Comparative study of mechanical properties and heat of hydration of fine recycled aggregates and limestone fillers cement mortars

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ABSTRACT

Huge quantities of crushed concrete and construction waste demolition are produced annually around the world, and their potential use as substitution of natural aggregates in concrete formulations has been widely studied. However, most of existing studies have mainly been dedicated to the use of recycled gravel and sand. Due to the lack of further investigations concerning the possibility of using the fine fraction of recycled aggregates smaller than 80µm, the aim of this paper is to achieve a better understanding of the impact of a partial replacement of Portland cement by those fine recycled aggregates (FRA) in terms of hydration, microstructural and mechanical properties. A comparison of performances obtained by replacing cement with limestone filler (LF) is also proposed in the present study.

Substitution rates of cement of 0, 10 and 20% by weight were considered. Five mixes of paste cement and mortar were prepared with a fixed ratio of water to binder of 0.5 and a normalized sand to binder ratio of 3.

The hydration kinetics by isothermal calorimetry on cement paste, showed a decrease in the heat released by addition-based mixtures compared to ordinary cement paste. Compressive strength results obtained on mortars at 7, 28 and 90 days respectively were almost similar between mixtures based on FRA or LF.

Keywords: addition, fine recycled aggregates, limestone fillers, hydration kinetics and isothermal calorimetry

I. INTRODUCTION

The use of recycled aggregates derived from construction and demolition wastes considerably increases in the concrete industry in order to reduce the consumption and preserve natural resources for future generations (Assaad and Vachon, 2021; Meng et al., 2018). For some years now, the valorization of demolition wastes through partial replacement of natural coarse aggregates in concrete has been defined by standards that fix the rate of replacement depending on the sites of construction. Amongst them, the European Standard NF EN 206/ CN authorizes a quantity of recycled concrete aggregate which concern gravel and sand only and depends on the nature of the aggressive environment.

The several codes and standards have limited the use of fine recycled aggregate fraction in mortar and concrete, due to their inferior physical and mechanical properties. The small fractions of recycled aggregate contain the old adhered mortar (Evangelista et al., 2015). Existence of old adhered mortar and the presence of pollution material as bricks, plaster and wood are responsible for lower the density and higher water absorption (Colman et al., 2020; Kirthika and Singh, 2020).

The annual global production of cement which is the main ingredient of concrete formulations is responsible for at least 5 % of the global CO_2 emissions(Hendriks et al., 1998; Naik and Moriconi, 2005). In fact, the production of 1 ton of Portland cement releasees the equivalent of 0.7 ton of CO_2(Kajaste and Hurme, 2016). Among the existing solution to remediate this problem, one can mention the partial substitution of cement by mineral additions (limestone filler, slag, fly ashes...).

In the present study, the scientific challenge is to evaluate the properties of the cement paste and mortar formulated with a partial replacement of Portland cement with fine recycled aggregates and to compare them with mixtures incorporating limestone filler.

II. EXPERIMENTAL PROGRAM

A. *Materials and mixtures*

The Portland cement CEM I 52.5 N CE CP2 NF according to (EN NF 197-1, 2000), having a density of 3120 kg/m^3 and a specific surface area of 930 m^2/kg from BET measurements, was used in this study. The Fine Recycled Aggregates (FRA) were issued from recycling platform of demolition wastes located in Quimper, France. These latter were crushed afterwards into particles smaller than in the laboratory. Their density is 2300 kg/m^3 while the specific surface area measured by BET is 6377 m^2/kg. Finally, the limestone filler (LF) used is a BETOCARB HP (Erbray, France). Its density is 2710 kg/m^3 and the specific surface area provided by BET is of 382 m^2/kg. The chemical composition and physical characteristics of tested materials are detailed in Table 1.

Table 1: Chemical composition and physical characteristics of cement and additions

	OPC	FRA	LF
Chemical composition (%)			
SiO_2	21,3	50,19	1,2
Al_2O_3	5,51	10,22	/
Fe_2O_3	2,96	2,5	/
CaO	65,39	16,83	97,5
MgO	1	0,79	/
SO_3	3,1	0,86	0,01
K_2O	0,04	2,61	0,0012
Na_2O	0,01	1,04	0,0008
Physical characteristics			
Density (kg/m^3)	3120	2300	2700
Blaine (m^2/kg)	4035	/	4480
BET (m^2/kg)	930	6377	382

Ten formulations were tested in the present study: five cement pastes and five mortars respectively, having a common water to binder ration 0.5. The Portland cement was replaced by 0%, 10% and 20% by mass with FRA or LF respectively. The nomenclatures of tested samples according to their respective composition are given in Table 2. The tested samples were cured by immersion in water at 20±1°C.

