Development of Complete Processing Circuit for Waste Concrete Recycling

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Abstract: Management of construction waste is big challenge to solve resource exhaustion and environmental pollution. Currently, waste concrete major portion of construction waste is simply crushed and used as a low application such as paving materials, back filling, etc. To meet the demand of recycled aggregate specification for higher value application and to reuse cement material which is by-product of crushing stage, the advanced processing circuit is needed. In this study, complete recycling processing circuit of waste concrete was developed to recycle all the materials from waste concrete. To enhance liberation between aggregate and cement mortar and to produce high quality recycled aggregate for concrete making, autogenous milling and heat pretreatment were used in crushing stage. After 10 minute breakage process, high quality recycled coarse aggregate was produced. The fine size fractions were further separated using a hindered-settling column into two products 1) underflow, 2) overflow. The underflow sample was a high quality fine recycled aggregate which can be used for concrete making, and the overflow sample was an enriched cement material can be also used for CO₂ sequestration by mineral carbonation. As a result, all the material from waste concrete can be reused for resource circulation by developed complete recycling circuit.

Key words: Waste concrete, Recycled aggregate, Hindered settling, Carbonation, Autogenous mill

1 Introduction

Recently, the importance of resource recycling is gaining a great interest due to the resource exhaustion, environmental pollution, and increasing price of natural resource. The recycling in waste management has been encouraged for many decades, and is considered essential treatment method now. It is beneficial for not only the management of waste, but also the reducing of consumption of natural resources and huge energy consumption to treat of natural resource.

The construction and demolition waste comprises the major industrial waste generated in Korea. According to the ministry of environment, 62 million tons of construction waste were generated in 2007[1], and is projected to increase to over 300 million tons in 2020, as many buildings reach the end of their 30 years life. Among total waste, the proportion of concrete waste was about 30% in Korea. Due to its large volume, recycling of concrete waste is the most important aspect of the waste management.

Generally, the waste concrete is reused as a recycled aggregate after crushing process. This method has some merits not only management of construction waste but also resolution of unbalanced natural aggregate problem. Currently, there are about two hundreds waste concrete processing plants producing recycled aggregate in Korea. Almost all of the circuit is consisted of several stage of crushing steps primarily with jaw crusher and simple separation process to remove foreign material. The recycled aggregate from these current circuits has a low quality and most of them are down cycled for usage as paving material, back-filling material, concrete bricks, etc. It cannot be reused for replacement of natural aggregates because cement mortar is not separated perfectly from aggregates. These kinds of recycled aggregates tent to be weaker, more porous and have a higher value of water absorption. When these aggregates are used in concrete making, there are problems of higher total water demand, low compressive strength and durability [2-3]. And recycled fine aggregate by-product of breakage process is not almost recycled due to its low quality.

In this study, a new processing circuit is developed for complete recycling of all the materials produced from waste concrete. From the waste concrete, high quality recycled coarse/fine aggregate for concrete making and purified cement materials can be produced. The autogenous milling and heat pretreatment method were used to enhance liberation between aggregate and cement mortar. And purification process for fine aggregate and cement material was conducted using hindered settling column separation. Finally, refined cement material was reused for carbonation process to restore CO₂ and to produce calcium carbonate by indirect method.
2 Materials and Methods

2.1 Samples
The waste concrete sample used in this study was a product of a primary jaw crusher product installed at the waste concrete processing circuit in Korea. Currently, construction and demolition waste are discharged with many foreign materials. So, foreign materials such as wood waste, asphalts waste, and blocks should be separated before breakage process to breakage pure waste concrete. The separated waste concrete samples were dried and sieved into various size fractions of \( \sqrt{2} \) series from the maximum size of 150mm.

