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Study of mechanical behavior and self-cementing properties of recycled concrete aggregates under repeated loading

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ABSTRACT

It is known that the strength and stiffness of unbound base and subbase layers prepared with recycled concrete aggregates (RCA) increase over time, known as self-cementing properties of RCA. However, the influence of self-cementing properties on the permanent and resilient deformation behavior has not been thoroughly studied. In this study, the permanent and resilient deformation behavior of two RCA, ORCA and NRCA (old and fresh crushed RCA), after different curing times (1, 180, 360 and 720 days), were investigated by conducting a series of repeated load triaxial tests. The results show that the permanent deformation of NRCA, crushed recently, decreases to a negligible value after curing 180 days, and then reaches a constant value. While the resilient modulus of NRCA increases steadily with curing time till the studied curing time (720 days). Besides, the long-term storage reduces the self-cementing properties of ORCA. As a result, the negligible self-cementing properties have no influence on the permanent and resilient deformation behavior of ORCA.

Keywords: recycled concrete aggregates, permanent deformation, resilient modulus, self-cementing properties, repeated load triaxial test, unbound granular materials.

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). The traditional method to treat those wastes, disposed in landfills, is gradually being abandoned by more and more countries due to the environmental and economic concerns. 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; Yaghoubi et al., 2018).

After pavement construction, a continuous increase of strength and stiffness of pavement base and subbase layers built with recycled concrete aggregates (RCA) can be observed (Korkiala-Tanttu et al., 2014; Lancieri et al., 2006), due to the hydration of unhydrated cement inside RCA, known as self-cementing properties. Some researches have been conducted to study the self-cementing properties of RCA (Arm, 2001; Jitsangiam et al., 2015; Poon et al., 2006). Arm (2001) and Jitsangiam et al. (2015) investigated the effect of self-cementing properties on resilient modulus. It was found that resilient moduli show a clear increase with curing time. 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. However, the influence of self-cementing properties on the mechanical performance has been rarely studied.

In this work, the influence of self-cementing properties on the permanent and resilient deformation behavior of RCA was explored. Firstly, the self-cementing properties of two RCA (NRCA and ORCA) were evaluated by pH value measurements and calorimeter tests. Then, the permanent and resilient deformation behavior were investigated by conducting a series of repeated load triaxial tests on NRCA and ORCA specimens, after different curing times (1, 180, 360 and 720 days).

MATERIALS AND METHODS

The two different RCA materials, NRCA and ORCA, sourced from different demolished buildings and crushed in France with unknown compositions, were used in this study. NRCA was crushed at the beginning of the study in 2020 (new RCA), while ORCA was crushed in 2012 (old RCA). After crushing process, two RCA were reconstituted to a same grading curve close to the mean value of the upper and lower limits used for pavement base and subbase layer (NF EN 13285, 2018), as shown in Figure 1. 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/m³ (NRCA) and 2.0 Mg/m³ (ORCA). The main properties of two RCA materials are summarized in Table 1.

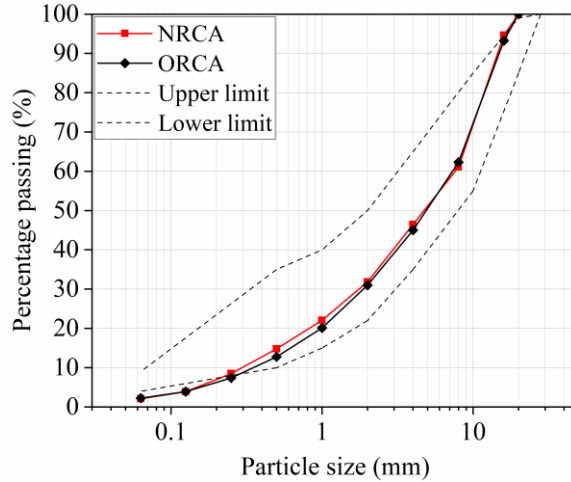


Figure 1. Particle size distributions of NRCA and ORCA.

