Non-Destructive Testing of Recycled Aggregate Concrete

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Abstract. Currently, recycled aggregate concrete is a widely used building material. Due to negative influences on concrete’s mechanical properties, it is mostly used in low-valued applications. Nevertheless, high quality recycled concrete aggregates derived from a good quality original concrete can be used in high-valued applications, such as precast concrete. These high quality aggregates can be obtained by optimizing the crushing process. To ensure recycled aggregate concrete quality, the influence of different parameters on its mechanical and durability properties must be established. The quality of recycled concrete in high-valued applications can easily be measured via non-destructive tests. In this research project, the properties of recycled aggregate concrete are tested in a non-destructive way in order to establish a correlation between the different properties. Results of several laboratory tests show a good relation between the static elastic modulus and the dynamic elastic modulus, calculated by measuring the ultrasonic pulse waves and resonance frequency. Nevertheless, a study to transfer this knowledge into practice will demonstrate the applicability of the results.

1. Introduction

Construction and demolition waste is, based on volume, the largest waste stream in the European Union. It represents about one third of all waste produced [1]. With a proper management, this large stream of potential recycled materials can have many advantages in the building industry. It can have economic advantages, such as reducing transport costs and increasing the income situation of the recycling industry, and environmental advantages, such as reducing landfill, CO₂-emissions and the need for natural resources [2].

An annual report of COPRO shows Flanders produced 14M tons of recycled aggregates in 2016 [3]. This includes different types and qualities of recycled materials. In NBN B15-001:2018, two qualities are defined: A+ and B+. A+ comprises recycled concrete aggregates (RCAs) with a water absorption (WA₂₄) below 10% while B+ aggregates comprises mixed recycled aggregates (MRA) with a WA₂₄ below 15%. Higher quality and lower WA₂₄ (<5%) results from optimising the crushing process of RCAs derived from pure concrete waste. When correctly sorted, this can be one third of the construction and demolition waste (CDW) [4]. Due to this higher quality, these aggregates can be used for high value applications such as precast concrete.

More systematic research is necessary to examine the feasibility of recycled concrete aggregates in precast concrete. Early age evaluation and quality control of different properties of concrete containing...
RCAs is important due to higher variability of the quality of concrete products with recycled aggregates. For this reason, quality control by assessing concrete properties using non-destructive testing methods can play an important role in the assessment of the feasibility of RCAs in precast concrete.

Non-destructive testing can only provide an indirect approach to their performance, but the measured properties can be quantified and compared with allowable thresholds. Concrete is, in contradiction with steel where the use of non-destructive testing (NDT) has already been established, a heterogeneous material consisting of various resources, which increases the variability of the test results. In this paper, different non-destructive test methods are tested to assess their usefulness with recycled aggregate concrete (RAC) and compared to each other.

2. Experimental design

2.1. Methodology

Different concrete mixtures were prepared to determine the relationship between different non-destructive tests on RAC. The mixtures were composed to test a range of strength classes between C30/35 and C70/80. The variation in strength classes was defined by varying the W/C-ratio (0,40; 0,45; 0,50; 0,55; 0,60 and 0,65). Three different substitution degrees of coarse aggregates substituted by RCAs were 0%, 20% and 50%; these were used to reveal the influence of RCAs. A superplasticizer (ViscoCrete 3095 N) was added to the mixtures to obtain a slump class of S4. The mixtures were produced using a two-step mixing process, where half of the water is added to fulfill the aggregates absorption rate, then the cement is added followed by the remaining water. For each mixture, several cubes and cylinders are made to carry out all of the non-destructive tests, measuring 150x150x150mm and 150x300mm, respectively. After a minimum curing age of 90 days, various non-destructive test on all concrete mixtures were carried out to assess the feasibility on RAC. The following seven parameters were tested: static E-modulus, electrical resistance, water absorption by immersion, water absorption by capillarity, Figg permeability, impact resonance frequency and ultrasonic pulse velocity. The results of electrical resistance, water absorption by capillarity and Figg permeability tests were insignificant so are not furtherly discussed here.

2.2. Materials

Three types of aggregates are used in this research’s concrete compositions: sand 0–4 mm, limestone 8–20 mm and coarse RCAs 8-20 mm. Only coarse recycled aggregates are used to replace the coarse aggregates in volume in the conventional concrete mixtures. The RCAs were produced in a recycling plant in Flanders. Their grading curve is similar as the coarse natural aggregates its grading curve (Figure 1). The coarse recycled concrete aggregates can be classified as type A+, according to standard NBN EN 12620.

