Modified Recycled Concrete Aggregates for Asphalt Mixture Using Microbial Calcite Precipitation

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Highlights:

- Recycled concrete aggregate (RCA) was pretreated by microbial calcite precipitation.
- The surface treatment reduced the porosity and permeability of RCA by 32% and 86.5% respectively.
- Chemical bond was developed at the interface of RCA/asphalt binder after this treatment.
- The surface treatment improved the bonding strength of RCA/asphalt binder by 55%.

Abstract: Using recycled concrete aggregate (RCA) in asphalt mixture has many economic and environmental benefits for our society. However, due to the poor adhesion of RCA to asphalt binder, the replacement of normal aggregate with RCA will lead to a reduction in the properties of asphalt mixture. This paper presents a new approach to overcome this deficiency by treating RCA with microbial carbonate precipitation to develop chemical bonds between RCA and asphalt binder. This study

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firstly investigates the effect of this surface treatment on the properties of RCA. The experimental results showed that the capillary water absorption and porosity of the treated-RCA could be reduced by 86.5% and 32% respectively as compared to the untreated-RCA. In addition, this study investigates the influence of this surface treatment on the interfacial behavior of RCA to asphalt binder by means of standard boiling test and direct tension test. According to the test results, the adhesion behavior of the treated-RCA to asphalt binder could be improved by 2 grades as compared to the asphalt mixture with untreated-RCA. Moreover, the bonding strength of treated-RCA to asphalt binder was also improved by 55%. The formation of chemical affinity between treated-RCA and asphalt binder as shown FTIR spectra is explanation for the enhancement in the bonding strength and water susceptibility for the treated-RCA asphalt mixture.

Keywords: Recycled concrete aggregates; Surface treatment; Microbial carbonate precipitation; Chemical affinity; Asphalt binder

1. Introduction

Waste cement concrete is a highly polluting material, and many attempts have been made to reuse this waste material.[1-4] Recycling concrete aggregate (RCA) in new cement concrete or asphalt mixture is one of the most effective and environmental friendly ways.[5-15] This reusing process leads to a number of typical issues associated with sustainability, such as (a) lack of land resources for disposing demolished concrete debris, and (b) depletion of quality primary natural aggregates for cement concrete or asphalt mixture production.[16] However, many studies have shown that the use of RCA in cement concrete or asphalt mixture usually leads to a considerable reduction in the strength and durability of RCA productions.[5-13] These unfavorable properties are associated with the poor interfacial bond between RCA and binder, as well as the porous microstructure in the interfacial transitive zone for RCA productions. So far, removing the porous lay on the surface of RCA or reducing its porosity is considered the most effective way to improve the properties of RCA productions. Several related techniques have been developed by a number of researchers.[8, 15-19]

Microbial carbonate precipitation (MCP), referring to the technique of using bacteria to induce calcium carbonate crystal precipitation, is thought to be an effective method to improve the properties of RCA.[16, 18-32] The mechanism of MCP is based on the enzymatic hydrolysis of urea to ammonia and carbon dioxide,[16,24,33] and the process of MCP has been described as follows:

$$(NH_2)_2CO + 2H_2O = CO_3^{2-} + 2NH_4^+ \quad (1)$$

$$Bp.cell + Ca^{2+} = Bp.cell - Ca^{2+} \quad (2)$$

$$Bp.cell - Ca^{2+} + CO_3^{2-} = Bp.cell - CaCO_3 \quad (3)$$

where bacillus pasteurii bacteria (Bp. Cell) can attract Ca ions (Ca^{2+}), which react with carbonate ions (CO_3^{2-}) originating from urea $((NH_2)_2CO)$ hydrolysis.

The enhancement mechanism of MCP on the properties of RCA is realized in two methods, namely bio-deposition and bio-cementation. Bio-deposition refers to bacteria induced $CaCO_3$ precipitation to fill the pores of RCA.[28] Bio-cementation refers to the bacteria induced $CaCO_3$ precipitation functioning as binder material to increase the strength of RCA.[28]

Currently RCA treated by MCP has been used to replace natural aggregate to produce cement concrete and achieve satisfactory mechanical properties.[16, 18-32] However, few studies have been reported using this treated-RCA in asphalt mixture. Asphalt is acidic in asphalt mixture so that alkaline aggregates like limestone is usually required to yield good aggregate-asphalt adhesion.[34-36] When alkaline aggregates are mixed with acidic asphalt at high temperature, the asphalt exhibits physical adhesion to the surface of aggregates and a related chemical reaction takes place.[35] The treated-RCA covered by a layer of alkaline calcite precipitation was thus expected to yield chemical bonding between aggregate and asphalt binder. In addition, the rough surface of RCA provides the space for mechanical interlocking in the interface and led to an effective bonding.[11] Therefore, using treated-RCA in asphalt mixture may be more effective than that in cement concrete. In addition, using treated-RCA in asphalt mixture is especially importance in China due to the road construction is highlighted as part of the Chinese ‘five-year plan’, in which the overall mileage of expressways will be up to 85,000 km until 2030. At the same time, it was reported that about 200 million tons of waste concrete were produced annually in Mainland China.[2,4] Therefore, the use of RCA treated by MCP to replace natural alkaline aggregates in the production of asphalt mixture can provide both social and economic benefits.

The motivation of this work is firstly to investigate the effect of MCP treatment on the properties of RCA. The permeability resistance of RCA was investigated by using a capillary water absorption test. The porosity and pore size distribution were determined by using Mercury intrusion porosimetry (MIP). X-ray diffraction was used to determine the mineralogical composition of microbial calcite precipitation. Then, the potential application of the treated-RCA in asphalt mixture was investigated. The interfacial behavior between asphalt binder and treated-RCA was investigated by using direct tensile test and water boiling method. Fourier transform infrared spectroscopy was used to characterize the phase and mineralogy composition of the interface between RCA and asphalt binder.

