Book Chapter Recycled Aggregate

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Quality Improvement of Recycled Aggregate using Thermal-Mechanical-Chemical Process

Introduction

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The demolition of concrete structures produces a large amount of waste. It leads to a potential problem of the landfill in the near future because more aged concrete structures need to be demolished [1]. The waste is also generated from the construction process. The construction sector in Europe generates 50% of the waste originating from the construction and demolition waste (CDW) of all total waste. Until now, concrete and mortar are the most popular materials in the construction world. In addition, for every ton of material mined, on average more than 85% is wasted [2]. CDW has become one of the major problems in the construction industry as it directly impacts the environment. It is estimated that around 35% of CDW ends up in landfills globally; therefore, an effective CDW process is required to minimize the environmental's negative impacts [3]. This issue has been a concern in the development of a national policy worldwide to prevent large landfills by a regulating measure to enhance recycling and recovery [2] Especially in developing countries, more actual efforts are on demands even there is a national waste regulation; however, the implementation in the local level is a shortage [4].

Another critical issue regarding the use of concrete is the depletion of fresh natural aggregate as one of the primary materials in concrete manufacturing. Despite the truth is that there are still plentiful natural resources available for the supply of the construction industry; however, attention should be paid to the long-term negative environmental impacts caused by the extraction of non-renewable raw materials. In addition, the process includes extensive deforestation, topsoil abrasion, air and water pollution [5]. Materials are taken and produced from a considerable distance from where the project site is built. In addition to the extraction time, which harms the environment, transporting materials from the production site to the project site also affects the environment because transportation requires fuel and contributes pollutants to the air. In addition, natural aggregates require a very long time to form. If the level of uptake is very high, the level of availability will be lower and depleted [6]–[8].

Furthermore, concrete as a construction material affects global warming by adding CO_2 to the air. All these processes not only cause material extinction, environmental damage, emissions to the air but also will indirectly have an impact on human health. Thus, alternative materials that are more environmentally friendly and sustainable are urgently needed at this time [6]–[8].

Using recycled aggregate is an example of efforts to solve the problem [9][10][11]. For this purpose, several criteria have been studied [12]. In addition, recycling materials from demolished building waste is an alternative to reduce the exploitation of depleted natural aggregates and overcome environmental problems due to landfills. In addition, this solution provides economic benefits. Rapid infrastructure development demands many construction materials. Recycled aggregate can be obtained quickly from CDW and post-disaster building debris. Some countries already have regulations in using recycled aggregate as a construction material. Aggregate recycling centers around major cities have been established. To reduce transportation costs, mobile crushing installations are also used [9], [13], [14].

However, another problem has been arisen in using recycled aggregate concrete. As reported by [15], [16], the conventional recycled aggregate concrete has about 20-26% lower compressive strength than concrete with natural aggregate. In addition, according to the series of tests, it shows that the mechanical behavior of concrete made from natural aggregates is still superior to that of concrete using recycled aggregate [17], [18]. Recycled aggregate, produced only by crushing concrete waste in smaller sizes according to the size of coarse aggregate or fine aggregate, cannot have the same quality as natural aggregate. This recycled aggregate has the property of water absorption and low density. This is due to the presence of old mortar content on the surface of the recycled aggregate.

Furthermore, the examination of the recycled aggregate has been extended to the microstructures of interfacial transition zone. It is revealed that due to the existence of old mortar, recycled aggregate shows a higher porosity and lower solid profile compared to the new aggregate, leads to lower mechanical properties of recycled aggregate concrete [19]. Thus the surface of the recycled aggregate must be clear from the old mortar so that the quality increases; as a result, the concrete produced with recycled aggregate can also increase its quality. Therefore, the study on improving the quality of recycled aggregate is on-demand worldwide.

To separate the old mortar on the aggregate surface, several studies have been carried out. Pulsed power technology has been applied to produce high-quality aggregates [20]–[22]. The Marx generator was used as a source of pulsed power. Several parameters such as the number of discharges, the amount of voltage, and the discharge medium were studied to produce the optimum quality [20]. An effort to remove old mortar, pre-soaking in chemical solution was carried out in [23]. Recycled aggregate was pre-soaked in a solution of HCL, H_2SO_4, and H_3PO_4 with a concentration of 0.1 mol for 24 hours. After that, it was continuously immersed in distilled water for 24 hours. There has been an improvement in the quality of both RAC and concrete made with RAC. Pre-soaking with chemical solutions can accommodate remove residual mortal without hazarding the quality of the recycled aggregate.

