Journal of Asian Concrete Federation
Vol. 8, No. 2, pp. 9-22, Dec. 2022
ISSN 2465-7964 / eISSN 2465-7972
DOI http://dx.doi.org/10.18702/acf.2022.12.8.2.9


**Technical Paper**

# Development of 100-MPa green reactive powder concrete using 100% recycled aggregates

**Undram Naidanjav*, Munkhtuvshin Ochirbud, Donguk Choi**
(Received April 11, 2022; Revised October 20, 2022; Accepted November 08, 2022; Published December 31, 2022)

**Abstract:** Reactive powder concrete (RPC) utilizing recycled resources such as silica fume, fly ash, waste glass powder, and recycled fine aggregates (RFA) was developed based on an experimental packing density methodology. Primary aim was to develop 100-MPa grade RPC using 100% RFA. Two different mix series were studied: First series (Series 1) was a control group and used conventional ingredients: ordinary Portland cement (OPC), silica fume, and silica sand. Second series (Series 2) also used OPC and, in addition, heavily utilized recycled resources such as silica fume, fly ash, waste glass powder, and RFA. Chemical admixtures (superplasticizer and defoaming agent) were used in all mixes. From Series 1, 100-MPa grade RPC was developed at water-binder ratio (w/b) = 0.22. From Series 2, the comparable strength grade RPC was developed at w/b = 0.18. It is shown that environmental-friendly RPCs can be systematically fabricated using 100% recycled sand and up to 30% substitutive cementitious materials.

**Keywords:** Reactive powder concrete, Recycled fine aggregates, Waste glass powder, Packing density.

## 1. Introduction

Reactive powder concrete (RPC) is a type of ultra-high-performance concrete with high strength and low porosity. Because RPC typically has very dense structure, it also has excellent durability. RPC is often composed of fine powders such as Portland cement, various cementitious materials, silica sand, quartz powder, and steel fibers [1]. The recycling of waste materials today toward its efficient reuse has a huge positive impact on the environment. For the RPC, $CO_2$ emission is high due to high cement content. Many constituent materials used to produce RPC such as silica fume, silica sand, and quartz powder are often expensive. To reduce the environmental impact of RPC, the substitutive cementitious materials can be extensively used such as silica fume, fly ash, ground granulated blast furnace slag, etc. Also, recycled sand produced from construction and demolition waste may be utilized for the development of eco-friendly high-strength cementitious composites [2-6]. Mao et al. [4] reported fabrication of green RPC using up to 30% replacement of natural sand with recycled powder. Salahuddin et al. [5] reported that 108 MPa RPC was successfully fabricated using partial replacement (up to 50% replacement) of natural sand with recycled sand, but the strength degraded at 75% replacement.

Existing studies on the packing density of concretes provide a powerful tool for the researchers to design high-strength and ultra-high-strength cementitious composites. For the mix design, the packing characteristics of all constituent materials such as Portland cement, substitutive cementitious materials, and aggregates are approached in a scientific way to reach an optimal combination of these materials that results in the minimum void ratio (or maximum solid ratio). Another important factor is the presence of the optimum amount of water which should lubricate the solid constituents. Stovall et al. [7] proposed the linear packing density model (LPDM) for granular mixtures which has shown good performance in determining the optimal proportions of cementitious mortars and concretes. Richard and Cheyrezy [1] suggested the removal of coarse aggregates to optimize the granular mix that allows a homogeneous and dense cement matrix with high mechanical performance. They also suggested that the main parameter for assessing the quality of the granular mixture is its water demand: i.e. The minimum quantity of water must be added to the powders to obtain fluidification. Zhang et al. [2] studied the green RPC with compressive strength of 200 MPa which was successfully prepared by utilizing composite mineral admixtures consisting of 10% silica fume, 25% fly ash, and 25% slag to

***Corresponding author Undram Naidanjav** *is a Research Scholar at Hankyong National University, Anseong, 17579, South Korea.*

