

Water absorption variability of recycled concrete aggregates

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The programme ValReCon20 has demonstrated the possibility of replacing up to 100% of coarse virgin aggregates with coarse recycled concrete aggregates (CRCA) in concrete of strength class C25/30. Recycled concrete from building demolition is a heterogeneous material, resulting in a higher standard deviation of many properties of CRCA. One of the important properties of CRCA, needed to design concrete mixes, is water absorption, but the heterogeneous nature of CRCA makes it harder to predict the actual amount of water that will be absorbed by CRCA during the mixing process. This paper compares the effects of over- and underestimation of the water absorption of CRCA. Various properties were investigated and the results show large differences in the workability and density of fresh concrete, water absorption by submersion and capillarity of the hardened concrete, dynamic modulus of elasticity and mechanical strength properties.

Notation

A	constant
a	total volume of air
c	absolute volume of cement
D	maximum particle size (mm)
d	sieve width (mm)
$f_{c,cub}$	compressive strength
K	cement constant
w	total volume of water
y	pass-through sieve D mm (%)
ρ_a	absolute density (kg/m^3)
ρ_{rd}	apparent dry density (kg/m^3)
ρ_{ssd}	saturated density (kg/m^3)
σ	standard deviation

Introduction

Most aggregates currently used in concrete are of natural origin, excavated from quarries or dredged from river and sea beds, leading to ecological pressure. Fortunately, however, building demolition produces recyclable debris. In 2012, more than 11 Mt of rubble were processed as recycled aggregates. This was further divided into three main aggregate categories – recycled concrete, red brick and mixed (Ovam, 2014). The research presented here is limited to the use of coarse recycled concrete aggregates (CRCA). Currently, most recycled aggregates are used in low-grade applications such as road foundations and lean concretes. Consumer distrust and the behaviour of recycled aggregates are the two main reasons why they are currently restricted to low-level use. However, research has shown that recycled debris can

replace coarse natural aggregates in several concrete high-end applications (Boehme *et al.*, 2012; Pavlu and Boehme, 2013).

One important difference between CRCA and natural aggregates is water absorption. The high water absorption of CRCA is linked to the presence of old mortar (de Juan and Gutierrez, 2009). Dry recycled aggregates behave like sponges in fresh concrete, thus impacting on the water/cement ratio (w/c) ratio. This ratio represents the water mass to cement mass ratio in a concrete mix, and is used as an indicator of durability and strength development.

When aggregates with high water absorption are used in concrete, the w/c ratio may be replaced by the effective water/cement ratio (w/c_{eff}), which uses the total amount of water minus the amount of water absorbed by the aggregates. NBN B 15-001 accepts this use as a durability criterion for designing concrete (WTCB, 2005). In the case of natural aggregates with water absorption values of less than 1%, the difference between w/c and w/c_{eff} is negligible. However, CRCA can have water absorption values up to 10% (Boehme *et al.*, 2012) and therefore mixtures containing 1000 kg of CRCA in 1 m^3 of concrete can easily contain 100 l of absorption water.

Besides their high water absorption values, a critical difficulty when working with CRCA is their heterogeneous nature. While natural aggregates generally come from the same resource, CRCA have several origins and qualities, leading to quality variation between different batches (Boehme *et al.*, 2012; Padmini and Ramamurthy, 2009). The real water absorption of CRCA in

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concrete plants is only periodically checked, with frequency depending on the standard used. Another problem CRCA concrete plants encounter is the variability of aggregate water content. While some plants have a continuous system in place to monitor this parameter, most plants rely on a daily sample. Any error in one of these two parameters leads to an over- or underestimation of the amount of compensation water.

In the study reported in this paper, five different types of concrete were created with deliberate errors in estimation of water absorption of CRCA in order to simulate the constraints at industrial plants.

