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# **Effect of self-cementing properties on the mechanical behaviour of recycled concrete aggregates in unbound pavement layers**

Chong Wang<sup>a,\*</sup>, Cyrille Chazallon<sup>a,b</sup>, Peng Jing<sup>c</sup>, Pierre Hornych<sup>d</sup>

<sup>a</sup> ICUBE, UMR 7357, CNRS, Université de Strasbourg, INSA de Strasbourg, Strasbourg, France

<sup>b</sup> Laboratory of Rd. and Traffic Engineering, Shandong Jianzhu University, Jinan, People's Republic of China

<sup>c</sup> College of Metropolitan Transportation, Beijing University of Technology, Beijing 100124, China

<sup>d</sup> MAST-LAMES, Gustave Eiffel University, Nantes Campus, Bouguenais, France

Corresponding author: Chong WANG

Tel.: +33768787850

Email: [chong.wang@insa-strasbourg.fr](mailto:chong.wang@insa-strasbourg.fr)

# **Effect of self-cementing properties on the mechanical behaviour of recycled concrete aggregates in unbound pavement layers**

**ABSTRACT:** Recycled concrete aggregates (RCA) are increasingly being used in pavement base and subbase layers to replace the natural unbound granular materials (UGM), while the influence of their self-cementing properties on the mechanical behaviour has not been thoroughly studied. In this paper, the self-cementing properties, permanent deformation and resilient deformation behaviour of two RCA, NRCA and ORCA, showing significantly different self-cementing properties, after curing for different times (1, 180, 360 and 720 days), were investigated by pH value measurements, calorimeter tests and repeated load triaxial tests (RLTT). The results show that the self-cementing properties can significantly improve the mechanical behaviour of RCA, which is comparable to that of lightly treated materials. The permanent deformations of NRCA, showing strong self-cementing properties, decreases to a very low value quickly after curing for 180 days, and then stabilizes. While the resilient modulus of NRCA increases continuously with curing time, up to the studied curing time (720 days), 4.3 times larger than that curing for 1 day. It was also found that the traffic loads can damage the bonds between particles formed due to the self-cementing properties. On the contrary, for ORCA, showing negligible self-cementing properties, curing has no influence on the mechanical behaviour.

## **1. Introduction**

In Europe, over 800 million tonnes of construction and demolition wastes (CDW) are produced each year (Eurostat, 2018), with concrete wastes representing up to 75% of total CDW by weight (Nwakaire et al., 2020). To achieve a sustainable development of pavement construction, recycling and reuse of concrete wastes into pavement base and subbase layers has become a

topic of global concerns in recent years (Lu et al., 2021; Poltue et al., 2020; Saberian et al., 2018; Yaghoubi et al., 2018).

During the hydration process of cement, part of the cement particles are surrounded by the hydration products, preventing further hydration of inside cement particles (Lin & Meyer, 2009; Mills, 1966). As a result, those unhydrated cement particles may never be hydrated. However, the crushing process, to produce recycled concrete aggregates (RCA), can release those unhydrated cement particles (Amin et al., 2016), which will hydrate slowly with moisture after the pavement construction and form bonds between particles. Consequently, the unbound RCA base and subbase layers gradually evolves into bound layers, and a continuous increase of strength and stiffness of unbound pavement base and subbase layers can be observed even up to 10 years after construction (Korkiala-Tanttu et al., 2014; Lancieri et al., 2006; Y. H. Wang et al., 2016), known as self-cementing properties of RCA.

Permanent and resilient deformation properties determined by repeated load triaxial tests (RLTT) are the most important parameters for pavement design, to estimate the resistance to rutting and cracking under traffic loading. A lot of research has been conducted during the past years to study the permanent and resilient deformation behaviour of RCA in unbound pavement base and subbase layers. Gabr and Cameron (2012) observed a significant decrease of permanent deformation of RCA with a decrease of water content, and concluded that the studied RCA have better performance than the studied quartzitic aggregates. Arulrajah et al. (2013) performed RLTT on RCA, crushed brick (CB) and waste rock (WR) with varying water contents. They found that RCA have better performance over CB and WR, with the smallest permanent deformations and highest resilient moduli for different water contents. Lu et al. (2021) showed that permanent deformations of RCA and recycled clay masonry (RCM) blends increase with increasing RCM content. C. Wang et al. (2022) found that RCA with low strength and containing a high amount of rounded particles can lead to high permanent and resilient

deformations. Although these research results have demonstrated the feasibility of using RCA in pavement base and subbase layers, to the authors' knowledge, the influence of self-cementing properties on the permanent and resilient deformation behaviour has been rarely studied.

