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# PROPERTIES OF CONCRETE USING CRUSHED STONE POWDER WITH VARIOUS SPECIFIC SURFACE AREAS

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Abstract. Many countries use crushed stone and crushed sand as the aggregate for concrete. However, a large amount of crushed stone powder is produced as by-products in the manufacturing process. Unless effective utilization of crushed stone powder is considered, it is not a sufficient measure in terms of sustainability. In this study, the properties of concrete using crushed stone powders with different specific surface areas are investigated. As the results, a strong correlation was found between the unit water content of concrete and the total surface area of the crushed stone powder contained in the concrete. Furthermore, it was concluded that the correlation between the strength index, the $CO_2$ index, and the virgin resource index of concrete using crushed stone powder depends on the types of crushed stone powder and crushed sand.

Keywords: Crushed stone powder, fine aggregate, fresh concrete, hardened concrete, specific surface area.

## 1. Introduction

Crushed stone and crushed sand are often used as the aggregate for concrete in many countries. In the future, concrete aggregates would rely on crushed stone and crushed sand because natural aggregate, such as sea sand is probably prohibited from collecting. The production methods of crushed stone and crushed sand are classified into two types, such as a dry process type and a wet process type. In the dry process type, a large quantity of crushed stone powder is simultaneously produced as by-products. The Japan Crushed Stone Association estimates that 12 million tons of crushed stone powder are produced annually. In the wet process type, although crushed stone powder and clay fraction can be removed, sludge water and a dehydrated cake must be disposed. In recent years, the dry process type has become more popular because of its production efficiency and ease of handing waste disposal [1]. However, unless effective utilization of crushed stone powder is considered, a part of the natural resources will be unused, which is not a sufficient measure from the perspective of sustainability. In the world, studies on the effective use of crushed stone powder in concrete have been carried out, but they are few [2, 3].

In 2009, the quality requirements of crushed stone powder were standardized by the Japanese Industrial Standards, JIS A 5041. However, no specification is available on the specific surface area of the crushed stone powder. The authors studied the fluidity of mortar using crushed stone powders with various specific surface areas [4]. They found that the water-cement ratio of mortar has a high influence on the fluidity of mortar with the crushed stone powder and, if the crushed stone powder with a large specific surface area is used, the fluidity of the mortar decreases. However, these findings are limited to mortar. The properties of concrete using crushed stone powders are not clear.

In this study, the properties of the fresh and hardened concrete using crushed stone powders with various specific surface areas were examined. Furthermore, $CO_2$ emission and the amount of virgin resource input for each concrete mix were estimated.

## 2. Manufacturing of crushed sands and crushed stone powders

Figure 1 shows the simplified flow chart of the production processes of crushed sand and crushed stone powder in this study. In the dry process type, crushed stone powder Type A and crushed sand DS are produced at first. Then crushed stone powder Type A is sorted by specific surface area as Type B and Type C. DS contains crushed stone powder Type D. DS150 is produced by removing crushed stone powder of 150 $\mu$m or less contained in DS. In the wet process

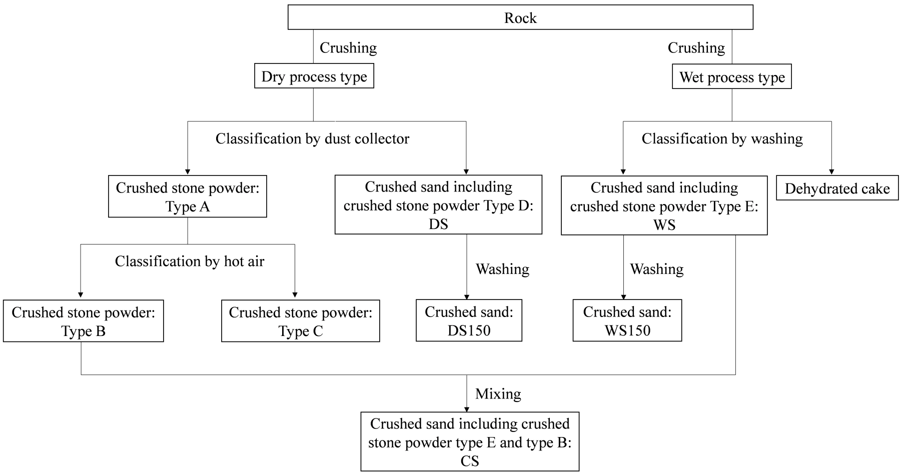


Figure 1. Production processes of crushed sands and crushed stone powders.