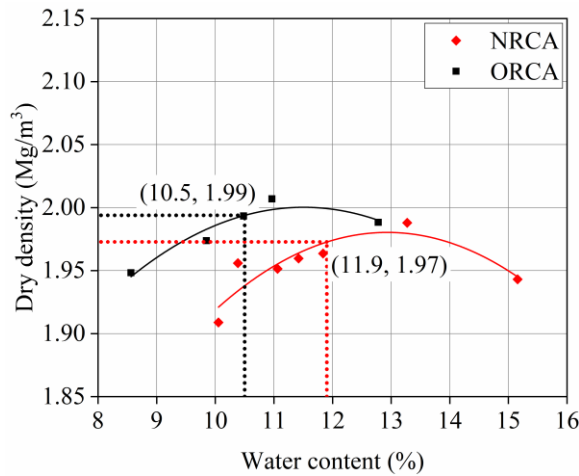


Figure 2. Modified Proctor curves of NRCA and ORCA

Table 1. Properties of RCA materials.

Materials	Particle density-coarse (10-20mm) Mg/m ³	Water absorption-coarse (10-20mm) %	Fine content (63µm) %	Grading mm	pH
ORCA	2.57	4.30	2.2	0/20	10.53
NRCA	2.65	4.64	2.1	0/20	13.07

Self-cementing properties

To assess self-cementing properties of NRCA and ORCA, pH value (BS 1377-3, 2018) and heat of hydration (NF EN 196-9, 2010) were measured. For pH value measurement, 30 g of RCA fines aggregates (0-2 mm) and 75 g of distilled water were mixed and stirred for 2 minutes. Then, the pH value of each suspension was measured by a pH meter. The heat of hydration was measured

by semi-adiabatic method. The previously weighted 360 g RCA and 180 g water were mixed quickly and placed in calorimeter device to measure the heat of hydration of RCA for 24 hours.

Repeated load triaxial tests

For repeated load triaxial tests (RLTT), the mixtures with targeted water content were compacted in a split mould to the targeted dry density. Same targeted water content (OMC-1%) and targeted dry density (maximum dry density at the targeted water content) were selected from the Modified Proctor curves (Figure 2) for two RCA mixtures. Finally, the specimen was demolded and wrapped with plastic bags and stored indoors for 1, 180, 360 and 720 days.

A procedure following the European Standard NF EN 13286-7 (2004) was employed to study the permanent and resilient deformation behavior of RCA under the traffic loadings, which consists of a conditioning phase and followed by a resilient phase. In the conditioning phase, the specimen was subjected to a constant confining pressure (70 kPa) and a cyclic axial stress (340 kPa) at the frequency of 1 Hz for 20000 loading cycles. After the condition phase, six different confining pressures, 20 kPa, 35 kPa, 50 kPa, 70 kPa, 100 kPa and 150 kPa, and two different cyclic deviator stress q (low stress level and high stress level) for each confining pressure were applied on the specimen at a frequency of 0.1 Hz for 100 cycles, to study resilient deformation behavior. The stress paths for the RLTT are shown in Figure 3. The deviator stress q and mean normal stress p are defined by:

$$q = \sigma_1 - \sigma_3 \quad (1)$$

$$p = \frac{\sigma_1 + 2\sigma_3}{3} \quad (2)$$

where σ_1 is the vertical stress and σ_3 is the confining pressure.

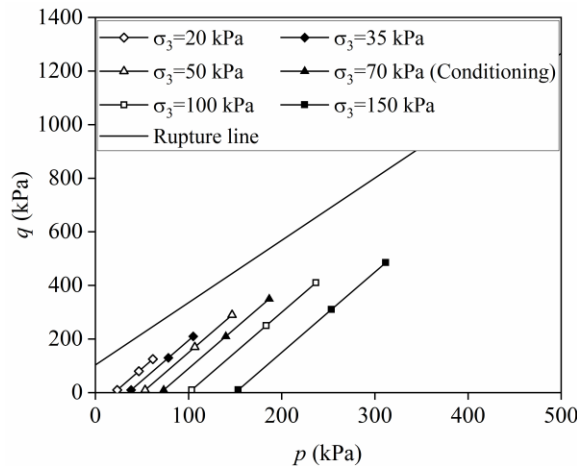


Figure 3. Stress paths for repeated load triaxial tests.