Some laboratory test programs were undertaken to study the self-cementing properties and their effect on the mechanical behaviour of RCA. Arm (2001) studied the growth in stiffness of RCA by conducting both laboratory tests and field measurements. It was found that resilient moduli show a clear increase with curing time, especially in the first months. Poon et al. (2006) reported that self-cementing properties are most likely governed by the fine fraction of RCA (< 0.15 mm and 0.3-0.6 mm), as the increase of compressive strength was only observed with these two fine fractions. Jitsangiam et al. (2015) also observed an increase of resilient modulus with curing time and found that adding other non-active materials can reduce the effect of self-cementing properties. Amin et al. (2016) confirmed the presence of residual unhydrated cement in RCA by measuring the heat of hydration, with large heat release when RCA were mixed with water. Paige-Green (2010) observed a relationship between self-cementing properties and initial pH values of RCA, and concluded that RCA show self-cementing properties if the pH value is above 9.5, and particularly above 11.

Thus, this study aims to explore the influence of self-cementing properties on the permanent and resilient deformation behaviour of RCA. Firstly, the self-cementing properties of two RCA, NRCA and ORCA, showing significantly different self-cementing properties, were evaluated by pH value measurements and calorimeter tests. Then, the influence of self-cementing properties on the permanent and resilient deformation behaviour was investigated by conducting a series of RLTT on NRCA and ORCA, after curing for different periods (1, 180, 360 and 720 days), which gives a complementary point of view on the long-term performance of RCA in unbound pavement base and subbase layers.

## 2. Materials and methods

### 2.1 Materials and physical properties

The two RCA materials used in this study (NRCA and ORCA), crushed in two recycling plants in France, were sourced from different demolished buildings with unknown compositions, representing the typical available local RCA products. NRCA (New RCA) was crushed at the beginning of the study in 2020, as an RCA with significant self-cementing properties. While ORCA (Old RCA) was crushed in 2012, and stored outdoor in big plastic bags to prevent humidity and carbonation, representing RCA with negligible self-cementing properties. It was assumed that most of the residual unhydrated cement of ORCA had reacted with moisture during the long-term storage, reducing the self-cementing properties of ORCA (Kim et al., 2014).

After the crushing process, the two RCA were reconstituted to a same 0/20 mm grading curve, close to mean values between the upper and lower limits used for pavement base and subbase layer, (NF EN 13285, 2018), except for the fine contents which are slight lower than the minimum specified value, to represent standard unbound granular materials, as shown in Figure 1. The main physical properties of the two RCA are summarized in Table 1. Each result is the average value of two or three measurements. The water absorptions of NRCA and ORCA, varying between 4.3% and 10.86% for different fractions, are higher than those of natural aggregates, typically lower than 3%, and increase with the decrease of particle size, which can be attributed to the attached mortar (Belin et al., 2014). The Los Angeles coefficients (LA), Micro-Deval coefficients (MDE) and water-soluble sulfate contents (SS) of the two RCA materials are within the specified limits ( $LA \leq 40$ ,  $MDE \leq 35$  and  $SS \leq 0.7\%$ ), fulfilling the requirements of RCA for a pavement base layer (NF EN 13285, 2018). It can be observed that

the two RCA have similar and admissible physical properties, since they were both sourced from demolished buildings.

Figure 2 shows the Modified Proctor curves of NRCA and ORCA. The optimum moisture contents (OMC) of NRCA and ORCA are 12.9% and 11.5% respectively, significantly higher than those of most natural aggregates (typically between 4 % and 6 %) due to the attached mortar. The maximum dry densities (MDD) are 1.98 Mg/m<sup>3</sup> (NRCA) and 2.0 Mg/m<sup>3</sup> (ORCA).

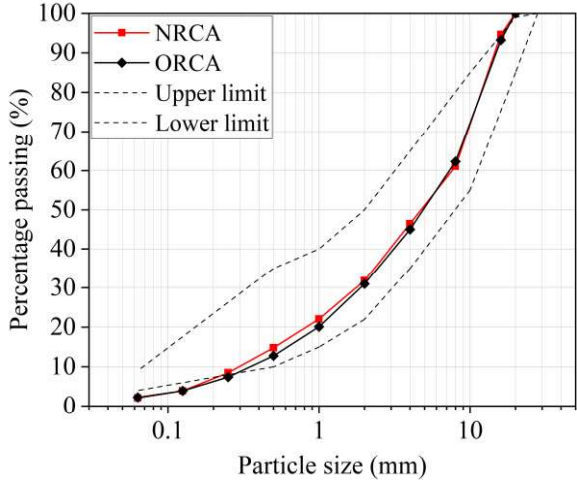


Figure 1. Particle size distributions of NRCA and ORCA.

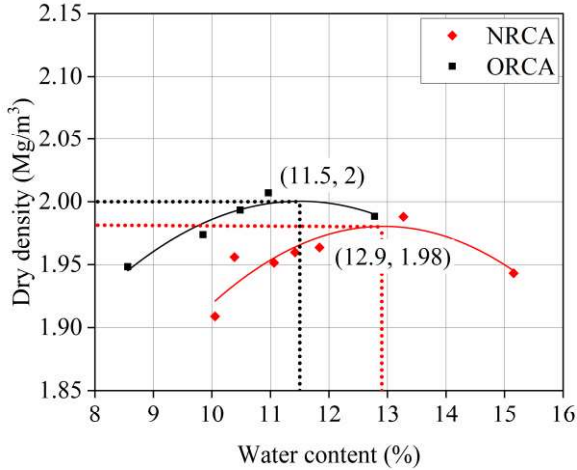


Figure 2. Modified Proctor curves of NRCA and ORCA.

