exposed to high temperatures. This analysis reveals discrepancies in the results obtained by several authors due to insufficient characterization of the type of concrete used. Thus, they have shown that the granite aggregates used in brésille is different from the siliceous aggregates used in Europe. For this, it is necessary to take into consideration the country, the test methodology and the composition of the concrete, more particularly the mineralogical, chemical and physical characteristics of the aggregates. The objective of this work is to provide a comparison of a mechanical property of ordinary concrete and its evolution with temperature (300, 600 and 800 ° C) in the case where the composition of the cement pastes and the mortar as well as their volumes remained the same in all samples. The parameter that will change was the mineralogical nature of the aggregate.

. For this, ordinary concretes containing different types of aggregates (calcareous, siliceous and silico-calcareous) were made. Compressive strength was measured for all concretes. An analysis of the various research works on the effect of the type of aggregates on the mechanical behavior of ordinary concretes subjected to high temperature was carried out.

II. MATERIALS AND METHOD

II.2. Material

This Three series of concrete specimens were prepared. The first one was made with siliceous aggregates (C-S), the second series with silico-calcareous aggregates (C-SC) while the third series was made with calcareous aggregates (C-C). Their characteristics chemical nature is given in Table 1. The physical and mechanical characteristics of aggregates are presented in Table 2. Portland Cement CEM II/B-L-42.5 N was used for all concrete mixtures.

Table 1. Chemical characteristics of aggregates.

Composition (%)	**SiO_2**	**Al_2O_3**	**Fe_2O_3**	**CaO**	**MgO**	**SO_3**	**K_2O_3**	**Na_2O**	**Cl^-**
C	1.86	0.69	0.38	93.27	3.69	0.09	0.16	0.09	0.06
SC	13.42	2.72	2.85	74.73	4.83	0.093	0.51	0.06	0.05
S	93.09	1.10	1.53	5.17	0.46	0.1	0.13	0.44	0.01

Table 2. Physical and mechanical characteristics of aggregates.

Aggregate's type	**C**		**SC**		**S**	
	0-3	3-8	0-3	3-8	0-3	3-8
ρ_{abs} Absolute density (g/cm^3)	2.55	2.66	2.66	2.62	2.67	2.5
γ_{app} bulk density (g/cm^3)	1.57	1.54	1.54	1.39	1.57	1.43
Los Angeles (%)	16.67		17.71		21.37	
Porosity (%) [a]	38.4	49.06	42.1	46.9	38.43	46.07
Fineness modulus of sand 0 / 3	2.53					

II.Mixture proportions

Mixture design was made according to DREUX-GORISSE formulation method [19]. The same cement content (340 kg/m^3) was used in all mixtures with a water to cement ratio (W/C) of 0.6. Mixtures proportions are given in Table 4. Cubic specimens 100 x 100 x 100 mm^3 were prepared to use in all tests. Specimens were cured in moisture for 28 days (20 ± 2°C, RH>95%) before testing.

Table 3. Composition of the studied concretes

Mixtures	**Cement (kg/m^3)**	**Water (L)**	**Aggregate size range**		**Compressive strength at 28 days ((MPa)**
			0-3(kg/m^3)	**3-8 (kg/m^3)**	
C-C	340	224	688.28	1037.06	34.58
C-SC	340	224	717.97	1017.64	38.24
C-S	340	224	702.78	1103.78	33.61

After curing in normal conditions all specimens were undergone a pre-drying (at 100 ºC) until mass constant to evaporate the maximum of free water in the cementitious structure and avoid spalling risks of specimens in the furnace during heating.

Using an electronic furnace, specimens were subjected to temperature rise with a constant rate of 1°C/min up to the target temperatures of 300, 600 and 800 °C. After reaching the target temperatures specimens were left in oven for 1h at each temperature. Then, the specimens were remained inside until the furnace cooled down to 25°C. Applying a slower speed, it allows chemical reactions to proceed; and avoid spalling of concrete [7].

III. RESULTS AND DISCUSSION

III.1. Compressive strength

Fig 1 has shown the reduction factors of the residual compressive strength of ordinary concrete (Fc (T) / Fc (20)) from international studies published between 2011 and 2021, compared to the values proposed by Eurocode2 part 1-2 [20] [17] [21] [22] [23] [24] [25] [26] [6].