2. Preparation of materials and testing methods

2.1 Preparation of recycled concrete aggregate (RCA)

Two types of RCA samples namely RCA1 and RCA2 were used in different laboratory tests in this paper. RCA1 producing from 3-year old mortar columns made by ordinary Portland cement was used to prepare for capillary water absorption test and the bonding strength test. The related water-cement ratio (W/C) and sand-cement ratio are 0.45 and 2, respectively. In this test, a total of 12 RCA1 samples were produced and the related dimensions of each RCA1 sample were 70.7×70.7×70.7mm (Length×Width×Height). RCA2 was used to investigate the related resistance to moisture damage of RCA-asphalt mixture using water boiling method. RCA2 particles with a size of 13.2 mm to 19 mm were produced from the broken old concrete. The original compressive strength of these concrete prisms was about 25 MPa.

Matrix asphalt No.70 was adopted to test the interfacial behavior between asphalt binder and RCA, and the property values are summarized in Table 1 according to Standard Test Methods of Asphalt and Bituminous Mixtures for Highway Engineering (JTJ 052-2000) of China.[37] Ordinary Portland cement was used as mineral filler. The Blaine surface area and specific gravity of the ordinary Portland cement were 3734 cm^2/g and 3.1 g/cm^3, respectively

Table 1. Properties of No.70 asphalt binder

Properties	Test result	Standard
Needle penetration(5s, 100g, 25℃)/(0.1mm)	72.1	60-80
Softening point(R&B)/℃	48.5	≥46
Ductility(5cm.min^{-1}, 15℃)/cm	≥140	≥100
Solubility(Trichloroethylene)/%	99.8	≥99.5

2.2 Bacterial strain and culture medium

Bacillus pasteurii purchased from the German Collection of Microorganisms and Cell Cultures (DSMZ) was used to modify RCA by means of inducing the precipitation of $CaCO_3$. This bacillus was chosen due to the great potential for precipitation of calcium carbonate and the lack of pathogen city under extreme conditions. Culture medium for preparing bacterial stock cultures contained the following ingredients:[33] beef extract (3g/l), peptone (10 g/l), urea (20 g/l), NaCl (5 g/l) and NH_4Cl (10 g/l). All these ingredients were prepared in deionized water to avoid the influence of contaminating ions on the culture medium.

The culture medium, in an Erlenmeyer flask, was sterilized by autoclaving for 30 min at 121 °C and then was inoculated with bacillus pasteurii bacteria from the stock culture. Then the Erlenmeyer flask was put on a rotary shaker (30 °C, 170 rpm) up to 24 hours, after that, the bacteria medium was centrifuged for 5 min at 6000r/min, and the final density was 109 cells/ml. [33]

2.3 Bacterial treatment procedure

In this paper, old cement mortar particles (OMP) removed from RCA2 was used as a new bacterial carrier due to the following two main advantages:[38-39] (a) OMP was porous and rich in the gradient of $CaCO_3$. The porous structure of OMP is highly effective for transferring calcite precipitation into RCA. $CaCO_3$ acts as nuclei in OMP is capable of promoting the formation of calcite precipitation; (b) OMP is an alkaline material, and the related high pH value will improve calcite precipitation efficiency during the MCP treatment process.[16,31,40-41]

Bacterial treatment procedures of RCA include the following steps as shown in Fig.1: (a) OMP (pH 9~10) removed from RCA2 was crushed and sieved by using a 5mm sieve. This OMP was used as the bacterial carrier; (b) Bacillus pasteurii bacteria and OMP were mixed together and placed on the surface of RCA; (c)

Culture medium was sprayed at regular time intervals (3 hours interval for the first 24 hours and 12 hours interval afterward); and (d) After 7 days, OMP was removed and the treated-RCA was kept in a dry condition for the following tests.

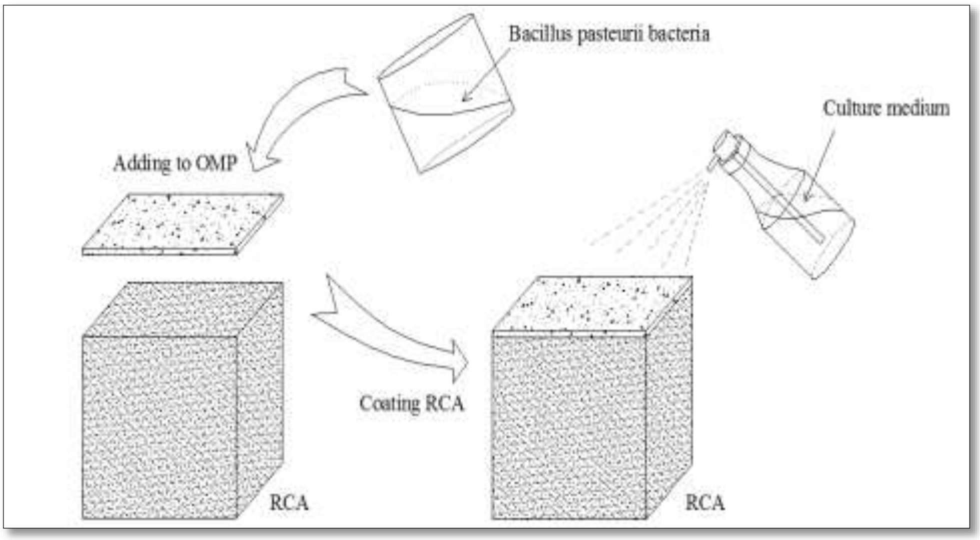

Figure 1. A schematic view of MCP treatment procedures using old cement mortar particles (OMP) as the bacterial carrier.