With the purpose of reducing the amount of old mortar in the surface of recycled aggregates, an autogenous cleaning process was introduced. The concrete produced from this kind of recycled aggregate reached the compressive strength where a slight reduction was about 8.9% compared to natural aggregate concrete [24]. Similarly, the improved quality of recycled aggregate concrete has been reviewed by two approaches: treatment methods to improve recycled aggregate quality and strengthen the old mortar. The first method was implemented by removing the attached mortar, and the second method was conducted by adding pozzolan or emulsion polymer to fill the microcracks and surface coating [25] or improving the mixing process [26].

A combination of thermal-mechanical-chemical processes has been proposed to produce a higher quality of recycled coarse aggregate (RCA) [27], [28]. The treatment process is continuously carried out sequentially to obtain a better quality of RCA. This process is quite capable of producing RCA with better quality than the RCA obtained by the conventional methods [15]. The process consists of the heating process followed by the grinding process and the last process of soaking with chemical solutions. The treatment process does not require high-power equipment. Therefore, it is suitable for application in developing countries.

RCA Production

According to [29], when concrete material is exposed to the temperature of 200 degrees Celsius, the excess water lies in microstructures, mostly in the boundary between cement paste and aggregate is exploded due to pores hydro-pressure. The explosion weakens the bond between two materials and leads to delamination. This mechanism is adopted to weaken the bond between the aggregate surface and mortar. Then, the grinding process is required of the separation more effectively achieved by rubbing either among the aggregate surfaces or between iron balls provided during the grinding process with the aggregate surfaces. Soaking the product in an acid solution helps the cleaning of old mortar continuously [23]. **Figure 1** explains the recycling process of thermal (heating), mechanical (grinding), and chemical (acid solution soaking) to reduce the amount of old mortar in the aggregate surface.

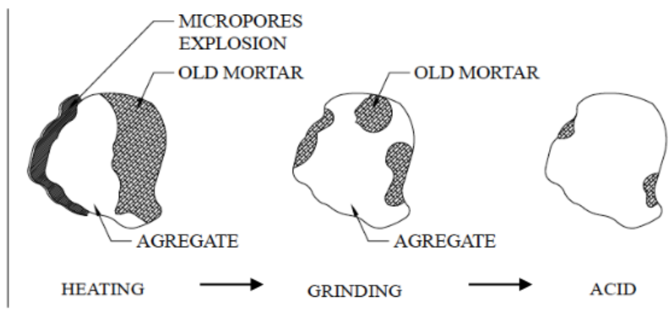

Figure 1. RCA Production Process

Thermal-Mechanical Process

The first combination is thermal-mechanical by heating and grinding process. Lumped concrete waste was prepared with the size around 10-20 cm in diameter. The concrete lumped was put into the oven and heated at a temperature up to 100 degrees Celsius for 24 hours. The heated lumped concrete directly was brought to a grinding machine for a number of 500 cycling processes. The rubbing process was provided the rotation of the machine and the impact of the iron balls inside the machine. This type is regarded as heating-grinding recycled coarse aggregate (HG RCA).

Thermal-Mechanical-Chemical Process

Meanwhile, the second is a combination of thermal-mechanical-acid by heating, grinding, and soaking process. The first of two processes mentioned earlier in HG RCA are the same, and it is continued by soaking the product in an acid solvent, sulfuric acid (H_2SO_4), for 24 hours. Sulfuric acid helps release the attached mortar around the aggregate surface by converting it into a water-soluble coagulant. This type is regarded as heating-grinding-acid recycled coarse aggregate (HGA RCA).

Physical Properties of Recycled Aggregate

According to visual examination as presented in **Figure 2**, generally, in most aggregate parts, both HG RCA and HGA RCA surfaces are clean from the old mortar. Although the old mortar has separated from the aggregate surface, the figures show the difference in the surface of the RCA covered with the mortar. The appearance of HGA RCA is a slight cleaner from cement paste than the appearance of HG RCA. Soaking in chemical solutions causes detachment of cement paste more effectively so that the HGA RCA possesses cleaner surfaces.