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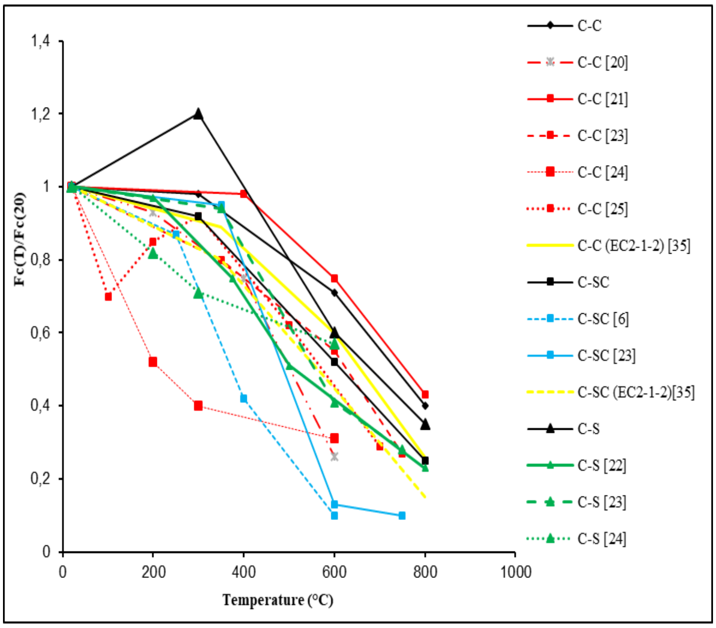


Fig.1 Evolution of the residual compressive strength of concrete as a function of temperature.

From Fig.1 we see that, up to 300 °C, the compressive strength decreases slightly by 0.28% and 0.91% for concrete with silico-calcareous aggregates and concrete with calcareous aggregates respectively. This can be explained by an accumulation of water at the paste-aggregate interface. This high amount of water creates a more porous area in which cracking will be initiated in concrete. In addition, the quality of the paste-aggregate bond strongly depends on the geometry of the aggregates and on their mineralogical nature (calcareous, siliceous ... etc.) [17] [26] [23] [22] [6]. Hager et al [27] explained the phenomenon of decreased resistance through dehydration that occurs in CSH gel reduces its volume, which in turn increases the porosity of the cement matrix.

On the other hand, for concretes based on siliceous aggregates (C-S), there is a slight increase in resistance of 10% at 300 °C. This increase according to Fares, H.et al [8, 28] is due to additional hydration of the anhydrous cement due to the large water movements which occur during heating between 100 and 300 °C. Consequently, the grains of anhydrous cement were rehydrated. As for Behnood et al [29]and Ghandehari et al [30], they attributed this increase in resistance to water departure between particles of CSH (Van Der Waals forces) [31].

At 600 ° C, all the samples showed a reduction in compressive strength of 47%, 62% and 71% for C-C, C-S and C-SC respectively. At this point, perhaps the microstructure is rapidly deteriorated by a chemical transformation of the crystalline brucite and the decomposition of hydration products such as the evaporation of bound water in the CSH [27, 32]. These intrinsic chemical transformations produce more cracks leading to an increase in porosity of around 15% .
Concrete with calcareous aggregates (C-C) had higher residual strength compared to that with siliceous aggregates. This can be explained by the improved matrix-aggregate transition zone mainly due to the

reaction of calcareous with calcium aluminates in the cement paste, thus forming the calcium carboaluminates [9, 23]

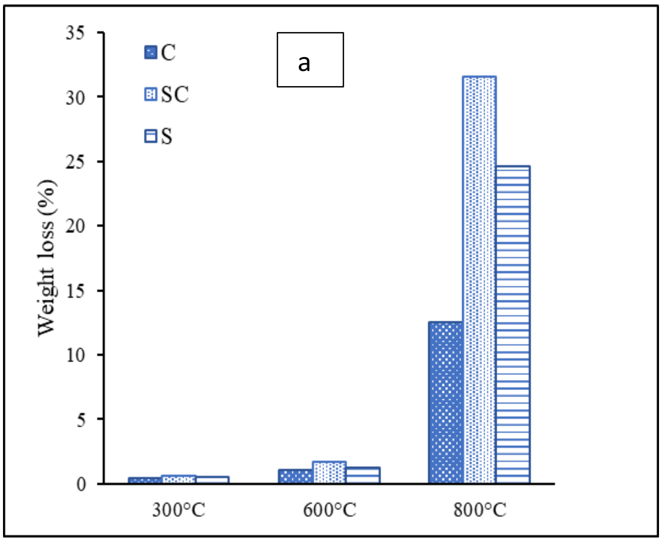
In addition, the decrease in the resistance of C-S and C-SC is due to the bursting of silica and its transformation from α quartz to β quartz at 573°C accompanied by a change in volume from 1% to 5.7 % [7] [33]. The researchers [9], [27, 32] explained this loss by micro-cracking at the paste-aggregate interface [34]. The better performance of C-C compared to C-S, in residual compression, is probably due to a better bond between the calcareous aggregates and the paste. Quartzite aggregates are round with a smooth surface unlike calcareous aggregates which are crushed with a rough texture. Other researchers, Onundi, L.O et al [32], showed that calcareous aggregates provide concrete with higher fire resistance and better spalling resistance than siliceous aggregates. This is mainly because the calcareous aggregates have a higher thermal capacity (specific heat), which is beneficial in reducing spalling and increasing fire resistance.

