The Process Development of Glass Cullet and Recycled Glass Aggregate for Improving Recycling Rate

Hansol Lee
Korea university of science and technology https://orcid.org/0000-0001-7069-8414
Hoon Lee (hoonlee@kigam.re.kr)
https://orcid.org/0000-0003-0599-0229

Research

Keywords: waste glass bottles, cullet, color sorting, recycled glass aggregate, crushing, discrete element method

Posted Date: July 19th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-709571/v1

The process development of glass cullet and recycled glass aggregate for improving recycling rate

Hansol Lee[1] and Hoon Lee[2]*

[1]Resources Recycling, University of Science and Technology, Daejeon, Republic of Korea, 34113

[2] Mineral Resources Research Division, Korea Institute of Geoscience and Mineral Resources, Daejeon, Republic of Korea, 34132

* Correspondence: hoonlee@kigam.re.kr

Abstract

Due to depletion of resources and the spread of environmental pollution, the sustainability of raw materials is emerging as an important issue. Glass bottles are one of the products that are easy to recycle, and many studies have been conducted to improve the recycling rate. In this study, we attempted to develop the waste glass bottles process that can be recycled into a glass cullet and recycled glass aggregate. To produce a cullet from waste glass bottles(WGBs), color quality standards must be satisfied. Therefore, we applied a multistage color sorter to the experiment. The recycled aggregate glass must adjust the particle size. Thus, we experimented with the optimum crusher selection test when applying the crushing process. And, we confirmed the appropriateness of process by aspect ratio analysis of product. In addition, we confirmed the trends in the data required to set the optimum design and operating conditions of the selected vertical shaft impact(VSI) crusher using discrete element method(DEM) simulations.

Keywords: waste glass bottles, cullet, color sorting, recycled glass aggregate, crushing, discrete element method

1. Introduction

Increasing consumption patterns globally are resulting in depletion of resources and the spread of environmental pollution; therefore, the sustainability of raw materials is emerging as an important issue. Various studies have been conducted on the sustainability of raw materials; nevertheless, many products are disposed in landfills or incinerated due to economic constraints. Landfill and incineration can cause many problems, such as air pollution and heavy metal leaching; a better future-oriented method should be suggested [1-3].

In 2019, the amount of waste glass bottles (WGB) generated was about 615,000 tons in Korea. The associated recycling rate is reported to be approximately 79.0% and 486,000 tons [4]. Since 2010, the recycling rate of WGBs of over 75% has been achieved, but is about 10% lower compared with Germany and Japan, countries with advanced recycling systems and strategies. In addition, since only manufacturers with an annual delivery of more than 10 tons, sales of more than 1 billion won, and annual imports of more than 300 million won in the previous year are obligated to recycled producers, it is difficult to confirm an accurate amount of WGBs [5]. Furthermore, glass bottles are easily broken and the recycling of mixed glass bottles is difficult, hence over 200,000 tons of WGBs have been dumped in landfills.

Various studies have been conducted to recycle landfill-WGBs. For example, the foam glass production study [6-9], the cement replacement study [10-13], the aggregate replacement study in concrete [14-19], and the waste glass utilize study in mortar [20-24] are published. In the above studies, they have assessed that the alkali-silica reaction (ASR) generated when WGB and concrete are mixed can be controlled with additives and by adjusting the particle size. In addition, we found that the pozzolanic reaction caused by the hydration reaction of glass and cement improves the physical properties of concrete. Hence, we believe that the WGBs can be recycled into a construction material. Most of the studies on WGBs have focused on recycling methods, but studies on the treatment process are minimal. It is very important to study the optimum treatment process because the economic aspect is essential to the WGB-recycling process. Therefore, in this study, the optimum process design, which can be recycled as a glass cullet and recycled glass aggregate, was investigated.

To produce a cullet from WGBs, color quality standards must be satisfied. Therefore, we applied a multistage color sorter to the experiment. The recycled aggregate glass must adjust the particle size. Thus, we experimented with the optimum crusher selection test when applying the crushing process. A shredder, hammer crusher, roll crusher, and vertical shaft impeller (VSI) crusher were used in the experiment, and the particle size and aspect ratio of the product were confirmed. Subsequently, we ran an EDEM simulation based on DEM to identify data trends needed to establish optimum design and operating conditions. The results obtained satisfy all standards and we believe that this study contributes to increasing the WGB recycling rate.

2. Waste glass bottle recycling process

In Korea the WGBs used domestically and commercially have collected by both local governments and private enterprises. The hand-picked WGBs have cleaned and then delivered to an intermediate-treatment enterprise. Fig. 1 shows the WGB recycling process that were applied with the various separation methods, in this study. The recycling process produces a glass cullet or a recycled glass aggregate, according to the intended use. The collected WGBs were divided using a trommel screen and particles of 10 mm or larger were for recycling into a glass cullet, and under 10 mm for the recycled glass aggregate. The iron and non-iron impurities were removed using magnetic and eddy-current separation, while light materials such as paper were eliminated by air separation. A multi-stage color sorter was used because the glass cullet can be produced in a single color only. In addition, the crushing process was applied to adjust particle size of recycled glass aggregate.

