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Assessment of a microwave-assisted recycling process for the recovery of high-quality aggregates from concrete waste

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A B S T R A C T

This study presents an innovative method for concrete waste up-cycling based on concrete weakening through microwave heating before impact crushing. Two series of tests were conducted in order to assess the influence of the aggregate properties (size distribution, mineralogical nature) and the influence of the operating conditions of the microwave heating pretreatment on concrete fragmentation; and thus to evaluate the feasibility and the robustness of this process. Experiments were carried out on lab-made, cylindrical concrete specimens and on no-slump concrete waste with a multimode cavity microwave equipment (2.45 GHz, 6 kW) and an impact crusher. Results showed that microwave heating always induced an embrittlement of concrete samples which resulted in lower fracture energy, higher fragmentation of samples and higher liberation of aggregates (i.e. free of cement paste). A microwave-assisted comminution process is therefore an effective recycling technique for the recovery of high-quality aggregates from concrete waste.

1. Introduction

Concrete is the world's most widely used construction material but its production has negative impacts on the environment and on our future capacity to meet an ever-increasing demand. The global construction industry uses approximately 1.5 billion tonnes of cement and 9 billion tonnes of sand, gravel, and crushed rock every year and the demand for concrete is expected to grow to approximately 16 billion tonnes a year by 2050 (Mehta and Monteiro, 2005). However, mining large quantities of raw materials often results in extensive deforestation or denudation and top-soil loss (Mehta, 2001). A growing demand for aggregates, especially in large metropolitan areas, leads to increased transportation distances, costs and by extension environmental impacts. This leads to a rising demand for alternative aggregate resources such as recycled aggregates from Construction and Demolition Waste (CDW).

The traditional recycling circuit for CDW includes crushing steps that do not permit recovery of liberated, i.e. cement free, aggregates. Indeed, these techniques apply high compressive stresses that are rather inefficient for the intended objective. Because of the high compressive strength of concrete, they yield extensive comminution not only of the concrete matrix but also of the aggregates themselves. Moreover, the amount of liberated aggregates is very low. As a result, recycled concrete aggregates contain various amounts of adhered cement mortar which negatively affect the workability and mechanical properties of concrete (Kim et al., 2012; Ulsen et al., 2013). Therefore, recycled concrete aggregates are not beneficiated as aggregates for new concrete manufacturing but they are mainly downcycled as road pavement materials. A breakthrough method for liberating aggregates from concrete waste is then required to produce high quality recycled aggregates.

Different mineral dressing operations have been proposed to remove the cement paste from coarse recycled aggregates. Among these techniques, microwave heating technology has recently been recognized as one possible solution for producing clean aggregates from concrete waste (Tsujino et al., 2008; Akbarnezhad et al., 2011; Lippiatt and Bourgeois, 2012; Menard et al., 2013). This technology uses microwave electromagnetic energy to induce concrete embrittlement. Its principle is based on the selective effects of internal heating on different mineral phases when submitted to microwaves which create stresses due to differential thermal expansion. Moreover, microwave heating can also generate significant pore pressures due to the rapid formation of steam from water within the material. These internal mechanical stresses produce fractures, especially at the interfacial transition zone (ITZ) which is located between aggregates and the cement paste, leading therefore to a weakening of the material (Lippiatt and Bourgeois, 2012). Regarding liberation of aggregates, i.e. production of aggregates without adhering cement paste, Akbarnezhad et al. (2011) reported that microwave heating alone allowed partial liberation of aggregates from laboratory cast concrete samples. When a mechanical rubbing stage was used after microwave heating, then aggregates of higher quality were obtained since rubbing improved the removal of adhering weakened cement paste and the breakage of the mortar lumps

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Table 1
Composition and properties of the concrete specimens.

		SC_fine	SC_medium	SC_coarse	S_medium
Mineralogical nature of aggregates		Alluvial silico-calcareous aggregates			Crushed siliceous aggregates
Particle size distribution (in wt.%)	8–20 mm		5.5	3	1.9
	6.3–8 mm		22.5	64	19.4
	4–6.3 mm		35.5	33	38.5
	2–4 mm	83	30		32
	<2 mm	17	6.5		8.3
Compressive strength (MPa)		30.3	19.8	13.7	22.7