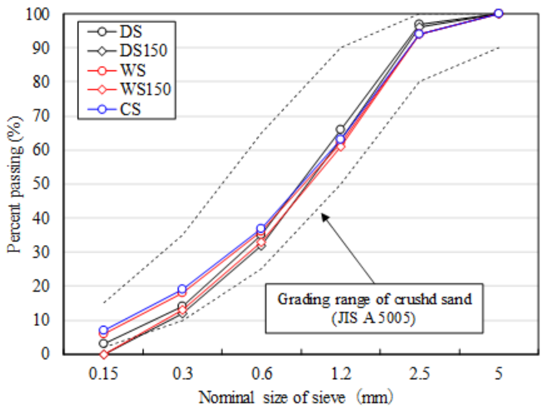


Figure 2. Grain size accumulation curve of crushed sand.

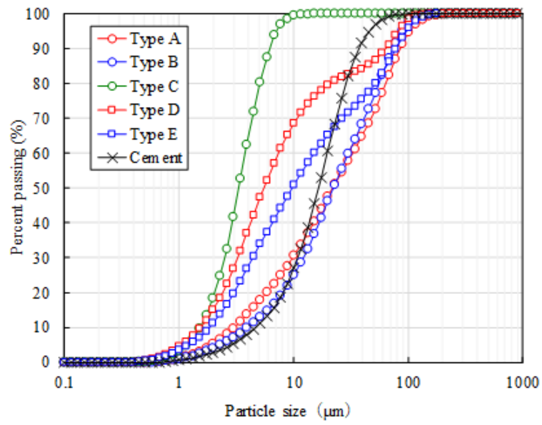


Figure 3. Grain size accumulation curve of crushed stone powder .

type, crushed sand WS and a dehydrated cake are produced. The dehydrated cake is, however, not the target of this study. WS contains crushed stone powder Type E. WS150 is produced by removing crushed stone powder of 150 $\mu$m or less contained in WS. Finally, the crushed sand CS is produced by mixing WS and crushed stone powder Type B.

In this study, the effect of the combination of crushed stone powder and crushed sand on the properties of concrete is examined. Table 1 gives the types and physical properties of crushed sand and crushed stone powder.

## 3. Outline of experiment

### 3.1. Materials

Table 1 gives the types and physical properties of concrete materials used in this study. As mentioned earlier, in this experiment, two types of dry type crushed sand, three types of wet type crushed sand, and five types of crushed stone powder were used. The specific surface area of crushed stone powder was measured using a laser diffraction particle size analyzer. The specific surface area of the crushed stone powder was in the range from 6360-22337 cm$^2$/g. Figures 2 and 3 show the grain size accumulation curves of crushed sand and crushed stone powder, respectively. The particle size of crushed stone powder is less than 150 $\mu$m as per JIS A 5041.

### 3.2. Production and mix proportions of concrete

A total of 12 mixtures were planned to produce. Concrete was produced in a laboratory at a temperature of 20 řC with a 60 L twin-shaft batch mixer. Cement, fine aggregate, crushed stone powder, and coarse aggregate were first dry mixed for 15 seconds, and then further mixed for 90 seconds after adding water and chemical admixture. The water-cement ratio (W/C) was 60% for all the mixtures. The amount of air entraining (AE) water reducing agent was 1.2% to cement mass. Table 2 lists the mix proportions of the concrete. When mixing concrete, the slump target was $12.0 \pm 2.0$ cm and air content target was $4.5 \pm 1.0$%; the slump and air content were adjusted based on the unit quantities of water and AE agent, respectively.