Table 2: Mortars and Pastes mixtures proportions

	MR	M10FRA	M10LF	M20FRA	M20LF	PR	P10FRA	P10LF	P20FRA	P20LF
Cement (g)	450	405	405	360	360	450	405	405	360	360
FRA (g)	/	45	/	90	/	/	45	/	90	/
LF (g)	/	/	45	/	90	/	/	45	/	90
Water (g)	225	225	225	225	225	225	225	225	225	225
Sand (g)	1350	1350	1350	1350	1350	/	/	/	/	/

Table 3: Evolution of binder density for reference mortars and mortars with FRA and LF

Mixtures	MR	M10FRA	M10LF	M20FRA	M20LF
Binder Density (kg/m^3)	2564	2546	2555	2528	2546

B. Tests procedure

The early age evolution of heat released by hydration reactions of cement pastes formulations were measured by using a multi-channel isothermal calorimeter TAM Air device. For each formulation, the binders were mixed with water and immediately after mixing, two samples of 4-6 g were recovered into standard plastic vial and placed into the isothermal calorimeter. Both the total heat and heat rate were continuously recorded for 6 days at 20°C.

The compressive strength and dynamic young modulus test were performed at 7, 28 and 90 days respectively of three mortar specimens of dimensions 40x40x160 mm^3, according to NF EN 196-1 (AFNOR, 2016, pp. 196–1) and ASTM E1876-15 (ASTM, 2015) standards.

The porosity accessible to water of mortars was also measured at 7, 28 and 90 days according to NF P 18-459 (AFNOR, 2010, p. 18) standards . Firstly, the samples were put in a desiccator and subjected to vacuum pressure of 0.25 bar for 4 hours. By keeping the vacuum pressure, they were immersed in a first time up to half height with water for 44 hours, and were totally immersed afterward for 24 hours. At the end, each sample was weighed in water and in air respectively. They were finally oven- dried at 105 °C to constant mass. The porosity was determined as the average of values measured on three specimens.

III. RESULTS AND DISCUSSIONS

A. Heat of hydration

The heat rate and the total heat of hydration per gram of the binder were presented in Fig 1 . It was observed that the shape of heat of hydration profile of mixtures were similar to the reference paste PR whatever the replacement rate and the nature of additive. On the other hand, the heat generated by the pastes containing FRA or LF was lower than that generated by PR. The position of hydration peak, does not seem to be influenced by the presence of either FRA or LF. The decrease in both heat flow and reaction heat was accentuated when the substitution rate has increased. This result can be explained by to the dilution effect (Deboucha et al., 2017) (Bordy et al., 2017). After 120 h of hydration, the total heat released e by P10FRA, P10LF, P20LF and P20FRA respectively represents 93%, 93%, 88% and 87% of that of PR. This indicates that both FRA and LF are not inert and partially reacted with cement.

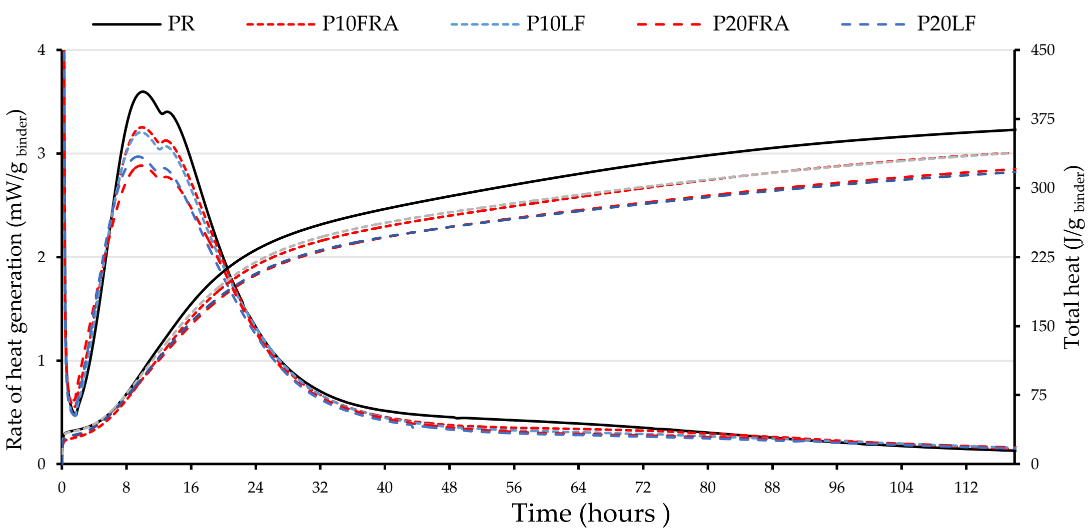

Fig 1: Hydration heat of the reference paste and the cement paste containing FRA or LF