RESULTS AND DISCUSSION

Self-cementing properties

The pH values of NRCA and ORCA are also shown in Table 1. The results show that the pH value of NRCA (13.07) is much higher than that of ORCA (10.53), indicate a much stronger self-cementing property of NRCA while a negligible self-cementing property of ORCA after long-term storage (Bestgen et al., 2016; Poon et al., 2006).

Figure 4 shows the total released heat of NRCA and ORCA, resulting from the hydration of unhydrated cement. It shows that the heat was released once the water was added to the two RCA. The released heat of NRCA is around 14.7 J, while only 2 J of hydration heat was released by ORCA due to the long-term storage. As a result, self-cementing properties of NRCA are much stronger than these of ORCA, in agreement with the pH value measurement.

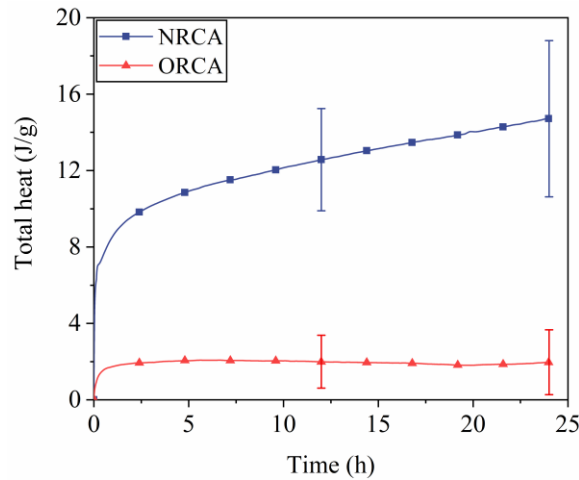


Figure 4. Hydration heat of NRCA and ORCA.

Repeated load triaxial tests

Figure 5 (a) and (b) show the permanent axial deformation ϵ_1^p and the water content of each NRCA and ORCA specimen, after different curing times. To better show the effect of self-cementing properties on permanent deformation, Figure 6 plot the final ϵ_1^p of NRCA and ORCA after 20000 loading cycles versus curing times. For NRCA, crushed recently, showing strong self-cementing properties, the results show ϵ_1^p decreases quickly after curing few months (180 days), then the influence of self-cementing properties on ϵ_1^p is diminished as ϵ_1^p reaches to a constant value. A power relationship can be obtained between final permanent axial deformation and curing time t , as can be seen in Figure 6. As for ORCA, stored for a long time, showing negligible self-cementing properties, ϵ_1^p is influenced by water content as other unbound granular materials (Jing et al., 2018; Soliman & Shalaby, 2015), instead of self-cementing properties, as can be seen in Figure 5 (b).

