Modification on Recycled Aggregates and its Influence on Recycled Concrete

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Abstract. Recycled aggregates produced from waste concrete are widely accepted as green building material. However, demolition processes will bring recycled aggregates with a lower apparent density, bulk density whereas a higher porosity, silt content, water absorption, crushing index value when compared with natural aggregates. So the strengthening and modification of recycled aggregates have become a prominent technological issue in the producing process. This paper introduces current modification methods on the recycled aggregates, which mainly include: (1) physical technology, its basic idea is to remove the waste cement paste adhered to recycled aggregates, such processions as rubbing, heating, particle shaping, and micro-heating; (2) chemical technology, carried out by immersing recycled aggregates in different kinds of chemical grout, which can be mixed with additive Kim powder, silica fume, fly ash, and any other fine mineral powder or slag; (3) carbonation technology, when newly collected crushed aggregates are put into atmosphere with high CO2 concentration, the adhesive cement paste can react with CO2 and produce CaCO3 that will precipitate in the capillary pores or cracks, which will improve properties of recycled aggregates; (4) nano technology, the use of nanomaterials can promote the hydration reaction, react with cement based materials, fill pores and control the process of crystallization. Conclusions are put forward and several problems concerning modification need to be considered for further research and application are proposed and discussed. Compared with natural concrete, RAC is superior to environmental value in the reduction of CO2 emission in Life Cycle Assessment.

1. Introduction
The demolition of buildings will produce more than 200 million tons of solid wastes in China every year, and 80% are waste concrete, however, there are still no effective disposal measures. The building wastes need to be buried or piled up after demolition thus will occupy more arable lands or even bring about pollution to the lands. Therefore, it’s urgent to develop the recirculation and reutilization of building resources. Among them, recycled concrete aggregates are available impetus[1]. This improves efficiency of recycling of concrete and provides a topic linked to sustainability of cement based materials.
Researchers all over the world have conducted majority experiments on modification of recycled aggregates, these modifications can be summarized as physical technology, chemical technology, carbonation technology and nano technology.

2. Physical Technology

2.1. Abrasive Grinding Method
For grinding the preliminary crushed concrete blocks (diameter 5~40mm), the use of ball mill or rod mill to remove effectively the adhesive hardened cement pastes can produce high quality recycled aggregates, this idea can be described as abrasive grinding method[2]. The ball mill usually has dry treatment or wet treatment, while the rod mill is usually designed for wet treatment. Take the example of ball mill, its working principle is shown in Figure 1. This device is provided with several partitions, between the partitions there is a lot of steel balls. The interactive collisions between steel balls and recycled aggregates or interactive collisions simply between recycled aggregates will remove the adhesive cement paste and thus improve the properties of recycled aggregates. However, the abrasive grinding equipment will always lead to higher energy consumption and lower efficiency, besides, the device and grinding blocks will suffer a lot from serious wear and tear.

![Figure 1. Ball milling equipment of abrasive grinding method](image)

2.2. Particle Shaping Method
The configuration and structural principle of the particle shaping equipment are shown in Figure 2. This equipment consists of host system, dust removal system, electric control system, lubricating system and pressure sealing system. The host system is provided with a vertical totary impeller (the aggregates projection disk). Recycled aggregates that need to be modified are introduced into the machine from the upper inlet and then are divided into two streams; one part falls into the impeller cavity and is projected with high speed (the maximum can be 100m/s) due to the centrifugal effect; another falls along the aggregates distribution system of the host and its aggregates then collide with the ones projected from the impeller. After several times’ collisions the recycled aggregates will be crushed and modified. In this process, the equipment consumes less energy and has a longer service life because the high-speed recycled aggregates rarely contact with the machine wall, it’s also convenient to install, operate and repair the equipment. After the process, the recycled aggregates will have smooth surface, good particle shape, and the bulk density will be improved with higher purity[3].
2.3. Microwave-Assisted Method
A novel microwave-assisted method may be effectively used to partially remove the adhering cement paste by developing high temperature gradients and high thermal stresses within the mortar, especially at the interfacial zone with the gravels. Furthermore, recycled aggregates exposed to microwaves can significantly increase other properties. The Pilot microwave heating system is shown in Figure 3. Unlike conventional heating method, microwave-assisted method needs lower temperature, less energy and shorter duration which would eliminate degradation of recycled aggregates during processing as well as the potential durability concerns. According to experimental studies[4], concrete prepared with microwave-treated recycled aggregates can significantly enhance the mechanical properties such as the compressive and flexural strengths and modulus of elasticity.