**Munkhtuvshin Ochirbud** *is Researcher at Hankyong National University, Anseong, 17579, South Korea*

**Donguk Choi** *is NRF Research Professor, Hankyong National University, Anseong, 17579, South Korea*

replace Portland cement. Agharde and Bhalchandra [3] studied the mechanical properties of RPC made using fly ash. The study was performed to verify the effect of replacing silica fume by fly ash to achieve economy without any significant change in the properties of RPC. They found that the replacement of fly ash up to 40% was economical to achieve high compressive strength up to 90 MPa. Dawood et al. [6] reported the use of supplementary cementitious materials such as crushed glass, steel slag, and silica fume that has resulted in many advantages such as the reduction of the solid waste materials and production of the eco-friendly RPC. They studied the use of 8% of glass powder, 12% of slag, and 10% of silica fume as a partial replacement of cement in combination with suitable chemical admixture that allowed a reduction of the cement content by as much as 30%.

In the current study, authors developed 100-MPa grade green RPC that utilized recycled resources such as silica fume which is by-product of ferrosilicon alloy production, waste glass powder manufactured by crushing and fine grinding waste glass bottles, type-F fly ash which is a by-product of coal-burning power plant, and recycled sand made from waste concrete satisfying KS F 2573 [8]. In this study, the optimal mixture design was determined by an experimental packing density methodology suggested by Li and Kwan [9]. The purpose of this study was to systematically develop environmental-friendly RPC of 100-MPa grade that used 100% recycled sand which also significantly utilized the substitutive cementitious materials such as silica fume, fly ash, and waste glass powder. It is stressed that, to author's knowledge, no attempts have been reported to fabricate a green 100-MPa grade RPC with 100% replacement of natural sand with recycled sand.

## 2. Materials and test methods

### 2.1 Mixture constituents

Ordinary Portland cement (OPC) conforming to KS L 5201 [10] (42.5 MPa grade), silica fume (SF), and waste glass powder (WGP) were used in all mixes in Series 1 while fly ash was also utilized for Series 2. One purpose of including the fly ash in Series 2 was to utilize the additional byproduct material to develop an environmental-friendly RPC. The other purpose was to improve workability of the fresh mortars with the ball-bearing effect provided by the perfectly spherical morphology of fly ash. Chemical composition of all binder materials was examined using the X-ray fluorescence spectrometer (XRF) as shown in Table 1. Fine waste glass powder (WGP) with the mean particle size of 12.5 μm, produced by fine grinding waste glass bottles, was utilized in all mixes in this study [11]. Scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) were also used for the determination of the morphology and the chemical composition of WGP, which is a relatively new material for application to RPC, as shown in Fig. 1. The specific gravity of the OPC, SF, WGP, and fly ash is 3.15, 2.22, 2.5, and 2.5, respectively. The particle size of OPC and all cementitious materials were determined by laser particle size distribution analyzer as shown in Fig. 2.

Two different fine aggregates were used: Silica sand (SS) and recycled fine aggregates (RFA). Bulk specific gravity (BSG), water absorption, dry rodded unit weight, % passing 0.08 mm sieve, and fineness modulus (FM) of the fine aggregates were determined following KS F 2504 [12], as shown in Table 2. In Table 2, it is seen that the $BSG_{SSD}$ of SS and RFA is 2.67 and 2.52, and the water absorption is 0.46% and 2.63% for SS and RFA, respectively. The low density and the high absorption of RFA are due to the fact that the RFA includes adhered mortar from original concrete which cannot be completely removed during the manufacturing process of the recycled aggregates. It is well known that the adhered mortar impedes bond between the matrix and the aggregates and reduces strength of concretes including the recycled aggregates [13].