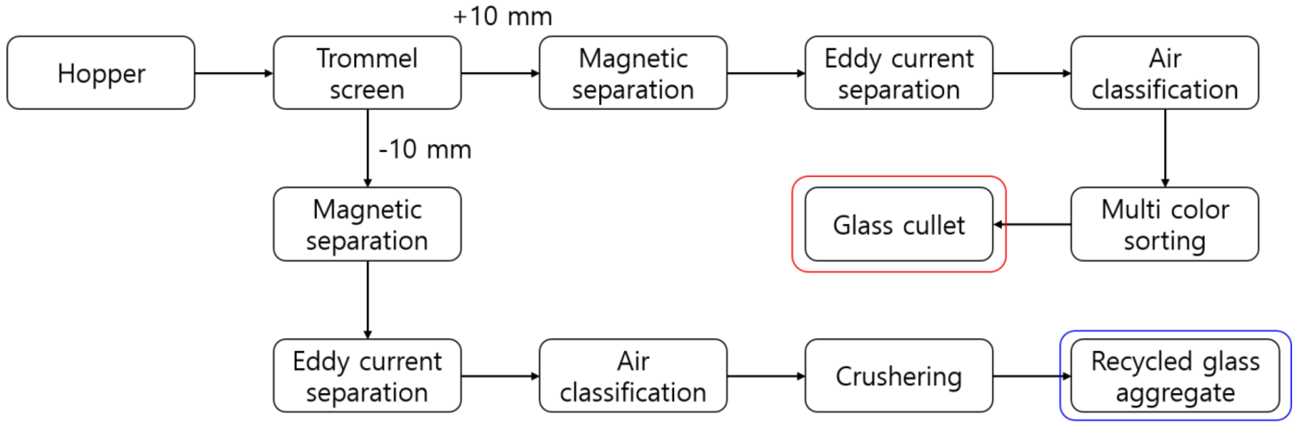


Figure 1. Waste glass bottle recycling process

3. Experiment

3.1.Mateials

The sample used in this study was supplied by Indong GRC, which is a WGB intermediate treatment enterprise in Korea. Most of the foreign substances were removed by hand separation, magnetic separation, eddy current separation and air separation. The sample was a mixture of three colors, green, amber, and clear with a weight ratio of 4:4:2. As confirmed in the process in Fig 1, the sample was tested by size, with particles 10 mm or over 10 mm for the glass cullet(Fig. 2a) and under 10 mm for the recycled glass aggregate(Fig. 2b).

(a) (b)

Figure 2. a) Sample of glass cullet(+10 mm) b) Sample of recycled glass aggregate(-10 mm)

We analyzed the samples to confirm the physical and chemical attributes. First, we analyzed the particle size distribution of the samples using a dry sieve. The glass cullet does not have a standard particle size distribution; therefore, only samples used for the recycled glass aggregate, was analyzed. The particle size distribution analysis progressed through sieve sizes of 10.0 mm, 5.0 mm, 2.5 mm, 1.2 mm, 0.6 mm, 0.3 mm, 0.15 mm as per the KSF 2527 experimental method [25]. Table 1 shows the results of the particle size distribution analysis. Based on this we determined that an additional crushing process is needed to satisfy the standard quality particle size distribution of the recycled aggregate.

To identify constituent and mineralogical attributes, we conducted XRD (X-ray diffraction), XRF (X-ray fluorescence), SEM-EDS (Scanning electron microscope - Energy dispersive X-ray spectrometer) analyses. Table 2 contains the information of the equipment used in this study. According to the results of the XRD analysis shown in Table 3, the sample was amorphous and presented calcite and quartz peaks. As per the XRF analysis (Table 3), the sample was composed of approximately 72% SiO_2, 12% Na_2O, and approximately 8% CaO. Fig. 4 shows the results of the SEM-EDS analysis, and Si, O, Na, and Ca were identified as major constituents, displaying the same trend as the XRD and XRF. The various analyses identify the sample used in this study as soda glass, which consists of Na_2CO_3, SiO_2, CaO, and not borosilicate glass or lead glass. Furthermore, the difference in results was not according to the particle size for any of the analyses.