3. Chemical Technology
Chemical technology is mainly about recycled aggregates’ treatment of immersing (soaking) and drying by using specific chemical grout which will cohere or fill the micro-cracks or micro-pores in recycled aggregates, this technology achieves the purpose of modification by changing the chemical composition of recycled aggregates’ surface and makes them denser or improves their strength[5].

The available chemical grout can be listed as follows:

3.1. Polymer Emulsion
Polymer emulsion solution can be used to improve the properties of recycled aggregates, especially recycled fine aggregates. The tests of mortar blocks made of recycled fine aggregates after the modification of polymer emulsion solution showed that: the flexural strength improved obviously, while the compressive strength has little improvement[6].

Yang studied the strengthening of recycled aggregates by using cement grout with different kinds of high activated superfine mineral additives[7], the result is listed in Table 1. Compare the results of
physical properties before and after strengthening, so were the mechanical results of recycled concrete made of modified recycled aggregates. Although the amounts of additives, mix proportions, and any other environmental conditions in these two experiments have some variations, they can still imply the strengthening degrees of the mixed grout.

### Table 1. Experimental results of different polymer emulsion

| Chemical grouts                      | Physical properties of RA | Mechanical properties of recycled concrete |
|--------------------------------------|---------------------------|--------------------------------------------|
|                                      | Water content /%          | Water absorption rates /%                  | Apparent density /(kg/m³) | Crushing index value /% | 28d compressive strength (MPa) | Growth rate of strength /% |
|--------------------------------------|---------------------------|--------------------------------------------|---------------------------|------------------------|--------------------------------|----------------------------|
| untreated                            | 2.58                      | 6.77                                      | 2470                      | 16.73                  | 30.78                         | 0                          |
| Neat cement grout                    | 3.37                      | 6.93                                      | 2580                      | 13.24                  | 31.10                         | 1.04                       |
| Cement grout with additive slag      | 3.78                      | 7.51                                      | 2570                      | 13.12                  | 33.08                         | 7.47                       |
| Cement grout with additive diatomite | 2.71                      | 7.13                                      | 2523                      | 12.11                  | 36.39                         | 18.23                      |
| Cement grout with additive silica fume | 2.79                    | 7.43                                      | 2534                      | 12.80                  | 35.72                         | 16.05                      |
| Polymer emulsion solution            | 2.63                      | 6.34                                      | 2500                      | 11.80                  | 37.58                         | 22.09                      |

3.2. **Polymer emulsion and cementitious grouts**

For modification of recycled aggregates, activators have similar function and mechanism to mixed cement grout. Immersing the recycled aggregates with inorganic composite alkaline activator and organic compound acid ester activator respectively, the test results are shown in Table 5[8].

### Table 2. Experimental results of different activator

| Aggregates                             | Water absorption rates /%  | Crushing index value /% | Apparent density /(kg/m³) |
|----------------------------------------|---------------------------|-------------------------|---------------------------|
|                                        | 10min                     | 1h                      | 24.1                      | 2269                     |
| Untreated                              | 3.80                      | 6.25                    |                           |                         |
| Inorganic impregnating solution        | 2.60                      | 5.42                    | 18.9                      | 2290                     |
| Organic impregnating solution          | 3.50                      | 5.73                    | 22.5                      | 2289                     |

When considering the water absorption rate, crushing value, apparent density and other indicators, the properties of recycled aggregates with inorganic impregnating solution are slightly better than those with organic impregnating solution. The different performance indicators of recycled aggregates, when treated with organic impregnating solution, won’t increase obviously.