2.4 Testing methods

In this study, a total of six different tests were carried out to examine the performance of treated RCA and it's asphalt productions. These tests include X-ray Diffraction Analysis, capillary water absorption test, porosity and pore size distributions test, FTIR, boiling water test and direct tensile test.

2.4.1 X-ray Diffraction Analysis

X-ray diffraction was used to determine the mineralogical composition of microbial calcite precipitation of RCA. It was carried out using X'PertPrRO PANalytical X-ray Diffractometer with graphite monochromatized Cu Ka radiation operating at 40 kV and 200 mA. Scanning was conducted at fixed time intervals. The related time interval and step length were 4 s and 0.02°, respectively. The step scan was set for scattering angle (2θ) ranges of 10-75°.

2.4.2 Capillary Water Absorption Test

Capillary water absorption test is one simple and effective measure to evaluate the penetration resistance of RCA.[33] RCA samples were adopted in this test and this basic test includes the following procedures: (a) prior to the test, all RCA1 samples were dried at 45 °C in an oven until mass loss was less than 0.1% (after 24 h interval); (b) all RCA1 specimens were weighed and coated with wax at four surfaces adjacent to the treated surface to avoid the absorption of water; (c) RCA1 samples were immersed at a depth of 10 mm below water as shown in Fig.2; (d) RCA1 samples were taken out of the water at regular time intervals (5 min, 10 min, 20 min, 30 min, 60 min, 90 min, 120 min, 180 min, and 240 min) for the measurement of mass, then the RCA1 samples were immediately returned into water. It is noted that the surface of RCA1 samples should be cleaned with a wet towel before mass measurement.

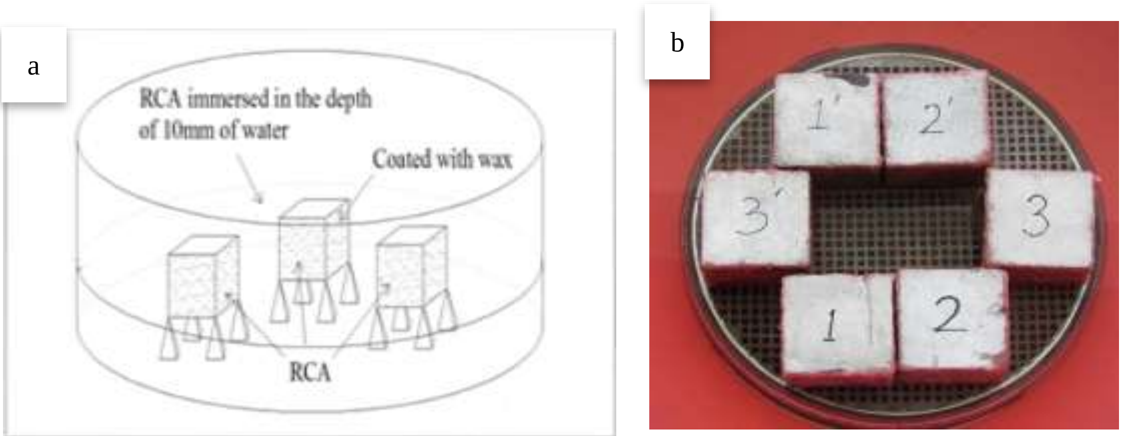

Figure 2. (a) A schematic diagram and (b) samples for capillary water absorption test

2.4.3 Porosity and Pore Size Distributions of RCA

Porosity and pore size distributions are major factors controlling the durability and strength of aggregates.[42-43] In this test, AUTOSCA-GT60 Mercury Intrusion Porosimetry (MIP) equipment, which is capable of determining the distribution of pore size varying from 10nm to 200μm, was used for the measurement of porosity and pore size distributions. Spherical specimens were extracted from the surface of

RCA2 samples. These extracted specimens were dried in an oven at round 60°C for 24 hours prior to testing. The contact angle and mercury surface tension used were taken to be 140° and 480.0 erg/cm^2, respectively.

2.4.4 Fourier transform infrared spectroscopy (FTIR)

Fourier transform infrared spectroscopy was used to characterize the change of chemical bonds in the interface between RCA and asphalt binder. Analysis of infrared absorption spectra was conducted for the surface layer with the Nicolet 5DXC FTIR spectrometer. The samples prepared for FTIR test were taken from the interfacial zone after direct tensile strength test. These samples were firstly washed by using trichloroethylene until no asphalt binder can be observed on the surface, then washed by anhydrous alcohol again. These samples were dried in an oven (50±2°C) for 24 hours and ground to pass through a 45μm sieve. In the present test, three samples of each mix were coated with a KBr pellet. IR spectra were obtained in the absorption mode with a resolution of 400 cm^{-1} and 4000 cm^{-1} scans.

2.4.5 Direct Tensile Strength Test

The bonding strength between the treated-RCA and asphalt binder was examined using direct tensile test. A total of six specimens including treated and untreated RCA specimens were prepared for direct tensile strength test. Dimensions of RCA specimens were 70.7 mm in height, 70.7 mm in width and 70.7 mm in thickness. Fig.3 shows the typical procedures of preparation work of a sample for direct tensile strength test. The thickness of asphalt film shown in Fig.3a is 10mm. Noting that the RCA samples were preheated at 140°C for 40–50 min before asphalt binder was poured into the gap and the filling temperature of asphalt binder was 140 °C. The specimen was glued to the steel plate with epoxy resin. Great attention should be paid on the gluing process of the specimens to the plates to ensure proper alignment between the plates and the specimen axis. The whole experiments were carried out in a controlled environmental chamber, in which testing temperature was kept at 20±2°C for a long time. Specimens were placed in this chamber at least 3 h until the inner component of specimens was homogenized at desired temperature. The strain-loading rate used to evaluate the fracture characteristics of interface between RCA and asphalt mixture was 0.5 mm/min.