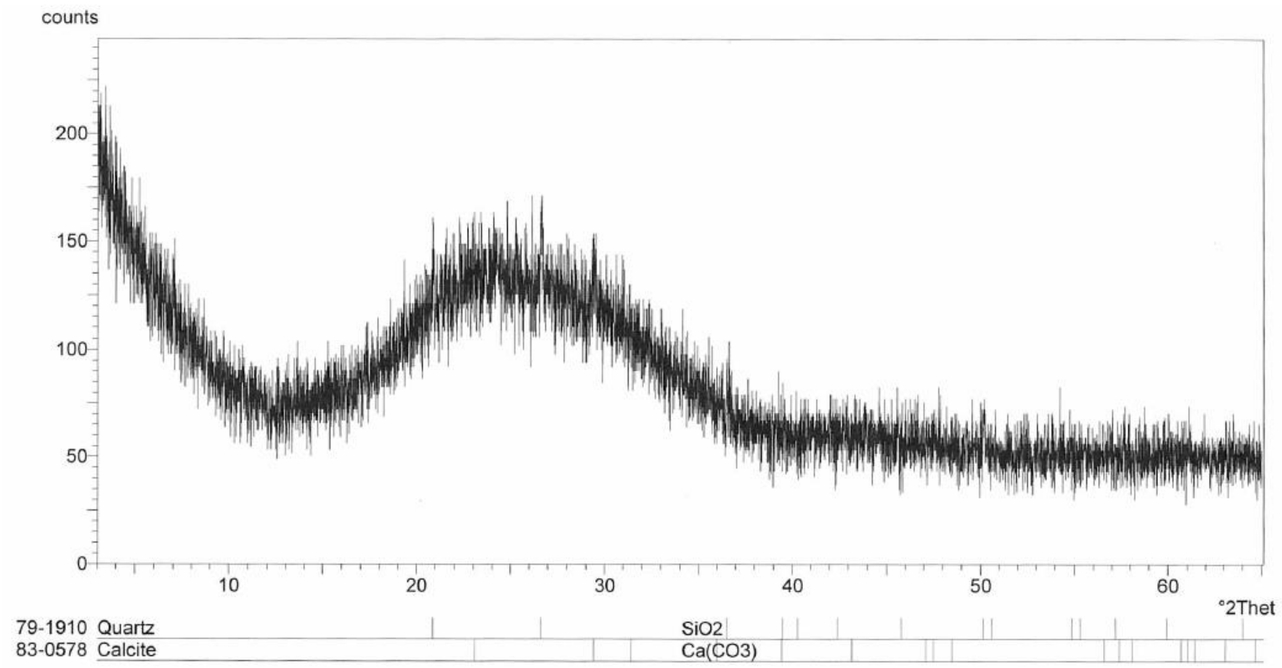


Figure 3. XRD analysis result of sample

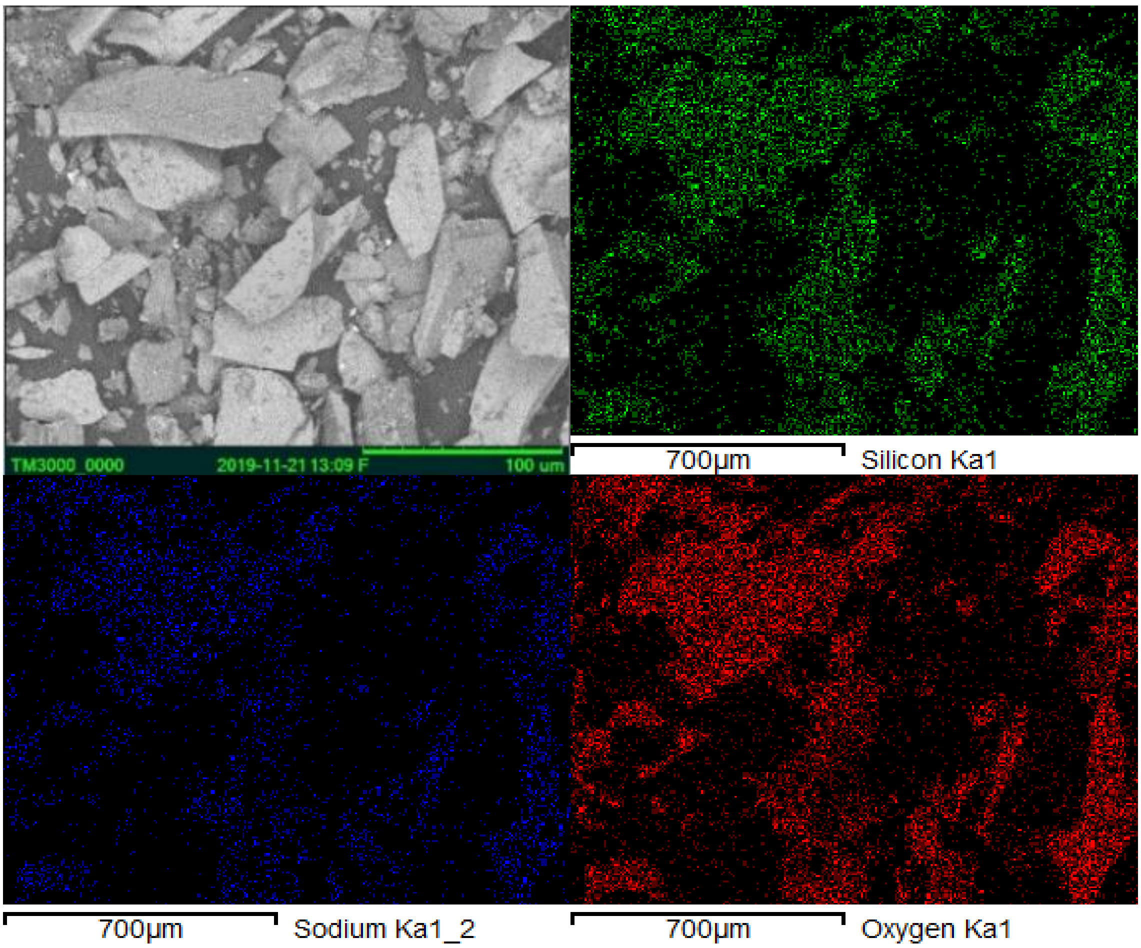
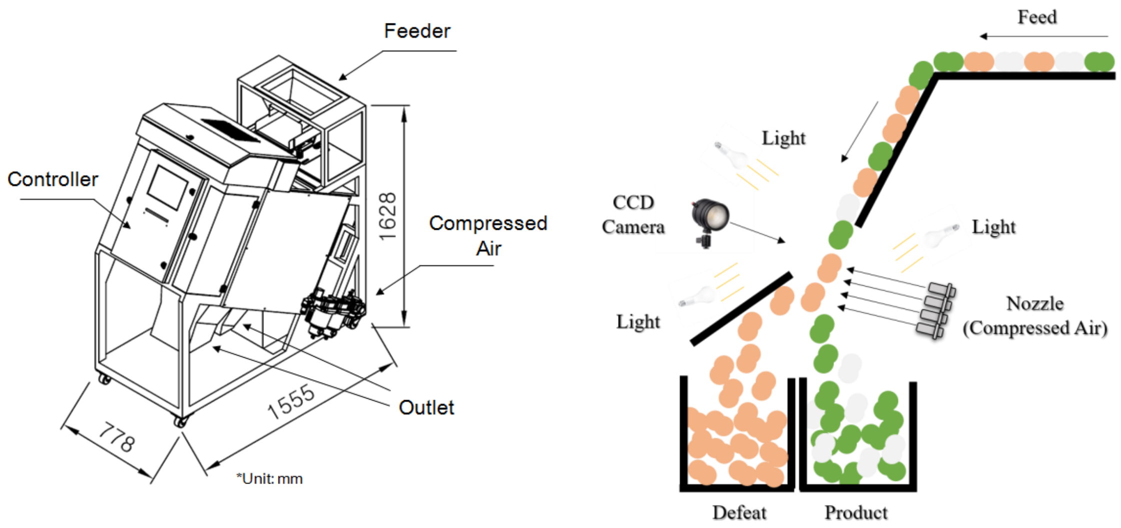


Figure 4. SEM image of sample

3.2. Experiment equipment

3.2.1. Color sorter

Recycling WGBs into cullet is the most economical method, however, color classification is essential for this process. To achieve the quality standard, an experiment was conducted by applying an optical sorter which was manufactured to identify the different color mixing rates for each color. The color sorter is compartmentalized according to the supply method of the feed: as chute and belt types. Fig. 5a presents a schematic diagram of the chute type color sorter used in this study [26]. Fig. 5b shows the fundamental structure of the chute-type color sorter. The color sorter supplies the sample uniformly using a vibration feeder, the quantity of light transmitted is measured by a high-resolution CCD line camera, and then the color data of the samples are collected in a color sorter. Based on the collected data, the product that is not the designated input color for the sorter is separated into a 'defeat box' by an air nozzle. The major experimental conditions for the color sorter are color separation order, color sensitivity, feed rate, air pressure, and particle size. In this study, we referred to the study by Lee [27], to maintain a consistent experimental environment and all the conditions except for the color selection order were fixed and tested.



