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An environmentally friendly method to improve the quality of recycled concrete aggregates

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HIGHLIGHTS

- A safe, clean, and low cost method is proposed to treat RCAs.
- Properties of RCAs can be improved by the new treating method.
- Compressive strength of concrete can be improved by 25% after treating the RCAs.
- Waste solution of the treatment can be used to improve strength of concrete.

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ABSTRACT

Recycled concrete aggregates (RCAs) have inferior qualities compared with natural aggregates, mainly attributed to the porous nature of the attached cement mortar. To improve the quality of the RCAs, an environmentally friendly and cost-effective method is proposed to treat RCAs in this study. In this method, RCAs are first soaked in acetic acid solution, in which the acetic acid reacts with cement hydration products attached to the surface of the RCAs. This reaction weakens the attached mortar, making it possible to remove it from the RCAs by mechanical rubbing later. The treated RCAs have lower water absorption and less cement mortar attached. Once used as aggregates in new concrete, these RCAs can enhance the compressive strength of the concrete at 28 days up to 25%. It is safe and clean to apply this new method since no dangerous chemical is used and no detrimental chemicals are introduced into the treated RCAs. More importantly, zero hazardous waste solution is generated since the waste solution of the treatment can be used to produce high value-added products, permanently store CO_2, and regenerate acetic acid. As an example, the waste solution of the treatment was used as admixture for new concrete, which improved the strength of the concrete by 14%.

1. Introduction

Concrete, as the most widely used construction materials, creates two major negative impacts on environment. On one hand, manufacturing of concrete consumes large amounts of natural resources. For example, current concrete industry demands more than 20 billion tons of raw materials (coarse aggregate) every year, and this demand will be doubled in the next 20–30 years [1,2]. On the other hand, all produced concrete will be demolished sooner or later, creating a large amount of Construction and Demolition (C&D) waste, especially concrete waste. Actually, C&D waste has already become one of the largest waste flows in the world. An estimated 900 Mt of C&D wastes are produced every year in Europe, the US and Japan [3]. In the mainland of China, more than 200 Mt of waste concrete are currently produced every year [4].

A promising method to mitigate these two negative environmental impacts is recycling C&D wastes to produce alternative aggregates for concretes. However, Recycled Concrete Aggregate (RCAs) are mainly limited to low-value added applications such as roadbed materials because of their inferior qualities compared with Natural Aggregates (NAs). This is because a layer of residual cement mortar is coated on the surface of the NAs in the RCAs. The porous nature of this residual mortar introduces undesirable properties to the RCAs, including higher water absorption, lower strength, and higher crushing value. Consequently, concrete made from RCAs usually has lower workability and higher creep and shrinkage than those of concrete using NAs [2,5–7].

A viable way to improve the quality of RCAs is to remove the porous residual cement mortar from the NAs. To this end, a few

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methods have been developed, including thermal process [8–12] and chemical process [13,14]. In thermal process [8], RCAs are first heated to a temperature high enough to dehydrate the cement hydration products. This process can significantly weaken the residual mortar so that it can be separated from the NA by mechanical rubbing. However, heating the RCAs not only consumes large amount of thermal energy, but also produce additional carbon dioxide emission. Chemical process uses a low-concentration acid (hydrochloric acid, sulfuric acid, and phosphoric acid), instead of heating, to weaken the cement mortar attached to the RCA, as demonstrated in [13,14]. To this end, RCAs are first soaked in hydrochloric acid or sulfuric acid solution to dissolve some hydration products of the cement. Some loose and cracked mortar can be removed from the RCAs by this treatment, leading to up to 28% reduction in water absorption of RCAs. The mechanical properties of the concrete produced with the treated RCAs as aggregate can be significantly improved. However, strong acids (hydrochloric acid and sulfuric acid) are used in this method, which not only poses a threat to the safety of the workers, but also adds detrimental ions such as Cl^- and SO_4^{2-} to the RCAs. These ions can cause durability issues in concrete with these RCAs. Therefore, large amount of water is needed to wash the treated RCAs. However, disposal of this washing water and the residual of the treatment solution will create new environmental problems.