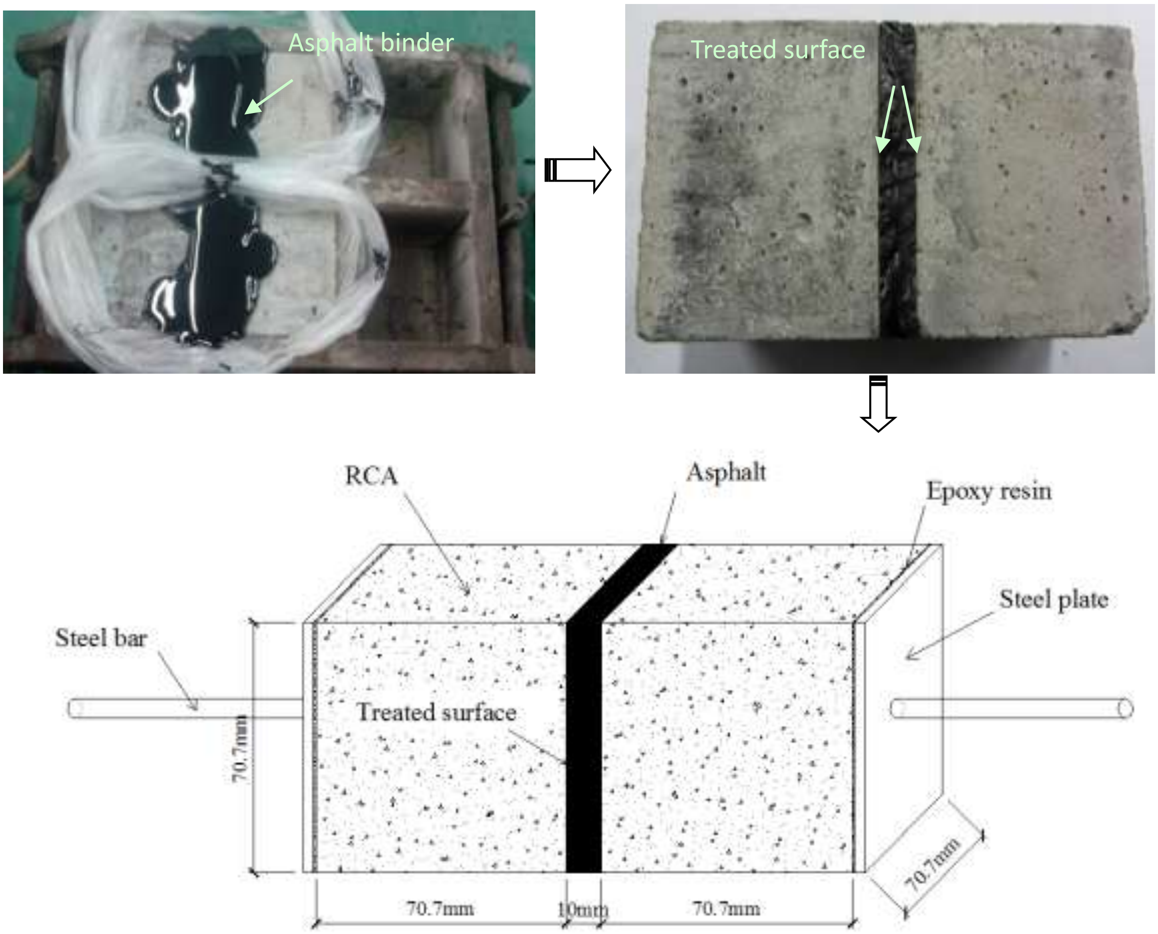

Figure 3. A schematic view of test setup for direct tensile strength test

2.4.6 Boiling Water Test

The boiling water test is a simple test to assess the effect of water on the adhesion between aggregate and asphalt binder. This test involves immersion of asphalt binder-coated aggregate in boiling water and evaluation of the retained coated area by visual rating. According to ASTM D3625 and Chinese Boiling Test,[35,44] 250 g clean aggregate particles (particle size between 13.2 mm and 19 mm covered with asphalt) were placed in approximately 800 mL distilled boiling water for 3 min. The quality of aggregate adhesion is classified by the observations of the conditions of the asphalt film left on the particles according to Table 2.[35,44]

Table 2. Grade of aggregate adhesion to asphalt according to Chinese code[35,44]

Condition of asphalt film left on the particles after 3 min of boiling	Grade
Full aggregate surface still covered by asphalt, and no film is removed	5
Less than 10% of the asphalt-covered area is removed, and the film is not significantly deformed	4
Less than 30% of the asphalt-covered area is removed. Part of the film is significantly deformed but still stays on aggregate surfaces	3
More than 30% of the asphalt-covered area is removed. A significant part of the film is deformed but stays on the aggregate surfaces	2
The aggregates are substantially bare, and the rest of the asphalt 1 film is totally deformed or floats in water	1

3. Results and discussion

The mineralogical composition of aggregate plays an important role in determining the mechanical properties and durability properties of asphalt mixture. To better understand the effect of surface treatment on the properties of RCA/asphalt mixture, the mineralogical composition of both untreated-RCA and treated-RCA was examined by XRD. The program MDI Jade 5.0 was used to process the XRD analysis, and the results are shown in Fig.4. The figure indicates that the predominant crystalline phase of treated-RCA was calcium carbonate and the main polymorph was calcite. A large amount of vaterite crystals were also detected in treated-RCA, while the untreated-RCA was mainly composed of calcite crystal. The strength or relative strength for the diffraction peak corresponds to a phase correlates with the content of that ingredient, i.e., the higher crystal phase content, the larger the diffraction peak.[45]

It is noted that in Fig.4, the MCP treatment increased the diffraction peak of calcite and vaterite crystal significantly. This phenomenon indicates that bacteria are highly effective to induce vaterite and calcite crystals in RCA.