Table 1. Physical properties of RCA materials.

Property	NRCA	ORCA
Apparent density $\rho_a$ /coarse (10-20 mm)	2.65	2.57
Mg/m <sup>3</sup> sand (4-10 mm)	2.66	2.61
fine (1-4 mm)	2.60	2.66
Water absorption coarse (10-20 mm)	4.64	4.30
at 24 hours WA <sub>24</sub> / % sand (4-10 mm)	5.81	5.19
fine (1-4 mm)	10.86	8.65
Fine content before compaction (63 $\mu$ m)/ %	2.1	2.2
Rounded particle content/ %	4.1	1.1
Los Angeles coefficient	30.8	32.2
Micro-Deval coefficient	21.6	21.3
Water-soluble sulfate content/ %	0.23	0.13
pH value	13.07	10.53

## 2.2 Self-cementing properties

pH value and heat of hydration are parameters widely used by researchers (Amin et al., 2016; Kim et al., 2014; Paige-Green, 2010; Poon et al., 2006) to evaluate self-cementing properties of RCA. Only 0-2 mm fine aggregates, previously dried in the oven at 60 °C, were used to evaluate self-cementing properties of RCA, as self-cementing properties are mainly influenced by fine particles (Poon et al., 2006). For pH value measurements, 30 g of RCA fine aggregates (0-2 mm) and 75 g of distilled water were mixed and stirred for 2 minutes (BS 1377-3, 2018). Then, the pH value of the suspension, stored for 24 h, was measured by a pH meter.

The heat of hydration was measured by the semi-adiabatic method (NF EN 196-9, 2010). To reach an equilibrium temperature, the mixing water, RCA fine aggregates and the calorimeter device were stored in the test room at a temperature of 20±5 °C for at least 24 hours prior to the test. Then, the previously weighted 360 g of RCA and 180 g of water were mixed quickly and placed in the calorimeter device to measure the heat of hydration of RCA for 24 hours. Another



calorimeter, containing the same mass of water (180 g), was considered as the reference calorimeter.

### 2.3 Specimen preparation, RLTT apparatus and test program

For RLTT, all the samples were prepared using a standard procedure (NF EN 13286-7, 2004). Firstly, the aggregates were mixed with water, to the targeted water content, and then sealed in plastic bags for 24h for moisture homogenization. After that, each sample, with a diameter of 150 mm and a height of 285 mm, was compacted in a split mould to the targeted dry density, by a vibrating hammer, in 7 layers. To improve the comparison of the permanent and resilient deformation behaviour of the two RCA, tests were performed at the same targeted water content (OMC-1%) and targeted dry density (optimum dry density at the targeted water content), selected from the Modified Proctor curves (Figure 2), as summarized in Table 2. Finally, the specimens were demolded, wrapped in plastic bags and stored indoors for 1, 180, 360 and 720 days at a temperature of  $18 \pm 5$  °C, to study the effect of self-cementing properties on the permanent and resilient deformation behaviour of RCA.

Table 2. Targeted water content and dry density.

Materials	Optimum moisture content (%)	Maximum dry density (Mg/m <sup>3</sup> )	Targeted water content (%)	Targeted dry density (Mg/m <sup>3</sup> )
NRCA	12.93	1.98	11.9	1.97
ORCA	11.51	2	10.5	1.99

After curing for specific periods (1, 180, 360 and 720 days), the specimen weight was first measured to check that no water evaporated during the curing stage. The mass loss of each specimen after curing was less than 0.04% (30 g). Subsequently, the specimens were installed in the triaxial cell. The repeated load triaxial tests (RLTT) were performed using a large-scale triaxial apparatus (Wykeham Farrance), for 150 mm diameter specimens, with a servo

pneumatic loading system, as shown in Figure 3. The axial strain and radial strain were measured using three Hall-Effect transducers, attached to supports anchored inside the sample. After RLTT, the tested sample was cut into 3 layers, and the water content of each layer was measured. Duplicate samples were tested for each curing time.

The RLTT tests were performed following the procedure of the European Standard NF EN 13286-7 (2004), to study the permanent and resilient deformation behaviour. This procedure consists of a conditioning phase (permanent deformation test) followed by a phase of study of the resilient behaviour, which is not presented in this article. During the conditioning phase, the specimen was subjected to a constant confining pressure (70 kPa) and a cyclic axial stress (340 kPa), at a frequency of 1 Hz. 20000 loading cycles were applied, and the permanent and resilient deformation behaviour with the number of load cycles were studied.