Table - 1. Chemical composition of binder materials determined by XRF

| Materials | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | CaO | MgO | $SO_3$ | LOI |
|---|---|---|---|---|---|---|---|
| OPC | 20.79 | 4.833 | 3.339 | 59.751 | 2.813 | 2.507 | 4.31 |
| Silica fume | 92.6 | 0.359 | 0.964 | 0.952 | 1.03 | 0.805 | -- |
| Waste glass powder | 68.5 | 2.26 | 0.399 | 10.7 | 1.76 | 0.089 | -- |
| Fly ash | 66.235 | 20.447 | 4.715 | 2.528 | 0.991 | -- | 2.21 |

Table - 2. Physical properties of silica sand and recycled fine aggregate

| Type | $BSG_{SSD}$ | $BSG_{OD}$ | Water absorption (%) | Unit weight (kg/m$^3$) | FM | % Passing 0.08 mm sieve |
|---|---|---|---|---|---|---|
| Silica sand | 2.67 | 2.66 | 0.46 | 1503 | 2.15 | 0.046 |
| RFA | 2.52 | 2.45 | 2.63 | 1469 | 2.66 | 3.782 |

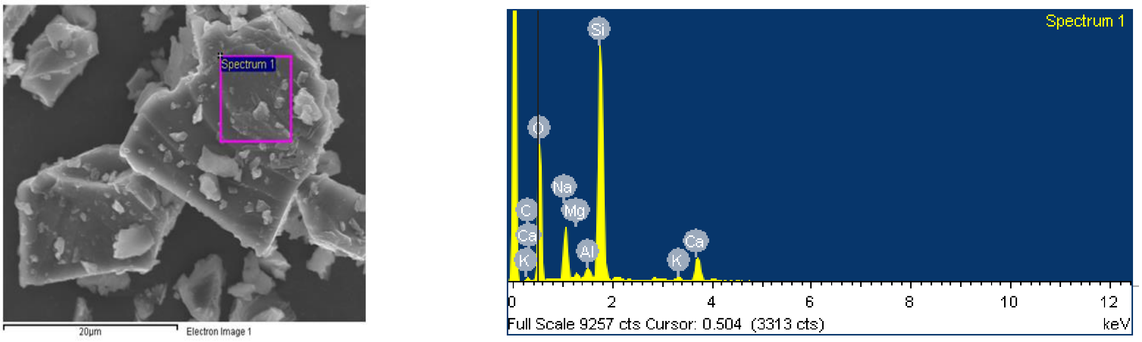



Fig. 1: SEM image and EDS of waste glass powder

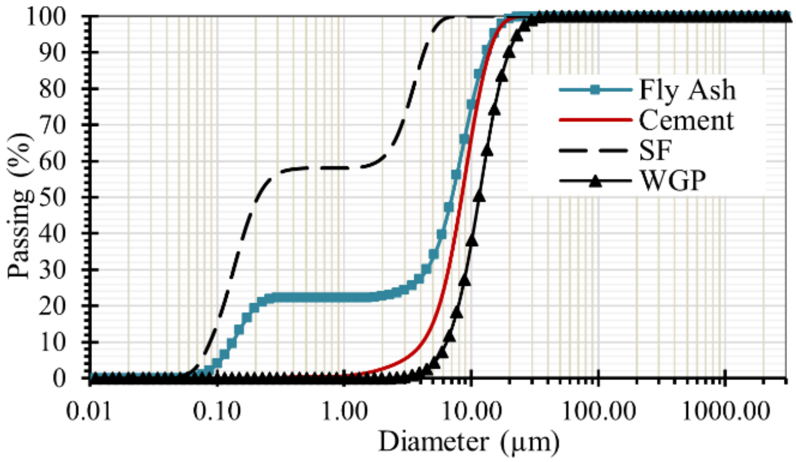



Fig. 2: Particle size distribution of cement, silica fume (SF), fly ash and waste glass powder (WGP)