With an aim to overcome the drawbacks of existing chemical process, this study proposes using low concentration acetic acid to treat RCAs so that high quality aggregates can be produced. This new method is illustrated in Fig. 1. RCAs will first be soaked in low concentration acetic acid (1–5%). Acetic acid can react with calcium hydroxide, calcium carbonate (in carbonated RCAs), and calcium silicate hydrate in the cement mortar attached to the surface of the RCA as described by

$$CH + CH_3COOH_{(l)} \rightarrow Ca^{2+}_{(aq)} + CH_3COO^-_{(aq)} + H_2O_{(aq)}, \quad (1)$$

$$CaCO_3 + CH_3COOH_{(l)} \rightarrow Ca^{2+}_{(aq)} + CH_3COO^-_{(aq)} + CO_{2(g)}, \quad (2)$$

$$C\text{-}S\text{-}H + CH_3COOH_{(l)} \rightarrow Ca^{2+}_{(aq)} + CH_3COO^-_{(aq)} + H_2O_{(aq)} + SiO_{2(s)}, \quad (3)$$

where CH is calcium hydroxide, C-S-H is calcium silicate hydrate. These reactions can weaken the attached mortar, making it possible to remove most of them from the RCA by mill crushing in the next step, as shown in Fig. 1. This treatment can significantly enhance the quality of produced aggregate since much less mortar is attached to it.

Compared with existing chemical processes, this new method enjoys many advantages:

1) Lower cost: Acetic acid is cheaper than strong acid such as HCl and H_2SO_4. More importantly, acetic acid can be partially regenerated as shown in Fig. 1.
2) Safer: Acetic acid solution is much milder, posing less threat to the safety of the workers. It is also much easier to ship acetic acid than strong acids (hydrochloric acid, sulfuric acid, and phosphoric acid).
3) Cleaner: No detrimental ions are introduced into RCAs. Unlike in the case of using hydrochloric acid or sulfuric acid, no chemical ions such as Cl^- and SO_4^{2-} will be introduced into the RCAs. No evidence so far suggests that acetate ions can cause deterioration of concrete [15–17]. Therefore, there is no need to wash the treated aggregates, which will save a large amount of water and the cost of the treatment.

More importantly, value-added applications or products can be made from the waste solution of the treatment, which is rich in calcium and acetate ions. For example, CO_2 can be bubbled into the solution so that some Precipitated Calcium Carbonate (PCC) can be produced, as shown in Fig. 1. Through properly controlling the reaction conditions, vaterite, one metastable polymorph of calcium carbonate can be produced [18]. In ambient environment, vaterite has higher solubility and surface free energy than those of other two polymorphs of calcium carbonate (aragonite and calcite). Together with its biocompatibility, colorlessness, low density, and porous structure [19,20], vaterite is a high value-added product which has found many applications in drug delivery, paper making, reaction catalyzing, pollution adsorbing, plastics and rubbers manufacturing. Vaterite can be transformed into calcite without through the intermediate phase aragonite through a dissolution-recrystallization process. In this process, vaterite dissolves releasing calcium and carbonate into solution, which then re-precipitates on the surface of the growing calcite crystals [21]. Due to this phase transformation process, metastable $CaCO_3$ can be used as a binder to cement aggregates together, as demonstrated in recent applications in concrete [22]. In this way, calcium in RCA can be recycled as binder again.

Producing PCC from the waste solution can permanently store CO_2 in the produced PCC to further reduce the carbon emission of concrete. In addition, acetic acid can be recovered by CO_2 bubbling because carbonic acid is stronger than acetic acid. The rest solution can also be directly used as admixture for concrete, which can enhance the compressive strength of concrete, as demonstrated in this study, or to produce calcium acetate, which is even more expensive than the acetic acid.

The major objective of this paper is to confirm that high quality aggregate can be produced by treating RCAs in low concentration acetic acid and that waste solution of the treatment can be used

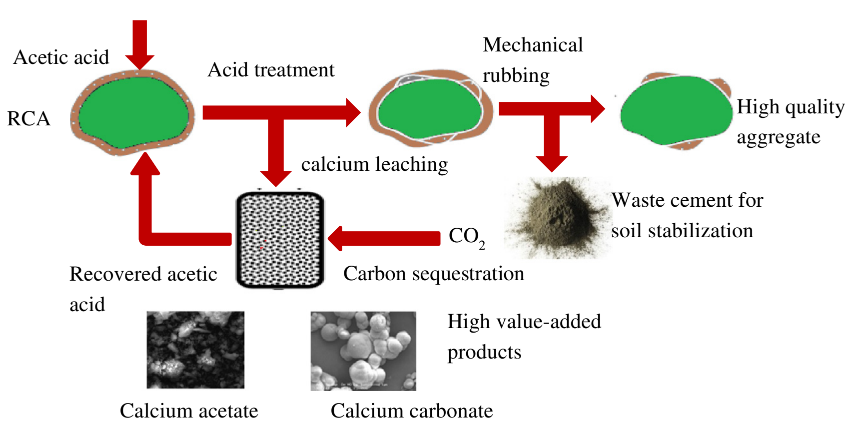

Fig. 1. New approach to treat RCA for value-added products.