Research programme

The geometric and physical properties of one batch of CRCA, resulting from housing demolition, were determined. These properties were aggregate size, grading, flakiness, density, water absorption, micro-deval and Los Angeles abrasion value. To measure the variability of water absorption, 50 different 1 kg samples were taken from this batch of CRCA. Taking into account the range of water absorption ($\pm 2\sigma$), five different concrete mixtures were made. Workability and density tests were conducted on the fresh concrete. After a 28 d curing period at 20°C and 90% relative humidity, water absorption (submersion and capillarity), dynamic modulus of elasticity, compressive strength and tensile strength tests were conducted on the hardened concrete.

Aggregate properties

Two different aggregates were used in the experiment. Local washed sea sand 0/4 was used as fine aggregate and CRCA 8/20, originating from local housing demolition, was used as coarse aggregate. The combination of these two aggregates led to a gap-graded concrete design in which fraction 4/8 was missing. The choice to remove the 4/8 fraction was due to price on the one hand and, on the other, the fact that previous research has proven that CRCA 4/20 properties are less favourable than those of CRCA 8/20 (Boehme *et al.*, 2012). The different properties of the aggregates used are shown in Table 1.

Mixture design

The reference concrete mixture was designed to meet environmental class EE3 concrete requirements, which comprise frost and contact with rain (Anon, 2012). This implies a maximum w/c of 0.55, a minimum cement dosage of 300 kg/m³ and minimum compressive strength of C25/30. The concrete skeleton was designed by using the least-squares method and a Bolomey A16 equation (Belgische Betongroepering, 2009; Boehme *et al.*, 2012)

$$y = A + (100 - A)(1/D)^{1/2}$$

where y is the pass-through sieve D mm (%), d is the sieve width (mm), D is the maximum particle size (D_{\max}) (mm) and A is a constant.

Low-alkali cement (CEM III/A N LA 42.5) was used to reduce the risk of alkali-silica reaction. The total amount of water added in the mixing process was influenced by the water absorbed by the aggregates, which was added to the amount of water required for both hydration and workability. In the case of the reference concrete, the total amount of water was 220 kg/m³ (165 + 55 kg/m³). When less water is added to compensate for water absorption, an amount of free water is absorbed by the aggregates. This leads to a decrease in total concrete volume while the amount of cement added to the mixture remains constant. The resulting concrete will thus have a higher amount of cement dosage per cubic metre. Unfortunately, this effect, combined with a lower amount of free water, results in a lower effective w/c. The opposite is true when the water absorption of aggregates is overestimated. This leads to an increase in free water, resulting in a higher w/c. The five different mixes used in this work are detailed in Table 2.

Cubes (150 × 150 × 150 mm) and prisms (100 × 100 × 500 mm) were prepared for all the mixtures and both were used to determine the dry density of fresh and hardened concrete. The cubic specimens were also used to measure compressive strength and dynamic

	CRCA			Sea sand			Standard
	Value	σ	Class	Value	σ	Class	
Aggregate size: mm	8/20	—	—	0/4	—	—	NBN EN 933-1:2012
Flakiness	13.3	1.3	Fl15	—	—	—	NBN EN 933-3:2012
Shape	11.3	1.64	—	—	—	—	NBN EN 933-4:2008
Micro-deval	32.3	2.6	MD35	—	—	—	NBN EN 1097-1:2011
Los Angeles abrasion	38.7	1.4	LA40	—	—	—	NBN EN 1097-2:2010
Absolute density, ρ_a : kg/m ³	2694	153	—	2641	63	—	NBN EN 1097-6:2006
Apparent dry density, ρ_{rd} : kg/m ³	2352	134	—	2589	62	—	NBN EN 1097-6:2006
Saturated dry density, ρ_{ssd} : kg/m ³	2479	141	—	2608	62	—	NBN EN 1097-6:2006
Water absorption: %	5.4	0.77	—	0.75	0.1	—	NBN EN 1097-6:2006

Table 1. Geometrical and physical properties of aggregates

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	M1	M2	M3	M4	M5
Cement (CEM III/A N LA 42.5): kg/m ³	305	302	300	298	295
Free water: kg/m ³	151	158	165	172	178
Sea sand 0/4: kg/m ³	794	787	781	775	769
CRCA 8/20: kg/m ³	1050	1042	1033	1025	1017
Used water absorption of CRCA: %	3.85	4.63	5.40	6.17	6.95
Theoretical density of fresh concrete: kg/m ³	2355	2344	2334	2325	2314
w/c ratio	0.50	0.52	0.55	0.58	0.60

Table 2. Mix designs

modulus of elasticity, and prisms were used to test for flexural strength and splitting tensile strength.

