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THE MICROSTRUCTURAL RESPONSE OF RECYCLED CONCRETE AFTER HIGH TEMPERATURE EXPOSITION AND RAPID COOLING

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Abstract: The recycled concrete is increasingly used in buildings. Lowered properties are claimed from the replacement of natural aggregates with recycled concrete aggregates. However, this reduction depends on the quality of the source concrete and the dosage. This latter should be kept below 50 %, in order to achieve the main mechanical properties, such as compressive strength and modulus of elasticity. In this manner, the cementitious material may be adequate to be used buildings. In the case the old source concrete exhibits a high quality, e. g. compressive strength above 60 Mpa, durability parameters can also be attained and the recycled concrete can be used for infrastructures. On the other hand, the behaviour to fire and the cooling process of recycled concrete still needs a detail clarification. The water chemically bond within the old mortar may largely influence the performance during fire. Concretes were prepared with a different cement dosage and water to cement ratio. They were crushed and the recycled concrete aggregates were aged up to 2 years. Recycled concrete with a natural aggregate replacement of 25% were prepared. The recycled concretes were exposed to 500 ^{o}C air or water quenched. The air coling promoted the formation of fine cracks with the microstructure within the old mortar or along the old mortar-new cementitious matrix interface. The rapid water quenching promoted a general widening of the crack to macrocracking, a partial detachment of the cementitious matrix along both the RCA and NA-cement-based matrix interface. Not rarely grain pull outs and a crack branching was seen in the water cooled specimens. For this latter rapid cooling procedure, the aggregates, particularly the Si-bearing aggregates showed an increased expansion and cracking a s compared to the air cooling procedure. A denser microstructure with a lower water to cement ratio and a higher cement dosage created a more susceptible microstructure with respect to the internal thermal stresses, that causes a widening of the cracking, rather than an increase in the microcracking frequency.

1 INTRODUCTION

In the construction sector, buildings and infrastructures are constantly subjected to environmental degradation. The increase in the average global temperature caused a higher frequency of the extreme events and fire further became a main concern. More resilient structures and changes in the concrete fire framework are highly required in the coming decades [1]. International standards mainly deal with the fire resistance of conventional concrete, although European standards provide indications on structural concrete containing recycled concrete aggregates [2]. At a temperature above 300 ^{o}C, surface spalling is observed in conventional concrete [3], and loss of strength and structural capability are observed [4].

Recycled concrete requires a standardization [5], that better explains the boundary conditions in the behaviour of such cementitious materials at a high temperature. The hydrated cement paste expands at a temperature up to 100 ^{o}C and contracts at a temperature up to 500 ^{o}C [6]. The cooling from 500 ^{o}C down to room temperature, causes expansion and cracking [7]. The similar coefficient of thermal expansion between the recycled concrete aggregates and the new cementitious matrix tends to positively influence the fire resistance of recycled concrete. Nonetheless, macrocracking may often be seen along the interfacial zones between the recycled concrete aggregates and the new mortar [8]. In the case of fire, the deterioration appears to increase with a higher dosage of recycled concrete aggregates as a replacement of natural aggregates [9]. Generally, the recycled concrete seems to exhibit a higher damage with both coarse and fine recycled aggregate concrete [10]. Nonetheless, a natural aggregate replacement with recycled concrete aggregate up to a maximum dosage up to 50 % seems to increase the fire resistance of recycled concrete [11]. The replacement of granite up to 75% by volume with waste concrete containing granite aggregates and heated at 500 ^{o}C, then soaked for 1-4 h and cooled at ambient temperature, shows a similar strength decrease at 4 hours as for conventional concrete. Apparently, the similarity of the material’s coefficient of thermal expansion along the interface reduces the micro/macrocracking [12]. A reduction in the water to cement ratio in recycled concrete containing siliceous-bearing aggregates, especially quartz, improves the fire resistance of concrete as compared to conventional concrete [13]. Not rarely, the recycled concrete exhibits a similar fire resistance as conventional concrete [14], although no indications on the residual mechanical properties or microstructural changes are explained.