| Materials | Type | Symbol | Physical properties |
|---|---|---|---|
| Water | Tap water | W | Density: 1.00 g/cm$^3$ |
| Cement | Ordinary portland cement | C | Density: 3.16 g/cm$^3$,<br>Specific surface area: 6315 cm$^2$/g (3300 cm$^2$/cm$^3$)<br>Arithmetic average particle diameter: 19.4 $\mu$m |
| Fine aggregate | Crushed sand (Dry type) | DS | Density: 2.62 g/cm$^3$, Absorption: 1.80%, Finess modulus: 2.85<br>Content of 75 $\mu$m or less: 4.0%<br>Content of 150 $\mu$m or less: 8.0% |
| | | DS150 | Density: 2.66 g/cm$^3$, Absorption: 1.48%, Finess modulus: 2.97<br>Content of 75 $\mu$m or less: 0%<br>Content of 150 $\mu$m or less: 0% |
| | Crushed sand (Wet type) | WS | Density: 2.65 g/cm$^3$, Absorption: 1.76%, Finess modulus: 2.84<br>Content of 75 $\mu$m or less: 2.3%<br>Content of 150 $\mu$m or less: 7.8% |
| | | WS150 | Density: 2.66 g/cm$^3$, Absorption: 1.42%, Finess modulus: 2.99<br>Content of 75 $\mu$m or less: 0%<br>Content of 150 $\mu$m or less: 0% |
| | | CS | Density: 2.63 g/cm$^3$, Absorption: 1.79%, Finess modulus: 2.80<br>Content of 75 $\mu$m or less: 5.0%<br>Content of 150 $\mu$m or less: 9.1% |
| | Crushed stone powder | Type A | Density: 2.684 g/cm$^3$<br>Specific surface area: 7120 cm$^2$/g<br>Arithmetic average particle diameter: 35.2 $\mu$m |
| | | Type B | Density: 2.682 g/cm$^3$<br>Specific surface area: 6460 cm$^2$/g<br>Arithmetic average particle diameter: 31.9 $\mu$m |
| | | Type C | Density: 2.687 g/cm$^3$<br>Specific surface area: 22337 cm$^2$/g<br>Arithmetic average particle diameter: 3.6 $\mu$m |
| | | Type D | Density: 2.783 g/cm$^3$<br>Specific surface area: 16825 cm$^2$/g<br>Arithmetic average particle diameter: 17.2 $\mu$m |
| | | Type E | Density: 2.772 g/cm$^3$<br>Specific surface area: 12914 cm$^2$/g<br>Arithmetic average particle diameter: 25.8 $\mu$m |
| Coarse aggregate | Sand stone | G1 | Maximum size: 20 mm, Density: 2.70 g/cm$^3$<br>Absorption: 0.47%, Finess modulus: 7.08 |
| | | G2 | Maximum size: 15 mm, Density: 2.69 g/cm$^3$<br>Absorption: 0.76%, Finess modulus: 6.35 |
| Chemical admixture | AE water reducing agent | – | Complex of lignin-sulfonic-acid compound and polycarboxylic acid ether |
| | AE agent | – | Denatured rosin acid compound-system anionic surface active agent |

Table 1. Constituent materials of concrete.

| No. | W/C [%] | W | C | DS 150 | WS | DS 150 | WS | CS | Type B | Type C | G1 | G2 | AE water reducing agent [kg/m$^3$] | AE agent [kg/m$^3$] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Quantity of material per unit volume of [kg/m$^3$] | | | | | | | | | | | | |
| 1 | 60 | 162 | 270 | 872 | - | - | - | - | - | - | 410 | 613 | C×1.2% | 0 |
| 2 | | 162 | 270 | - | 872 | - | - | - | - | - | | | | 0 |
| 3 | | 165 | 275 | - | - | 846 | - | - | - | - | | | | 0.275 |
| 4 | | 168 | 280 | - | - | - | 844 | - | - | - | | | | 0.280 |
| 5 | | 165 | 275 | - | - | - | - | 850 | - | - | | | | 0.138 |
| 6 | | 165 | 275 | - | - | - | 830 | - | 26 | - | | | | 0.413 |
| 7 | | 170 | 283 | - | - | 777 | - | - | 51 | - | | | | 0.992 |
| 8 | | 165 | 275 | - | - | - | 805 | - | 52 | - | | | | 0.668 |
| 9 | | 168 | 280 | - | - | - | - | 787 | 51 | - | | | | 0.980 |
| 10 | | 173 | 288 | - | - | 766 | - | - | - | 50 | | | | 1.009 |
| 11 | | 170 | 283 | - | - | - | 786 | - | - | 51 | | | | 0.992 |
| 12 | | 180 | 300 | - | - | 668 | - | - | - | 118 | | | | 1.500 |

TABLE 2. Mix proportions of concrete.