(a) (b)

Figure 5. Schematic of the color sorter.

3.2.2. Crusher

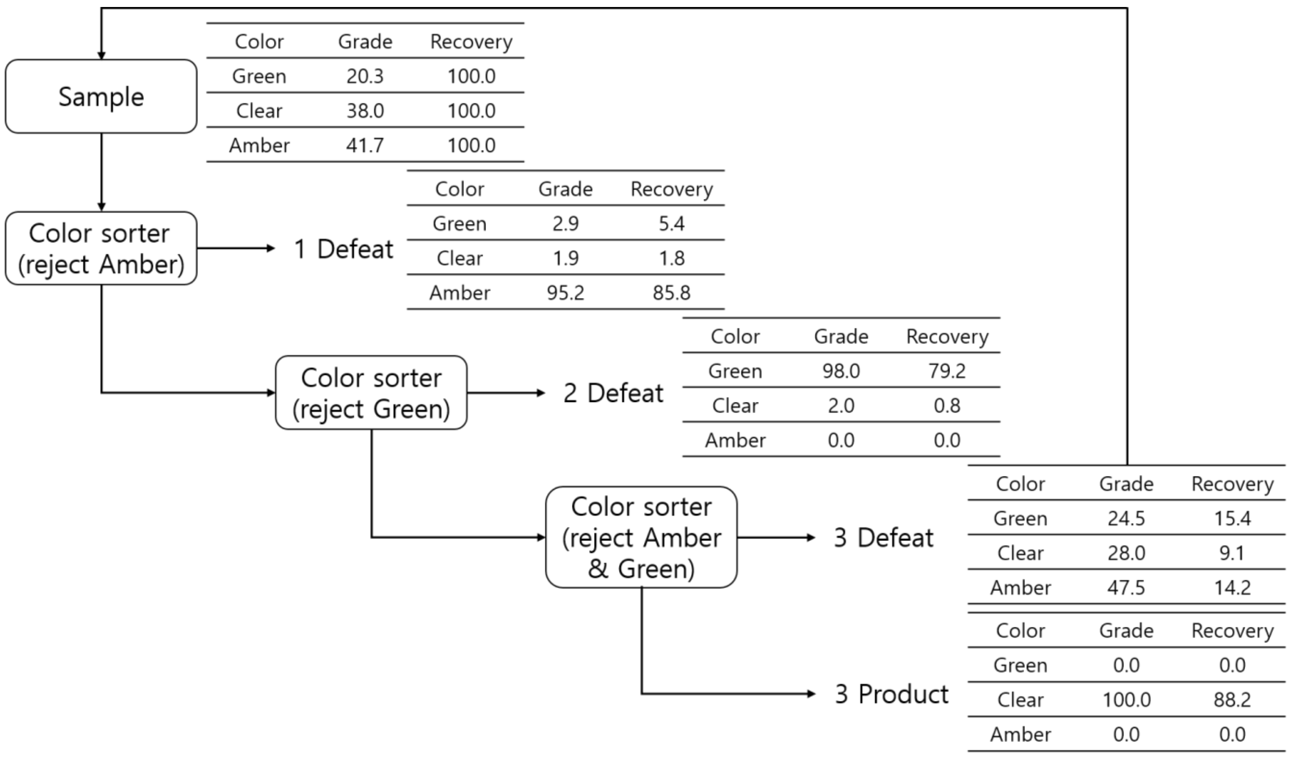
For recycling WGB under 10 mm into a recycled glass aggregate, satisfying the recycled aggregate particle size standard is essential. In this study, an experiment was conducted using four types of equipment: a hammer crusher, a shredder, a roll crusher, and a VSI crusher, which characteristically show the main force applied to the particles (Fig. 6). The key specifications and experimental conditions of the crusher used in this study are listed in Table 4. The shredder and hammer crusher were tested using the crusher specifications, and a roll crusher was used at a rotation speed of 280 rpm and a roll gap of 2.5 mm, which is obtained from the equation of Mineral Processing Design and Operations (Second Edition) [28]. The rotation speed of the VSI crusher can be controlled by a control box, and 1,000 rpm was used to test the WGB, which is more easily crushed than ores.

Figure 6. Crusher used in this study.