The aim of this work is to clarify the behavior of two concretes with a different cement dosage and water to cement ratio, crushed to produce recycled concrete aggregates (RCA) and recycled up to 25% as natural aggregates replacement. The two types of recycled concretes were exposed to high temperature and air as well as water cooled. The related changes in the microstructure were investigated.

2 EXPERIMENTAL PROCEDURE

Concretes were prepared with 100 % siliceous-limestone aggregates. A cement CEM I 42.5 N was used as a binder and the dosage was 320 Kg/m^3 (CPN C). The effective water to cement ratio (Weff / C ratio) was 0.47. The fly ash was added by 6 % weight of the cement dosage and a superplastizicer (dosage 0.9 % by cement weight) was added to the mix. The natural aggregates exhibited a water absorption of 0.7 %. Another type of concrete (CPN G) was prepared with CEM I 42.5 N, a dosage of 340 Kg/m^3 and an effective water to cement ratio of 0.37. Fly ash was added to 15 % of the cement dosage. The superplasticizer dosage was 1 %, referred to the cement mass.

The concrete blocks were crushed and the mixtures were prepared by adding 25 % recycled concrete aggregates in replacement of the natural aggregates. The recycled concrete aggregates were stored at ambient temperature 20 ± 5 ^{o}C and 65 ± 15 % relative humidity for two years prior to mixing. The recycled concretes were cast in 150 mm cubic formworks, demoulded and cured at > 95 % relative humidity: Prisms were sawn to produce the specimens (140 mm x 20 mm x 30 mm) to be tested (Figure 1).

Figure 1: Recycled concrete specimens CPN C (left) and CPN G (right).

The compressive strength at 28 days hydration was measured on the concrete cubes [15]. The recycled concrete prisms were heated for 3 hours in an electric furnace at 500 ^{o}C and air cooled. In order to simulate the firemen intervention in the case of fire, another batch of prisms was water quenched. This latter procedure promoted a rapid cooling of the specimens and an abrupt drop in the temperature of the specimens. An attempt was also done by heating the samples at 900 ^{o}C and applying both cooling procedures.

Nonetheless, the small dimension of the specimens and the sudden change in the temperature with the water quenching procedure, caused a disintegration of the specimens, especially of the recycled concretes. Therefore, heat exposure at temperatures > 500 ^oC require further investigations.

The determination of the damage degree was done by means of a visual inspection. Binocular lenses, optical microscopy and a scanning electron microscopy (SEM) in back scattered mode were used. The working distance ranged from 7 mm to 9 mm, the voltage was 15 KV and the chamber pressure was 60 Pa.

3 RESULTS AND DISCUSSION

The CPN C concrete with natural aggregates shows a compressive strength value of 51.9 ± 0.4 MPa after 28 days of hydration, while the recycled concrete with 25 % RCA replacement of the natural aggregates shows a value of 44.4 ± 1.9 MPa. The CPN G concrete with natural aggregates, exhibited a value strength of 68.9 ± 6.1 MPa, while the recycled concrete with 25% RCA replacement of the natural aggregates shows a value of 46.1 ± 2.3 MPa. The higher binder content and the lower water to cement ratio as well as the higher fly ash content of the CPN G promote higher strength values as compared to the CPN C specimens. The compressive strength provides an indication of the mechanical performance of the materials and represents a possible reference point for the characterization of the damage and the development of the microstructure, after the heating and the cooling procedures.

The microstructure of the CPN C untreated reference specimens exhibits a relatively compact cementitious matrix, with a satisfactory adhesion with the natural and reclced concrete aggregates (Fig. top-left and top right). Occasionally, some isolated shrinkage microcracks are observed. These latter are caused by the hydration-curing conditions, since the specimens were not exposed to high temperature. The air cooling from 500 ^oC of the recycled concrete specimens promotes the formation of some microcracks [7], altough the damage tends to be relatively limited, due to the low (25%) dosage of the RCA [9]. The microcracks are mainly present within the cementitious matrix, or they run across the old mortar adhered to the natural aggregates, although with a similar mineralogical composition [12]. Not rarely, detachments are seen along the cementitious matrix-natural aggregates interface (Fig. 2 bottom-left).
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The water quenched CPN C microstructure shows an increased amount of microcracks, due to the rapid cooling procedure, that leads to abrupt stresses within the microstructure. Microcracks propagate along the old mortar-new cementitous matrix interface and within the old mortar RCA (Fig. 2 bottom-right). A fine crack pattern with a discontinous presence within the cementitous matrix is also seen.