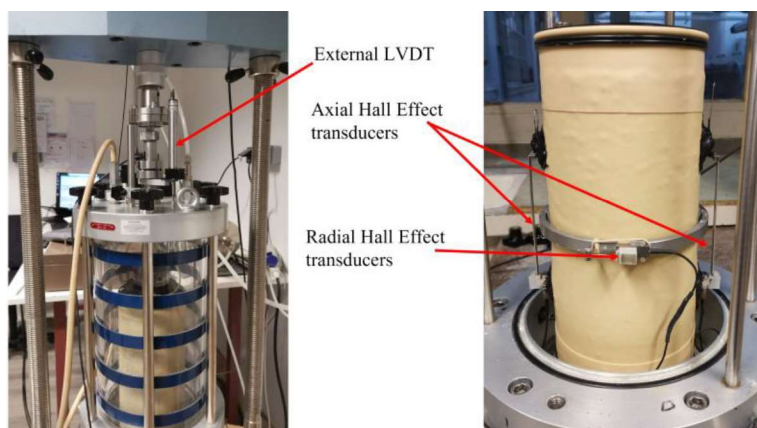


Figure 3. Triaxial apparatus and instrumented specimen.

### 3. Results and discussion

#### 3.1 Self-cementing properties

The pH values of the two RCA are given in Table 1. The results show that the pH value of NRCA (13.07) is much higher than that of ORCA (10.53). Several researchers have also evaluated self-cementing properties of RCA using pH values, ranging from 8.5 to 12.6 (Paige-Green, 2010; Poon et al., 2006). They have shown that RCA with high pH values (above 11)

exhibit self-cementing properties, while those with low pH values (less than 11) show no self-cementing properties. According to these results, NRCA exhibits self-cementing properties while ORCA exhibits negligible self-cementing properties after long-term storage.

Figure 4 shows the rate of heat generation and the total released heat of NRCA and ORCA, due to the hydration of unhydrated cement. It appears that the hydration of unhydrated cement takes place immediately after mixing the RCA with water, even for ORCA, with a maximum rate of heat generation at the beginning of the test, which then decreases quickly in the next few hours. For NRCA, the initial rate of heat generation is 2.3 mW/g and this value gradually decreases to a stable value after 24 hours. By contrast, ORCA has a much lower rate of heat generation (0.48 mW/g) and lower duration of the heat release (1 hour). As a result, after 24 hours, the average released heat of NRCA is 14.7 J, in good agreement with the value (lower than 15 J) reported by Oksri-Nelfia et al. (2016). The released heat of ORCA is much lower (1.97 J), indicating that the self-cementing properties of NRCA are significant while those of ORCA are negligible, which is in good agreement with the measured pH values. These results also indicate that long-term storage can decrease self-cementing properties of RCA, as observed also by Kim et al. (2014).

It is pointed out that for the typical Portland cement, the curves of rate of heat generation present two main peaks (Hewlett & Liska, 2019). The first peak, observed a few minutes after mixing, which is visible for both RCA in Figure 4, is due to the initial rapid hydration of tricalcium aluminate phases ( $C_3A$ ) and alite ( $C_3S$ ). Then, after a few hours, and up to several days, the hydration of  $C_3S$  and the formation of calcium silicate hydrate (C-S-H) phase lead to the second, main exothermic peak (around 10 hours) (Hewlett & Liska, 2019; Kim et al., 2014), and the strength and stiffness of cement paste develop in this phase. This second peak, in which the strength and stiffness develop, is not visible on the curves of NRCA and ORCA (Figure 4).

However, the longer duration of the heat release of NRCA (until 24 hours) suggests that a small amount of calcium silicate hydrate (C-S-H) phase is formed.

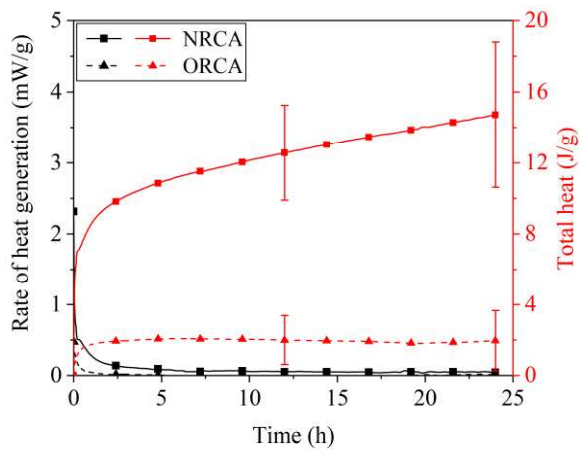


Figure 4. Hydration heat of NRCA and ORCA.