The properties of the different aggregates are displayed in Table 1. The sieving curve (NBN EN 933-1: 2012), oven-dried particle density $\rho_{RD}$, the saturated surface dried particle density $\rho_{SSD}$, the apparent particle density $\rho_A$ and the water absorption after 24h (NBN EN 1097-6:2013) were tested.

| Aggregate | $\rho_{RD}$ [kg/m³] | $\rho_{SSD}$ [kg/m³] | $\rho_A$ [kg/m³] | WA24 [%] |
|-----------|---------------------|----------------------|-----------------|-----------|
| Sand (0–4mm) | 2650 | 2660 | 2670 | 0,2 |
| Limestone (8–20mm) | 2650 | 2670 | 2690 | 0,5 |
| RCAs (8–20mm) | 2410 | 2500 | 2650 | 3,7 |
2.3. Concrete mixtures
The amount of cement CEM I 52,5 R was kept constant at 320 kg/m³. The concrete mixtures are displayed in Table 2. Every mixture is defined by a code. The code consists of two parts, the first part describes the type of aggregates in the mixture: N stands for only natural aggregates in the mix; R20 stands for a replacement of 20% V/V of limestone by RCAs and R50 stands for a replacement of 50% V/V. The second part of the code describes the W/C-ratio: 0,40; 0,45; 0,50; 0,55; 0,60 and 0,65.

Example: R20-0,50: concrete mixture with 20% V/V replacement of natural aggregates (NA) by RCAs and a W/C-ratio of 0,50.

Table 2. Mixture composition

| Mixture | Cement [kg/m³] | Water [kg/m³] | Sand 0–4mm [kg/m³] | Limestone 8–20 mm [kg/m³] | RCAs 8–20 mm [kg/m³] |
|---------|----------------|---------------|---------------------|---------------------------|------------------------|
| N-0,65  | 320            | 207           | 769                 | 1046                      | -                      |
| N-0,60  | 320            | 190           | 794                 | 1067                      | -                      |
| N-0,55  | 320            | 175           | 815                 | 1078                      | -                      |
| N-0,50  | 320            | 159           | 839                 | 1098                      | -                      |
| N-0,45  | 320            | 143           | 861                 | 1116                      | -                      |
| N-0,40  | 320            | 127           | 884                 | 1113                      | -                      |
| R20-0,65| 320            | 207           | 772                 | 837                       | 194                    |
| R20-0,60| 320            | 190           | 795                 | 853                       | 198                    |
| R20-0,55| 320            | 175           | 817                 | 862                       | 203                    |
| R20-0,50| 320            | 159           | 839                 | 876                       | 204                    |
| R20-0,45| 320            | 143           | 862                 | 890                       | 208                    |
| R20-0,40| 320            | 127           | 875                 | 906                       | 212                    |
| R50-0,65| 320            | 207           | 777                 | 520                       | 483                    |
| R50-0,60| 320            | 191           | 799                 | 526                       | 494                    |
| R50-0,55| 320            | 175           | 822                 | 536                       | 504                    |
| R50-0,50| 320            | 159           | 844                 | 545                       | 508                    |
| R50-0,45| 320            | 143           | 868                 | 553                       | 518                    |
| R50-0,40| 320            | 127           | 878                 | 563                       | 525                    |
3. Results

3.1. Static elastic modulus (NBN EN 13290-13)

The static elastic modulus of concrete is an important parameter in case of structural use of concrete. Generally, the E-modulus decreases when RCAs are used in concrete [5, 6]. The results of this test series confirm the results of other research studies. The static E-modulus decreases when more RCAs are added to the mixtures (Figure 2). All mixtures show a general decrease of 11–12% when 50% of the coarse aggregates are replaced by RCAs. However, this decrease becomes less when the W/C-ratio is higher. The mixtures with W/C of 0.6 and 0.65 have a decrease of 9% and 7% with 50% replacement.

3.2. Water absorption by immersion (NBN B15-215)

The static elastic modulus of concrete is an important parameter in case of structural use of concrete. Generally, the E-modulus decreases when RCAs are used in concrete [5, 6]. The results of this test series confirm the results of other research studies. The static E-modulus decreases when more RCAs are added to the mixtures (Figure 2). All mixtures show a general decrease of 11–12% when 50% of the coarse aggregates are replaced by RCAs. However, this decrease becomes less when the W/C-ratio is higher. The mixtures with W/C of 0.6 and 0.65 have a decrease of 9% and 7% with 50% replacement.
The water absorption by immersion was measured by weighing the saturated mass and the dry mass of the concrete specimen. The increased water absorption in mixtures with RCAs is the result of their presence. The RCAs consist of a certain amount of mortar attached to the natural aggregates. The high porosity of this mortar content results in a higher water absorption of the aggregates. In this case, the water absorption of the limestone is 0.5%, while the water absorption of the RCAs is 3.7%. The equivalent water absorption of all aggregates will increase when RCAs replace NA, thus resulting in a higher water absorption by immersion of the concrete cubes.