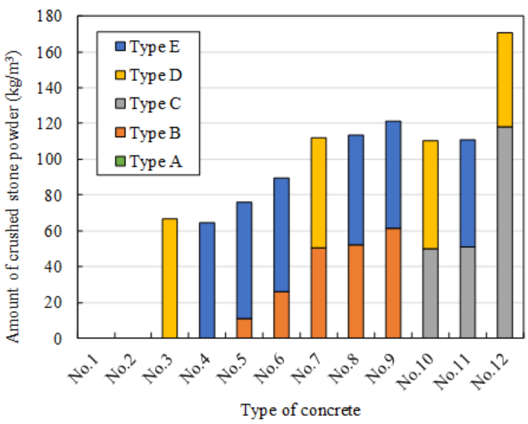


FIGURE 4. Amount of crushed stone powder of 150 $\mu$m or less for each mix proportion.

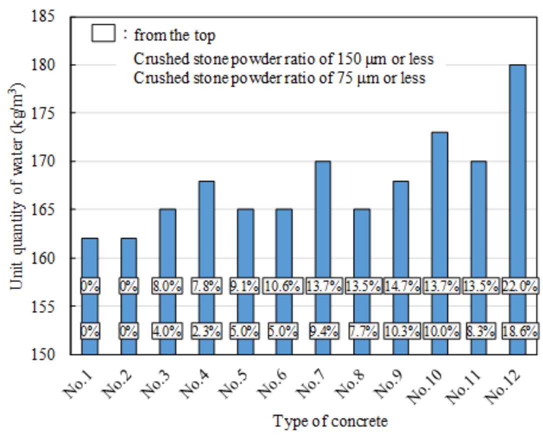


FIGURE 5. Unit water content of each mix proportion.

Figure 4 shows the amount of crushed stone powder of 150 $\mu$m or less for each mix of concrete. The amounts of crushed stone powder for each mix proportion were in the range of $0 - 170.5$ kg/$m^3$. They are included the amount of crushed stone powder in the crushed sand as well. Figure 5 shows the unit water content of each mix proportion. In addition, this figure shows the crushed stone powder ratios of 150 $\mu$m or less and 75 $\mu$m or less. The crushed stone powder ratio is defined in this study as the ratio of the absolutely dry mass of crushed stone powder mass to that of the fine aggregate.

### 3.3. TEST METHODS FOR PROPERTIES OF CONCRETE

For fresh concrete, slump, air content, and bleeding were measured as per JIS A 1101, A 1128, and A 1123, respectively. For hardened concrete, compressive strength and Youngs modulus were measured as per JIS A 1108 and A 1149, respectively. The shape of the specimens used for the test of hardened concrete is a cylinder with a diameter of 100mm and a height of 200mm. The number of samples in the test at each age is three.

## 4. RESULTS AND DISCUSSIONS

### 4.1. UNIT WATER CONTENT

Figure 6 shows the relationship between the crushed stone powder ratios of 150 $\mu$m or less and 75 $\mu$m or less and the unit water contents. A correlation exists between the crushed stone powder ratios and the unit water content. The unit water content is specified as 175 kg/m$^3$ or less in the Standard Specifications for Concrete Structures (Japan Society of Civil Engineers (JSCE)). The fine particle content of 75 $\mu$m or less is specified as 9% or less in JIS A 5005. These results indicate that the crushed stone powder ratio of 75 $\mu$m or less should be less than 15% to satisfy the JSCE specifications. Therefore, it has been suggested

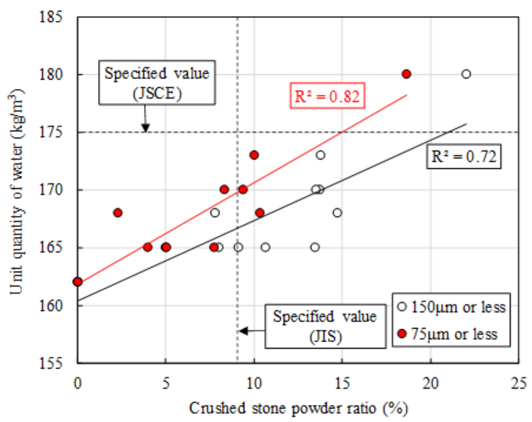


Figure 6. Relationship between crushed stone powder ratio and unit quantity of water.