B. Compressive strength and Dynamic modulus

The Fig 2 and 3 shows the results of the compressive strength and dynamic modulus evolutions of mortars at 7, 28 and 90 days. The partial substitution of cement by FRA or LF caused a decrease over time of mechanical properties compared to those of reference mortar MR. It can also be observed that the higher the substitution rate, the higher the decrease. The compressive strength of samples formulated with 10% of cement substitution were reduced by 11% for M10FRA and of 14,5% M10LF at 28 days, while a reduction of 15 % is observed at 90 days for both. For samples formulated with for 20 % of cement replacement, the drop in compressive strength is of 18 % at 28 days and of 23% at 90 days for both. Such diminutions are caused by to dilution effect s(Cyr et al., 2006).

Another interesting aspect concerns the comparison of mixes formulated with FRA and those formulated with LF. One can notice an increase of compression strength at 28 and 90 days of about 2 MPa for both M10FRA and M20FRA compared to M10LF and M20LF respectively. The differences observed here between mixes incorporating FRA and those incorporating LF can be explained by the reactivity of residual anhydrous phase in FRA (Bordy et al., 2017) combined with the effects of their high specific surface area g (6377 kg/m² for FRA compared with 382 m²/kg for LF) which play the role of nucleation sites for hydrates formation (Cyr et al., 2006). Similarly, to the compressive strength, the dynamic modulus of mortars with FRA or LF substitutions is lower by about 9% of the reference mortar modulus at both 28 or 90 days.

