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Technical Paper

Quality improvement of recycled concrete aggregate by a large-scale tube mill with steel rod

Lapyote Prasittisopin*, Chawis Thongyothee, Phattarakamon Chaiyapoom and Chalermwut Snguanyat

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Abstract: Research has been reported on using a steel rod in the rotary or ball mill resulting in an increase of grinding efficiency of recycled concrete aggregate (RCA). Information of the process and steel rod parameters is explored in large-scale production. In particular, energy consumption used during grinding RCA in laboratory can be misled unless the large-scale grinding production is operated. This study aims to investigate process and steel rod parameters on the performance characteristics of ground RCA (G-RCA) and its grinding energy efficiency of the large-scale rotary mill of the capacity of 500-liter per batch. The process and steel rod parameters investigated include revolution count (Rev), contacted surface area (S_a) between steel rod and RCA particle, and weight (W) of steel rod. The characteristics of the G-RCA include its gradation, yield retained on a 4.75-mm sieve, density, and water absorption. Results indicated that early grinding operation has greater efficiency to improve RCA quality and consumes less grinding energy than the later grinding operation. Grinding RCA at the Rev of 250 counts is sufficient to improve its quality for this tube mill. The grinding efficiency increased while grinding using the steel rods having higher S_a or smaller rod sizes.

Keywords: recycled concrete aggregate, tube mill, steel rod, revolution count, contacted surface area, mass.

1. Introduction

It is well known that concrete industry has a major contribution to the environment impoverishment. The concrete industry faces a challenge on aggregate shortage because of collective demand of aggregates used for making concrete, especially in the developed countries. Concrete manufacturing is notable for a massive consumption of natural aggregates (NA) and in many areas the NA becomes diminished. It brings about an idea of regeneration of alternative aggregates from concrete waste in demolition sites, which can be reused for building a new construction project. [1-6] The aggregate from concrete is referred to as recycled concrete aggregates (RCA). The regeneration of RCA not only mitigates the aggregate shortage challenge, but eliminates concrete waste from a construction site also. Unfortunately, because 98% of the RCA was reported in 2007 to be utilized for roadbed, the utilization of RCA was not efficient for making a more value-added product such as concrete. [7]

Although many construction projects allow using the RCA in concrete for replacing the NA, the utilization of RCA is still limited. Only partial replacement can be used for making fresh concrete. This is due to the lower concrete quality. The RCA that is regenerated from crushed concrete waste contains two components: aggregate component and residual mortar component. When the RCA is used to produce a concrete product, various performance characteristics of the RCA concrete are found to be lower than the NA concrete. [8-9] Kim et al. [10] reported that volume of the residual mortar in RCA directly affected the concrete compressive strength and modulus of elasticity. Fathifazl et al. [11] reported that creep and drying shrinkage characteristics were also influenced by the volume fraction of RCA and residual mortar volume. These were due to an increase of total mortar (fresh plus residual mortar) content of the RCA concrete than the NA concrete. The volume of residual mortar attached to RCA seems to be one of the main rea-

Corresponding author Lapyote Prasittisopin is a researcher at Siam Research and Innovation, SCG Cement -Building Materials, Thailand.
Chawis Thongyothee is a researcher at Siam Research and Innovation, SCG Cement -Building Materials, Thailand.
Phattarakamon Chaiyapoom is a researcher at Siam Research and Innovation, SCG Cement -Building Materials, Thailand.
Chalermwut Snguanyat is a group leader at Siam Research and Innovation, SCG Cement -Building Materials, Thailand.

sons for the inferior performance of the RCA concrete. Removing this RCA residual mortar can result in a quality enhancement of concrete performance.

RCA quality enhancement methods have been widely investigated such as grinding, RCA-surface coating with cement and geopolymer paste, carbonating the RCA's surfaces, and frequency-generating methods. [12-20] One of the methods is to remove the residual mortar attached to aggregate and results in improved RCA quality (such as reduced water absorption and increased specific gravity). The residual mortar has high porous structure and it is a cause of its higher water absorption and lower specific gravity. To remove the residual mortar results in an improvement of RCA quality, and when used in concrete, better performance of concrete is obtained. A concrete mixture containing RCA with lower water absorption and higher specific gravity (or less residual mortar) generally has the lower water content. The lower water content consequently leads to improved performance characteristics of the mixture. However, few methods are being successfully used to produce high quality RCA in a production scale. This includes a mechanical grinding method. [7, 12-13] The mechanical grinding can be done such as in a rotary/tube mill and ball mill in order to remove the residual mortar attached to the aggregate. Removing residual mortar from RCA (only the natural aggregate is left behind) results in reduced water absorption and increased specific gravity, and consequently leads to higher RCA quality. This is due to the fact that the water absorption of the aggregate is lower than the residual mortar and the specific gravity of the aggregate is higher than the residual mortar. Yet, this mechanical grinding method typically consumes a large amount of grinding energy and can be cost-inhibitive to the production of RCA concrete [16, 20-21]. The cost of grinding may be relatively higher than the cost of producing the NA. This makes the RCA concrete uncompetitive to the NA concrete. Isaji and Nagoya-shi [14] invented a rotary mill where grinding media such as a steel rod and ball were used in order to increase its grinding efficiency. This was a result from the fact that while grinding, not only were the RCA particles crushed by each other, but also the RCA particles were crushed by the grinding media. In comparison, the grinding process without rods, where only the RCA particles are ground by each other, usually consumes more grinding energy.