2.2 Thermal pretreatment
To enhance the liberation between aggregate and cement mortar in waste concrete, thermal pretreatment was performed before breakage process. When the concrete was heated, the bonding strength at the grain boundary between aggregate and cement mortar is weakened. It is because that there is a difference of thermal expansion coefficient between two materials. The thermal expansion coefficient of aggregate (5~13 x \( 10^{-6} \)) is smaller than one of cement mortar (11~20 x \( 10^{-6} \)). So the crack can be developed at the grain boundary after thermal pretreatment, and the possibility of preferential breakage along the grain boundary increase [4]. In this study, heat pretreatment was conducted in an oven for 1 hour at 400 \( ^\circ \)C.

2.3 Breakage process for recovery of high quality recycled aggregate
In breakage process, an autogenous mill was used for recovery of high quality recycled aggregate. An autogenous milling uses a cylindrical-shape mill chamber like a ball mill, and the breakage process occurs by rotating the mill chamber. The major difference between autogenous mill and ball mill is the grinding media. In ball mills, the charge comprises a large volume of steel balls. In autogenous mills, the grinding medium comprises lumps of the ore being ground. It is generally regarded that two mechanisms operate within autogenous mills; impact (gentle breakage), and abrasion/attrition. Generally, it is known that preferential breakage can be occurred between two other materials by gentle breakage [5]. In autogenous mill, a rotating drum throws large rocks in a cataracting motion which causes impact breakage of larger rocks and compressive grinding of finer particles. The impact energy that the particle receives is relatively low compared to compressive forces exerted by crusher. Therefore, the specific energy that particles receive may not be sufficient enough to propagate cracks through aggregates in concrete blocks, but along the boundaries between the cement paste and aggregates, especially when the bonding strength between them is weakened by heating.

Abrasion and attrition, another breakage mechanism, result from the scraping of one surface on another against a rigid face of particle against particle, leaving the parent particles largely intact. So the cement mortar attached to aggregate surface can be easily removed by this breakage mechanism in autogenous milling. Therefore high quality recycled aggregate can be produced from waste concrete crushed using the autogenous mill due to the enhancement of liberation between aggregate and cement mortar by abrasion and preferential breakage along the boundaries between the cement mortar and aggregates.

The autogenous mill used in this study has a mill chamber with a diameter of 2,000mm and a length of 800mm and has a 2 lifter inside the mill chamber. The rotation speed is fixed at 20rpm which is a 70% of critical speed of mill chamber and the percentage of mill volume occupied by the sample is 10%, which is about 300kg.

2.4 Purification process of waste concrete fines
The waste concrete fine (4.75mm) produced from breakage process is consisted of fine aggregate and cement materials. To enhance the quality of each material for recycling, purification process is needed. Because two materials have different particle size and density, hindered settling separation process was conducted for purification.

The column used in this study was fabricated using 152.4 mm inner diameter and 1,240 mm height acrylic pipe. The hindered-settling separation system consists of a volumetric feeder, pressure gauge, pinch valve and control panel. Pressure gauge measures the pressure inside the column, which is displayed as a relative pressure value, i.e. set point. The set point is defined as the relative value that represents the total pressure of the inside of the column. At the bottom of the column, teeter water is injected, and samples are fed at the top of the column by volumetric feeder. In the column materials are separated by upward water velocity and their settling velocities decided by their sizes and densities. To investigate the effect of the teeter water flow rate, 9.46 L/min, 11.35 L/min, and 13.25 L/min of flow rate were used with a fixed set point at 15, a feed rate at 550g/min, a feed water flow rate at 7.57 L/min. The underflow and the overflow samples were collected when a steady-state is reached and were analyzed for weight and size distribution and other physical properties.

2.5 Carbonation process using purified waste cement fines
The purified cement material which is an overflow sample from hindered settling separation process was recycled for carbonation process to restore CO₂. The particle size of purified cement material used this process is smaller than 0.075mm (200mesh), and XRF(Shimadzu, XRF-1700) and XRD (Bruker, XRD-D5005) analysis were conducted.