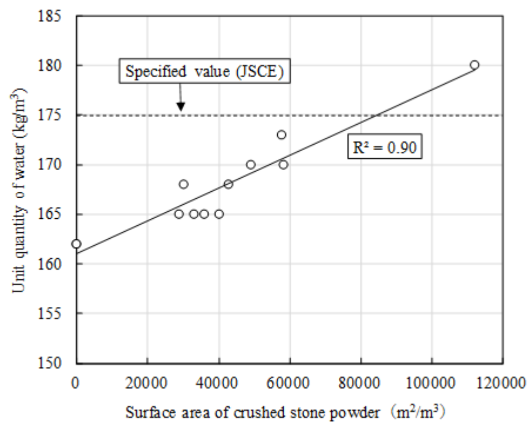


Figure 7. Relationship between surface area of crushed stone powder and unit quantity of water.

that the specification of JIS A 5005 (9%) of the fine particles content can be moderated for concrete.

In this study, the total surface area of the crushed stone powder with particle sizes of 150 $\mu$m or less was calculated, and the relationship between the total surface areas of the crushed stone powder and the unit water content is shown in Figure 7. It was found that the total surface areas of crushed stone powder have a stronger relationship than the crushed stone powder ratio because the determination coefficient is improved. Therefore, it can be concluded that the specific surface area of the crushed stone powder is an effective index for evaluating the fluidity of concrete.

## 4.2. Amount of AE agent

Figure 8 shows the relationship between the amount of AE agent and the crushed stone powder ratio. The amount of AE agent increases with increase in the crushed stone powder ratio. It is well known that air is difficult to be entrained when concrete has fine particles of 0.15 mm or less. The results of this study confirms it.

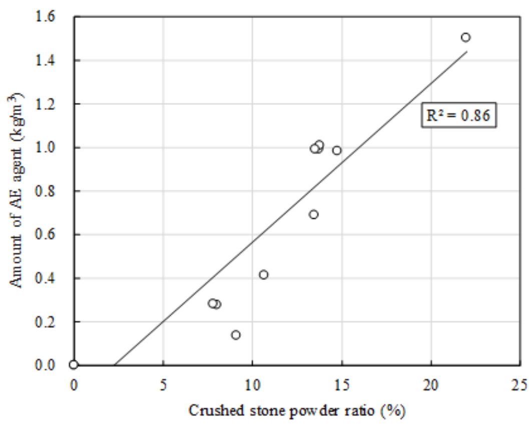


Figure 8. Amount of AE agent.

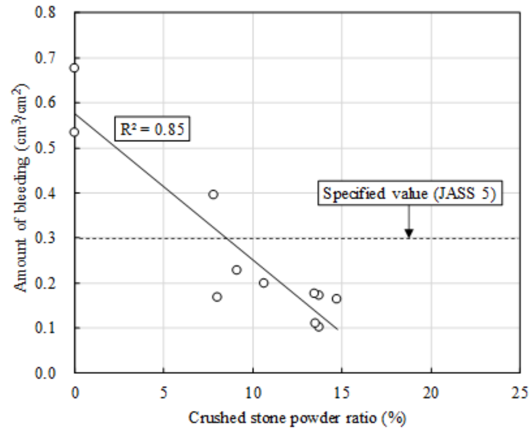


Figure 9. Amount of bleeding.

## 4.3. Amount of bleeding

Figure 9 shows the relationship between the amount of bleeding and the crushed stone powder ratio. To ensure the water-tightness of concrete, the amount of bleeding is specified as 0.3 cm$^3$/cm$^2$ or less by the Japanese Architectural Standard Specification 5 (JASS 5) [5]. The experimental results indicate that the amount of bleeding is 0.3 cm$^3$/cm$^2$ when the crushed stone powder is 8.5%. Based on this result, controlling the amount of crushed stone powder is required to reduce bleeding.