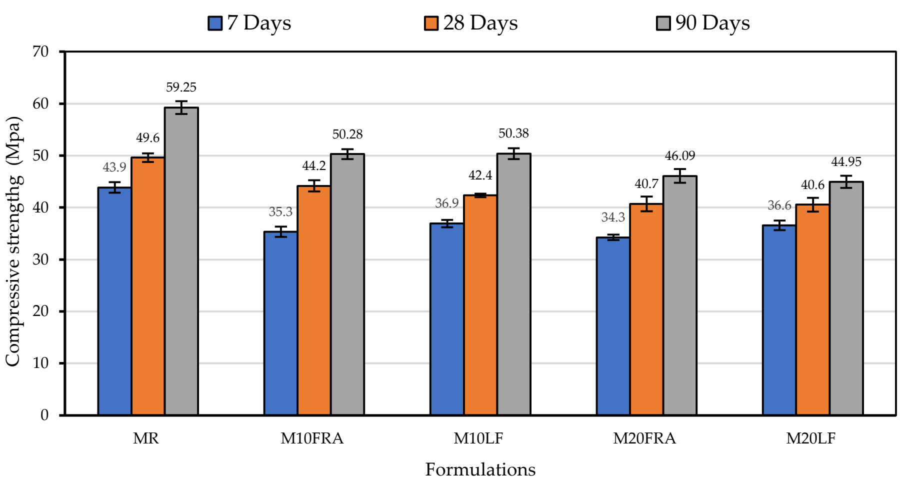

Fig 2: Compressive strength for reference mortars and mortars with FRA and LF

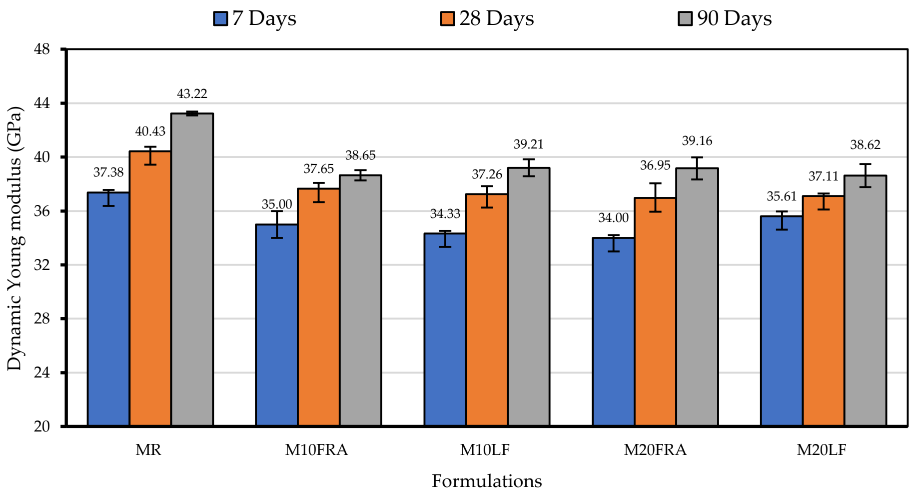

Fig 3:Dynamic modulus for reference mortars and mortars with FRA and LF

C. Water Porosity

The water porosities of mortar were measured on three specimens 40x40x80 mm^3 a at 7, 28 and 90 days. The Fig 4 shows the evolution of total porosity for all tested materials. The replacement of cement by either FRA or LF increases the total porosity due to the dilution effect combined with the drop in the density of the binder as observed in Table 3. At 7 days, Mortars incorporating FRA showed the highest values of total porosity, 18.02% for M10FRA and 18.54% for M20FRA respectively. These values represent an increase of 3% and of 6 % respectively compared to the reference mortar MR. They can be explained by the high porosity of FRA and their high absorption rate (Yammine et al., 2020). At 28 and 90 days respectively, formulations with 10 % of cement replacement exhibit similar values of water porosity with an increase of about 2 to 3 % compared to the reference mortar MR whatever the type of the substitution. Concerning formulations with 20 % of cement replacement by FRA, the porosity values are 6.6% and 5.6% higher than that of MR at 28 days and 90 days respectively. Mortars incorporating 20% LF f have porosity values 8.8 % and 6.9% higher that MR at 28 days and 90 days respectively. Between 28 days and 90 days, it can be observed that that the FRA- based mixes become less porous than those LF-based ones. These results can be explained by the reactivity of the residual anhydrous phases in FRA, and are consistent with the evolution of mechanical properties.

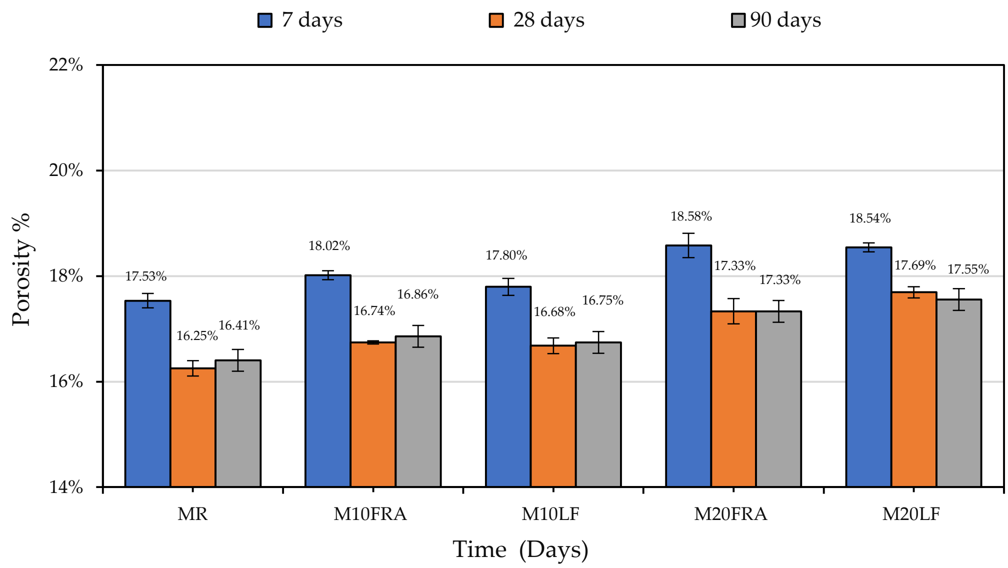

Fig 4: Water accessible porosity for the reference mortar and mortars with FRA and LF at 7, 28 and 90 days.

IV. CONCLUSIONS

The conclusions drawn from the experimental results obtained in this investigation on the mortars and cement paste based in Fine Recycled Aggregates and other based in Limestone filler are as follows:

- The partial replacement of cement with FRA or LF causes a decrease in mechanical properties due to dilution effect
- The substitution rates have a significant influence on the properties of cement pastes and mortars at the fresh and hardened states.
- The FRA are not inert as interpreted from the heat release, due to hydration reaction of residual clinker
- The replacement of cement by FRA results in a 15-20 % reduction in the compressive strength in mortar at 90 days, however, they can be applied to structural applications.

As a continuation of this work, several tests will be carried out for different durability parameters as gas permeability and mercury intrusion porosimetry. They will be realized in order to see the influence of FRA on the pore structure i.e. the size and connectivity of the pores. As a perspective, it will be relevant to study the influence of the FRA dosage and fineness on the development of drying and autogenous shrinkage.

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