In this study, the indirect method was used for carbonation process. In indirect carbonation process (Fig. 1), an acid is used to extract Ca²⁺ ion from cement material. And then carbonation process is preceded by injecting CO₂ gas. After reaction process between Ca²⁺ ion and injected CO₂ gas, produced CaCO₃ is precipitated. The hydrochloric acid and acetic acid were used to investigate the extraction efficiency as a function of acid type. After mixing 15g cement particle and 300ml distilled water, the pH of solution was controlled by 1N acid. The solution was sampled at regular time to analyze the content of extracted ion using ICPS spectrometer (Shimadzu, ICPS-1000). The residual solid material was also analyzed for residual ion content.

At acidic condition, the carbonation process was not preceded, because the injected CO₂ form cannot react with extracted Ca²⁺ ion. So pH of solution raised using 1N NaOH for carbonation process. The 1ml/min. of CO₂ was injected into solution, and XRD analysis was conducted to analyze element of precipitated solid material.

3. Results and discussion

3.1 Breakage process for recovery of high quality recycled aggregate

Fig. 2 shows the breakage result during 10 minute using autogenous mill as a function of pretreatment method. As it can be seen Fig. 2, crushed particles can be divided into three groups. One is the waste concrete fines (-4.75mm), other is the recycled coarse aggregate (4.75 x 40mm) which has the same particle size as natural aggregate, and another is uncrushed waste concrete lump (+40mm). These three groups of particle can be easily separated by simple screening. This phenomenon is appeared at both pretreatment methods. However, the breakage efficiency was different as a function of pretreatment method. The ratio of uncrushed particle of heat treated sample is much less than no treated sample.
degree of breakage increased as impact energy accumulated during breakage process. However, in case of concrete waste without any treatment, the strength of concrete waste is maintained and the impact energy caused by autogenous mill is not sufficient to break the samples additionally when a certain degree of breakage is exceeded.

The effect of heat pretreatment can be also confirmed by the recovery ratio of recycled aggregate. The mass ratio of coarse size recycled aggregate (37.4mm x 4.75mm) was about 25% in case of heat treated sample, but only 12% was recovered in case of sample without any treatment. And the fine particle recovery ratio of heat treated sample was also 2 times more than fine particle recovery ratio of sample without any treatment.

To evaluate physical characteristics of coarse size recycled aggregate, the crushed products were sieved into the size fractions of √2 series. The density and water absorption of each size fraction was determined according to the Korea Standard (KS F 2503). Fig. 4 shows the water absorption (%) of each size interval and 1st grade recycled coarse aggregate standard (below 3%). Except recycled aggregate produced from heat treated 5 minute crushing, almost all the larger size fractions were satisfied with the 1st grade specifications for concrete making. Therefore high quality recycled coarse aggregate can be produced from pilot scale autogenous milling test after 10 minutes of breakage time.

3.2 Purification of waste concrete fine using hindered settling column

The hindered settling column separation process was conducted to separate recycled fine aggregate and cement particle from the crushed waste concrete fines (-4.75mm). As mentioned earlier, the teeter water speed which is a major parameter to decide separation range was changed with fixed feed rate and set point. A heavier and larger particle can be separated as teeter water speed increased. After steady-state was reached at each experiment condition, an underflow sample and an overflow sample were collected and analyzed for the physical characteristics and the size distributions.

The mass ratio of overflow and underflow sample is 3:7. The major chemical composition of separated materials is shown in Table 1. The main difference between underflow and overflow composition is SiO₂ and CaO. In underflow sample, the ratio of SiO₂ is bigger than overflow sample. However the CaO is mainly concentrated on the overflow sample. This means that fine aggregate was concentrated at underflow sample, and cement material was mainly distributed at overflow sample. Therefore, separation between fine aggregate and cement material can be achieved by hindered settling separation process.