## 4.4. Compressive strength and Young's modulus

Figure 10 shows the relationship between the crushed stone powder ratio and the compressive strength of concrete. This figure indicates that the compressive strength decreases with increase in the crushed stone power ratio. When the crushed stone powder is used, the compressive strength decreases by up to 21.4% and by 20.0% at 7 days and 28 days, respectively.

Figure 11 shows the relationship between the compressive strength and the Young's modulus of concrete. This figure also shows the calculated results using the equation specified in the JSCE Standard

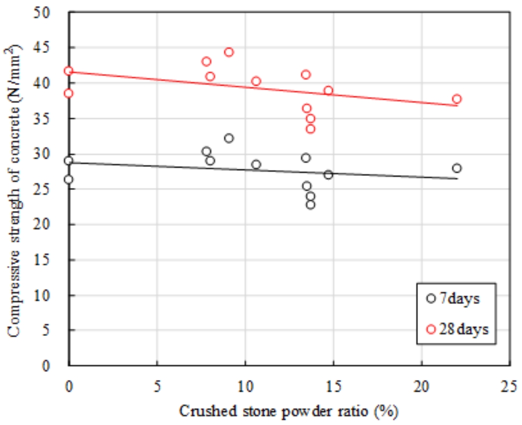


Figure 10. Compressive strength.

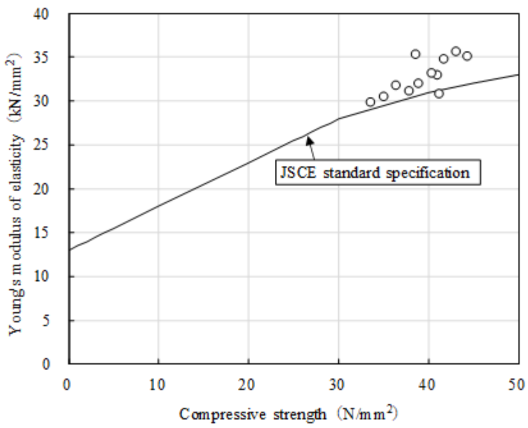


Figure 11. Relationship between Young's modulus and compressive strength.

Specifications for Concrete Structures [6]. The ratio of the experimental value to the calculated value of the Young's modulus of concrete were in the range 0.99 to 1.15. It can be said that the calculated results estimate the experimental results well almost appropriately.

## 5. Environmental assessment

### 5.1. Outline

The importance of sustainability has recently been emphasized in the concrete industry [7]. Sustainability is considered from the following three aspects: social, economic, and environmental. In the future, all technologies in the concrete industry will be evaluated from the perspective of sustainability; thus, all technologies in the concrete industry must be advanced based on the above-mentioned three sustainability aspects. In particular, reducing $CO_2$ emissions is currently an urgent issue in the world. In this study, the effect of using the crushed stone powder is evaluated from the perspective of sustainability, such as safety in terms of compressive strength and environmental performance in terms of $CO_2$ emissions and virgin resource input.

### 5.2. Calculation methods

The amounts of $CO_2$ emissions and virgin resource input for each mix proportion were calculated. The inventory data relating to the $CO_2$ emissions are obtained from "Environment text of concrete (Draft)" [8]. Table 3 gives the unit-based $CO_2$ emissions in this study. This study additionally considered $CO_2$ emissions associated with kerosene consumed in the mixing and classification of crushed stone powder. However, the $CO_2$ emissions associated with electricity was not considered, because the breakdown of the quantity of electricity has not been clarified.

The amount of virgin resource input was determined by multiplying the virgin resource input ratio of each material by a unit amount per 1 m3 of concrete. The virgin resource input ratio of cement

| Items | Unit-based $CO_2$ emissions |
|---|---|
| Water | 0.348 kg-$CO_2$/m$^3$ |
| Cement | 769 kg-$CO_2$/t |
| Crushed sand | 3.9 kg-$CO_2$/t |
| Kerosene | 2.50 kg-$CO_2$/L |

Table 3. $CO_2$ emission unit.

is 0.811 [9], and that of crushed stone powder A, B, and C is 0 because they are by-products that can be discarded. The virgin resource input ratios of the other materials are set at 1.0.