(Akbarnezhad et al., 2011). These findings were similar to the results obtained by Lippiatt and Bourgeois (2012) who observed improved liberation of both aggregates and cement phases after impact fragmentation of microwave heated lab made concrete samples. These results confirm the potential of microwave heating for selective liberation of concrete's raw constituents i.e. cement paste and aggregates, hence their possible reuse as raw constituents for clinker manufacturing and concrete production respectively. Another technology based on microwave heating was investigated by Tsujino et al. (2008). This technology involved aggregate surface modification by applying a coating of a strongly dielectric binder to the surface of coarse aggregates before being used to make concrete, with a twofold objective: increasing concrete strength and improving aggregate liberation when processed with microwave heating. Recycled coarse aggregates were of high quality (Tsujino et al., 2008; Noguchi et al., 2011). Although it was demonstrated that this technique has potential for improving concrete waste recycling, its requirement of specially designed material (i.e. concrete with modified surface aggregates) makes it unusable on existing concrete waste.

This work aimed to assess the feasibility of combining microwave heating pretreatment and impact crushing for achieving selective fragmentation and liberation of concrete's natural aggregates. It investigated the effect of aggregate properties (size distribution, mineralogy) and process properties (power and exposure time) on process performance. Its sensitivity to each of these variables was also studied.

2. Materials and methods

2.1. Concrete samples

Two types of concrete samples were used in this study: lab-made concrete specimens and no-slump concrete waste samples.

Lab-made concrete specimens were cast as cylinders 40 mm in diameter and 80 mm in height for this investigation. They were manufactured using CEM 1 52.5 N Portland cement, cement to concrete ratio of 400 kg/m^3 (wet basis) and a water-to-cement ratio of 0.6 (mass basis). Aggregates used were either silico-calcareous (SC) or siliceous (S). Three aggregate sizes were used (fine, medium and coarse) but the volume fraction of aggregates was kept constant at 0.63 m^3/m^3 of concrete on a wet basis. The composition and properties of these specimens are given in Table 1. As shown in Table 1, these formulations led to normal strength concretes.

Table 2
Composition and properties of the no-slump concrete waste.

Mineralogical nature of aggregates		Alluvial siliceous and calcareous aggregates
Average particle size distribution of the aggregates (in wt.%)	8–20 mm	53.8
	6.3–8 mm	7.5
	2–6.3 mm	3.9
	<2 mm	34.8
Compressive strength (N/mm^2)		39.2

No-slump concrete waste samples, commonly known as dry cast concrete, correspond to the waste of concrete delivered by dump trucks i.e. the excess concrete which was not used at a construction site. It was collected from a French company specializing in earthwork and public works. This concrete was made with 80.3% of alluvial siliceous and calcareous aggregates, of which 61.3% was coarse aggregates (6.3–20 mm) and 38.7% was sand (0–4 mm), 17.0% of CEM 1 52.5 N Portland cement and 2.7% of water. The water-to-cement ratio was 0.16. The composition and properties of this concrete waste are given in Table 2. After collection, this concrete was cast into a slab and left to cure for 5 months. Once cured the concrete was crushed in a jaw crusher with a closed-side setting of 80 mm.

2.2. Experimental set-up

Microwave heating was carried out in a 2.45 GHz laboratory microwave oven manufactured by Sairem. This equipment generates up to 6 kW of microwave power in a multimode cavity. Concrete was then comminuted using a laboratory Hazemag impact crusher with rotation speed of 290 rpm.

The performance of the microwave heating process, as defined by the selectivity of the fragmentation process, was evaluated through batch tests performed on 400–450 g concrete samples with size between 50 and 80 mm.

- The first series of experiments was carried out with the lab-made concrete specimens in order to investigate the influence of aggregate properties.
- The second series of experiments was performed using the no-slump concrete waste samples in order to study the effect of operating variables, namely power (kW) and exposure time (min) and thus energy absorbed by the sample (kWh/t). The latter was

Table 3
Operating conditions of the microwave heating stage before impact crushing.

		Operating conditions of the microwave heating stage		Energy absorbed by the sample (kWh/t)	Replicates number
		Power (kW)	Exposure time (min)		
Series n°1	SC_fine	–	–	–	≥2
		4.5	0.5	37.7	
	SC_medium	–	–	–	
		4.5	0.5	36.5	
	SC_coarse	–	–	–	
		4.5	0.5	37.6	
	S_medium	–	–	–	
		4.5	0.5	36.5	
Series n°2	No-slump concrete waste	–	–	–	≥3
		1	0.5	7.1	
		4.5	0.5	32.4	
		1	5	77.2	
		4.5	5	348.6	