In these test results, an increase in water absorption is noticed for all the mixtures when 50% of the NA are replaced by RCAs. Figure 3 shows a larger increase with the mixtures with a higher W/C-ratio. The influence of the RCAs decreases when mixtures with a lower W/C-ratio are tested.

3.3. Impact resonance frequency (NBN B15-230)

The resonance frequency is a material property used to determine the quality of concrete. The resonance frequency is used to calculate the dynamic elastic modulus. The dynamic elastic modulus, determined by the resonance frequency by longitudinal vibrations, is calculated by Equation 1 [7]:

\[
E_{DL} = 4 \times 10^{-6} \times L^2 \times f_L^2 \times \rho
\]  

(1)

with
\[L = \text{length of the specimen [mm]}\]
\[f_L = \text{longitudinal resonance frequency [Hz]}\]
\[\rho = \text{dry density [kg/m}^3]\]

A decrease of the W/C ratio has a positive influence on the resonance frequency. It increases up to 7200 Hz for the mixtures with a W/C-ratio of 0.4 (Figure 4). The influence on the results of the resonance frequency is negligible for a replacement ratio up to 50% of the NA by RCAs.

![Figure 4. Resonance frequency vs W/C-ratio](image-url)
3.4. Ultrasonic pulse velocity (NBN EN 12504-4)

The time necessary for a pulse wave to go through concrete is measured to determine the pulse velocity. This concrete parameter is, just as the resonance frequency, used for the calculation of the dynamic elastic modulus. Equation 2 can be used for this [8]:

\[
E_d = \frac{\rho \times v^2 \times (1 + \nu) \times (1 - 2\nu)}{(1 - \nu)}
\]  

(2)

With

- \(E_d\) = dynamic modulus of elasticity [MPa]
- \(v\) = pulse velocity [km/s]
- \(\nu\) = coefficient of Poisson [-]
- \(\rho\) = density of concrete [kg/m\(^3\)]

Figure 5. Pulse velocity vs W/C-ratio

The pulse velocity increases as the W/C-ratio decreases. Therefore, it is an indicator for the quality of the concrete. Figure 5 shows the same tendency as the results for the impact resonance frequency. The decrease of the pulse velocity, due to the presence of RCAs in the mixtures is rather small. A small decrease up to 6% is noticed for the mixtures with 50% replacement in comparison with the mixtures with no RCAs.

4. Determination of the dynamic E-modulus (ultrasonic vs resonance method)

As mentioned before, the dynamic elastic modulus can be calculated both with the ultrasonic pulse velocity and the resonance frequency. Both calculations are mentioned before. The results of these test series show a difference in E-modulus calculated in both ways. The same mixtures gave a difference in dynamic elastic modulus around 20%. Nevertheless, the presence of RCAs in the mixtures hardly influences the correlation between both parameters, shown in Figure 6. The line of best fit of the three replacement rates are close together and the data points mix up. A more accurate correlation between the two dynamic moduli is noticed in the mixes with a lower W/C-ratio (higher quality).
Figure 6. Dynamic elastic modulus calculated based on pulse velocity and impact resonance

5. Conclusion
In this research project, the feasibility of different non-destructive test methods was tested on different mixtures with and without recycled concrete aggregates. Different W/C-ratios were used to evaluate different strength classes. The following three conclusions were drawn from the results.

Fundamentally, the static E-modulus, water absorption by immersion, impact resonance frequency and ultrasonic pulse velocity turned out to be acceptable non-destructive test methods to test the recycled aggregate concrete quality. Electrical resistance, water absorption by capillarity and Figg permeability tests showed no difference between mixtures.

Furthermore, the impact of 20% and 50% replacement of natural aggregates by recycled concrete aggregates on the concrete quality differs between the methods. The quality loss noticeable in the static E-modulus and water absorption by immersion is higher compared to the other tests. Resonance frequency and pulse velocity hardly changed when RCAs were added.

In addition, dynamic elastic modulus can be calculated both with pulse velocity and resonance frequency. The results of both calculations differs according to the test methods. Calculations based on pulse velocity gave a higher dynamic E-modulus compared with calculations based on resonance frequency.

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