Mixing procedure

Other research has demonstrated that the mixing process and duration can have a large impact on final recycled concrete quality (Tam *et al.*, 2005). The mixing sequence, power and timings were held constant to minimise their influence on the properties of different batches and the mixer was wetted before starting the procedure. The aggregates and 50% of the total amount of water (absorption water and free water) were added to the mixer and mixed for 10 min. The cement and the remaining water were then added and mixing continued for a further 10 min. Once the second phase of the mixing process was complete, the mixture was allowed to settle for 5 min. After mixing for a further 60 s, the properties of the fresh concrete were determined.

Experimental tests and results

Workability

Workability is an important parameter to determine how recycled concrete is best handled at a construction site. Previous research has shown a large correlation between mixing time, the use of plasticiser and workability (Boehme *et al.*, 2013). In this study, the mixing time was kept constant and no plasticisers were used. The consistency of the fresh concrete was measured using the Abrams slump test (EN 12350-2 (BSI, 2009a)) and the results are shown in

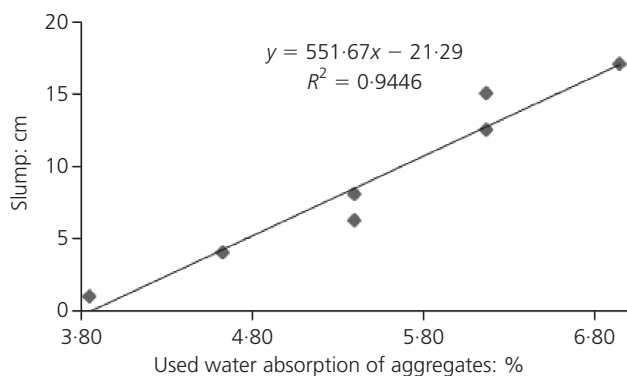


Figure 1. Influence of water absorption variability on workability

Figure 1. As shown in the figure, the relation between slump and amount of absorption water added followed a linear function, $y = 551.67x - 21.29$, with $R^2 = 0.94$. Every 1% difference between the used and the real water absorption of the recycled aggregates leads to a change of ± 5 cm in the measured slump.

Density

The method used for this test was according to EN 12350-6 (BSI, 2009b). The results are shown in Figure 2.

Due to the increased amount of free water in the mixture, the density of fresh and hardened concrete becomes significantly lower. The density of fresh concrete can be compared with the theoretical values given in Table 2. The real values are a little higher (+13 kg/m³) when using lower water absorption values, while the real density is 30 kg/m³ below the theoretical value for higher water adsorption values. Comparing the fresh density curves with the theoretical data shows an intersection near $x = 5.4\%$, the average water absorption of the aggregates used in mixture M3. This means that the density of fresh concrete can be used as an indicator to check the quality of the mixture when working with CRCA. The difference between hardened and fresh concrete is the result of