### 3.2 Permanent deformation

Figure 5 (a) and (b) show the evolution of the permanent axial deformations  $\epsilon_1^P$  with the number of load cycles in the RLTT tests, and the corresponding water contents of each NRCA and ORCA specimen, after different curing times. Due to the negligible self-cementing properties, ORCA specimens were cured only for 360 days. Table 3 summarizes the average values of  $\epsilon_1^P$  and permanent strain rate  $\Delta\epsilon/\Delta N$  at the end of each test, as well as their standard errors. For both RCA, permanent deformations  $\epsilon_1^P$  increases rapidly at the beginning of the cyclic loading, owing to particle rearrangement, and then stabilize, according to the criterion of the European standard (NF EN 13286-7, 2004), as the values of  $\Delta\epsilon_1^P/\Delta N$  are less than  $10^{-7}$  per cycle at the end of the tests.

To illustrate the effect of self-cementing properties on permanent deformations, Figure 6 presents the final permanent deformations  $\epsilon_1^P$  obtained after 20000 load cycles in function of the curing times. For NRCA, crushed recently, showing strong self-cementing properties, permanent deformations  $\epsilon_1^P$  decrease largely after 180 days of curing, and then tend to stabilize. Abu-Farsakh et al. (2015) observed that permanent deformations  $\epsilon_1^P$  of soils decreases largely

when they are treated with a small percentage of cement (0.5%), compared with untreated soils. Then, the effect of cement content on  $\epsilon_1^p$  decreases with increasing cement content, showing that the further hydration of cement has a limited effect on the reducing  $\epsilon_1^p$ . This is in good agreement with the evolution of  $\epsilon_1^p$  of NRCA, which tend to stabilize even after curing for longer time.

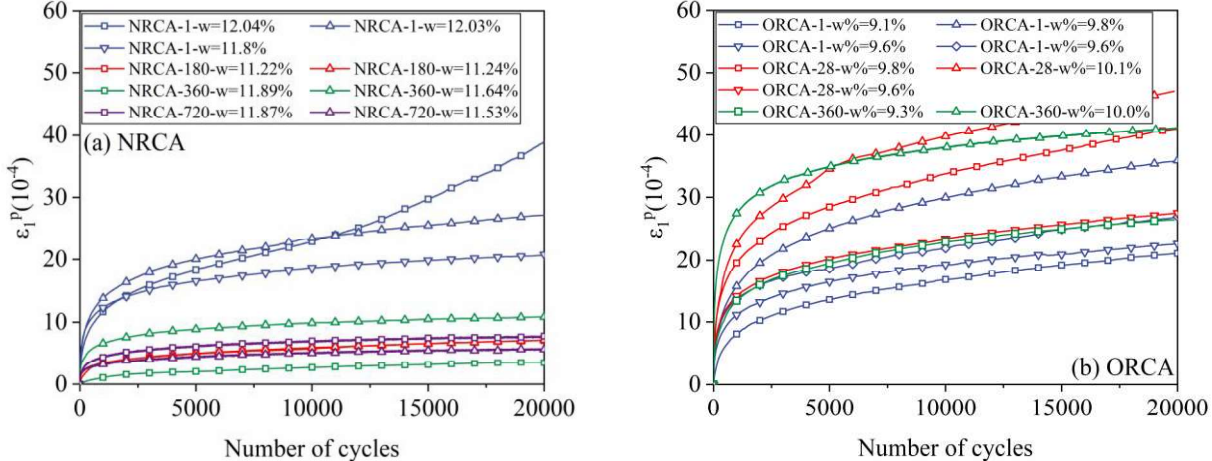


Figure 5. Evolution of permanent axial deformations  $\epsilon_1^p$  with the number of load cycles for NRCA and ORCA, after varying curing times: (a) NRCA; (b) ORCA.

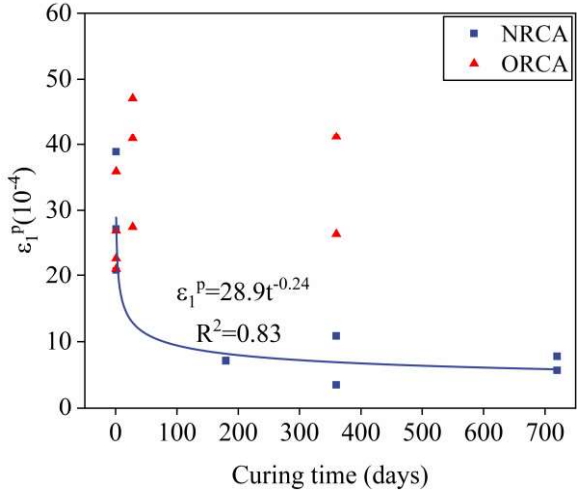


Figure 6. Final permanent axial deformations of NRCA and ORCA after 20000 load cycles, at different curing time.

For ORCA, showing negligible self-cementing properties,  $\epsilon_1^p$  does not vary with curing time, but is sensitive to water content variations, as for other unbound granular materials (Jing et al.,

2018; Soliman & Shalaby, 2015), as can be seen in Figure 5 (b). It can be noted that ORCA still presents a good performance, with values of  $\varepsilon_1^P$  after 20000 cycles are lower than  $50 \times 10^{-4}$  m/m.