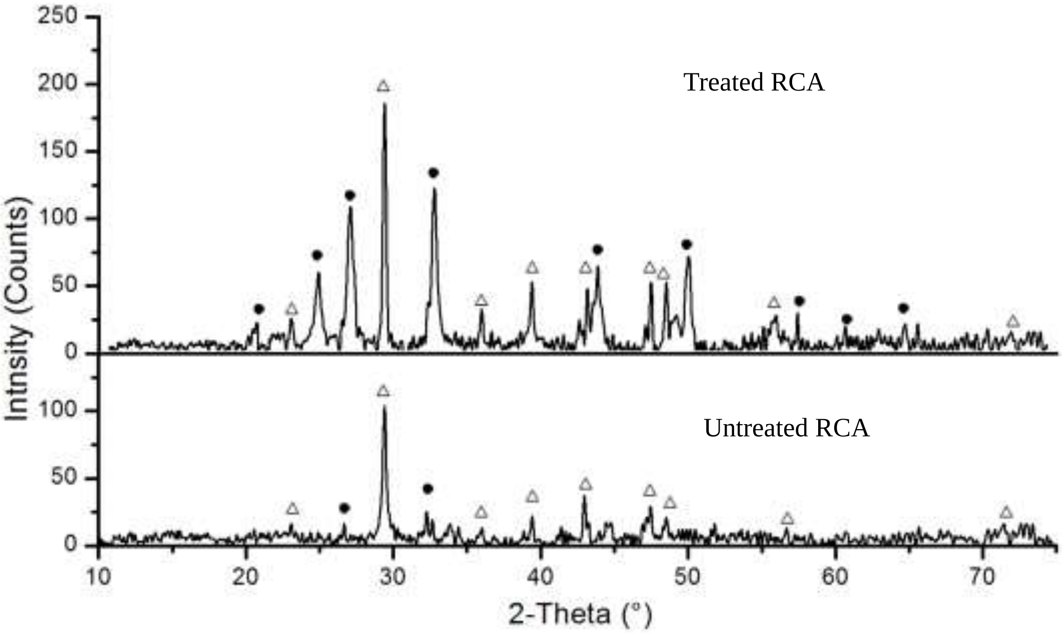

Figure 4. Influence of MCP on the mineralogical composition of RCA (△: Calcite; ●: Vaterite)

3.2 Capillary water absorption test results

The absorptive coefficient *K* was used to evaluate the capillary water absorption of RCA treated by using MCP. [33] This *K* is determined by the following expression:

$$\frac{Q}{A} = k\sqrt{t} \tag{4}$$

where *Q* is the weight of water absorbed at different time intervals; *A* is the cross section area of the RAC specimen in contact with water; *t* is the time interval. *K* is estimated from the slope ratio of water mass absorbed per square centimeter against the square root of time.

Fig.5 presents the effect of MCP on the absorptive coefficient *K* of RCA. It is clear from the figure that the MCP treatment greatly decreased the capillary water absorption of RCA. The average absorptivity coefficient K of untreated-RCA and treated-RCA was 1.63 and 0.22, respectively. The K is proportional to the permeability of aggregates in relation to their porosity. The K of treated-RCA reduced by more than 86.5% indicates that RCA samples after being treated exhibits lower porosity and relative stronger permeability resistance compared with untreated RCA samples.

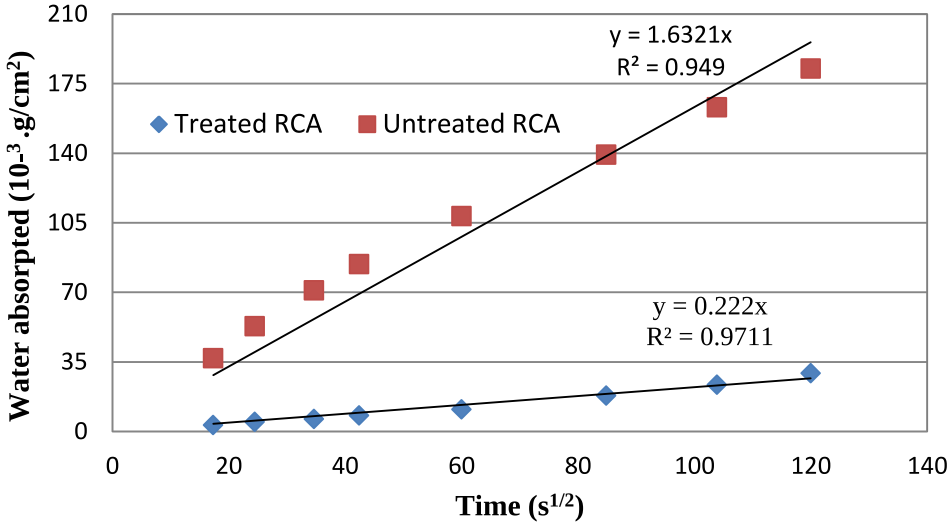

Figure 5. Influence of MCP on water absorptivity of RCA (Untreated-RCA with *K* value of 1.63, Treated-RCA with *K* value of 0.22)

3.3Porosity and pore structure

Porosity and pore size distributions are considered to be the major factors controlling the durability and strengths of aggregates, which further influence the properties of asphalt mixtures. Generally, aggregates with higher porosity and coarser pores are believed to exhibit low durability properties and low strength. Aggregates with low strength will acts as a "soft core", which can introduce significant stress concentration under loading to reduce the overall strength of asphalt mixture. Moreover, the higher porosity and coarser pores may cause water easily enter into asphalt mixture and therefore decrease the mixture's resistance to moisture damage.[8,12,46-47] Thus, the porosity and pore size distributions of RCA are very important for its productions, and the effects of MCP on the porosity and pore size distributions in RCA determined from MIP are discussed as follows.