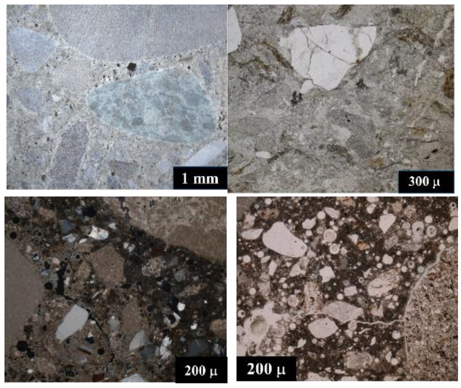

Figure 2: Recycled concrete specimens CPN C top-(left and top-right), CPN C air cooled (bottom-left), CPN C water quenched (bottom-right).

Fine cracks are also seen to connect the isolated round pores (Fig, 3 top-left). Some small aggregates surface grain pull outs can also be seen (Fig. 3 top-right). At 500 oC, the natural aggregates also may form microcracks. They are present within different types of natural aggregates. Si-bearing aggregates tend easily to microcracking and the stress arose during water quenching, also influences the surrounding cementitious matrix, which also starts to crack (Fig. 3 bottom-left).

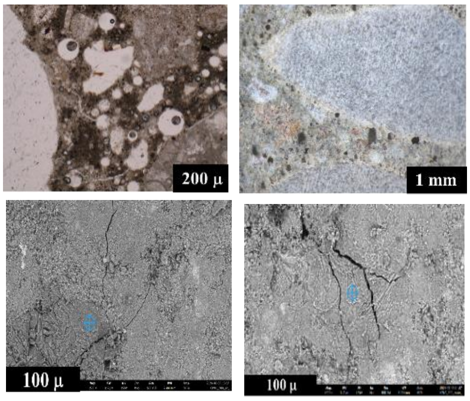

Figure 3: Recycled CPN C exposed to 500 oC and water quenched (top-left). Grain pull outs of the water quenched specimens (top-right). Cracking of a Si-bearing aggregate and location of the SEM-EDX analysis (bottom-left).

The chemical composition of the aggregate is measured with an EDX analysis (Table 1). However, aggregates with cracking exhibit a various chemical composition, that does not only refer to Si-containing rocks. In fact, Ca-bearing aggregates (Table 2) may also show cracking, that is emphasized by a branching morphology, due to the rapid water quenching procedure (Fig. 3 bottom-right).

Table 1: Recycled CPN specimen water quenched, Si-bearing aggregate.

Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.	Oxide Symbol	Stoich. Weight Conc.
8	O	Oxygen	73.166	59.900		
13	Al	Aluminum	0.435	0.600	Al2O3	1.386
14	Si	Silicon	23.864	34.300	SiO2	89.717
20	Ca	Calcium	2.536	5.200	CaO	8.896

Table 2: Recycled CPN specimen water quenched, Ca-bearing aggregate.

Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.	Oxide Symbol	Stoich. Weight Conc.
8	O	Oxygen	65.128	44.855		
13	Al	Aluminum	2.323	2.697	Al2O3	5.960
14	Si	Silicon	6.197	7.493	SiO2	18.739
16	S	Sulfur	1.303	1.798	SO3	5.249
19	K	Potassium	1.425	2.398	K2O	3.377
20	Ca	Calcium	23.625	40.759	CaO	66.676

The water quenching particularly promotes the natural aggregate (NA) cracking (Fig. 4 top-left) and the cracking along their interface. In this concern, a clear differentiation between RCA and NA thermal stress susceptibility in the water quenched sample, is not present.