Above 600 °C, the compressive strength loss of C-C concrete becomes more important due to the decarbonation of calcium carbonate. As for concrete based on siliceous aggregates, it has greater thermal stability [9].

The analysis of studies conducted on the evaluation of the mechanical property of concrete exposed to high temperatures reveals discrepancies in the results obtained by several authors due to insufficient characterization of the type of concrete used. The lack of standardization of tests and specimens was identified. Fig 1 shows that factors such as : cement dosage, type of aggregates, cure before the heating cycle, size of specimens (cylindrical or cube) and rate of heating-cooling are contributing to the divergence of results residual mechanical performance results[17]. From Fig 1 we note that four works of [17] [23] [25] [6] (concrete based on calcareous aggregates) show low values compared to EC2-2 [20]. By cons, our results and [21] reveal residual high resistance compared to EC2-2. This difference is due to the lack of application of the factors for reducing the residual strength of concrete in EC2-2[20]. Moreover, this distinction according to Razafinjato et al. [33]is due to the different properties of thermal expansion, conductivity, thermal capacity and mechanical resistance of aggregates which represent 80% of the total composition of concrete. In addition, G. Khoury [35] have shown that the type and properties of the coarse aggregate is probably the most important parameter in the behavior of concrete subjected to high temperature. Therefore, it is possible that two types of concrete with similar mechanical properties have different behavior in fire due to changes in the type of aggregate. Sellori et al [17]have shown that the granite aggregates used in Brésille are different from the siliceous aggregates used in Europe in their thermal behavior. For this, it is necessary to take into consideration the country and the mineralogical, chemical, thermal and physical characteristics of the aggregates to know the behavior of concrete subjected to high temperature.

III.2 Mass loss of aggregates

The mass loss values for the C, S and SC aggregates are shown in fig 2.



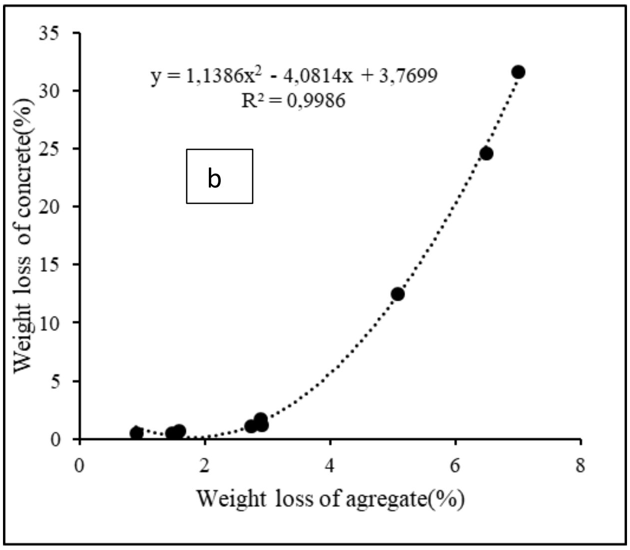


Fig 2. (a) Average mass loss values for C-aggregates, SC-aggregates and S-aggregates. (b) Correlation between the loss of mass of concrete and the loss of mass of aggregates.

The mass loss value is obtained by an average made on 10 grains for each mineralogical nature of aggregates. The mass loss measurements were only carried out on aggregates dried beforehand in the oven. From the fig 2, the aggregate mass loss values were almost similar up to 300 ° C. At 600 ° C, an increase in mass loss of aggregates of approximately 1.1% -1.7% compared to control samples. At 800 ° C., the loss of the SC aggregates increases significantly by 31% compared to the control. [23]explained this increase in the mass loss by the high porosity of aggregates and their significant thermal instability compared to siliceous and calcareous aggregates.

Fig 2.b shows a polynomial relationship between the mass loss of concretes and aggregates with R2 = 0.99. This reveals the importance of the properties of aggregates in the behavior of concrete subjected to high temperatures.

IV. CONCLUSION

Appropriate knowledge of the mechanical properties of concrete exposed to high temperatures is essential for the optimization of the design of fire-rated structures, post-fire analysis of structures and subsequent restoration or reinforcement.

This article presented an experimental study of macro and microstructural changes induced by the heating of concretes based on different types of aggregates. The following final notes summarize our main findings:

- The residual compressive strength of C-S is higher than that of C-C and C-SC at temperatures between 25 and 300 °C. However, between 300 and 600 °C, C-C has good fire resistance compared to C-S and C-SC. This is due to an improvement in the matrix-aggregates transition zone.
- The analysis of studies conducted on the evaluation of the mechanical property of concrete exposed to high temperatures reveal discrepancies in the results obtained by several authors due to insufficient characterization of the type of concrete used. The lack of standardization of tests and specimens was identified.

This study reinforces the importance of standardizing test procedures related to the properties of concrete in a fire situation so that all the results obtained are reproducible and applicable in other research.

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