Although adding the rod in the rotary mill is invariably beneficial, lack of information is explored on what characteristics of the rod should be used to optimize the grinding efficiency. To determine the grinding efficiency affected from various process and rod parameters, an objective of this study is to present the evaluation of using the steel rods at (1) different revolution counts (Rev), (2) contacted surface areas (S_a) between RCA particle and rod, and (3) different rod masses or weights (W). The S_a is referred to as the contact area between the surfaces of the steel rod and RCA particles, assuming that the all surface area of the rod is contacted to the RCA particles. A smaller rod represents a larger S_a. After optimizing the S_a, adding more rods at various sizes is determined to evaluate the effect of W on RCA characteristics. An output energy used while increasing Rev and varying rod parameters in the rotary mill is also assessed here. Test results offer the technical insight regarding the optimal conditions for Rev and the use of the steel rod in the rotary mill in order to enhance RCA quality as well as its grinding efficiency.

2. Experimental program

2.1 Materials

RCA was procured from a demolished concrete building internally. It was derived from office building in Bangkok around 100 years old. The RCA was 100% concrete materials and contained crushed calcium carbonate-based aggregate and residual mortar. After demolished, RCA was crushed into small fragments using an industrial jaw crusher with the maximum capacity of 85 ton/day. Its maximum jaw size was set at 38.1 mm (1½ in). The fragments were then sieved into several sizes. Figure 1 shows the crushed RCA particles. It is desired to give information on the strength of original concrete (i.e. core strength) which can affect the tested results shown in this work. Its gradation shown in Fig. 2 indicates that the crushed RCA particle is not fit within the limits of ASTM C33. [23] Figure 3 shows the smooth-surfaced steel rods with 3 different sizes used in this study. Based on the maximum size of crushed RCA, the steel rods were used at the diameters of 12.7 mm (½ in), 25.4 mm (1 in), and 38.1 mm (1½ in) with the weights of 1, 4, and 9 kg, respectively.Their characteristics are shown in Table 1. Their length was 1 m. This length is the maximum length of the steel rod that can be inserted inside the tube mill having the length of 1.2 m.

Fig. 1 – RCA particles after crushing

Table 1 – Characteristics of steel rod

Rod diameter (in)	W (kg)	S_a (cm^2)
1 ½	9	1200
1	4	800
½	1	400

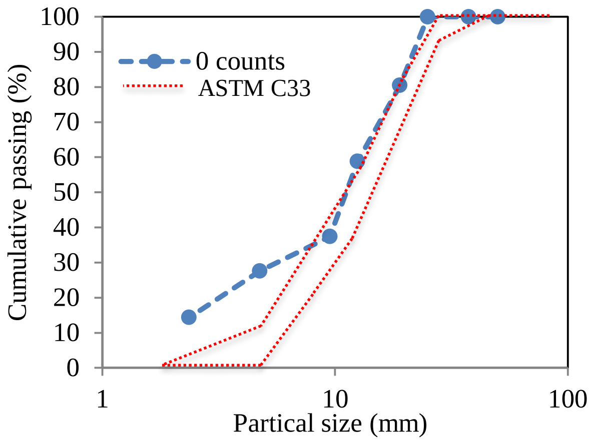


Fig. 2 – Sieve analysis of crushed RCA and ASTM C33 limits

Fig. 3 – Steel rods of 3 different sizes

2.2 Methods

2.2.1 Grinding process

After crushing, RCA was ground in a cylindrical 500-liter-per-batch rotary mill as shown in Fig. 4. The rotary mill was designed and established at Siam Research and Innovation Company, Saraburi, Thailand. It was fabricated using steel painted with blue color. An air dust collector was installed in the mill to separate small particles from the larger RCA particle for safety issue. Its grinding speed was set at 50 rpm and was operating in the ambient temperature about 30 ℃ to 35℃ and at the RCA quantity input of 400 liter per batch. The Rev of the mill was targeted at 250, 500, 750, and 1,000 counts. After reaching the targeted Rev, the rotary mill was automatically discontinued. The steel rod was added horizontally in the mill. Figure 5 shows the coarse and fine ground-RCA (G-RCA) particles. The fine G-RCA is disregarded in this study. Since it is mostly the residual mortar and can result in a deleterious effect when added in the concrete. The electrical power of the motor was recorded after the operation was finished. The G-RCA was stored at room temperature condition for assessing its performance characteristics thereafter. Performance characteristics of G-RCA evaluated includes its gradation, yield, saturated-surface-dried (SSD) density, water absorption, and output energy used. The G-RCA system without rods (no-rod system) was also tested for comparison.