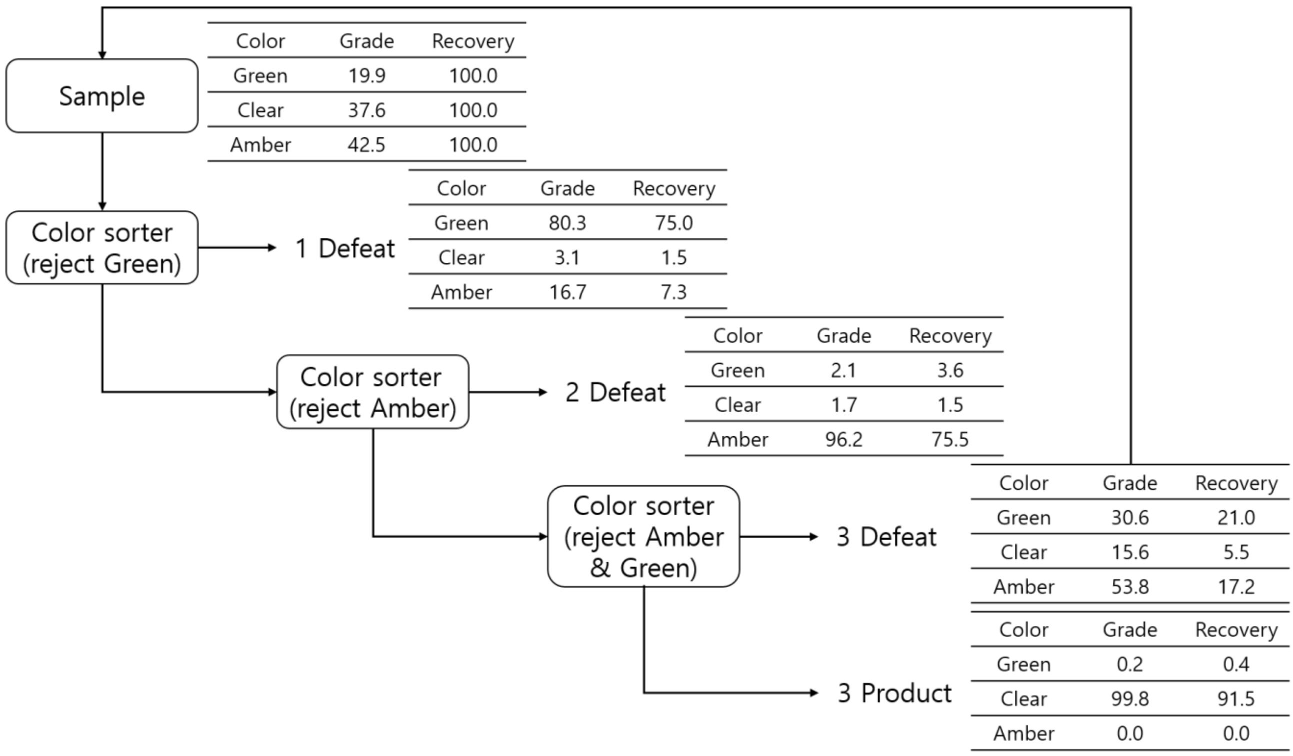
4. Results & discussion

4.1. Color sorting experiment result

To recycle mixed color WGB into a glass cullet, the color quality standard must be satisfied. The color quality standard, in terms of difference color rates, is under 5% for amber and green and is under 1% for clear. Since clear has the most stringent quality standards, it was fixed to the end of the sorting order, which has the least amount of WGBs to be removed. The order of green and amber were changed and tested as condition A and B. The condition A involves the removal in the following sequence: first amber, second green, third amber and green, while condition B is sequenced as first green, second amber, third amber and green. The general color sorting experiment removes the defeat color, which is usually a small portion. However, the sample used in this study contained the desired color at a lower rate, therefore we removed the desired color, instead. Fig. 7 presents the grade and recovery of each color according to the conditions, and we judged the possibility of recycling WGBs. The results for the condition A were as follows: amber grade at 95.2%, had a recovery of 85.8%, green grade at 98.0%, recovery of 79.2%, clear grade at 100.0%, and a recovery of 88.2%. We confirmed that the result of condition A satisfied the color quality standard for all colors. The results for the condition B showed green grade at 80.3%, with a recovery of 75.0%, amber grade at 96.2%, recovery of 75.5%, clear grade at 99.8%, and recovery of 91.5%. The condition B achieved the color quality standard for amber and clear products, but did not satisfy them for, green. In addition, the recoveries from condition B, has a lower value than A for all colors except clear. Because the RGB values of green and clear measured in color sorter were distributed similarly, the removal of green as the first action (as in condition B), also affected the clear, so we assessed that to be of a low grade. Therefore, the color quality standard of the glass cullet can be satisfied when separating the mixed-color WGB using condition A in the color sorter.



(a)



(b)

Figure 7. The results of color sorter experiment according to condition A and B.

4.2. Optimum crusher selection for recycled glass aggregate

4.2.1. Crushing experiment result

Recycling WGB into recycled glass aggregate must satisfy foreign substances and size distribution quality standard. According to KS F2576, the content of organic foreign substances such as plastic, wood, paper, and vinyl must be under 1% of the aggregate volume. In addition, the aggregate must not emit an odor or contain or chemical substances harmful to the environment. The majority of the foreign substances in the samples used in this study were removed by hand, eddy-current separation, magnetic separation, and air separation in the pre-treatment process, as we aimed to satisfy the foreign substance quality standard. The particle size distribution of recycled glass aggregate must satisfy the prescribed KS F2527 standard [25], displayed in Table 5. We conducted crushing experiments on WGBs less than 10 mm in size using a shredder, roll crusher, hammer crusher, and VSI crusher, and presented the particle size distribution of the crushed product in Fig 8. The particles smaller than 2.5 mm were 99.9%, 98.0%, 47.3% and 29.4% for the hammer crusher, VSI crusher, roll crusher, and shredder respectively. Under 0.3 mm, the percentage of particles crushed were, was a 46.7%, 24.3%, 5.7%, and 4.3% for the hammer crusher, VSI crusher, roll crusher, and shredder, respectively. As comparison with the prescribed particle size distribution, indicated that the products of the roll crusher and shredder did not meet the minimum particle size distribution standard because they were not adequately crushed. Shredder is generally applied to the dismantling of ductile and composite materials, and it was judged that the shredder was not suitable for crushing brittle materials such as glass. The roll crusher crushes by delivering a single compressive force, because of which the crushing of the WGBs, which have plate-shaped particles, was not accomplished. The over-crushing was observed in the hammer crusher, because the hammer impacts directly into sample. Furthermore, owing to the abrasion of the hammer, we decided that the hammer crusher was not suitable for crushing the WGBs. The VSI crusher is equipment that crushes particles based on an impact force, similar to a hammer crusher, but does not over-crushing the sample, since the force is delivered to the inner wall using an impeller. We, therefore, determined that the crushing occurred optimally only with the use of the VSI crusher which satisfied the particle size distribution quality standard of recycled glass aggregate.