These values of  $\varepsilon_1^P$  are lower than those of most traditional unbound granular materials, which generally present  $\varepsilon_1^P$  values between  $50 \times 10^{-4}$  and  $200 \times 10^{-4}$  m/m (Alnedawi et al., 2021; Jing et al., 2018).

To evaluate the performance of NRCA,  $\varepsilon_1^P$  values of NRCA after curing (for 180, 360 and 720 days) were compared with those of lightly cementitious treated materials, soils or granular materials treated with low content of cement (around 3%) (Ardah et al., 2017; Senanayake et al., 2022). It was found that after curing (for 180, 360 and 720 days), NRCA presents very low  $\varepsilon_1^P$ , lower than  $10 \times 10^{-4}$  m/m (see Table 3), similar to those of other lightly treated cementitious materials reported by Ardah et al. (2017) and Senanayake et al. (2022). In comparison, traditional unbound granular materials, tested in similar conditions, generally present  $\varepsilon_1^P$  values higher than  $50 \times 10^{-4}$  m/m after 20000 cycles (Alnedawi et al., 2021; Jing & Chazallon, 2020).

This shows that self-cementing properties can improve very significantly the resistance to permanent deformations of RCA.

Table 3. RLTT results on NRCA and ORCA, after different curing times.

Results	NRCA				ORCA		
	1 day	180 days	360 days	720 days	1 day	28 days	360 days
$\varepsilon_1^P$ ( $10^{-4}$ m/m)	28.9±5.3	7.1±0.03	7.2±3.7	6.7±1.0	26.7±3.3	38.5±5.8	34.3±6.8
$\Delta\varepsilon/\Delta N$ ( $10^{-7}$ m/m)	1.07±0.7	0.09±0.01	0.1±0.01	0.06±0.03	0.68±0.2	0.6±0.14	0.21±0.12
$M_r$ (MPa)	370.9 ±7.6	606.7 ±12.3	857.6 ±10.4	1598.7 ±41.8	395.3 ±8.4	406.9 ±1.1	408.9 ±7.5

### 3.3 Modelling of permanent deformation behaviour

To predict the evolution of permanent deformations of RCA, improved by self-cementing properties, the widely used model, proposed by Hornykh (1993) for unbound granular materials, was adopted to simulate the evolution of permanent axial deformations with the number of load cycles  $N$ :

$$\varepsilon_1^p = A \left( 1 - \left( \frac{N}{N_0} \right)^B \right) \quad (1)$$

where  $\varepsilon_1^p$  is the permanent strain (in  $10^{-4}$  m/m) after  $N$  cycles,  $N_0$  is the number of cycles before the first measurement ( $N_0=100$  in this study), parameter  $A$  represents the final permanent axial deformation and parameter  $B$  ( $B < 0$ ) controls the evolution of permanent deformation with increasing  $N$ .

According to the test results presented in Figure 6, a power relationship can be obtained between the final permanent axial deformation  $A$  and the curing time  $t$ . This relationship can be expressed as follows:

$$A = a \left( \frac{t}{t_0} \right)^b \quad (2)$$

where  $a$  and  $b$  are parameters ( $b < 0$ ),  $t$  is the curing time in days, and  $t_0=1$  day is the minimum curing time.

The evolution of permanent deformations with  $N$  was controlled by another parameter  $B$ , becoming flatter when  $B$  increases (absolute value). An exponential function is adopted to describe the relationship between parameter  $B$  and curing time  $t$ :

$$B = c \cdot e^{\frac{t}{t_0^d}} + B_0 \quad (3)$$

where  $c$ ,  $d$  and  $B_0$  are constant parameters.

Substituting (2) and (3) into (1), the proposed model, accounting for the effect of curing time  $t$ , can be obtained:

$$\varepsilon_1^p = a \left( \frac{t}{t_0} \right)^b \left( 1 - \left( \frac{N}{N_0} \right)^{c \cdot e^{(t/t_0)^d + B_0}} \right) \quad (4)$$

Since the curing time has no influence on  $\varepsilon_1^p$  of ORCA due to the negligible self-cementing properties, only the results of NRCA were used to model the permanent deformation behaviour. The average permanent deformations after different curing times, presented in Table 3, were used to determine the parameters of the proposed model, summarized in Table 4. Figure 7 presents a comparison between experimental results and predictions obtained with the model. The proposed model can fit the experimental data well, with a global coefficient of determination  $R^2$  above 0.95. The model can thus successfully predict the permanent deformations of RCA after different curing times.

Table 4. Parameters of the proposed model for NRCA based on curing times.