For further investigation, the quality of RCA includes density, water absorption, fineness modulus, and sieve analysis are examined. Almost similar properties are obtained compared to normal coarse aggregate, indicating the improved quality of the recycled aggregate. **Figure 3** shows the physical properties of recycled coarse aggregate along with normal coarse aggregate as a comparison.

Figure 2. Recycled Coarse Aggregate [27]

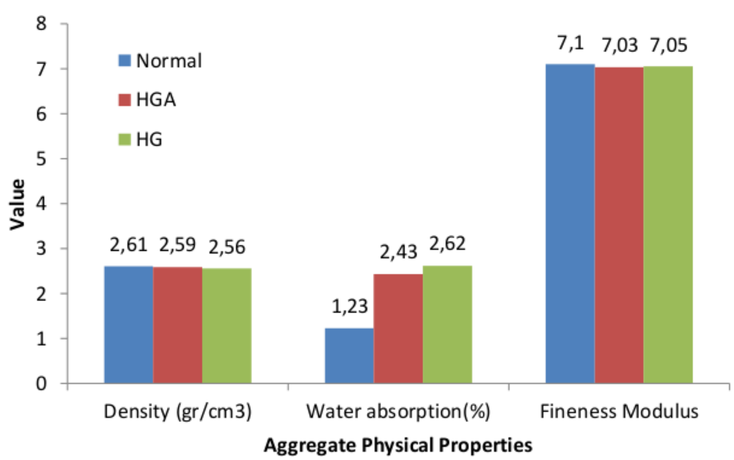

Figure 3. Aggregate Physical Properties

Mechanical Properties of RCA Concrete

New concrete production using two types of recycled coarse aggregate were conducted. Additionally, normal fresh coarse aggregate concrete was also produced. The water-cement ratio was kept at 48%. Specimens were cylinder concrete. The mixture proportion is shown in **Table 1**.

Table 1. Mixture proportion of concrete in 1 m^3 [27]

Concrete type	Concrete components (kg)			
	Cement	Water	Sand	Gravel
Normal coarse aggregate concrete	427	205	675	1013
HG recycled coarse aggregate concrete	427	205	667	1001
HGA recycled coarse aggregate concrete	427	205	671	1007

The mechanical properties of recycled aggregate concrete were obtained by subjected the concrete to compression, splitting-tensile, and flexure load. The value of compressive strength, modulus of elasticity, splitting-tensile strength, and flexure strength of RCA concrete, along with those of normal concrete are presented in **Table 2**. Generally, the mechanical properties of normal aggregate concrete are slightly higher than those of both types of RCA concrete. Furthermore, HGA RCA concrete retains better mechanical properties than those of HG RCA concrete. A different value on mechanical properties of two types of RCA is caused by their different quality. The continuous treatment process by immersing in acid solution further enhances the mechanical properties of HGA concrete. However, mechanical properties improvement is not significantly different between the two types of RCA; therefore, either HG RCA or HGA RCA is potential to utilize concrete making.

Table 2. Mechanical Properties of Concrete [27]

The Average of Mechanical Properties (MPa)	NCA Concrete	HGA Concrete	HG Concrete
Compressive Strength	41.77	39.79	39.32
Modulus of Elasticity	30280	29643	29472
Splitting-Tensile Strength	4.57	4.49	4.31
Flexure Strength	6.29	5.73	5.58

Surface Hardness of RCA Concrete

To ensure the surface hardness of concrete using RCA, the surface hardness test is carried out using the hammer test [30]. The surface hardness of the concrete is symbolized by the rebound number listed on the hammer after the test is carried out. The surface hardness of the concrete using normal aggregate is also used as a comparison. A total of 150 test points were carried out with the hammer test.

As illustrated **in Figure 4,** in terms of the average value of the rebound number, normal aggregate concrete reaches the highest value, followed by HGA RCA concrete, and the smallest is HG RCA concrete. The average rebound number of HGA RCA concrete is 8% smaller than the rebound number of normal aggregate concrete. At the same time, the rebound number of HG RCA concrete is 12% different from the rebound number of normal aggregate concrete. Between HGA RCA concrete and HGA RCA concrete, rebound numbers are not significantly different, only 4%. The surface hardness properties obtained from this rebound number are not only related to strength but also to the durability properties associated with abrasion resistance [31].