### 4. Carbonation Technology

Carbonation will contribute to volume change, normally because the precipitation of CaCO3 mainly fill empty spaces in the capillary pores and cracks, thus leading to the reduction of porosity in the cement paste. Meanwhile, both the densification and strength will be improved. This is really a theoretically feasible technology for recycled aggregates’ modification. The carbonation mechanism is shown in Figure 4.
Kou[9] chooses recycled mortar aggregates (RMA) to illustrate the relevant carbonation problems. RMA1 and RMA2, with sand to cement ratios of 3.0 and 2.5, and water to cement ratios of 0.55 and 0.45, respectively. And their carbonated counterparts are CI-RMA1 and CI-RMA2, respectively. Carbonation test is conducted in a steel airtight container with a CO2 concentration higher than 99%. The physical properties of aggregates are shown in Table 3. After carbonation, each type of RMA was used to prepare recycled concrete, which will be tested for subsequent durability properties, such as compressive and tensile splitting strength, slump, drying shrinkage and chloride penetrability.

**Table 3. Physical properties of aggregates**

| Property               | Particle size (mm) | Aggregate type | Density (Kg/m³) | Water absorption (%) | 10% Fine value (KN) |
|------------------------|-------------------|----------------|------------------|----------------------|--------------------|
|                        | Natural granite   | RMA1           | RMA2             | CI-RMA1              | CI-RMA2            |
| Density (Kg/m³)        | 20                | 6260           | 2326             | 2355                 | 2345               | 2371               |
|                        | 10                | 6260           | 2326             | 2355                 | 2351               | 2379               |
| Water absorption (%)   | 20                | 0.89           | 11.82            | 9.30                 | 7.32               | 4.84               |
|                        | 10                | 0.87           | 12.25            | 10.81                | 7.57               | 4.95               |
| 10% Fine value (KN)    | 14                | 156            | 96               | 116                  | 108                | 134                |

The test results of the properties of different aggregates such as density, water absorption and 10% fine value are shown in Figure 5. It was found that the properties of carbonated RMA improved compared with uncarbonated ones, but still lower than Natural granite’s. And it also concluded that 24 h CO2 treatment was optimum.

**Figure 4.** Schematic diagram of carbonation mechanism

**Figure 5.** Development of compressive strength of concrete
The development of compressive strength of different concrete according to curing time is presented in Figure 5. Although the compressive strength of concrete prepared with RMA, carbonated or not, was still lower than that of control concrete at all tested ages, both the CI-RMA1 and CIRMA2 improved the compressive strength of the concrete significantly. At 90 days, the compressive strength of concrete made with CI-RMA2 was only 1% lower than that of control concrete. Besides, there is also an improvement in the resistance to chloride ion penetration for the concrete prepared with CI-RMA, and the drying shrinkage was decreased. Generally, carbonation is applicable for the modification of recycled aggregates.

5. NanoTechnology

Just as improving the performance of concrete, nanomaterials are also being used to enhance the performance of RAC. Compared with other methods, nanomaterials have unique advantages to improve the performance of RAC.

Zhang et al. [10] apply surface treatment to recycled aggregate (RA) by two slurries containing nanomaterials. The new ITZs in RAC containing RAs surface treated by either of the two Nano slurries (the Nano-silica + nCa slurry or the Cement + Nano-silica slurry) were significantly enhanced. And the slump of fresh RAC, compressive strength and resistance to chloride diffusion was improved. The width and elastic modulus of the old ITZs in RAC did not develop as time passed, regardless of surface treatment on RA using nanomaterials, mainly because few unhydrated cement particles existed in the old ITZs and nanomaterials were not able to penetrate into the old ITZs. Maybe this phenomenon could be improved by increasing the processing time. Zhang et al. [11] discussed the modification effects of a Nano-silica slurry on microstructure, strength, and strain development of RAC applied in an enlarged structural test. Together with NAC, non-modified and modified RAC were applied in three beams in a real project. It is verified that beneficial effects of the employed nano-slurry on both the mechanical properties of MRAC material, and the deformability against shrinkage and loads of MRAC applied in reinforced beams in a real project. The nano-silica slurry employed in this study have improved the properties of MRAC’s new ITZs between the old and new cement mortars, while the old ITZs between the virgin aggregate are not enhanced.