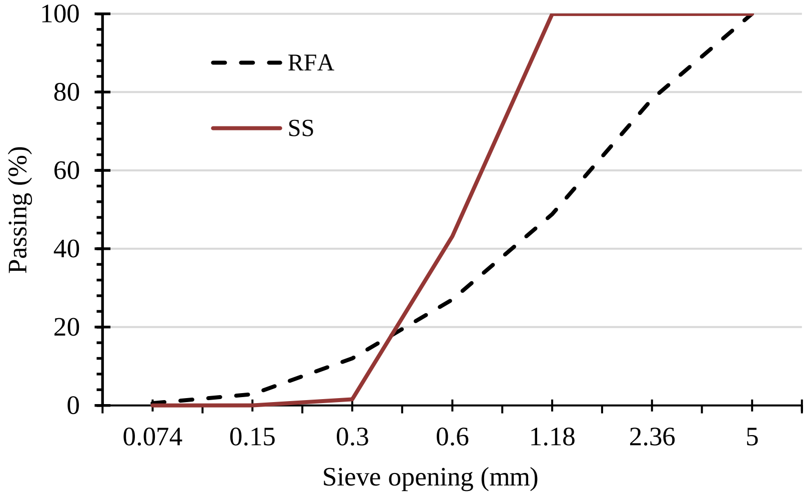
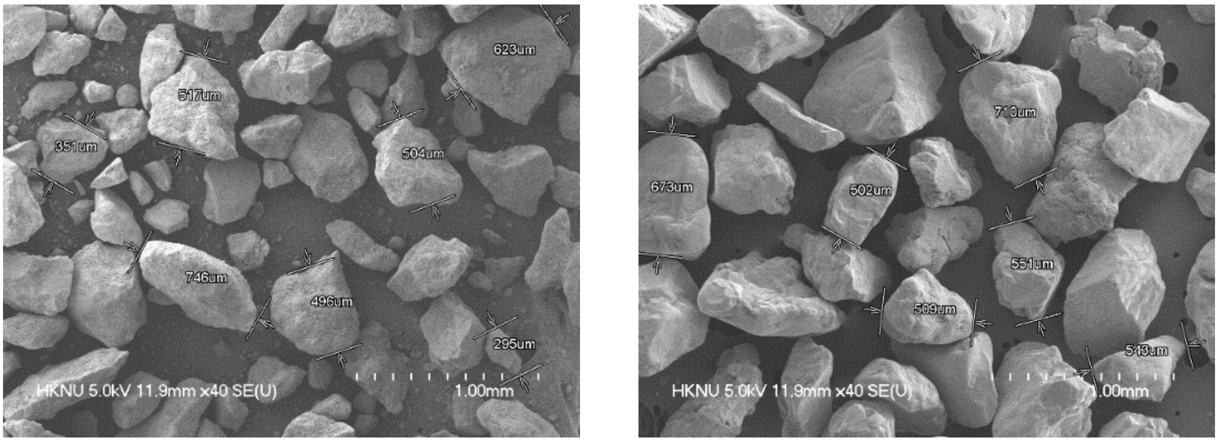



Fig. 3: (a) Gradation of fine aggregates




Recycled sand Natural silica sand

Fig. 4: (b) SEM image of fine aggregates

**2.2 Packing density**

Packing density provides an indication of how efficiently the particles fill a certain volume. In this study, an experimental packing density methodology suggested by Li and Kwan [9] was employed to determine the optimal combination of the constituents that gives the highest packing density. This methodology consists of two-stage approach: (1) Dry packing density test and (2) Wet packing density test.

A mixture of all dry constituents with the minimum void ratio was first determined by the dry packing density test. All constituents except SF and water were used in this stage. Mass of each dry constituent was determined that gives the minimum void ratio. Secondly, the wet packing density test used all constituents in the first stage plus water and SF. Mass of the constituents was determined that resulted in the minimum void ratio (or the maximum solid ratio). A cylindrical container with diameter of 100 mm and height of 175 mm was used for the packing density test in this study. Mixed dry ingredients or the wet mixtures were poured into the container to about one-third of the container height while this procedure was repeated three times. Each layer was loosely placed, or compacted 25 times by a tamping rod or vibrated for 15 seconds on the vibrating table. Mass of the container with the dry/wet constituents was measured immediately after the compaction. From the measured data, the void ratio (or solid ratio) was determined.