### 5.3. Amounts of $CO_2$ emissions and virgin resource input

Figure 12 and 13 show the amounts $CO_2$ emissions and the virgin resource input, respectively. The $CO_2$ emissions increase with increase in the crushed stone powder, because kerosene is consumed to produce the crushed stone powder. In contrast, the amount of virgin resource input decreases with increase in the crushed stone powder. The amount of $CO_2$ emissions and the virgin resource input were in the range of 215 – 244 kg-$CO_2$/m$^3$ and 2115 – 2276 kg/m$^3$, respectively.

### 5.4. Sustainability evaluation

Figure 14 shows an example of the correlation between the strength index, $CO_2$ index, and virgin resource index. Each index was defined based on the respective values of the reference concrete (No.1 mix proportion). The larger the area of the triangle, the higher the overall performance.

The results indicate that the relationships between the strength index, $CO_2$ index, and virgin resource index of concrete using the crushed stone powder depend on the types of crushed stone powder and crushed sand. It is concluded that evaluation from the perspective of environmental sustainability is also important for the mix proportion design of concrete using crushed stone powder. In addition, further data

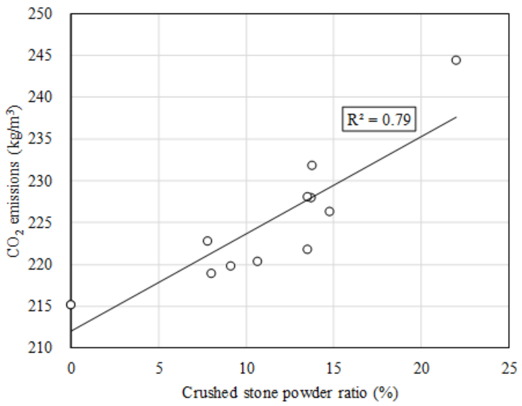


Figure 12. $CO_2$ emissions.

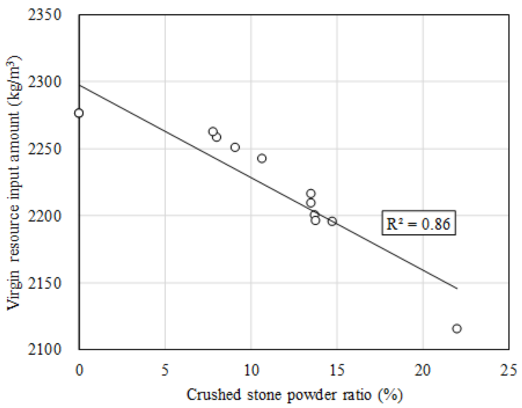


Figure 13. Amount of virgin resource input.

accumulation is needed to generalize the various performances of the combinations of the specific surface area of crushed stone powder and the type of crushed sand.

## 6. Conclusions

The following conclusions were drawn from this study:

- The specific surface area of crushed stone powder greatly affects the fluidity of concrete.
- Increasing the mixing ratio and the surface area of the crushed stone increase the unit water content of the concrete. However, controlling the amount of crushed stone powder is necessary for reducing the bleeding of concrete.
- Using crushed stone powder decreases the compressive strength of concrete up to 21.4
- The crushed stone powder reduces, the virgin resource input, but increases the $CO_2$ emissions.
- The relationships between the strength index, $CO_2$ index, and virgin resource index of concrete using crushed stone powder depend on the type of crushed stone powder and crushed sand.

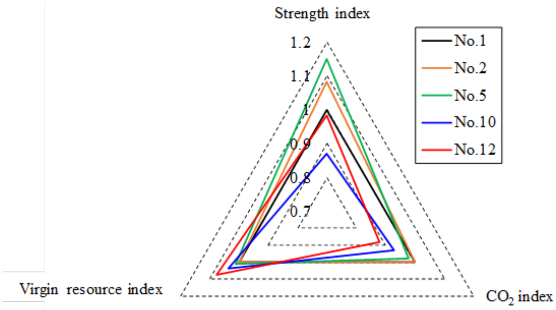


Figure 14. Sustainability evaluation.

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