RCA	$a$	$b$	$c$	$d$	$B_0$	$R^2$
NRCA	28.874	-0.243	0.169	-386.117	-0.479	0.960

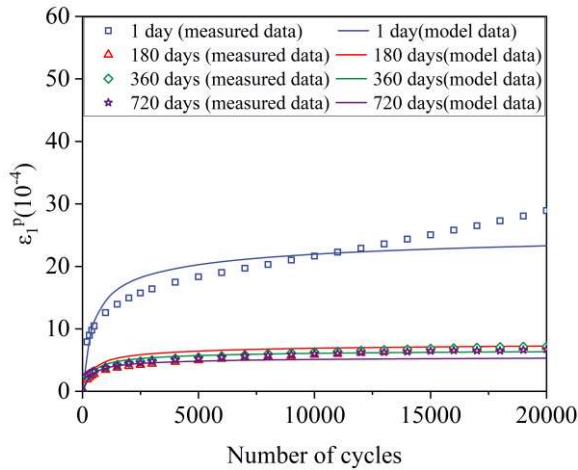


Figure 7. Average test results and model predictions of  $\varepsilon_1^p$  for NRCA, after different curing times.



### 3.4 Resilient modulus

During the permanent deformation tests, resilient modulus, defined as a ratio of applied axial deviator stress  $q$  ( $q=340$  kPa in this study) and recoverable axial strain  $\epsilon_1$ , can be calculated for each load cycle. Figure 8 plots the evolution of the resilient modulus  $M_r$  of NRCA and ORCA with the number of load cycles, for different curing times. Table 3 also summarizes the average final values of resilient modulus  $M_r$ , after 20000 load cycles. For NRCA, a clear increase of  $M_r$  with curing time can be observed due to the self-cementing properties. After curing for 180, 360 and 720 days, the average final resilient modulus  $M_r$  of NRCA is 606, 858 and 1600 MPa, increasing by factors of 1.6, 2.3 and 4.3, respectively, compared with the resilient modulus curing for 1 day (370 MPa). The resilient modulus of NRCA curing for 720 days (1600 MPa) is much higher than that of natural unbound granular materials, showing the excellent long-term performance. By contrast, for ORCA, the resilient modulus  $M_r$  remains constant, which is consistent with the evolution of permanent deformations.

Figure 8 also shows that for both NRCA and ORCA, the resilient modulus gradually increases during the first load cycles, and then gradually reaches a constant value, except for the NRCA specimens curing for 360 and 720 days. This behaviour is due to the particle rearrangement and consolidation during the permanent deformation test, also observed for unbound granular materials (Jing et al., 2019; Yang et al., 2008).

Interestingly, for NRCA specimens after curing for 360 and 720 days, resilient modulus decreases during the first load cycles, especially for NRCA curing for 720 days. This can be explained by the fact that for lightly treated materials, some weak bonds probably break under traffic loading, thus decreasing the resilient modulus. These results are consistent with observations made by other researchers on cement treated materials (Rios et al., 2014; Vranna & Tika, 2020; Chong Wang et al., 2023).

Figure 9 shows the evolution of the final resilient moduli of NRCA and ORCA with curing time. For NRCA, unlike permanent deformation, which stabilized after 180 days of curing, resilient modulus continues to increase up to 720 days of curing, which can be described by an exponential function. However, this observation is valid only for the studied material (NRCA), and until 720 days of curing. It is clear that with increasing curing time, the hydration of unhydrated cement will stop and resilient modulus will reach a constant value. This could be confirmed by tests with longer curing time.

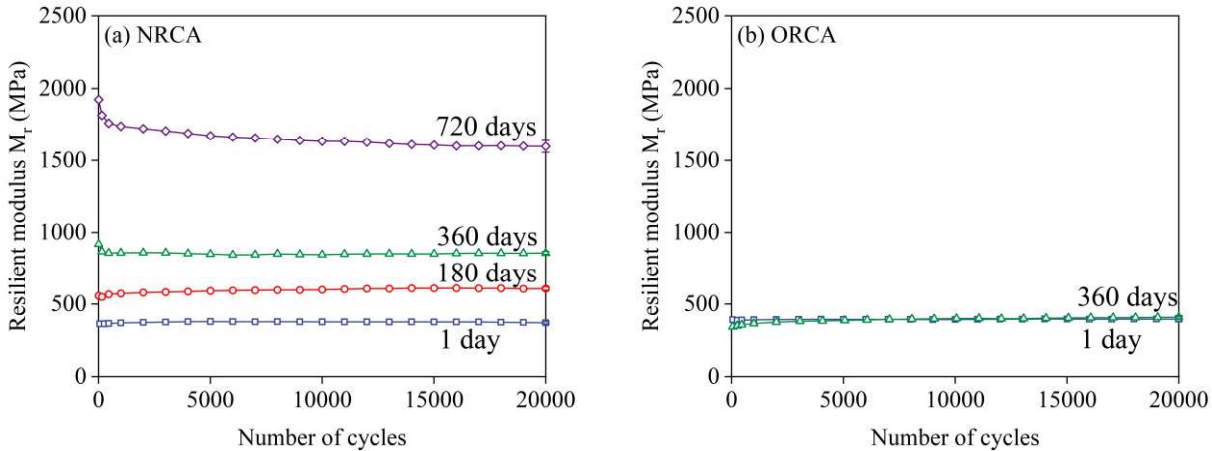


Figure 8. Evolution of resilient moduli of NRCA and ORCA with the number of load cycles, for different curing times: (a) NRCA; (b) ORCA.