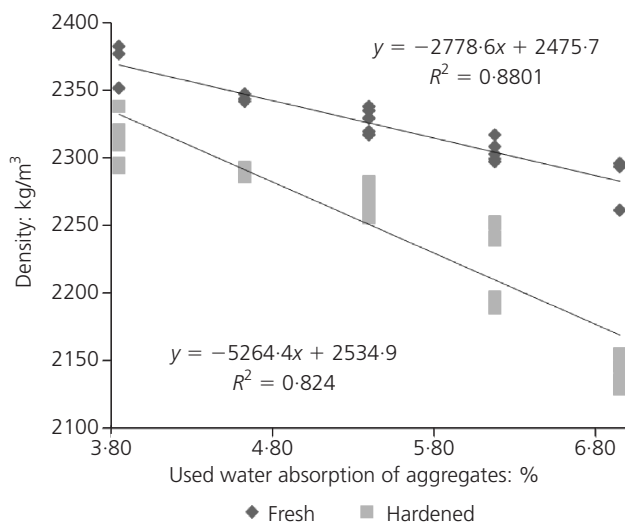


Figure 2. Influence of water absorption variability on density

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evaporation of free water and water inside the aggregates. The density of the hardened concrete samples in Figure 2, with the relation $y = -5264.4x + 2534.9$ ($R^2 = 0.82$), shows an increase in the difference between the density of fresh and hardened concrete when more absorption water is added. This will lead to an increase in porosity and permeability and probably result in decreased durability.

Compressive strength

Much research has already been reported regarding the influence of porosity of aggregates and the equivalent water absorption on the compressive strength of recycled concrete. Li *et al.* (2006), Kou *et al.* (2007), Tang (2007) and Jin *et al.* (2008) concluded that compressive strength decreases as equivalent water absorption increases, with possible decreases in strength of up to 10–25%. An abundance of water in a concrete mix has the same negative effect on compressive strength. Models indicate that compressive strength is inversely proportional to the square of the amount of water in the mixture

$$f_{c,cub} = K \left(\frac{1}{1 + (w + a)/c} \right)^2$$

where $f_{c,cub}$ is the compressive strength (N/mm²), K is a cement constant, c is the absolute volume of cement, w is the total volume of water and a is the total volume of air.

The formula $y = -244.42x + 49.38$, based on Figure 3, shows a linear decrease in compressive strength as a function of the amount of additional water added. Every 1% misjudgement of real water absorption leads to a change of 2.5 MPa or a difference of 7% in compressive strength.

Splitting tensile strength

Cheng (2005), Shi *et al.* (2010) and Zhou *et al.* (2010) investigated the influence of recycled concrete aggregates and w/c ratio on the splitting strength of recycled concrete. They all

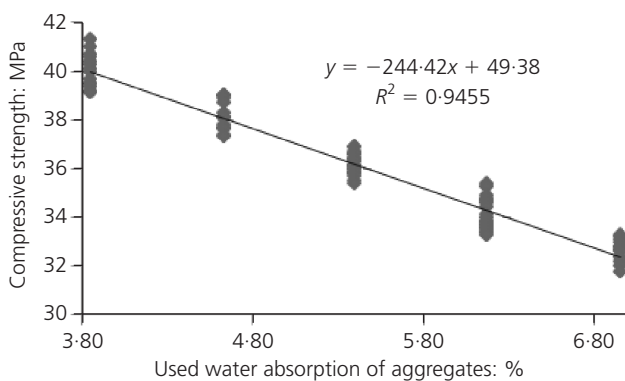


Figure 3. Influence of water absorption variability on compressive strength

concluded that an increase in water absorption led to a significant drop in splitting tensile strength. Figure 4 shows a linear decrease in splitting strength as a function of the amount of additional water added ($y = -78.73x + 6.28$). The total decrease between used water absorption values of 3.85% and 6.95% is 70%, much more significant than the corresponding 20% loss in compressive strength.

Flexural strength

Li and Xiao (2005) and Hu (2007) concluded that replacement of natural aggregates by CRCA has only a slight impact (up to 10%) on the flexural strength of recycled concrete. However, the equation produced from the results in Figure 5 ($y = -195.03x + 16.38$) shows that an error in used water absorption leads to bigger differences. The difference in used water absorption values of 3.85% and 6.95% leads to a loss in flexural strength of up to 70%.