Table 3 shows a summary of parameter values obtained from MIP test for treated-RCA and untreated-RCA samples. Obviously, the porosity and pore size distribution are influenced by the MCP treatment in a statistically significant way. The total porosities are 25.1% and 17.1% for untreated-RCA and treated-RCA, respectively. The total porosity directly affects the physical properties of aggregates including strength and durability. Since the porosity of treated-RCA was 32% lower than untreated-RCA, it is expected that this surface treatment can improve both the strength and durability of RCA, and further test should be conducted to study this potential positive effects, which were not covered by the present investigation. Table 3 also indicates that the pores with a size larger than 100 nm were 19.33% and 3.76% for untreated-RCA and treated-RCA, respectively. In porous inorganic materials, there is a direct relationship between the permeability and the volume of pores larger than about 100 nm.[43] The fact that the pores in these ranges in untreated-RCA were about five times higher than that in treated-RCA explains the lower resistance to permeability for untreated-RCA as compared to treated-RCA during capillary water absorption test, as shown in Fig.5.

Table 3. Porosity and mean radius of the attached mortar treated RCA

Sample	Total intruded vol (ml/g)	Mean radius (nm)	Bulk density (g/cm^3)	Total porosity (%)	Porostiy (d<100nm) (%)	Porosity (d≥100nm) (%)
Untreated-RCA	0.155	115.97	1.62	25.10	5.77	19.33
Treated-RCA	0.091	52.34	1.84	17.11	13.35	3.76

Fig.6 shows the variation of dV/d logR against pore diameter. For untreated-RCA, dV/d logR increases with the decrease of pore diameter, and reaches the highest value 0.168 at the diameter 210 nm. Thereafter, dV/d logR decreases with the decrease of pore diameter. For treated-RCA, a similar trend can be observed. However, the highest value of 0.145 appeared in the much finer region of pores, at the diameter 70 nm. These phenomena indicate that the MCP treatment is effective in reducing the pore size and porosity of RCA due to the production of calcite and vaterite crystals by bacillus pasteurii bacteria, as demonstrated by XRD test result (Fig.4 and Table 3).

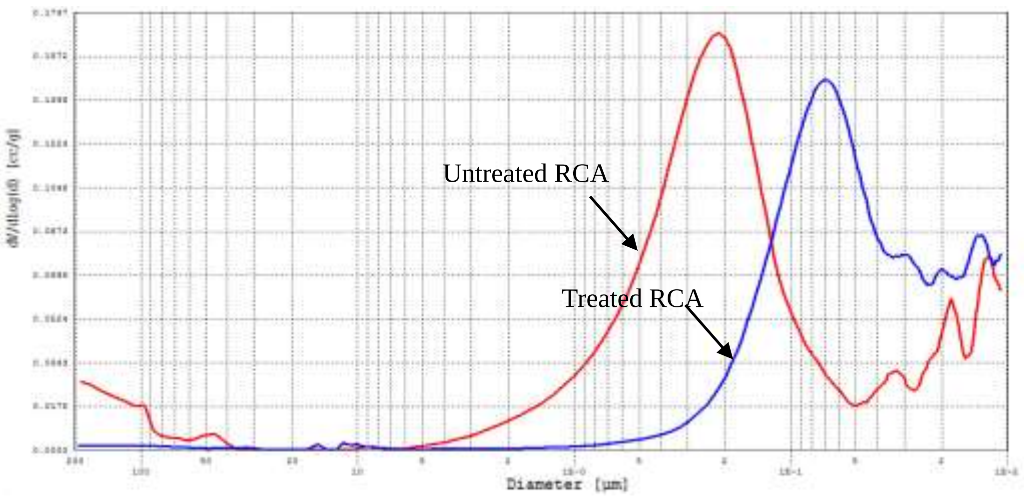

Figure 6. Influence of MCP on the pore size distribution of RCA

3.4 FT-IR spectra analysis

FT-IR spectrum of untreated-RCA/asphalt mixture is presented in Figure 7. Major vibration bands corresponding to OH stretching bond from $Ca(OH)_2$ (3643 cm^{-1}), ν_3 H_2O(3431 cm^{-1}), ν_2 H_2O (1633 cm^{-1}) and CO_3 bond from $CaCO_3$ (1422, 874 cm^{-1}) are observed.[48-51] Si (Si–O and Si–O–Si) and Al (Al–O and Al–O–Al) vibrational bands are detected in the 1200–400 cm^{-1} region, where the 1081 cm^{-1} and 459 cm^{-1} bands correspond to ν_3 (Si–O) and ν_4 (O–Si–O) stretching vibration of the SiO_4 tetrahedron, respectively, and 863–626 cm^{-1} regions correspond to Al–O–H bending vibration. [48-51]

FT-IR spectrum of treated-RCA/asphalt mixture is also presented in Figure 7. The 1420 and 874 cm^{-1} bands are attributed to CO_3 group mode of vibration. Comparing the FTIR spectrum of untreated-RCA mixture with that of treated-RCA mixture in Fig.7, it can be seen that the relative content of CO_3 group in treated-RCA mixture is significantly higher than that in untreated-RCA mixture, indicating that the bacteria used in the present study is effective in forming $CaCO_3$. Comparing Fig.3 with Fig.7, it is clear that the FR-IR test results are highly consistent with the XRD test results.