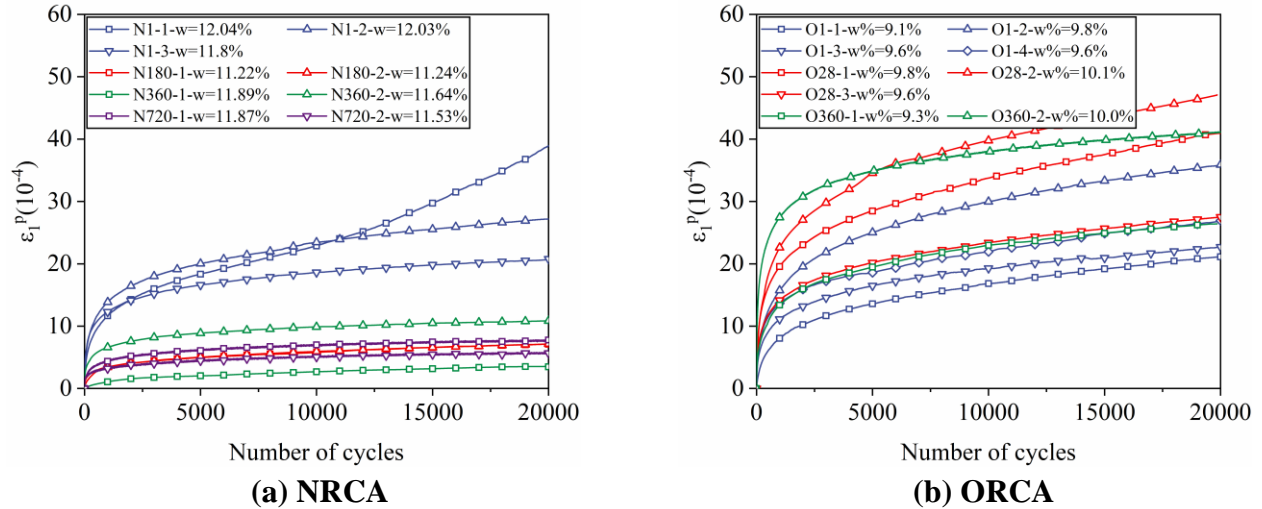


Figure 5. Permanent axial deformation ε_1^p of NRCA and ORCA after varying curing times: (a) NRCA; (b) ORCA.

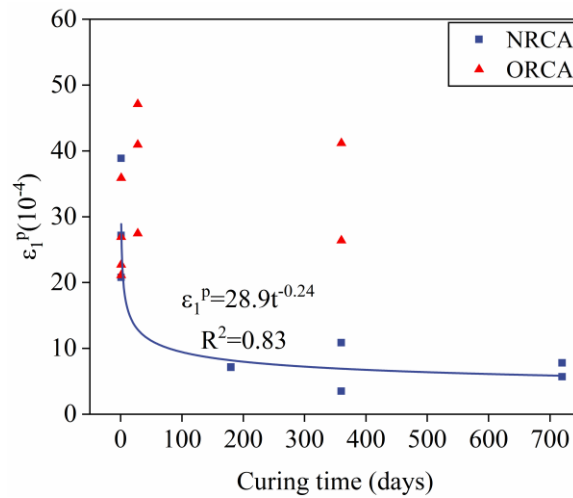


Figure 6. Final permanent axial deformation of NRCA and ORCA.

Figure 7 plots the resilient modulus M_r of NRCA and ORCA, during permanent deformation test, after different curing times. A clear increase of M_r for NRCA with curing time can be observed due to the self-cementing properties. By contrast, the final M_r of ORCA is constant, which is consistent with the evolution of permanent deformation.

An increase of M_r during the first load cycles can be observed, and then gradually reaches to a constant value, for both NRCA and ORCA after different curing times except the NRCA specimens curing 360 and 720 days. This behavior is due to the particle rearrangement and consolidation during the conditioning phase, which is observed also for unbound granular materials (UGM) in a shakedown state by other researchers (Jing et al., 2019; Yang et al., 2008). Interestingly, for NRCA specimens after curing 360 and 720 days, a decrease of M_r during the first

loading cycles can be observed, especially for NRCA curing 720 days. It indicates that some weak bonds between particles, due to the self-cementing properties, could break under the traffic loadings.