**2.3 Mixing**

All powder materials except sand were first mixed at low speed for 3m using a planetary mixer. Then sand prepared in surface saturated dry (SSD) condition was added and mixed at low speed for 3m for the dry packing density test. For the wet packing density test, all powder materials were first mixed using a planetary mixer at low speed for 5m. Then about 80% water with SP were added and the mixture was mixed at low speed for 5m. Sand and remaining 20% water with SP were added, mixed at high speed for 5m. After one minute pause, the mixture was finally mixed for additional 5m.

**2.4 Strength test**

Compressive strength was determined by testing 50 mm x 50 mm x 50 mm cube specimens. All specimens were demolded after 24 hours and continuously cured under water for the wet-cured condition. Heat-cured specimens were put into water and placed in the oven at 80°C temperature for 48h. 3d strength was tested for the heat-cured specimens. Compressive strength test of the wet-cured specimens was performed 7, 28, 56 days after casting. Flexural strength was determined 28 days after casting by testing 40 mm x 40 mm x 160 mm prisms under 3-point bending. All tests were performed using an Instron 4495 universal test machine (UTM) with capacity of 1,200 kN at crosshead rate of 1 mm/m. Three replicate specimens were tested.

**2.5 Density, absorption and voids**

The density, water absorption, and voids were determined after 28 days. 40 mm x 40 mm x 160 mm prisms were used. The measurement procedure following ASTM C642 [14] proceeded as follows:

(1) Oven-dry mass: The prisms were dried in an oven set at temperature of 110±5ºC for 24h. After removing the specimens from the oven, the specimens were allowed to cool in room condition and then the mass was measured. This sequence continued until the difference between values obtained from two successive values was less than 0.5% of the lowest value (Mass A).

(2) Saturated mass after immersion: The prisms were put under water at about 21ºC for 48h until two successive values of mass of the surface-dried sample at intervals of 24h showed an increase in mass of less than 0.5 % (Mass B)

(3) Saturated mass after boiling: Specimens were put under water and were subjected to temperatures over 100ºC for 5h. The specimens were then allowed to cool in room condition for not less than 14h to final temperature of 20~25ºC. The surface moisture was removed from the sample with a towel, and the mass was determined (Mass C).

(4) Immersed apparent mass: Specimen, after immersion and boiling, was suspended by a wire and apparent mass in water was determined (Mass D).

The density, water absorption, and voids were determined using Eqs. (1) through (4), where ρ is density of water:

$$\text{Absorption after immersion and boiling, \%} = [(C-A)/A] * 100 \quad (1)$$

$$\text{Bulk density, dry} = [A/(C-D)] * \rho = g_1 \quad (2)$$

$$\text{Apparent density} = [A/(A-D)] * \rho = g_2 \quad (3)$$

$$\text{Volume of permeable pore space (Voids), \%} = (g_2 - g_1) / g_2 * 100 \quad (4)$$

### 3.0 Packing density test and test results

### 3.1 Series 1

#### 3.1.1 Dry packing density, Series 1

The experimental packing density methodology employed in this study consists of two parts: Dry packing density and wet packing density. For the control mixtures in Series 1, OPC, WGP, and SS with particle size of 0.6 mm or smaller were used. The binder-to-sand ratio was fixed at 4:6 by vol. No filler materials were used. WGP partially replaced OPC while the replacement ratio changed as 0%, 10%, 15%, and 20% for Mix 1-0, 1-1, 1-2, and 1-3, respectively, as shown in Table 3. Table 3 also shows the ideal state for the Series 1 mixes in terms of the theoretical weight with zero void. Three different dry densities were measured: i.e. Loose density, rodded density, and density after vibration. The solid ratio and the void ratio were determined using Eqs. (5) and (6):