The 2925 and 2327 cm^{-1} bands are attributed to CH_2 and CH_3 group mode of vibration. Due to the solubility of asphalt binder in the trichloroethylene (99.8% in Table 1), the asphalt binder in the form of physical adsorption on the surface of RCA has been dissolved away when the samples were washed by trichloroethylene. Thus, the appearance of CH_2 and CH_3 group in FT-IR spectrum probably indicates the yield of chemical interaction between asphalt binder and aggregate. Moreover, the treated-RCA/asphalt mixture showing relative higher content of CH_2 and CH_3 group over untreated-RCA/asphalt mixture indicates the positive effect of MCP treatment on the improvement of chemical adhesion between aggregate and asphalt binder.

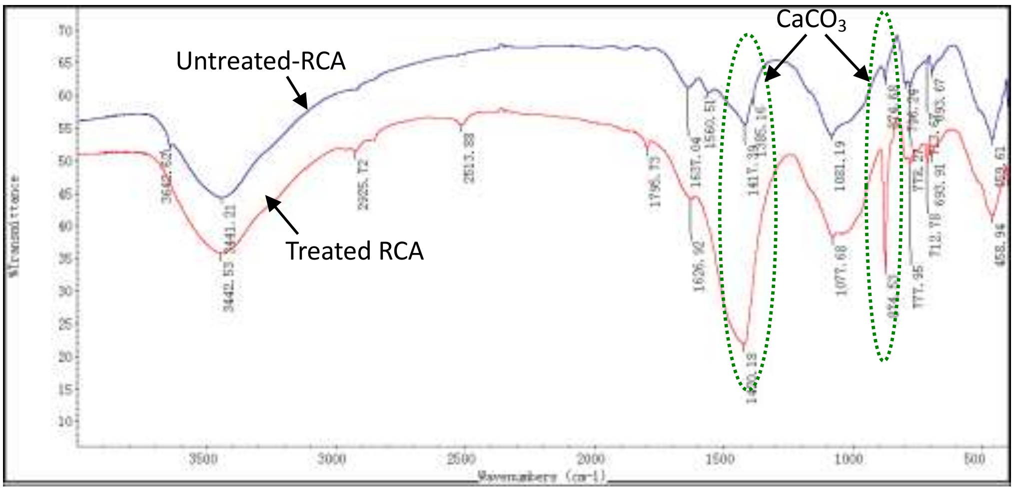

Figure 7. FT-IR spectra of the interface transition zone in RCA/asphalt mixture

(Samples washed by trichloroethylene and anhydrous alcohol prior to FTIR test)

3.5 Direct tensile strength **test**

Direct tensile strength is a very important measure to examine the parameters related to interfacial characteristics of asphalt mixture, and can be further used to assess the fracture properties of asphalt mixture.[52-54] The direct tensile strength can be determined as follow:

$$R_{DTS} = \frac{P_{max}}{A} \qquad (5)$$

where R_{DTS} is direct tensile strength, *MPa*; P_{max} is the maximum load of each stress elongation curve, *N*; A is the area of specimen, mm^3.

Fig.8 shows the results of direct tensile strength test of asphalt mixtures for untreated-RCA and treated-RCA, respectively. This figure shows that the direct tensile strength increases 55% after RCA was modified by MCP treatment. The enhancement in the bonding strength of treated-RCA asphalt mixture is plausibly due to the formation of chemical adhesion at the interface, as demonstrated by FTIR analysis (Fig.7).

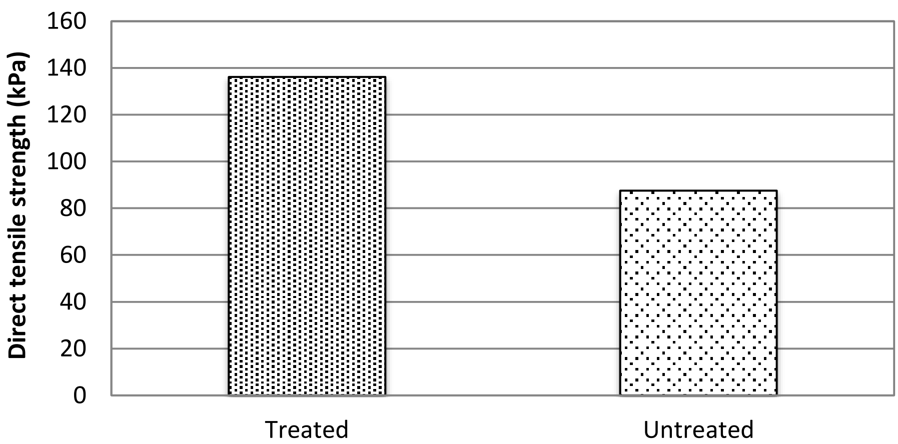

Figure 8. Influence of MCP treatment on the direct tensile strength

Fig. 9 shows the fracture mode in direct tensile strength experiment. In the untreated-RCA, the detachment of asphalt binder film away from aggregate can be observed during direct tensile process, which means a poor interface bonding between untreated-RCA and asphalt binder. While in the treated-RCA, the asphalt binder film was broken due to direct tensile force, indicating that the MCP treatment is effective in enhancing the interface bonding between aggregate and asphalt binder.