6. Conclusions

This paper has presented a critical review of existing and ongoing research on the modification of recycled aggregate. This review allows a number of significant conclusions to be drawn as follows:

1) Physical technology: with the help of the mechanical forces to remove the adhering cement pastes, then the ultimate recycled aggregates have high purity of gravels. However, this technology consumes more energy and resources, demands complicated equipments which tend to wear more serious, thus resulting in high cost. Therefore, physical technology is not suitable for long-term performance. Even so, the current recycled aggregates modification is mainly about physical technology.

2) Chemical technology: using chemical grout soaking to improve the performance of the adhering mortar in place of removing it. Although this technology has the advantage of convenient production process, considering the possible subsequent chemical reaction and the influence on the ultimate concrete strength or durability, this technology is still in the evaluation and discussion without been applied to engineering practice.

3) Carbonation technology: this technology has some commons with chemical technology based on the strengthening of cement pastes. Carbonization technology has the simple processes and environmental friendly advantages, but considering the cost of industrial carbon dioxide collection and carbonization room or conditions, there is a lot of subsequent research work to be done.

4) Nano technology: nanomaterials can reduce the amount of cement content, improve the mechanical durable properties of recycled concrete especially at early age. These are based on the optimization of nanomaterials for microscopic structures and the promotion of hydration reactions. But at the same time, nanomaterials are prone to agglomerate that difficult to be stirred evenly, dispersion is not good and easy to reunite. the workability of RAC is affected largely.
For the modification of RA, we should not confine in physical and mechanical properties or any other short-term researches. When taking account of recycled concrete’s long-term serviceability, it’s indispensable for us to conduct deep researches on strength stability and durability. Compared with natural concrete, RAC is superior to environmental value in the reduction of CO2 emission in Life Cycle Assessment[12]. Besides, the available equipment, recycling utilization rates and costs of recycled aggregates’ demolition and production should be evaluated. All these work also need to be incorporated with national conditions.

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References
[1] Silva R V., De Brito J and Dhir R K 2014 Properties and composition of recycled aggregates from construction and demolition waste suitable for concrete production Constr. Build. Mater. 65 201–17
[2] Chong H U and An T I 2006 Strengthening technique of recycled concrete aggregate 2006 74–7
[3] Jianbo Zhang, Yongsheng Wu 2010 Study on the strengthening of recycled aggregate China Resour. Compr. Util. 28 58–60
[4] Akbarnezhad A, Ong K C G, Zhang M H, Tam C T and Foo T W J 2011 Microwave-assisted beneficiation of recycled concrete aggregates Constr. Build. Mater. 25 3469–79
[5] Li J, Xiao H and Zhou Y 2009 Influence of coating recycled aggregate surface with pozzolanic powder on properties of recycled aggregate concrete Constr. Build. Mater. 23 1287–91
[6] Kou S C and Poon C S 2010 Properties of concrete prepared with PVA-impregnated recycled concrete aggregates Cem. Concr. Compos. 32 649–54
[7] Meixia ZHAO N Y W 2011 Research on intensifying technique of recycled aggregate New Build. Mater.
[8] Xuemei Wu , Yaobing Gao & J Y 2009 Experiment of recycled concrete made of recycled aggregates modified by soaking method Henan Constr. Mater. 56–7
[9] Shi-Cong K, Bao-Jian Z and Chi-Sun P 2014 Use of a CO2 curing step to improve the properties of concrete prepared with recycled aggregates Cem. Concr. Compos. 45 22–8
[10] Zhang H, Zhao Y, Meng T and Shah S P 2015 Surface Treatment on Recycled Coarse Aggregates with Nanomaterials J. Mater. Civ. Eng. 28 04015094
[11] Zhang H, Zhao Y, Meng T and Shah S P 2015 The modification effects of a nano-silica slurry on microstructure, strength, and strain development of recycled aggregate concrete applied in an enlarged structural test Constr. Build. Mater. 95 721–35
[12] Xiao J, Li A and Ding T 2016 Life cycle assessment on CO2 emission for recycled aggregate concrete Dongnan Daxue Xuebao (Ziran Kexue Ban)/Journal Southeast Univ. (Natural Sci. Ed. 46 1088–92