$$Solid\ ratio = \frac{Measured\ wt.}{theretical\ wt.} \quad (5)$$

$$Void\ ratio = 1 - solid\ ratio \quad (6)$$

Table 4 and Fig. 4 show the results of the dry packing density test. As shown in Table 4, the void ratio varies depending on the method of compaction and becomes smaller in the order of Loose > Rodded > Vibrated while the void ratio is 0.309, 0.306, 0.303, and 0.300, respectively, for Mixes 1-0, 1-1, 1-2, and 1-3 after vibration. The dry packing density test results show that the void ratio is the smallest when 20% of cement is replaced by WGP by vol. for Mix 1-3 after vibration at 30.0%. Current results indicate that, rather than using the single binder (OPC) with natural silica sand, utilizing binary binder system of OPC and WGP with natural silica sand results in an improved particle packing. Although the particle sizes between OPC and WGP do not differ much as shown in Fig. 2, the overall effect of particle packing is more efficient with addition of WGP with particle sizes in between the OPC and the natural silica sand.

Table - 3. Mix proportion for dry packing density test: Series 1 (unit: kg/0.001374m$^3$)

| Mixture | OPC | WGP | SS | Theoretical wt. |
|---|---|---|---|---|
| 1-0 | 1.731 | 0 | 2.052 | 3.783 |
| 1-1 | 1.558 | 0.137 | 2.052 | 3.748 |
| 1-2 | 1.471 | 0.206 | 2.052 | 3.730 |
| 1-3 | 1.385 | 0.275 | 2.052 | 3.712 |

Note: 0.001374 m$^3$ is container volume used in this study.

Table - 4. Results of dry packing density test: Series 1

| Mixture | Method of compaction | Measured wt. (kg) | Theoretical wt. (kg) | Solid ratio | Void ratio |
|---|---|---|---|---|---|
| 1-0 | Loose | 2.102 | 3.783 | 0.556 | 0.444 |
| | Rodded | 2.422 | 3.783 | 0.640 | 0.360 |
| | Vibrated | 2.614 | 3.783 | 0.691 | 0.309 |
| 1-1 | Loose | 2.088 | 3.748 | 0.557 | 0.443 |
| | Rodded | 2.405 | 3.748 | 0.642 | 0.358 |
| | Vibrated | 2.599 | 3.748 | 0.694 | 0.306 |
| 1-2 | Loose | 2.078 | 3.730 | 0.557 | 0.443 |
| | Rodded | 2.391 | 3.730 | 0.641 | 0.359 |
| | Vibrated | 2.599 | 3.730 | 0.697 | 0.303 |
| 1-3 | Loose | 2.065 | 3.712 | 0.556 | 0.444 |
| | Rodded | 2.404 | 3.712 | 0.648 | 0.352 |
| | Vibrated | 2.599 | 3.712 | 0.700 | 0.300 |

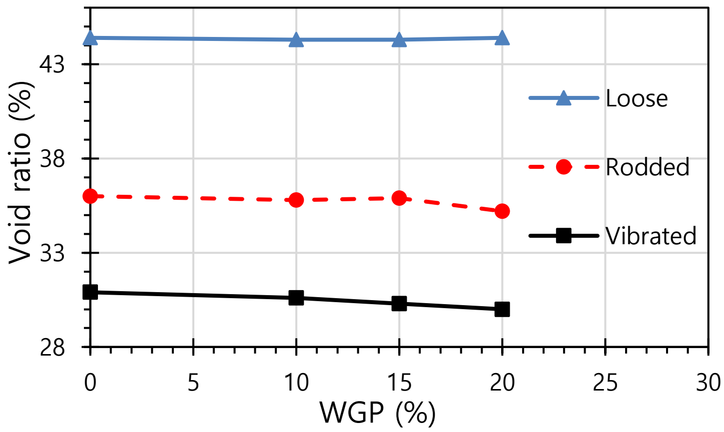



Fig. 5: Dry packing density test results: Series 1

**3.1.2 Wet packing density, Series 1**

Water and SF were used in addition to OPC, WGP, and SS for the wet packing density test. OPC-to-WGP ratio was 4:1 as a result of the dry packing density test. SF was added by 0%, 5%, 10%, and 15% of binder (OPC+WGP), as shown in Table 5. Water/binder ratio (w/b) was 0.22. Table 6 shows the mix design of the wet packing density test. Polycarboxylic acid base superplasticizer (SP) was used in all mixes. As silica fume with extremely small particle sizes and large specific surface tends to increase viscosity of the mixture, increasing amount of SP was used with larger replacement ratio of the binder (OPC+WGP) with SF to keep the mortar flow uniform. Small amount of defoaming agent (DF) was also used.