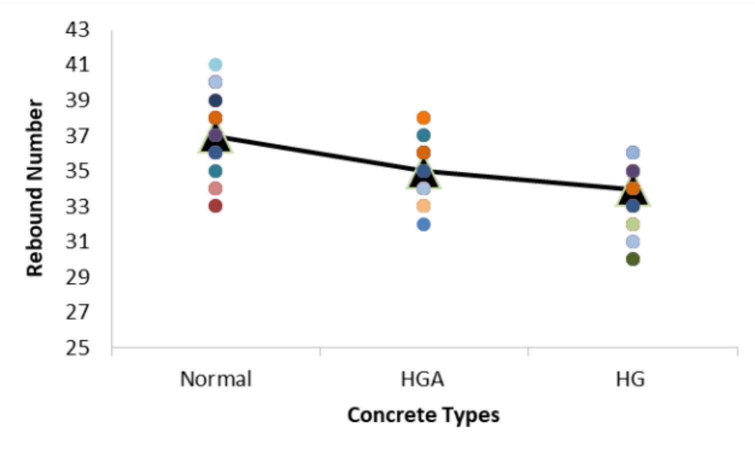

Figure 4. Average Rebound Number of NCA and RCA Concrete

Ultrasonic Wave Velocity of RCA Concrete

Ultrasonic wave velocity is measured on HGA RCA concrete and HG RCA concrete. Ultrasonic wave velocity in normal aggregate concrete was also measured. Regarding the average value in several tests, the highest velocity is seen in normal aggregate concrete of 4468.2 m/s. Compared to the velocity of normal aggregate concrete, the value in HGA RCA concrete is slightly lower, which is about 3% different. Even, in HG RCA concrete, this value is 8.5% smaller than the value in normal aggregate concrete. The velocity is not much different between HGA RCA and HG RCA concrete itself, which is around 5%, where HGA RCA concrete provides a higher velocity than HG RCA concrete. **Figure 5** presents an overview of the ultrasonic pulse velocity in normal and RCA concrete.

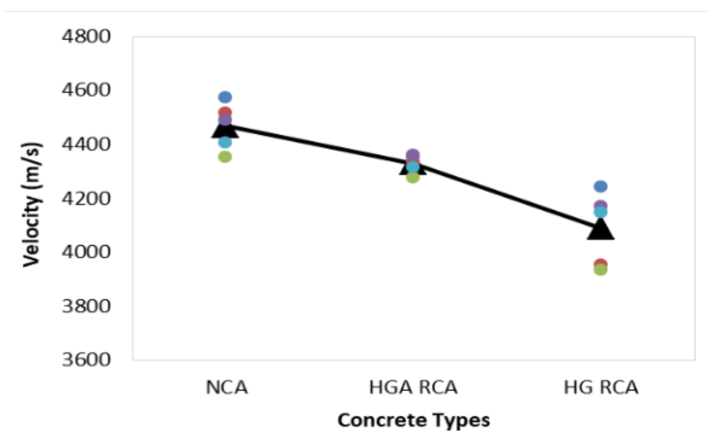

Figure 5. Ultrasonic Pulsed Velocity of Concrete

The velocity of ultrasonic waves can indicate the level of density in the concrete material. In concrete with good quality, the value of the wave propagation speed shows a more excellent value because of the denser characteristics of the concrete. On the other hand, low-strength concrete is usually porous so that the resulting wave velocity is lower [30]–[33]. The HGA RCA concrete velocity can show a slightly higher than the value of HG RCA concrete because fewer pores exist due to the better reduction of old mortar. Thus, it provides a better bond between the HGA RCA surface and the new cement paste in the interfacial transition zone.

Conclusion

Both HG and HGA RCA nearly have a similar quality to natural coarse aggregate in terms of density, water absorption, and sieve analysis. Furthermore, the mechanical properties, including the compressive strength, modulus of elasticity, splitting-tensile strength, and flexure strength of HG RCA concrete is presenting slightly less values than those of HGA RCA concrete. Similarly, HG RCA concrete's surface hardness and ultrasonic wave velocity are slightly smaller than those of HGA RCA concrete. The chemical process during HGA RCA production is making the process of removing the old cement paste from the aggregate surface more effectively than that of HG RCA; therefore, the HGA RCA presents better performances than those of HG RCA. More delamination of the attached mortar increases the bonding of the interfacial transition zone between the new cement paste and the recycled coarse aggregate surface. However, the properties between HG RCA concrete and HGA RCA concrete are not significantly different, even compared to those of NCA concrete. Thus both types can be potentially used as construction materials in the near future.

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