Three test parameters of the process and steel rod evaluated in this study are the Rev, S_a, and W. It should be noted that the effect of steel length was disregarded here. The Rev was determined at 0, 250, 500, 750, and 1,000 counts as the W was fixed at 13 kg and S_a was fixed at 2,800 cm^2. As aforementioned above, the length of the rod was controlled at 1 m and this seems to be the maximum length that can be inserted in the mill for optimizing the S_a. In addition, only one type of steel rods (smooth surface or rounded bar) was assessed herein. The deformed bar was not in evaluation. Assessing the S_a was carried out at 2,800, 3,600, 4,400, and 5,200 cm^2 while the W and the Rev were fixed at 13 kg and 1,000 counts, respectively. Assessing the W was carried out at 9, 13, and 15 kg while the S_a and the Rev were fixed at 2,800 cm^2 and 1,000 counts, respectively. The variation of the S_a and W can be conducted by changing the rod size and number. Triplicated samples were determined for each condition.

Fig. 4 – Cylindrical 500-liter rotary mill for RCA

Fig. 5 – G-RCA (coarse and fine)

2.2.2 Characterization of RCA

The G-RCA was sieved to determine its gradation following ASTM C33 [19] and the coarse and fine G-RCA were separated and weighed for each condition. The yield of coarse G-RCA was calculated by Eq. (1). The coarse aggregate here is defined as the aggregate that is retained on a 4.75 mm (No. 4) sieve. The higher yield represents the higher weight of coarse RCA. It is noted that the higher weight of resulting coarse RCA means either the more volume of residual mortar attaching the aggregate or the coarse G-RCA particle is not broken down. In the latter case, the yield is reduced. This case is not effective because less coarse G-RCA is obtained. The amount of coarse G-RCA for replacing the NA is reduced.

$$\text{Yield (\%)} = (\text{W of G-RCA} / \text{W of input RCA}) \times 100 \quad (1)$$

The SSD density and water absorption of coarse G-RCA for each condition were assessed following ASTM C128. [24]

2.2.3 Analysis of Output Energy Used

An output energy used is referred to as an electrical energy consumption of motor of the rotary mill. This was measured using a wattmeter. The output energy used in each grinding condition was calculated by the following equation. Higher output energy used results in the higher operation cost, leading to reduced grinding efficiency.

$$\text{Output energy use} = [E/(W_0 \times Y)] \times 100 \quad (2)$$

where E = electric power measured by wattmeter (W·h); W_0 = input weight of RCA (kg); and Y = yield of coarse G-RCA (%)

3. Results and discussion

Based on the grinding process and the parameters of the steel rod, the discussion of experimental results can be divided into three parts: the effects of Rev, W, and S_a.

3.1 Effects of Rev

After grinding, the gradation of G-RCA was characterized and shown in Figure 6. The steel rod was used and fixed at W = 13 kg and S_a = 2,800 cm^2. Results indicate that when comparing the Rev of 0 count with the Rev of 250, 500, 750, and 1,000 counts, the gradation tends to fit within the ASTM C33. There is no apparent difference of the gradation of the G-RCA when the G-RCA was ground from 250 to 1,000 counts. The remixing concrete has been done if the RCA gradation does not meet the ASTM C33. [25] When casting a concrete with crushed RCA of which its gradation does not fit within ASTM C33 limits, the segregation of the fresh concrete assumedly occur. Balitsaris [26] reported that concrete containing a failed aggregate may result in the decreases of durability performance of concrete such as cracking, chloride permeability, and drying shrinkage. The better gradation of the G-RCA with rods is corresponded with the gradation enhancement for making a good concrete.

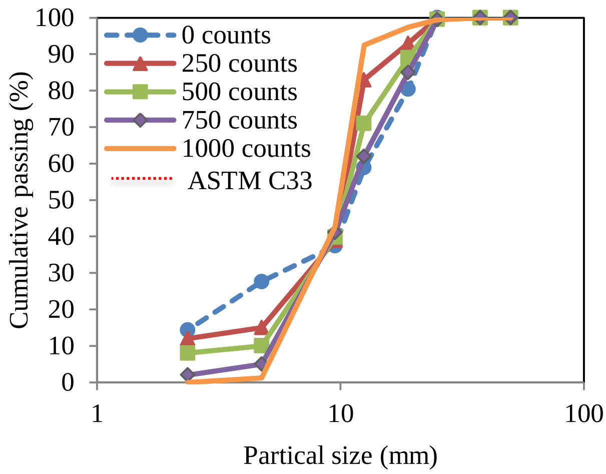


Fig. 6 – Sieve analysis of G-RCA at different Rev and ASTM C33 limits

The influence of the Rev on yield of G-RCA is shown in Fig. 7 when the tube mill contains the rod having the W and S_a of 13 kg and 2,800 cm^2. Results indicate that increasing the Rev leads to the reduction of yield. The rate of the yield reduction is approximately 0.024% per count when the Rev increases from 0 to 1,000 counts. Although the reduction rate of the yield during early grinding process (from 0 to 250 counts) is 0.068% per counts which is approximately 7 times higher than the reduction rate of the yield during the later grinding process (from 250 to 1,000 counts). This indicates that the early grinding process (up to 250 counts) can greatly and effectively remove the residual mortar. After grinding for some periods, the effect of the yield reduction of the G-RCA is lessened.