Modulus of elasticity

Air present inside concrete decreases its dynamic modulus of elasticity because the velocity of sound through air is lower than the velocity through concrete. Since CRCA contain more air than natural aggregates, their use will decrease the dynamic modulus of elasticity of recycled concrete (Padmini and Ramamurthy,

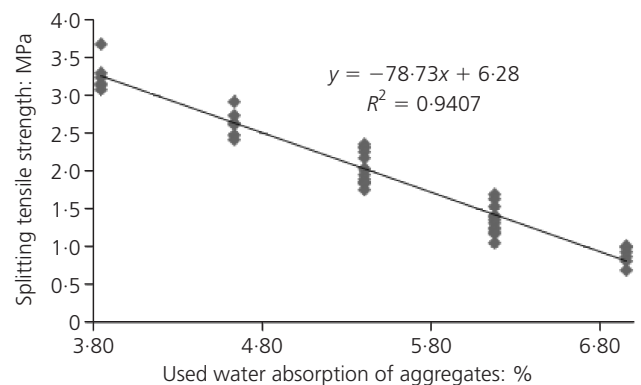


Figure 4. Influence of water absorption variability on splitting tensile strength

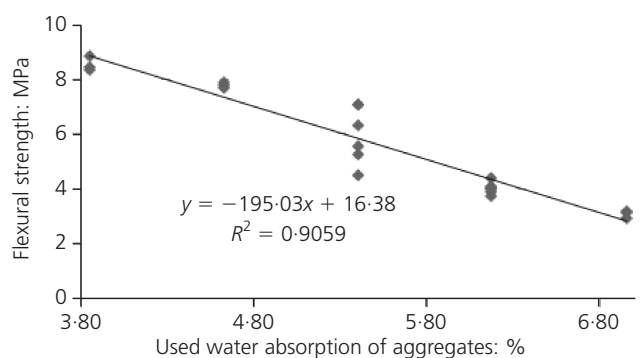


Figure 5. Influence of water absorption variability on flexural strength

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2009). Adding more water to a concrete mixture will lead to more pores after the evaporation process (Belgische Betongroepering, 2009). Overestimation of the water absorption of CRCA leads to a significant drop in modulus of elasticity.

As shown in Figure 6, every 1% of additional water added leads to a drop of 5 GPa in modulus of elasticity. This decrease is one of the reasons why the reduction in compressive strength is less significant than those in flexural and splitting strengths.

Conclusions

An overestimation of aggregate water absorption influences concrete quality in a similar way as an increase in w/c ratio – both lead to mechanical property loss and an increase in workability. These effects are not only due to an increase in free water, they are also amplified by a reduction in cement dosage. Water absorption underestimation effects are limited to workability loss, which can be compensated for by an increase in superplasticiser dosage. However, this increase, combined with a higher cement dosage, leads to more expensive concrete mixtures.

Fresh concrete density can be used as quick indicator to reveal errors in used water absorption values. Other quality tests used in standards are always based on mechanical properties measured after 28 d of hardening, which makes them unsuitable for use on construction sites.

Variability in CRCA water absorption is a problem for the industry. New industrial techniques such as mortar removal to reduce aggregate water absorption and prewetting systems to saturate aggregates without the need to determine the exact aggregate water absorption could be a solution. However, if those types of industrial processes are not used, the best way to cope with the situation is aggregate water absorption underestimation. While this leads to more expensive concrete, it is easier to remedy through the use of superplasticiser than having to deal with mechanically weak concrete.

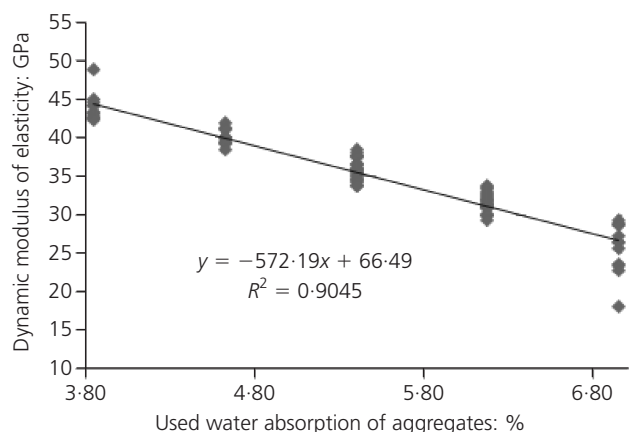


Figure 6. Influence of water absorption variability on dynamic elasticity modulus

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