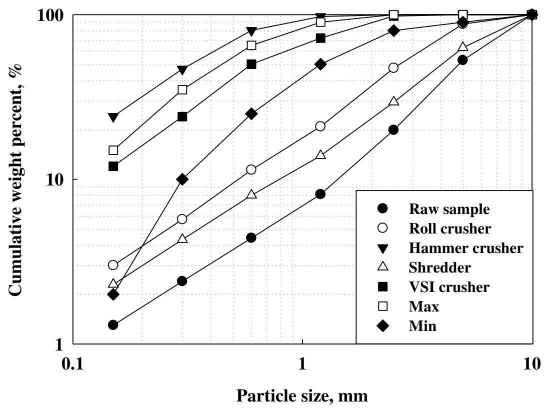


Figure 8. The particle size distribution of crushed product according to crusher

4.2.2. Aspect ratio analysis result

According to BS 812 [29], in the case of using crushed mix color WGBs as recycled glass aggregate, the angularity or absence of round aggregate particles is a very important attribute since it affects the convenience of handling the mixture of the aggregate and binder. In Zingg's classification system [30], when the aspect ratio of the particle exceeds approximately 1.5, it is mentioned that the mixture was significantly influenced by a rolling motion and the associated traction. In addition, BS 812 defined elongated particles as those with an aspect ratio greater than 2.2. Consequently, in this study, we measured the aspect ratios of the WGBs before and after crushing and confirmed them on a graph of cumulative frequency. The aspect ratio was measured using the *ImageJ* program, which can measure and analyze length, area, and circumference. After capturing the image of the sample, it is imported to Image J and the shadow is removed, and the clarity enhanced using a contrast function. Then, to demarcate and divide the particle boundary accurately, it was measured and analyzed in the binary mode. Fig 9 presents the *ImageJ* process.

Figure 9. Aspect Ratio measurement using *ImageJ*

Fig. 10 shows the aspect ratio results of the feed and VSI crusher product for each particle size. From Fig 10, it can be seen that approximately 20% of the natural sand particles had an aspect ratio value over 1.5. In the case of the feed, the aspect ratio of over 1.5 for 10.0-5.0 mm, which is a relatively large particle, was about 18% similar to that of natural sand, but the 5.0-2.5 mm and 2.5-1.2 mm particles were confirmed to be about 50%. In the case of the product, the aspect ratio over of 1.5 for 10.0~5.0 mm increased by about 22% compared to feed particles, but the 5.0~2.5 mm and 2.5~1.2 mm particles decreased by about 20%. In addition, we confirmed the aspect ratio of over 2.2, which was defined by BS 812 as an elongated particle standard, was lower than that of natural sand for all particle sizes. The box plot in Fig. 11 shows that the aspect ratio of the product had a low value with an average distribution as compared with natural sand for all particle sizes. Thus, an aspect ratio higher than that of natural sand could be obtained through crushing by VSI crusher, so we ascertained that the WGB was appropriate for recycling into a glass aggregate.

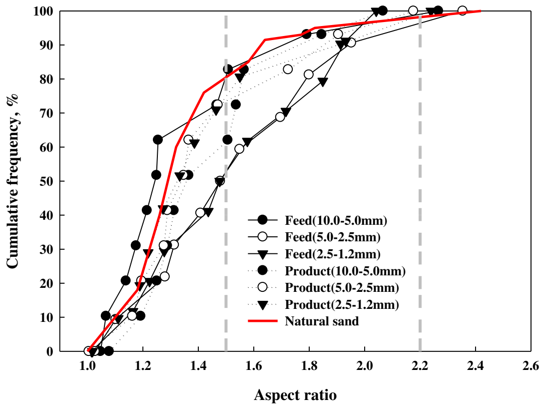


Figure 10. Cumulative frequency of aspect ratio

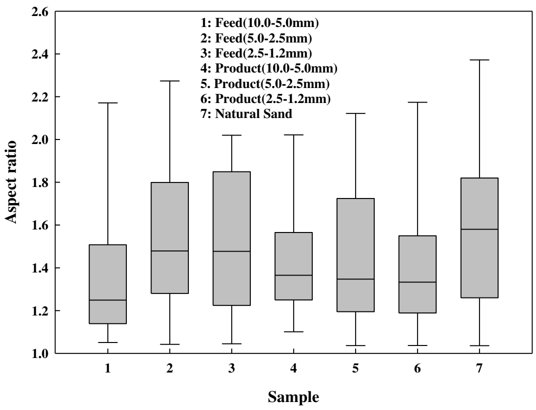


Figure 11. Aspect ratio box plot

4.3.VSI crusher DEM simulation

The crushing process uses the most energy in the recycling process can be improved through optimal design and operating conditions, increasing the economic feasibility. We confirmed the trends in the data required to set the optimum design and operating conditions of the selected VSI crusher using DEM simulations. We replicated the VSI crusher using CAD, and then conducted simulations after importing it into EDEM, which is a 3D particle dynamics interpretation program based on DEM. In this simulation, we set the length and rotation speed of the impeller as experimental parameters, and the experimental conditions are presented in Table 6. In addition, the physical properties of the WGB and VSI crusher and the aspect ratio of 1.5 of the particles were applied through the aspect ratio analysis.

(a) (b) (c).

Figure 12. EDEM simulation of VSI crusher(a: 0.3 m, b: 0.5 m, c: 0.7 m, rotation speed: 100 rpm).

We measured the force applied to the particle and the total particle numbers in the domain through simulation. The number of particles was measured based on the particles existing in the domain of equal size during the simulation and is presented in Fig 13. The total number of particles in all the conditions reached in a steady state after 7 seconds. In addition, it was found that the greater the length and rotation speed of the impeller, the greater the number of particles in the domain. Among these, the number of particles was more affected more by the length of the impeller than the rotation speed. Based on the above results, we measured the tendency of the force applied to the particle in the simulation results 7 to 10 s. Fig 14 shows the results of the force applied to the particle as particle to particle and particle to the inner wall. In all conditions, the added force from the particle to the particle was higher than the force added through the inner wall to the particle. Thus, the VSI crusher helps evaluate that the crushing rate for collisions among particles is higher than that between particles and inner walls. Fig 15 presents the results of the force applied to the particle according to the length and rotation speed of the impeller. The length of impeller increased from 0.3, 0.5 to 0.7 m, and correspondingly the force applied to the particle increased. The rotation speed of impeller also increased from 1,000, 1,200 to 1,400 rpm, and the force applied to the particle increased accordingly. The greater the length and rotation speed of the impeller, the greater the force applied to the particle, but the length of the impeller was more affected by the force than the rotation speed. Consequently, we confirmed that the VSI crusher is more influenced by the impeller length than by the rotation speed. We assessed the trends in the data obtained in this study to be meaningful. However, in the future, to establish optimum design and operating condition settings, further studies should be conducted.