Figure 8 shows the effect of Rev of the rotary mill when using the steel rod having the W and S_a fixed at 13 kg and 2,800 cm^2, respectively. Results indicate that the amount of output energy used increases when the Rev increases. The rate of output energy used is 0.0071 W·h/kg/count. At early grinding process of the Rev from 0 to 250 counts, the rate of output energy used is 0.0017 W·h/kg/count, while the grinding at the later stage of the Rev from 250 to 1,000 counts indicates the rate of output energy used of 0.0071 W·h/kg/count. The amount of output energy used during grinding at the later stage is approximately 4.2 times higher than the grinding at the early stage. Regarding the energy consumption, grinding the RCA at the earlier stage is much more efficient than the grinding RCA at the later stage. Therefore, it seems to be the fact that grinding the RCA at the Rev of 250 counts is sufficient to improve its quality for this rotary mill. The evaluation of the effectiveness of each rotary mill is recommended to carry out to optimize its efficiency before operating.

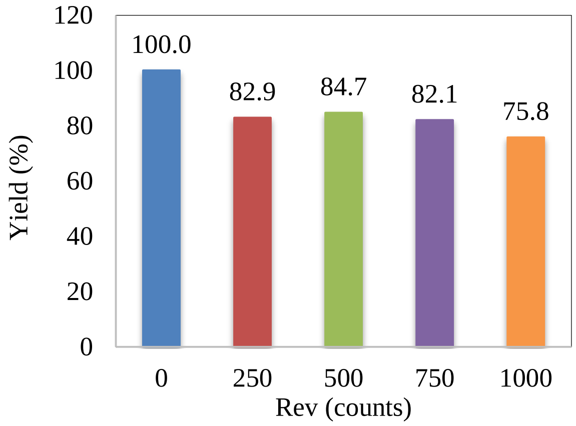


Fig. 7 – Effect of Rev of rotary mill on yield of G-RCA

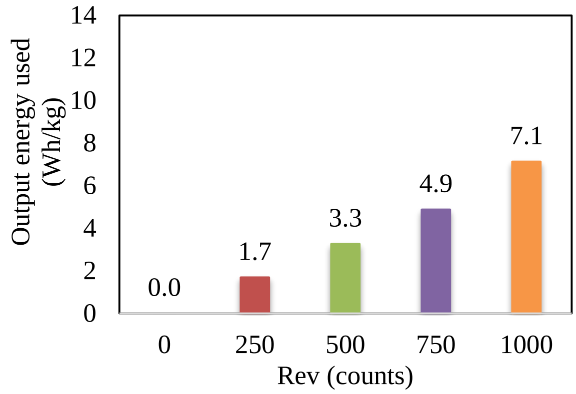


Fig. 8 – Effect of Rev of rotary mill on output energy used of G-RCA

3.2 Effects of W

Results of the sieve analyses of the G-RCA, input RCA, and ASTM C33 limits are shown in Fig. 9. Test results indicate that the gradations of the G-RCA tend to be closer within the ASTM C33 limits, compared to the input RCA. Reducing the W from 15 to 9 kg results in that the RCA gradation is closer to fit within the ASTM C33 limits. The gradation of the G-RCA with the W of 9 kg is fit within the ASTM C33 limits. Using the lighter steel rod likely leads to the better gradation of G-RCA. Nonetheless, the gradation of the input RCA is not fit within the ASTM C33 limits.

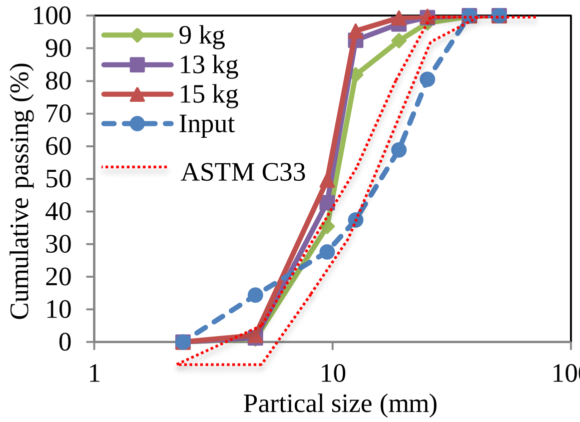


Fig. 9 – Sieve analysis of G-RCA at different W and ASTM C33 limits

Figure 10 shows the effect of the yield of G-RCA as a function of the Rev when different W of 9, 13, and 15 kg are used in the rotary mill. Results indicate that the yield of the G-RCA decreases as the Rev increases from 500 to 1,000 counts for all systems. Increasing the W from 9 to 15 kg leads to reduced yields for all rod systems. All yields of the rod systems are lower than the no-rod system. Using the rods with higher W (i.e., 15 kg) is believed to not only detach the residual mortar but also break the RCA particle. In contrast, using the rod with less W (9 kg) likely detaches the residual mortar only. This will be explained next in the density and absorption of G-RCA section.

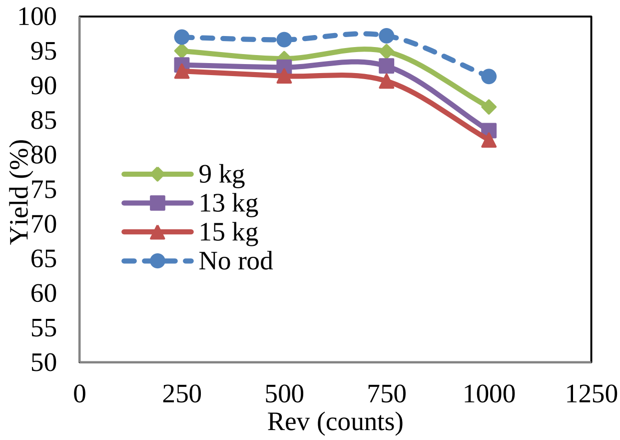
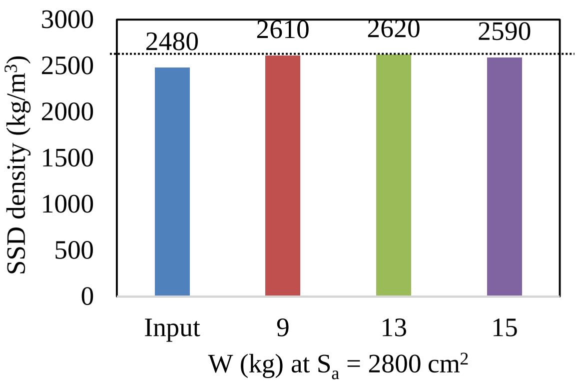
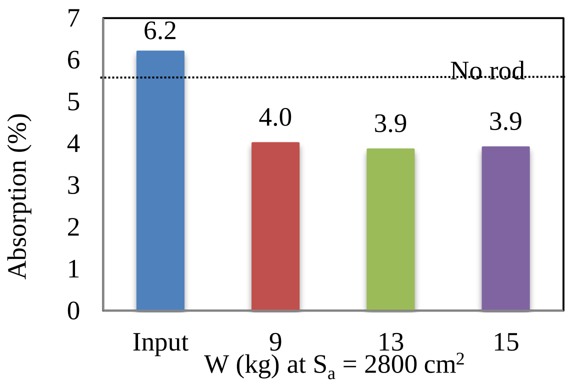


Fig. 10 – Effect of Rev of rotary mill on yield of G-RCA for different W

The influences of W at the same S_a of 2,800 cm^2 and the Rev of 1,000 counts on the SSD density and the water absorption of the G-RCA are shown in Fig. 11(a) and (b), respectively. Tested results regarding the SSD density indicate that when increasing the W from 9 to 15 kg, the SSD densities are not different. The SSD densities of the rod systems are within the range of 2,590 to 2,620 kg/cm^3. Based on test results, the W of the rod does not enhance the RCA quality. In addition, the SSD densities of all rod systems are 4% to 6% higher than the no-rod system. The steel rod is suggested to be used in the RCA rotary mill for improving SSD density. When comparing the SSD density of the G-RCA with the input RCA, there is an increase of the SSD density ranging from 110 to 140 kg/m^3. The quality improvement of the grinding process is valid here.



(a)



(b)

Fig. 11 – Effect of W at S_a = 2,800 cm^2 of rotary mill on (a) SSD density and (b) water absorption of G-RCA

Figure 11(b) shows the effect of W at similar S_a of 2,800 cm^2 on the water absorption of G-RCA. Results indicate that the water absorption for all systems is similar when the W increases from 9 to 15 kg. The dash-line represents no-rod system. Using different rod sizes do not alter the water absorption of the G-RCA and this result is similar with the result from the SSD densities in Figure 11a. From both test results, increasing the W is believed to lead to the unchanged characteristics of G-RCA. Comparing the rod systems to the no-rod system indicates that the water absorption of the rod systems is approximately 30% lower than the no-rod system. Alike the SSD density results, the efficiency of the RCA rotary mill is improved when the steel rod is present. When comparing the input RCA with the G-RCA, the reduction of the water absorption is around 35% to 40%, indicating that the high efficiency of the grinding process of the tube mill.

The effect of the W at similar S_a of 2,800 cm^2 on the amount of output energy used is shown in Figure 12. When grinding for 1,000 counts, results indicate that the less amount of energy used can be obtained when using lower W of the steel rod. The rod system with the W of 9 kg results in approximately 6% and 8% reduction in output energy used compared with the rod systems with W of 13 and 15 kg, respectively. This result suggests that the smaller size of the rod should be used in order to preserve the grinding energy. It should be noted that the cost of wears is disregarded here. Moreover, test results indicate not less than 50% reduction in output energy used of all rod systems compared with the no-rod system. The results of significant reduction in energy used in the rod system confirm that the rod should be added in the rotary mill for the enhancement of RCA quality with higher energy efficiency. It is noted that when the G-RCA is ground for 1,000 counts in the rotary mill without rod, its absorption is still too high (absorption is about 6%). To reduce the absorption of the no-rod system in order to be equal to the rod systems (absorption is about 4%), the tube mill is operated further. The tube mill of the no-rod system is ran for 2,000 counts to achieve the similar water absorption with the rod system or to reduce water absorption from 6% down to 4%. For this reason, the output energy used for the system without rod in Fig. 12 is about 12.6 W·h/kg and this is recorded when the grinding is operated for 2,500 counts, allowing the water absorption of both systems to be the same.

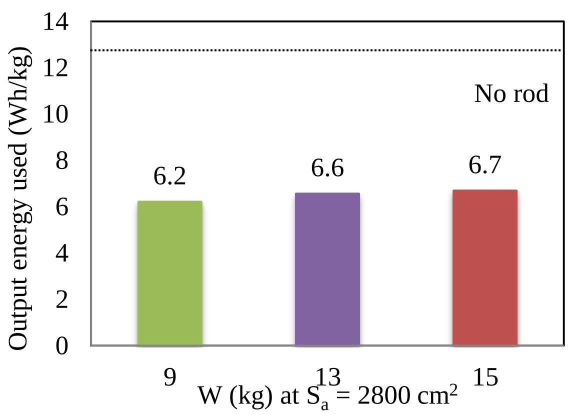


Fig. 12 – Effect of W at S_a = 2,800 cm^2 of rotary mill on energy output

3.3 Effects of S_a

The sieve analyses of the input RCA, G-RCA system operated for 1,000 counts having the steel rod with the S_a ranging from 2,800 to 5,200 cm^2, and the ASTM C33 limits are shown in Fig. 13. Increasing the S_a can be done by using the smaller steel rod. Results indicate that increasing the S_a from 2,800 to 5,200 cm^2 does not change the gradation of the G-RCA. However, comparing the gradation of the G-RCA to the input RCA indicates that the G-RCA for all S_a tends to fit within the ASTM C33 limits than the input RCA. As aforementioned, when casting a fresh concrete mixture using the crushed RCA, its segregation likely occurs. In term of the gradation of G-RCA, adding the steel rod in rotary mill allows the G-RCA to be more practical for use in concrete mixture.

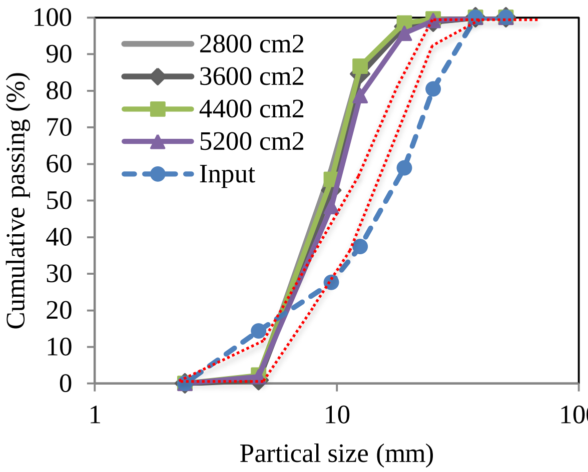


Fig. 13 – Sieve analysis of G-RCA at different S_a and ASTM C33 limits

Figure 14 shows the relationship between the Rev of the rotary mill having rod with the S_a ranging from 2,800 to 5,200 cm^2 and yield of the G-RCA. Results indicate that the yields of all rod systems having different S_a seem to be similar. The yield of the G-RCA at the Rev of 1,000 counts ranges about 75% to 78%. The S_a has less influence on the yield of G-RCA. When comparing the yield of the rod systems with the no-rod system, results indicate the yields of the rod systems for all S_a are higher than the no-rod system. This is the case assuming two possible phenomena: firstly, the G-RCA particles are less ground by the steel rods and less the impact energy of aggregate particles themselves. Secondly, impact energy between aggregate particles and the wall of the rotary mill are not sufficient. Both phenomena result in much residual mortar still attaching on the aggregate. This leads to lower density and higher water absorption as will be explained later.

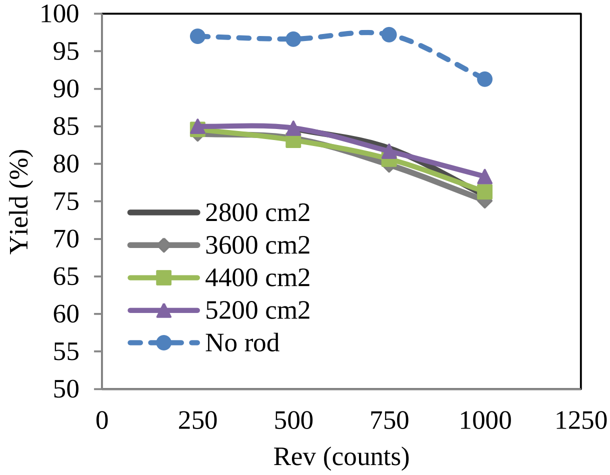
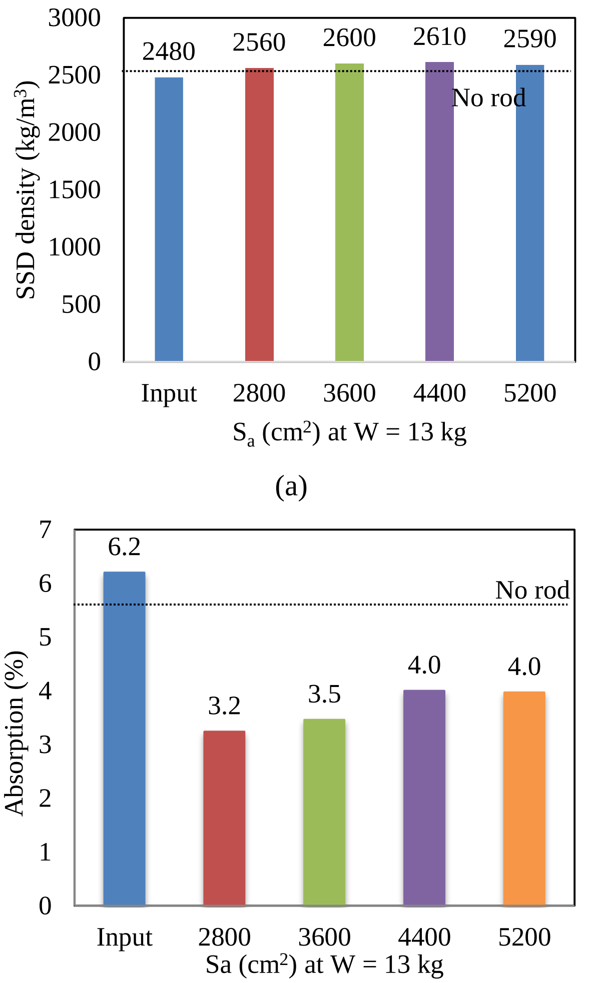


Fig. 14 – Effect of Rev of rotary mill on yield of G-RCA for different S_a



(b)

Fig. 15 – Effect of S_a at W = 13 kg of rotary mill on (a) SSD density and (b) water absorption of G-RCA

The relationships of the SSD density and water absorption of the G-RCA ground for 1,000 counts as a function of the S_a ranging from 2,800 to 5,200 cm^2 are shown in Fig. 15(a) and (b), respectively. Results in Fig. 15(a) indicate that the SSD densities of the rod systems range from 2,560 to 2,610 kg/m^3.

Its SSD density is not much influenced by changing the S_a. However, the SSD densities of the rod systems are approximately 6% to 8% higher than the no-rod which suggests that the RCA quality can be enhanced by adding the rod in the rotary mill. The SSD densities of the system having rod are approximately 8% to 13% higher than the input RCA system.

The effect of the S_a on the water absorption of the G-RCA ground for 1,000 counts is shown in Fig. 15(b). Results indicate that the water absorption of the G-RCA increases with increasing the S_a. The water absorption of the rod system with the S_a of 5,200 cm^2 is approximately 0%, 13%, and 20% higher than the rod systems with the S_a of 2,800, 3,600 and 4,400 cm^2, respectively. In other words, using the larger rod size in the tube mill can result in a greater reduction of water absorption of the G-RCA. Alike the results of the effect of the W on the water absorption shown in Fig. 8(b), all rod systems have lower water absorption than the no-rod system when ground at 1,000 counts. The rod systems of the S_a at 2,800, 3,600, 4,400 and 5200 cm^2 are approximately 44%, 38%, 30%, and 30% lower in water absorption than the no-rod system, respectively. Regarding the reduction of the water absorption, a steel rod should be used in the RCA tube mill. Results comparing the rod systems with the input RCA system indicate the significant reduction of the water absorption by 35% to 48%.