For the wet packing density test, the solid ratio can be calculated by Eq. (7).

$$\text{Solid ratio} = 1 - \text{entrapped air} - \text{water} \qquad (7)$$

In the ideal status (i.e., zero void), all space is filled by binder, sand, and water such that Eq. (8) holds:

$$\text{Theoretical wt.} = \text{solid wt.} + \text{water wt.} \qquad (8)$$

The volume of the mortars without air is determined by Eq. (9), with results as shown in the fifth column in Table 7.

$$\text{Measured vol. without air} = \frac{\text{Measured wt.}}{\text{Theoreticol wt.}} \qquad (9)$$

The volume of the entrapped air was obtained by subtracting the measured volume without air from the volume of the container. Table 7 and Fig. 5 show the results of the wet packing density test. As shown in Table 7 and Fig. 5, the void ratio becomes smaller in the order of Loose > Rodded > Vibrated, where Mix 1-1* has the smallest void ratio of 21.8% after vibration. Therefore, the mix design of Mix 1-1* was chosen as an optimum mixture of Series 1. Current test results show that, in the ternary binder system with silica sand, adding extremely fine SF to relatively coarser OPC and WGP results in an improved particle packing as shown in Fig. 5, while the experimentally determined optimum amount of SF is 5% of binder by vol. for Series 1.

Table - 5. Mix proportion of mixtures (by vol.) and water-to-solid ratio (W/S): Series 1

| Mixture | OPC | SF | WGP | SS | W | Total vol. | Solid vol. | W/S |
|---|---|---|---|---|---|---|---|---|
| 1-0* | 0.253 | 0 | 0.063 | 0.474 | 0.210 | 1 | 0.790 | 0.266 |
| 1-1* | 0.241 | 0.016 | 0.06 | 0.475 | 0.207 | 1 | 0.792 | 0.262 |
| 1-2* | 0.229 | 0.032 | 0.057 | 0.477 | 0.204 | 1 | 0.795 | 0.257 |
| 1-3* | 0.217 | 0.048 | 0.054 | 0.478 | 0.202 | 1 | 0.797 | 0.253 |

Note: Solid vol. = C+SF+WGP+SS.

Table - 6. Mix design for wet packing density test (unit: kg/m$^3$): Series 1

| Mixture | w/b | OPC | SF | WGP | W | SS | SP |
|---|---|---|---|---|---|---|---|
| 1-0* | 0.22 | 796 | 0 | 158 | 210 | 1266 | 14 |
| 1-1* | | 759 | 35 | 151 | 207 | 1269 | 17 |
| 1-2* | | 721 | 71 | 143 | 204 | 1273 | 20 |
| 1-3* | | 683 | 106 | 135 | 202 | 1276 | 22 |

Note: 0.5% DF of binder by wt. for all mixtures.