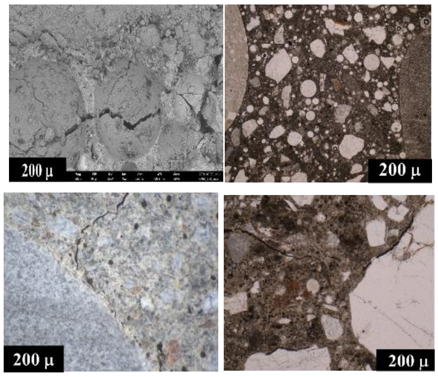

Figure 4: Recycled CPN C exposed to 500 oC and water quenched. Aggregates and interface cracking (top-left). CPN G reference specimens with a dense microstructure (top-right) and macrocracking in the air cooled CPN G (bottom-left). Widening of the cracks and microcracking in the water quenched CPN G specimens (bottom-right).

The CPN G recycled concrete with a higher cement dosage and a lower water to cement ration as compared to CPN C recycled concrete, exhibits a slightly more compacted microstructure (Fig. 4 top-right). Rare occasional microcracks are present. On the other hand, cracks on a more macroscopic level are seen with the binocular lenses along the natural aggregates-cementitious matrix and within the cement-based matrix (Fig. 4 bottom-left). Discontinuos microcracking is particularly visible in the vicinity of round pores. From the one side, the water quenching causes an increase and widening to macrocracking, which is present along the natural aggregate's interface and within the cementitious matrix. On the other side, a widening of the cracks rather than an increase in the frequency, seems to occur at low water to cement ratios and higher cement dosage (Fig. 4 bottom-right). A widening of the cracks along the natural aggregate-new cementitious matrix as well as along the interface old mortar and new cement-based matrix [8] are seen, especially for the water quenched specimens. The cracks seem similar in the width (Fig. 5 top-left). Therefore, the old mortar around the RCA may exhibit a residual porosity and the water chemically bond is released, due to the high temperature. This may cause an increase in the internal pressure within the RCA. On the other, hand, the new cement-based mortar also exhibits a porosity, likely higher than the old mortar, and the chemical bond water is also released from the new cement-based matrix. At the same time, the stress caused from the natural aggregates (NA) within the cementitious matrix also contributes to the cracking, especially in the water quenched specimens. All these components, e. g. RCA and NA, contribute to cracking and may be one of the reasons for the similar behavior of recycled and conventional concrete with respect to the fire resistance [14]. Multiple cracks of Si-bearing aggregates can also be seen in the air cooled CPN G (Fig. 5 top-right), while relatively long cracks (Fig. 5 bottom-left) and crack branching (Fig. 5 bottom-right) is seen for the water quenched CPN G specimens. This may be due to the more compact microstructure of the CPN G, which creates a highly susceptible microstructure with respect to the internal stress.

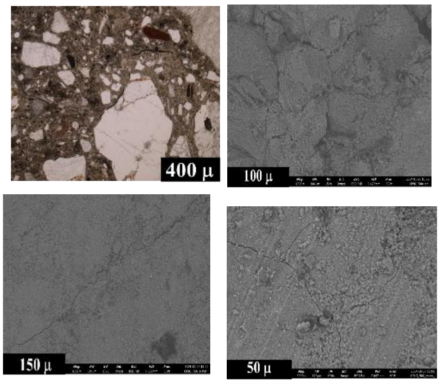

Figure 5: Recycled concrete CPN G water quenched. Cracks widening and detachments along the RCA and NA interface (top-left). Multiple cracks within Si-bearing aggregates in the air cooled CPN G (top-right). Long cracks (bottom-left) and crack branching in the water cooled CPN G (bottom-right).

4 CONCLUSIONS

Recycled concretes were exposed to 500 ^{o}C and then air or water cooled. Fine cracks formed with the microstructure. They often propagated within the old mortar or along the old mortar-new cementitious matrix interface. The water-cooling procedure promoted a widening of the cracks, which turned into a general macrocracking formation. Along the RCA and NA-cementitious matrix interface, a partial detachment was seen. The water-cooled specimens exhibited aggregate pull outs and a crack branching. The Si-bearing aggregates of the water quenched specimens exhibited a higher expansion and cracking as compared to the air-cooling procedure. A lower water to cement ratio and a higher cement dosage created a more compact and susceptible microstructure with respect to the internal thermal stresses. This promoted a widening of the cracks, rather than an increase in the microcracking frequency.

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