Figure 16 shows the influence of S_a of the steel rod in rotary mill having the W of 13 kg on the amount of output energy used when grinding at 1,000 counts. Results indicate that increasing the S_a from 2,800 to 5,200 cm^2 results in a reduction of the output energy used. The output energy used of the rod system with the S_a of 2,800 cm^2 is similar with the system with the S_a of 3,600 cm^2. While increasing the systems with the S_a of 4,400 and 5,200 cm^2 can lead to a reduction of energy used by about 3% to 4% when compared with the systems with the Sa of 2,800 and 3,600 cm^2, respectively. The results here are conformed the results of the W where using the smaller rod size results in the less amount of output energy used in Figure 12. In addition, comparing the effect of the S_a of the rod systems with the no-rod exhibited similar results with comparing the effect of W of the rod systems with the no-rod. Adding the rods having the S_a ranging from 2,800 to 5,200 cm^2 during RCA grinding leads to the 42% to 45% decrease in grinding energy. To increase the efficiency of RCA grinding in the rotary mill, the steel rod is needed. As explained before, the energy output used by the no-rod system is measured and calculated when the G-RCA is ground for 2,500 counts to achieve similar performance to the rod systems.

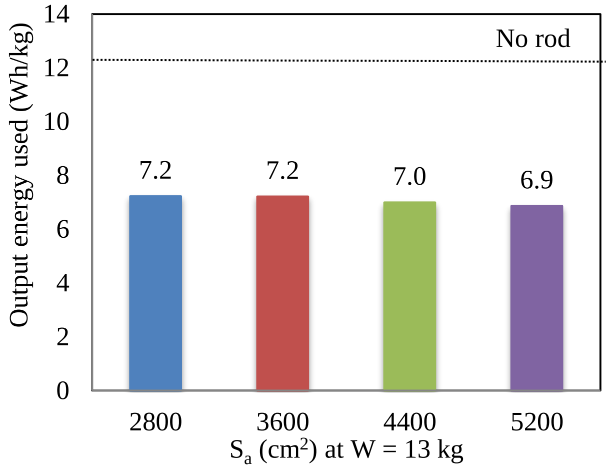


Fig. 16 – Effect of S_a at W = 13 kg of rotary mill on output energy used of G-RCA

A summary of the effects of the S_a and W on the G-RCA quality and mill's grinding efficiency is shown in Table 2. Results indicate that increasing the W has the negative effect on gradation and yield. In this case, not only is the residual mortar removed but also the G-RCA particle is seemingly broken down. The SSD density and water absorption are not influenced by increasing the W. When increasing the W, there is the deleterious effect on the grinding efficiency. The results of the effect of S_a on performance characteristics and grinding efficiency of G-RCA indicating that the gradation, yield, and SSD density are not affected by changing the S_a. When the S_a increases, the absorption has the negative effect, while the grinding efficiency has the positive effect.

Table 2 – Summary of the rod parameters on RCA characteristics and process output

Output	Increased W	Increased S_a
Gradation	-	0
Yield	-	0
SSD density	0	0
Water absorption	0	-
Grinding efficiency	-	+

Note: "-" negative result; "+" positive result; "0" unchanged result

To optimize the rod parameters, using the smaller rods with higher S_a is recommended because the grinding efficiency of the rotary mill increases when the S_a increases. Although when increasing the S_a, the absorption of the G-RCA also increases, using higher S_a is still recommended. This is due to absorption of all S_a varying in the rage of 3.2 and 4.0. Based on international standards (such as Japanese and RILEM), these absorption values are in the same classes; supposingly, less impact on final concrete performance. [27-28] Concerns do more focus on energy conservation instead.

4. Conclusions

RCA has the concern from users for use as concrete aggregate, especially for structural purposes. The improvement of RCA quality is needed such as grinding method. The study of the grinding method here is performed to assess the effects of process and steel rod parameters of the large-scale tube mill. This study provides the technical insight on the effects of the Rev, W, and S_a of the steel rod on gradation and performance characteristics of G-RCA as well as its grinding efficiency. Results indicated that:

(1) The early-stage grinding operation has greater efficient for better RCA quality output and minimize grinding energy than the late-stage grinding operation. The Rev of 250 counts seems to be sufficient to provide a good quality of the G-RCA for this tube mill.

(2) When increasing the W of the steel rod, the G-RCA had the inappropriate gradation, lower yield, decreased grinding efficiency, unchanged SSD density, and unchanged water absorption. From these results, increasing the W of the rod is not recommended to apply in the rotary mill of the RCA.

(3) Increased S_a of the rod resulted in unchanged gradation, yield, and SSD density, increased grinding efficiency, but reduced water absorption. This increased S_a of the rod or using smaller rods was suggested to be used in the RCA rotary mill to increase energy efficiency, even though the water absorption is worsen.

Results described here indicate that adding the rod is necessary for the RCA-quality enhancement during grinding. Each RCA production plant is needed to assess the optimum Rev to achieve the most efficiency, prior to begin production. Adding the smaller steel rods in the rotary mill during RCA grinding led to the significant reduction of grinding energy by approximately 42% to 45%, while the quality of G-RCA were better. By applying the knowledge of this study for enhancing the RCA quality using the large scale rotary mill having steel rods allows RCA more viable to be used as the concrete aggregate. Ongoing work is under investigation including the effect of the number of smaller steel rod on the G-RCA characteristics and the effect of G-RCA on performance of concrete.

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