As shown in Fig. 5-(a), as teeter water flow rate increased, the properties of underflow sample were enhanced, satisfying the 1st grade standard when the teeter waster flow rate was larger than 10L/min for the heat treated sample. The cumulative size distribution of the underflow material also satisfied the particle size standard of recycled fine aggregate for the concrete making.
making (Fig. 5-(b)). Therefore, the high quality fine size recycled aggregate could be produced from the hindered-settling separation process by removal of cement material. Moreover, the overflow material was enriched with the cement material and it could be reused for other process such as CO₂ sequestration by mineral carbonation.

3.3. Carbonation process to recycle purified cement material

For complete recycling of waste concrete, purified waste cement material from hindered settling separation was reused. The waste cement material can be directly reused for cement industry. Also it can be reused for carbonation process like MSWI (Municipal Solid Waste Incineration) bottom ash or steel slag to restore CO₂ gas, because it has a high content of Ca [6].

To investigate of extraction characteristics of Ca²⁺ ion as a function of acid type, the amount of extracted Ca²⁺ was analyzed at 5, 10, 15, and 30 minute using hydrochloric acid and acetic acid. The amount of extracted Ca²⁺ ion increased as extraction time increased until 15 minute. After 15 minute, the amount of extraction Ca²⁺ was almost the same. This trend was identical in case of acetic acid (Fig. 6). However, the optimum pH of each acid for maximum amount of Ca²⁺ (pH 2.5 in HCl, pH 4.5 in CH₃COOH) was different due to the dissociation constant of acid.

(a) 1.0N HCl at 25 °C for 30min.

(b) 1.0N CH₃COOH at 25 °C for 30min.

(b) Cumulative size distribution

Fig. 5 Physical characteristics of separated materials

The amount of extracted Ca²⁺ ion and purity is shown
in Table 2. Generally, strong acid can extract more ions than weak acid. But in this study, acetic acid extracted 3-4 times more ions than hydrochloric acid. The earlier stage of extraction process, extracted ions make a layer on the particle surface, and it prevents additional extraction reaction. Because it is formed quickly when strong acid is used, total amount of extraction ions is more in acetic acid [7]. In consideration of amount of extraction Ca$^{2+}$ ions and purity, pH 4.5 is optimum at both acids.

<table>
<thead>
<tr>
<th>pH</th>
<th>Extraction by HCl ($\text{Ca}^{2+}$ UG/ml)</th>
<th>Extraction by CH$_3$COOH ($\text{Ca}^{2+}$ UG/ml)</th>
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<tr>
<td>5.5</td>
<td>2492.1</td>
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<td>4.5</td>
<td>3270.82</td>
<td>12377.90</td>
</tr>
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<td>4552.34</td>
<td>10322.30</td>
</tr>
<tr>
<td>2.5</td>
<td>4613.04</td>
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4. Conclusion

To complete recycling all the materials from waste concrete, a new waste concrete processing circuit was developed (Fig. 8). An autogenous milling and heat pretreatment method were used to recover the critical point of conventional crushing stage for producing high quality recycled aggregate. Using a hindered settling column, recycled fine aggregate and cement material were refined. And purified cement material was used for carbonation process to restore CO$_2$ and to produce calcium carbonate. If 1 ton of waste concrete was handled using developed circuit in this study, 250kg of high quality recycled coarse aggregate, 200kg of high quality recycled fine aggregate, and 100kg of calcium carbonate can be produced. Moreover, two million tons of CO$_2$ can be restored annually if forty million tons of waste concrete was processed by developed circuit.

After carbonation process by injecting CO$_2$ gas, the precipitated solid was analyzed (Fig. 7). When hydrochloric acid is used, white colored calcium carbonate was formed, and it is a uniform cubic shape of 3. On the other hands, brown colored irregular shape calcium carbonate was formed by acetic acid.

Fig. 7 Photograph and FE-SEM image of precipitated solid after carbonation process

References: