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Plastic shrinkage and cracking risk of recycled aggregates concrete

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HIGHLIGHTS

- The influence of recycled concrete on shrinkage induced cracking was investigated.
- Plastic shrinkage and other properties are correlated at early age.
- A model for Young modulus versus hydration degree was proposed.
- An approach based on tensile strength was used to assess the cracking sensitivity.
- The cracking sensitivity is not proportional to the recycled aggregate content.

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ABSTRACT

This paper presents the results of experimental research on recycled concrete at early age. The influence of recycled gravel and sand (RG and RS) and initial water saturation of RG on plastic shrinkage and cracking sensitivity was investigated. Four initial water saturations were studied: 30%, 70%, 100% and 120% of saturated surface dried (SSD). The total water was kept constant for all the mixtures, so the added water was adjusted to take into account the absorption of the aggregates during the mixing process. Other concrete mixtures were designed using 30% and 100% of recycled gravel, and 30% of recycled sand. The gravel/sand ratios were adjusted to keep the maximum paste thickness (MPT) constant. To understand the evolution of early age parameters, a timeline was established and the analyses showed correlations between the evolution of plastic shrinkage and other properties at early age. The initial water saturation did not significantly affect the evolution of plastic shrinkage. Recycled aggregates actually show a relatively high rate of absorption during the first hour after mixing, i.e. before the development of plastic shrinkage. A stress/strength approach based on experimentally assessed parameters was used to compare the cracking sensitivity of different concretes with recycled aggregates. A high rate of substitution of recycled gravel or sand affected the early age properties of the recycled concrete and the cracking sensitivity especially when natural sand was replaced by recycled concrete sand.

1. Introduction

The extraction of construction materials grew by a factor of 34 during the twentieth century [1]. The global material extraction of construction minerals now represents more than 10 billion tons per year [2], which means approximately 1.5 t/cap/yr. Sustainable development has become a strategic issue and affects construction materials in terms of CO_2 emission, energy consumption and the use of natural raw materials. The changes towards a more sustainable economy require a reduction in resource use at a global level. Most of the environmental impacts of extraction and use of construction minerals occur at a regional level. All extraction activities of these materials cause damages to land, air and water ecosystems. Furthermore, energy use for extraction and transport needs to be considered. Similarly, a large part of the processing involves the production of concrete, which involves cement that is a major source of CO_2 emissions. Extractive operations often generate large volumes of waste; similarly, at the end of the life cycle high volumes of waste require disposal [3]. Therefore, many European countries have introduced new charges and taxes to reduce the demand for primary materials and encourage recycling [4]. In many urban areas, a critical shortage of natural aggregates is detected. At the same time, increasing quantities of demolished concrete from old structures are generated as waste material in these same areas.

The use of construction and demolition waste obtained from building demolition as recycled aggregates for the production of new concrete has become more common for the last decade. However, the influence of aggregates on short-term and long-term

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behaviour of concrete is significant [5–6]. Particle size distribution, shape, porosity (measured as water absorption), and initial water saturation affects workability, plastic stage properties, setting and hardening, strength, durability and time-dependent behaviour – shrinkage and creep. Generally, the absorption at 24 h [7] is taken as a reference to assess effective water and added water contents. However, setting of cement paste may occur before the full absorption of water by aggregates. Thus, the actual water content of cement paste is not the theoretical content and the water/cement ratio is modified. Therefore, the behaviour of concrete is influenced by the properties and the initial water saturation of aggregates.

According to Powers [8] plastic shrinkage may occur when the evaporation rate exceeds the bleeding rate. Early age cracking of horizontal concrete elements is likely to appear a few hours after it is cast, during setting and early hardening of concrete. The concrete cracking phenomena depend on several parameters, such as the magnitude and kinetics of shrinkage, the evolution of tensile strength or tensile strain capacity [9], the stiffness and the relaxation of the material. Two methods can be found in literature for analyzing the cracking sensitivity. The first one is based on the strain capacity [10–11] and the second on stress criteria [12–13]. On the other hand, the ACI [14] and other researchers [15–16] indicate a higher cracking risk when the deformation at early age exceeds the threshold of 1000 μm/m. According to Hammer [12], crack risk assessment from stress/strength is more reliable than using strain/strain capacity. If the tensile strength is lower than the stress level caused by restrained shrinkage, plastic shrinkage cracking occurs [12–13].

Many studies regarding the recycled concrete aggregates can be found in literature. These focus mostly on the effect of replacing natural aggregates by the recycled aggregates on long-term properties (strength, creep and drying shrinkage) [17–19] while the studies related to the plastic shrinkage concern concrete with natural or lightweight aggregates. The plastic shrinkage is actually influenced by the initial water saturation of natural aggregates [20–21]. The effect of lightweight aggregate saturation on autogenous shrinkage has already been investigated in literature [22]. The use of saturated lightweight aggregates is suggested to provide "internal" curing of the concrete. There is few published data on the influence of the recycled concrete on early age behaviour and plastic shrinkage.

The aim of the present experimental study is to quantify the cracking sensitivity of recycled concrete at early age, based on the monitoring of plastic shrinkage and mechanical properties. The experimental approach described in this paper is applied to concrete mixtures with different initial water saturation of recycled aggregates and different rates of substitution of natural aggregates by recycled gravel and sand. The water absorption and the saturation rates of the recycled aggregates used in this study were determined by combining experimental methods [23]. Plastic shrinkage measurements are associated with other experimental techniques to understand the evolution of plastic shrinkage and the influence of recycled aggregates. An approach based on direct tensile testing and calculated elastic stresses is then used to assess the cracking sensitivity. When the initial water saturation of recycled aggregates varied, the added water content was adjusted to keep the total water content (W_{tot}) constant. The results obtained for all the concrete mixtures with different rate of saturation and substitution of recycled aggregates are presented, analyzed and discussed.

2. Materials and methods

2.1. Experimental program and mixtures

The experimental program focuses on two parameters. The first parameter of the study is the initial water saturation of coarse aggregates. The concrete mixture was made with 0% of recycled sand (RS) at saturated surface dry condition (SSD) and 100% of recycled gravel (RG) at different initial water saturations: 30%, 70%, 100% and 120% of SSD state. The second parameter is the substitution of natural aggregates with recycled aggregates, all (gravel and sand) being at the SSD state. Seven mixtures were designed in this study. Table 1 summarizes the details of the investigated concrete mixtures.

Two types of aggregates were chosen for this study: natural and recycled aggregates. Natural aggregates (NA) were crushed dark limestone aggregates. Recycled aggregates (RA) were obtained by crushing unknown waste concrete from the recycling plant of DLB Gonesse (Paris region, France). The RA used in this study are classified as aggregates type I, R_{CU95} [24] with R_{CU95}: 95% of products contained in a recycled aggregate are: concrete, concrete products, mortar, concrete masonry units, natural stone. These aggregates can be considered as good quality RA. Higher proportion of other materials, such as coatings or wood, would result in higher absorption thus lower strength of new concrete. Higher sulfate content due to gypsum could cause reactions with water and hydration products and possible damage in new cement paste. The water absorption coefficient (as % of dried mass after 24-h immersion) of each type of aggregate was defined according to the pycnometer and hydrostatic weighing [23]. The properties of aggregates used in the experimental study and the fines from sieve analysis are summed up in Table 2. The waste concrete source influences the content and properties of residual paste of RA [25]. The RA used in this study showed relatively fast absorption, which is typical of high W/C ratio of initial concrete and weak paste aggregate interface. Thus the residual paste volume is relatively low and this type of RA allows reaching adequate properties of hardened concrete. The packing density of each aggregate was determined experimentally according to the method LPC N°61 [26]. The determination of the specific surface was made according to the BET method, based on the adsorption of nitrogen gas on a surface. The amount of gas adsorbed at a given pressure allows the determination of the surface area [27]. The chemical analysis of the recycled aggregate is given in the Table 3.

Table 1
Details of the investigated concrete mixtures.

RS(%)-RG(%)	WS (%)			
	30	70	100	120
0–0			✓	
0–30			✓	
0–100	✓	✓	✓	✓
30–0			✓	

Note: RS: recycled sand, RG: recycled gravel, WS: water saturation.

Table 2
Properties of aggregates.

	Natural aggregates			Recycled aggregates			
	Sand 0/4 mm	Gravel 4/10 mm	Gravel 6,3/2 0mm	Fines <63 μm	Sand 0/4 mm	Gravel 4/10 mm	Gravel 10/20 mm
Mineralogy	Sandrancourt	Dark limestone	Dark limestone	Unknown waste concrete		Unknown waste concrete	Unknown waste concrete
Water absorption WA_{24} (%)	1.2	0.56	0.53	–	10.7	5.3	4.9
Density	2.6	2.73	2.73	–	2.1	2.34	2.32
Fines <63 μm (%)	0.6	0.4	0.3	–	2	0.9	0.7
Fines <125 μm (%)	3	–	–	–	7	–	–
BET (m^2/g)	1.03	–	–	9.9	5.3	–	–
Packing density of aggregates g^*	0.693	0.588	0.586	–	0.755	0.580	0.561