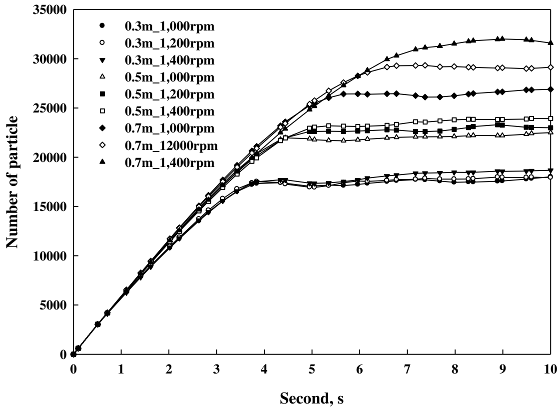


Figure 13. The number of particle in existing domain according to simulation time.

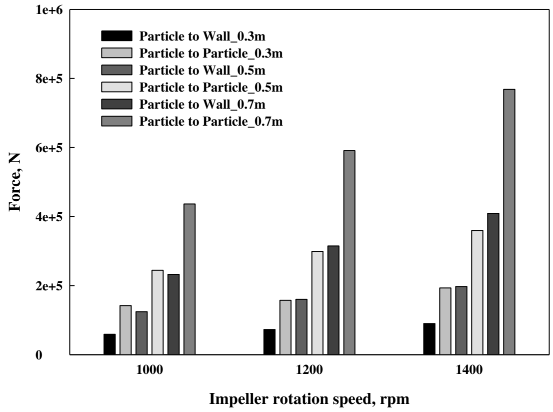


Figure 14. The force applied to the particle according to the method of delivery (Particle to Particle, inner wall to particle).

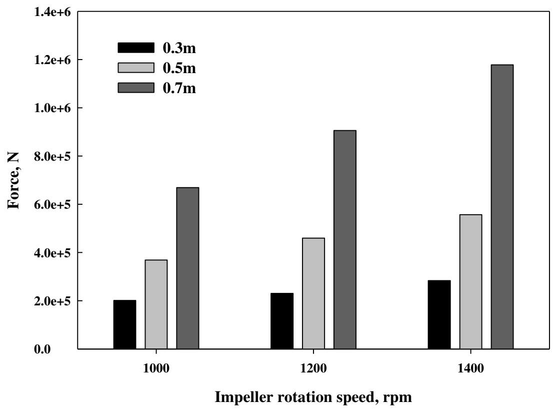


Figure 15. The force applied to the particle according to the length and rotation speed of the impeller.

5. Conclusion

In summary, we presented the optimum process for recycling WGBs into a glass cullet and recycled glass aggregate. To produce a glass cullet, we tested the optimum operating condition selection experiment using a color sorter. For recycling WGB as recycled glass aggregate, we conducted optimum crusher selection, aspect ratio measurements, and a DEM simulation experiment. The findings of this study are summarized as follows. As per various analyses, the sample used in this study was soda glass, which consists of Na_2CO_3, SiO_2, and CaO. To produce glass cullet, the color sorting is essential and removing the glass in the order of amber – green – amber, green is the optimal condition to satisfy the color quality standard. This result indicates that because the RGB value of green and clear inputs were distributed similarly, when green was removed preferentially, the ratio that needs to be removed is increased. The VSI crusher was selected to be the best suited for producing recycled glass aggregate through a crushing experiment. As a result of the aspect ratio analysis, an aspect ratio higher than that of natural sand could be obtained through crushing, and therefore the WGB is suitable for recycling into a glass aggregate. The trend of the number of particles and force of the VIS crusher had a linear relationship with the length and rotation speed of the impeller; of these, the length of the impeller was more affected by the. We assessed that the simulation results provided useful information for establishing the optimum design and operating conditions. In conclusion, this study provides information on the WGB recycling process, and we believe that this result will contribute to increasing the rate of recycling.

Availability of data and materials

All data generated or analyzed during this study are included in this article and its supplementary materials file. The raw data are available from the corresponding author upon reasonable request.

Acknowledgements

The authors wish to thank the Korea Environmental Industry & Technology Institute(KEITI) for the financial support for this work.

Authors' contributions

The corresponding author Hoon Lee has designed the study, and supervised in manuscript. The first author Hansol Lee have conducted lab experiment as well as to write manuscript. The authors read and discussion and approved the manuscript.

Funding

This work was supported by the Korea Environmental Industry & Technology Institute(KEITI) as "The domestic waste recycling technology development project" (No. 2019002750001).

References

1. Yamamoto T, Yasuhara A, Shiraishi H and Nakasugi O. Bisphenol A in hazardous waste landfill leachates. Chemosphere. 2001;42;415-418.
2. Ling HI, Leshchinsky D, Mohri Y and Kawabata T. Estimation of municipal solid waste landfill settlement. Journal of geotechnical and geoenvironmental engineering. 1998;124;21-28.
3. Vrijheid M. Health effects of residence near hazardous waste landfill sites: a review of epidemiologic literature. Environmental health perspectives. 2000;108;101-112.
4. Ministry of Environment. Waste recycling statistics. 2019
5. Korea Environment Corporation. Guidelines for the fulfillment of recycling obligations. 2014
6. Bai J, Yang X, Xu S, Jing W and Yang J. Preparation of foam glass from waste glass and fly ash. Materials Letters. 2014;136;52-54.
7. König J, Petersen RR and Yue Y. Fabrication of highly insulating foam glass made from CRT panel glass. Ceramics International. 2015;41;9793-9800.
8. Chen M, Zhang F-S and Zhu J. Lead recovery and the feasibility of foam glass production from funnel glass of dismantled cathode ray tube through pyrovacuum process. Journal of hazardous materials. 2009;161;1109-1113.

9. Hesky D, Aneziris CG, Groß U and Horn A. Water and waterglass mixtures for foam glass production. Ceramics International. 2015;41;12604-12613.

10. Chen G, Lee H, Young KL, Yue PL, Wong A, Tao T and Choi KK. Glass recycling in cement production—an innovative approach. Waste Management. 2002;22;747-753.