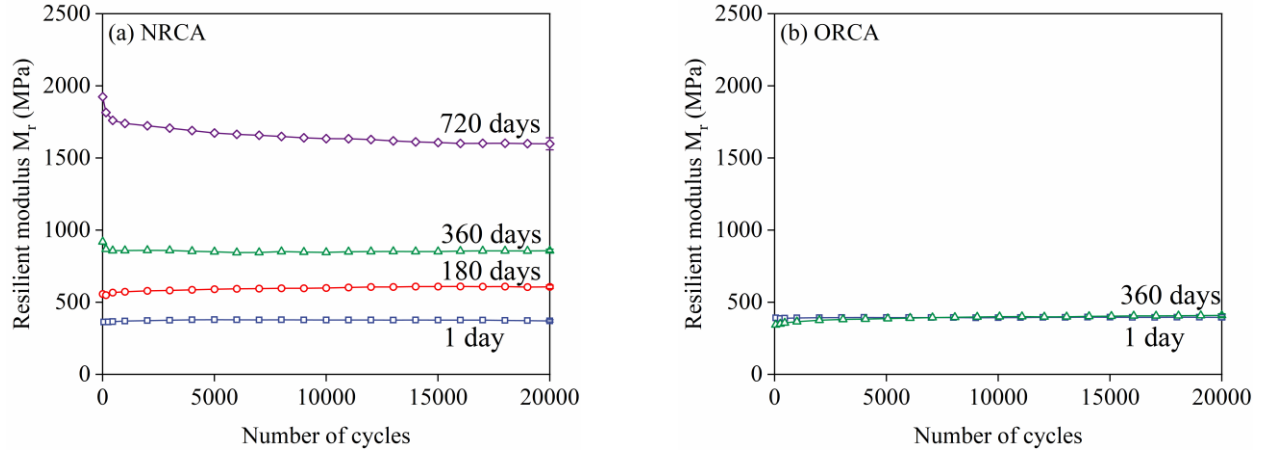


Figure 7. Resilient modulus of NRCA and ORCA during permanent deformation test: (a) NRCA; (b) ORCA.

Resilient modulus is a key input parameter in pavement design. The widely used k - θ model (Seed et al., 1967) was used to analyze the test results. The resilient modulus M_r and k - θ model are defined as:

$$M_r = \frac{q}{\varepsilon_1^r} \quad (3)$$

$$M_r = K_1 \theta^{K_2} \quad (4)$$

where q and ε_1^r is the deviator stress and resilient axial strain, θ is the bulk stress ($\sigma_1 + \sigma_2 + \sigma_3$), and K_1 and K_2 are model parameters determined by regression analyses.

Figure 8 (a) and (b) show the experimental data and k - θ model predictions of resilient modulus M_r for NRCA and ORCA after different curing times. It can be observed that k - θ model can fit the experimental results well, as all the coefficients of determination (R^2) are higher than 0.90, except for the NRCA specimens curing for 720 days ($R^2=0.761$). The scattered tested data of NRCA curing for 720 days are attributed to the low resilient deformations (high stiffness), under the tested stresses, as observed also by Jitsangiam et al. (2015). Besides, a significant influence of self-cementing properties on the M_r of NRCA can be observed (Figure 8 (a)), as M_r increases with curing time, under a same stress state, in accordance with previous studies (Arm, 2001; Jitsangiam et al., 2015). The increasing rate of M_r increases with curing time, until the tested curing time (720 days). For example, under the highest stress level ($\sigma_3=150$ kPa, high stress level), M_r increases 0.3 (180 days), 0.8 (360 days) and 2.2 (720 days) times than that curing 1 day. However, the curing time has no influence on the M_r of ORCA (Figure 8 (b)), as observed also from permanent deformation.

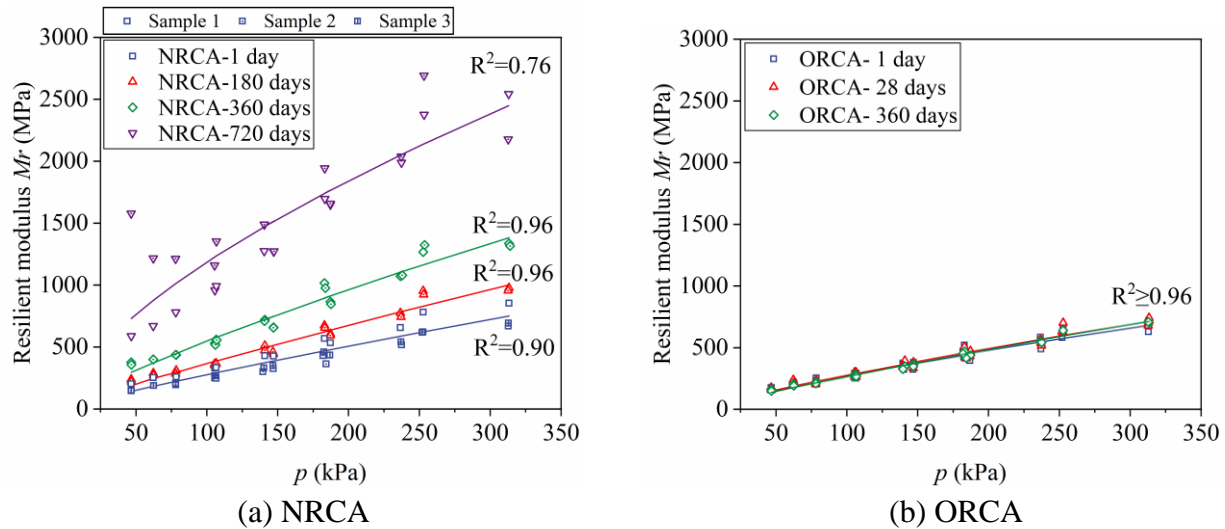


Figure 8. Test results and the k - θ model predictions of M_r for NRCA and ORCA after varying curing times: (a) NRCA; (b) ORCA.

Table 2 summarizes the k - θ model parameters for NRCA and ORCA, after different curing times. Figure 9 depicts the evolution of k - θ model parameters K_1 and K_2 of NRCA with curing time. Given that the self-cementing properties of ORCA are negligible, only the parameters of NRCA were presented. Parameter K_1 is an indicator of the resilient modulus magnitude, while K_2 represents the stress dependency of materials. It can be observed that K_1 increases while K_2 decreases with increasing curing time, indicating the improvement of stiffness and the reduce of stress dependency of NRCA as curing time increases, as observed also by other researchers (Arm, 2001; Jitsangiam et al., 2015). Furthermore, the variation of K_1 and K_2 is more pronounced with increasing curing time, which is in good agreement with the improvement of M_r .

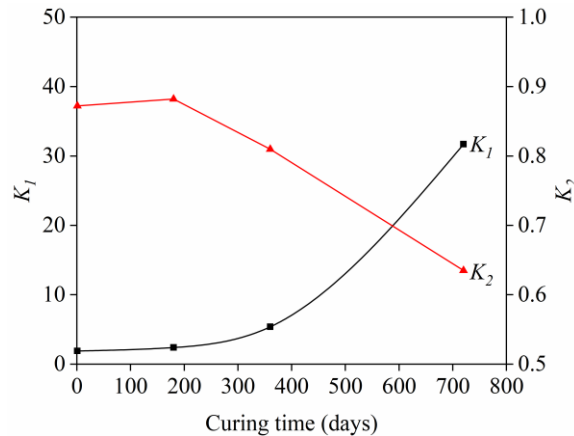


Figure 9. Evolution of k - θ model parameters K_1 and K_2 of NRCA with curing time

Table 2. Summary of k - θ model parameters for NRCA and ORCA.

Parameters	NRCA				ORCA		
	1 day	180 days	360 days	720 days	1 day	28 days	360 days
K_1	1.91	2.40	5.39	31.69	2.69	2.49	1.90
K_2	0.87	0.88	0.81	0.64	0.81	0.83	0.87
R^2	0.903	0.963	0.958	0.761	0.959	0.965	0.984

CONCLUSION

In this study, the influence of self-cementing properties on the permanent and resilient deformation behavior of RCA was investigated, by conducting a series of repeated load triaxial tests.

The results of pH values and heat of hydration measurements showed that the self-cementing properties of NRCA are very strong, indicated by high pH value and more total released heat, while the self-cementing properties of ORCA, after long-term storage, are negligible.

The permanent deformation of NRCA, with strong self-cementing properties, decreases quickly after curing 180 days, then reaches to a constant low value. During permanent deformation test, the resilient modulus of NRCA curing 1 and 180 days increase with loading cycles, while these of NRCA curing 360 and 720 decrease, to a constant value.

The resilient modulus of NRCA increases with curing time till the studied curing time (720 days). Besides, the increasing rate of resilient modulus also increases with curing time. The modelling results with k - θ model reveal that the stress dependency of M_r decreases with curing time.

While for ORCA, after long-term storage, the curing effect has no influence on the permanent deformation and resilient deformation behavior due to the negligible self-cementing properties.

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. 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, which should be further investigated.

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