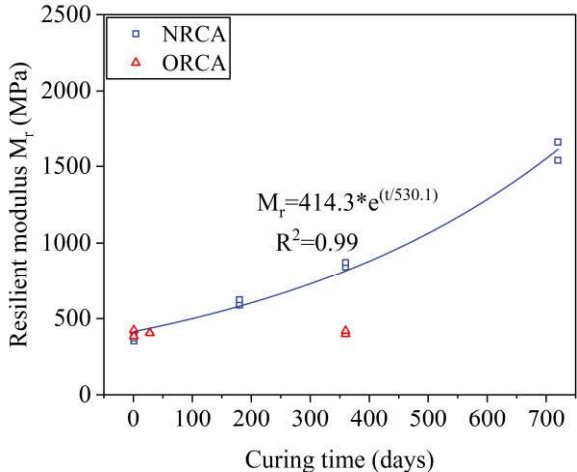


Figure 9. Evolution of final resilient moduli of NRCA and ORCA with curing time.

### 3.5 Discussion

The results presented above allow to understand the influence of self-cementing properties on the behaviour of RCA. The permanent deformations of NRCA decrease with curing, but tend to stabilize after curing for 180 days (Figure 6), while the resilient modulus continues to increase much longer with curing time, at least up to 720 days (Figure 9). Similar observations were made by Barbieri et al. (2022), who studied the effect of curing on the permanent deformations and resilient modulus of cement treated materials. They reported that the permanent deformations of cement treated materials become constant, while the resilient modulus continues to increase after curing for 180 days.

For unbound granular materials, deformations are governed by the densification, distortion and attrition of particles (Lekarp et al., 2000). However, once the bonds between particles are formed, due to the hydration of unhydrated cement, and provide sufficient resistance to the stresses induced by traffic loads, the densification, distortion and attrition of particles are reduced, and the permanent deformations decrease immediately. Then, once a sufficient level of bonding has been attained, the further hydration of unhydrated cement has a limited effect on the permanent deformations, since the previously formed bonds can already resist to the stresses due to traffic loads. As a result, the permanent deformations of NRCA stop decreasing after about 180 days of curing.

On the contrary, the further hydration of unhydrated cement increases the number of bonds, increasing the number of particle contacts and their contact area. Thus, the resilient modulus of NRCA continues to increase with curing time, until all the unhydrated cement is consumed, unlike the permanent deformation.

#### 4. Conclusions

In this study, the effect of self-cementing properties of RCA on their mechanical behaviour was investigated. Two different RCA, NRCA and ORCA, both sourced from demolished buildings, with different dates of manufacture, were selected. The self-cementing properties and mechanical behaviour of two RCA, after curing for different times (1, 180, 360 and 720 days), were investigated by pH value measurements, calorimeter tests and repeated load triaxial tests. Based on the test results, the following conclusions can be made:

The results of pH value measurements and calorimeter tests showed that the self-cementing properties of NRCA, which was freshly crushed, are very strong, indicated by a high pH value and total released heat. On the contrary, ORCA, crushed in 2012 and submitted to long term storage, presented only negligible self-cementing properties.

Repeated load triaxial tests indicated that the permanent deformations of NRCA decrease rapidly during the first months of curing, and then reach a constant low value after curing about 180 days, which is similar to values obtained on lightly cement treated soils or granular materials. For ORCA, the permanent deformations do not change with curing time, but are influenced by water content, like unbound granular materials, due to the negligible self-cementing properties.

The RLTT tests also indicated that the resilient modulus of NRCA increases continuously with curing time, up to the studied curing time (720 days). However, it was also found that cyclic loading can reduce the effect of self-cementing, by partially damaging the bonds formed between particles, as it was observed that for NRCA specimens curing for 360 and 720 days, the resilient modulus decreases slightly under cyclic loading. In contrast, curing time had no influence on the resilient modulus of ORCA.

Finally, the study shows that RCA with good self-cementing properties (like NRCA) represent excellent materials for use as unbound pavement layers, because their properties

increase significantly with time, and can reach, in the long term, much higher values than those of natural unbound granular materials, with levels of permanent deformation in RLTT tests as low as  $10 \times 10^{-4}$  m/m, and moduli of the order of 1600 MPa, 3 to 4 times higher than those of natural unbound granular materials. However, this evolution, evolved from unbound RCA layers, governed by rutting failure in the short term, to partially bound RCA layers, governed by fatigue and cracking in the long term, could lead to other deterioration mechanisms. RLTT tests have shown that traffic loads can damage some weak bonds formed by unhydrated cement, and this long-term behaviour, under cyclic loading, should be further investigated.

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Recycled concrete aggregate

Self-cementing properties

Permanent deformation

Resilient modulus

Repeated load triaxial test