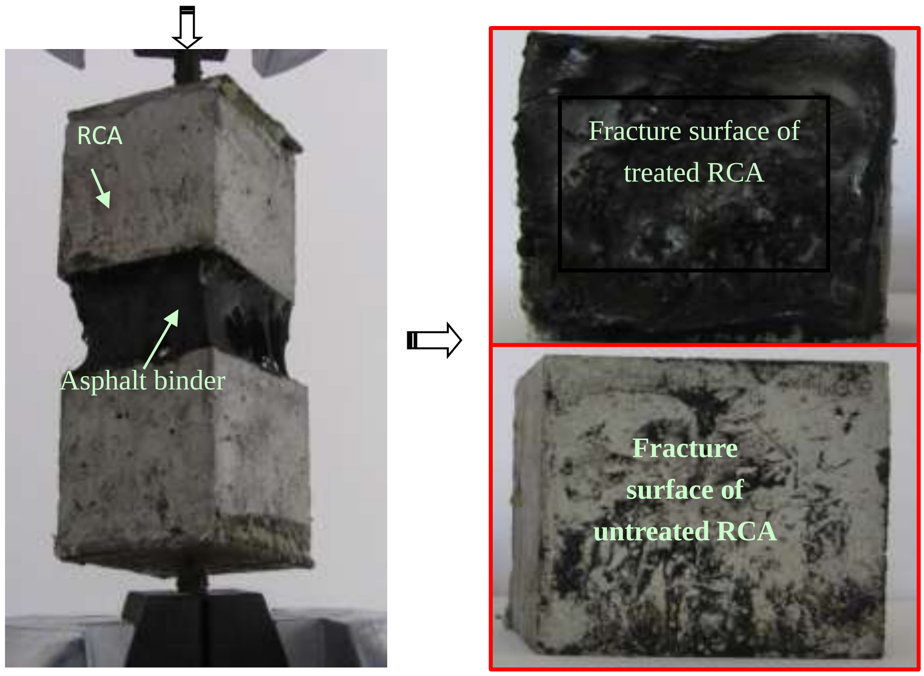

Figure 9. Influence of MCP on the fracture behavior of asphalt mixture

3.6 Boiling water test

Moisture damage can reduce the structural strength of asphalt mixtures. This is mainly due to the loss of the adhesion between aggregate and asphalt binder, or the loss of the cohesive strength within the asphalt binder under wet condition. The boiling water test is a qualitative test conducted on loose asphalt-coated aggregate to identify the durability of asphalt mixtures and their response to moisture ingress.[55]

Fig.10 shows the RCA samples before and after MCP treatment boiling water test. As shown in Fig.10a, the surface of untreated RCA was mainly composed of old cement mortar and original silica aggregate (acidic in character). The asphalt binder on the silica surface was removed after the boiling water test, and the mixtures with untreated-RCA showed excessive potential to moisture damage. With regard to Table

2, the adhesive behavior of the untreated-RCA/asphalt mixture is lower than Grade 3 and this adhesive behavior depends onthe surface characteristic of RCA. Fig.10b shows the treated-RCA was covered by a lay of alkaline carbonate precipitation when treated by MCP, and after boiling water test they were still covered by a lay of asphalt binder film. According to Table 2, the adhesive behavior of the treated-RCA/asphalt mixture reached the highest grade (Grade 5).

(a) RCA samples with acidic surface (left), and partial asphalt binder was removed from untreated-RCA sample (right)

(b) RCA samples covered by alkaline carbonate (left), and full surface covered by asphalt for treated-RCA (right)

Figure 10. Influence of MCP treatment on the moisture-damage of asphalt mixture

By comparing Fig.10a and Fig.10b, it is obvious that the surface treatment increases the resistance to moisture damage for RCA asphalt mixture. The enhancement effect is attributed to the same reason as mentioned above, where carbonate precipitation covered on the surface of treated-RCA results in strong chemical bonding between aggregates and asphalt binder.

4. Summary and conclusions

The high porous nature and acidic nature of recycled concrete aggregate (RCA) lead to the poor interfacial bond and high water absorption of RCA-asphalt mixture. As a result, the replacement of natural aggregate with RCA often results in the degradation of mechanical strength and durability of asphalt mixture. This paper studies a new surface modification of RCA with bacillus pasteurii bacteria to introduce alkaline carbonate precipitation in RCA. The effect of this surface modification on the properties of RCA and its asphalt production was investigated. Based on our experimental results, the following major conclusions can be made:

(1) The surface treatment of RCA by bacteria induces a large amount of calcite and vaterite crystals in RCA, as demonstrated by X-ray diffraction analysis results.

(2) The surface treatment improves the permeability resistance of RCA significantly. This phenomenon can be explained by the dense microstructure of RCA treated by microbial calcite precipitation, as demonstrated by MIP test results.

(3) FTIR analysis indicates the formation of chemical bonds at the interface between RCA and asphalt binder as a result of the interaction of acidic groups of asphalt binder with alkaline calcite precipitation of treated-RCA. Therefore, the bonding strength of asphalt mixture with treated-RCA increases 55% over asphalt mixture with untreated-RCA.

(4) The surface treatment enhances the moisture damage resistance of RCA-asphalt

mixture, where the adhesive behavior of asphalt mixture increases 2 grades when aggregate is pretreated by microbial calcite precipitation. The enhancement effect is attributed to the formation of chemical affinity between alkaline treated-RCA and acidic asphalt binder.

According to our results, microbial calcite precipitation is a useful method to enhance the properties of RCA and its asphalt production. Further tests should be conducted to study other potential effects which have not been investigated by present tests.

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