11. Islam GS, Rahman M and Kazi N. Waste glass powder as partial replacement of cement for sustainable concrete practice. International Journal of Sustainable Built Environment. 2017;6;37-44.

12. Polley C, Cramer SM and Cruz RVdl. Potential for using waste glass in Portland cement concrete. Journal of materials in Civil Engineering. 1998;10;210-219.

13. Vijayakumar G, Vishaliny H and Govindarajulu D. Studies on glass powder as partial replacement of cement in concrete production. International Journal of Emerging Technology and Advanced Engineering. 2013;3;153-157.

14. Jin W, Meyer C and Baxter S. " Glascrete"-Concrete with Glass Aggregate. ACI Materials Journal. 2000;97;208-213.

15. Idir R, Cyr M and Tagnit-Hamou A. Use of fine glass as ASR inhibitor in glass aggregate mortars. Construction and Building Materials. 2010;24;1309-1312.

16. Gautam S, Srivastava V and Agarwal V. Use of glass wastes as fine aggregate in Concrete. J. Acad. Indus. Res. 2012;1;320-322.

17. Corinaldesi V, Gnappi G, Moriconi G and Montenero A. Reuse of ground waste glass as aggregate for mortars. Waste Management. 2005;25;197-201.

18. Kou S and Poon CS. Properties of self-compacting concrete prepared with recycled glass aggregate. Cement and Concrete Composites. 2009;31;107-113.

19. Shao Y, Lefort T, Moras S and Rodriguez D. Studies on concrete containing ground waste glass. cement and concrete research. 2000;30;91-100.

20. Park S-B and Lee B-C. Studies on expansion properties in mortar containing waste glass and fibers. cement and concrete research. 2004;34;1145-1152.

21. Lu J-x, Duan Z-h and Poon CS. Combined use of waste glass powder and cullet in architectural mortar. Cement and Concrete Composites. 2017;82;34-44.

22. Du H and Tan KH. Use of waste glass as sand in mortar: Part II–Alkali–silica reaction and mitigation methods. Cement and Concrete Composites. 2013;35;118-126.

23. Tan KH and Du H. Use of waste glass as sand in mortar: Part I–Fresh, mechanical and durability properties. Cement and Concrete Composites. 2013;35;109-117.

24. Lu J-X and Poon CS. Use of waste glass in alkali activated cement mortar. Construction and Building Materials. 2018;160;399-407.
25. Korea standard. KSF2527 notice.2018.
26. Lee H, Kim K, Kim J, You K and Lee H. Breakage characteristics of heat-treated limestone determined via kinetic modeling. Minerals. 2018;8;18.
27. Lee H. Optimization of Color Sorting Process of Shredded ELV Bumper using Reaction Surface Method. J. of Korean Inst. of Resources Recycling. 2019;28;23-30.
28. Gupta A, Yan D. Mineral processing design and operation. 2dn ed. Oxford: El sevier; 2016
29. British Standards Institution. Part 1. Methods for determination of particle size and shape. London; 1975.
30. Zingg T. Beitrage zur schotteranalyse: Schweizerische Mineralogische und Petrographische Mitteilungen. Swiss Bulletin of Mineralogy and Petrology. 1935;15;38-139.

Table 1 Particle size distribution used raw sample in this study

Sieve size(mm)	10.0	5.0	2.5	1.2	0.6	0.3	0.15
Cumulative weight percent, %	100.0	52.8	19.9	8.1	4.4	2.4	1.3

Table 2 Analysis equipment information

Analysis	Company	Model
X-ray diffraction	PHILIPS	X'Pert MPD
X-ray fluorescence	Shimadzu	XRF-1800
Scanning electron microscope	HITACHI	TM3000
Energy dispersive X-ray spectrometer	OXFORD	SwiftED3000

Table 3 The major chemical component of sample(wt %)

Sample \ Component	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	TiO_2	MnO	P_2O_5	Ig.Loss
1	72.33	1.84	0.30	8.92	1.54	0.69	12.84	0.07	0.02	0.02	0.44
2	72.41	1.94	0.36	8.69	1.68	0.71	12.85	0.07	0.01	0.03	0.41

Table 4 The key specifications and experiment conditions of crusher

<table>
<tr><td rowspan="2">Shredder</td><td colspan="2">Rotation speed</td><td colspan="2">Capacity</td><td colspan="2">Motor power</td></tr>
<tr><td colspan="2">30 rpm</td><td colspan="2">0.0 Ton/h</td><td colspan="2">1.5 kW</td></tr>
<tr><td rowspan="2">Roll crusher</td><td>Rotation speed</td><td colspan="2">Capacity</td><td colspan="2">Roll diameter</td><td>Roll gap</td></tr>
<tr><td>280 rpm</td><td colspan="2">2 Ton/h</td><td colspan="2">254 mm</td><td>2.5 mm</td></tr>
<tr><td rowspan="2">Hammer crusher</td><td>Rotation speed</td><td colspan="2">Capacity</td><td colspan="2">Motor Power</td><td>number X length</td></tr>
<tr><td>2,800 rpm</td><td colspan="2">0.25 Ton/h</td><td colspan="2">2.2~3.7 kW</td><td>20 ea X 250 mm</td></tr>
<tr><td rowspan="2">VSI crusher</td><td colspan="2">Rotation speed</td><td colspan="2">Capacity</td><td colspan="2">Motor power</td></tr>
<tr><td colspan="2">1,000 rpm</td><td colspan="2">100 Ton/h</td><td colspan="2">150 kW</td></tr>
</table>

Table 5. Recycled glass aggregate particle size distribution quality standard

Particle size, mm	10 mm	5 mm	2.5 mm	1.2 mm	0.6 mm	0.3 mm	0.15 mm
Percentage of mass through sieve, %	100	90~100	80~100	50~90	25~65	10~35	2~15

Table 6. VSI crusher simulation conditions

Impeller length / Impeller speed	0.3 m	0.6 m	0.9 m
1,000 rpm	1	4	7
1,200 rpm	2	5	8
1,400 rpm	3	6	9