Table - 7. Results of wet packing density test: Series 1

| Method of compaction | Mixture | Measured wt. (kg) | Theoretical wt. (kg) | Measured vol. without air (mL) | Container vol. (mL) | Entrapped air vol. (mL) | Entrapped air vol. (%) | Entrapped air vol. (m3) | Water vol. (m3) | Solid ratio | Void ratio |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Loose | 1-0* | 3.251 | 2.430 | 1338 | 1374 | 36 | 2.61 | 0.0261 | 0.210 | 0.764 | 0.236 |
| | 1-1* | 3.241 | 2.421 | 1339 | 1374 | 35 | 2.51 | 0.0251 | 0.207 | 0.768 | 0.232 |
| | 1-2* | 3.217 | 2.411 | 1333 | 1374 | 31 | 2.93 | 0.0293 | 0.204 | 0.767 | 0.233 |
| | 1-3* | 3.193 | 2.402 | 1329 | 1374 | 45 | 3.29 | 0.0329 | 0.202 | 0.765 | 0.235 |
| Rodded | 1-0* | 3.262 | 2.430 | 1342 | 1374 | 32 | 2.28 | 0.0228 | 0.210 | 0.767 | 0.233 |
| | 1-1* | 3.269 | 2.421 | 1351 | 1374 | 23 | 1.67 | 0.0167 | 0.207 | 0.776 | 0.224 |
| | 1-2* | 3.235 | 2.411 | 1341 | 1374 | 33 | 2.39 | 0.0239 | 0.204 | 0.772 | 0.228 |
| | 1-3* | 3.218 | 2.402 | 1339 | 1374 | 35 | 2.53 | 0.0253 | 0.202 | 0.773 | 0.227 |
| Vibrated | 1-0* | 3.270 | 2.430 | 1346 | 1374 | 28 | 2.04 | 0.0204 | 0.210 | 0.770 | 0.230 |
| | 1-1* | 3.286 | 2.421 | 1358 | 1374 | 16 | 1.15 | 0.0115 | 0.207 | 0.782 | 0.218 |
| | 1-2* | 3.259 | 2.411 | 1351 | 1374 | 23 | 1.66 | 0.0166 | 0.204 | 0.779 | 0.221 |
| | 1-3* | 3.224 | 2.402 | 1341 | 1374 | 33 | 2.35 | 0.0235 | 0.202 | 0.775 | 0.225 |

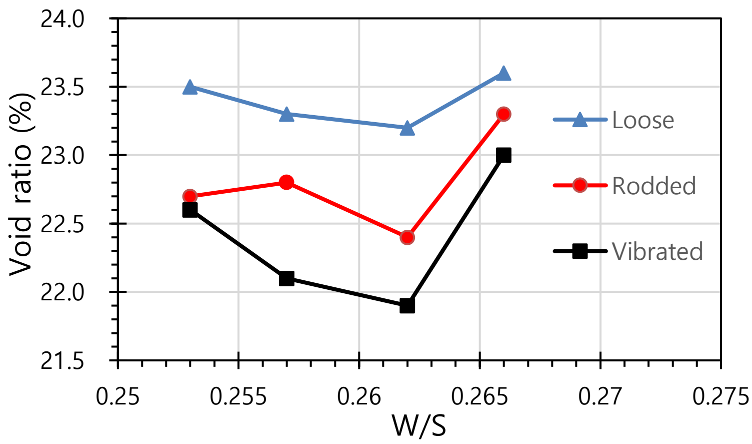



Fig. 6: Wet packing density test results: Series 1

### 3.2 Series 2

#### 3.2.1 Dry packing density, Series 2

In Series 2, all silica sand was replaced by recycled sand. The binder-to-sand ratio was the same as that in Series 1 (4:6 by vol.). For Series 2, fly ash was introduced to improve the flowability of the mixtures and further increase the use of recycled materials. It was first determined to use 10% fly ash replacement of OPC by vol. The optimum amount of WGP was then determined by dry packing density test with binder (i.e. OPC+fly ash) replacement of 0%, 5%, 10%, and 15% by vol. for Mixes 2-0, 2-1, 2-2, and 2-3, respectively, as shown in Table 8.

Table 9 and Fig. 6 show results of the dry density test of Series 2. In Table 9, the void ratio is 0.383, 0.385, 0.382, and 0.383, respectively, for Mixes 2-0, 2-1, 2-2, and 2-3 in the vibrated condition. Again, the void ratio in general decreases in the order of Loose > Dry rodded > Vibrated. The results showed that the binder (OPC+fly ash) can be replaced with 10% WGP at the lowest void ratio. It is noted that the minimum void ratio of 38.2% of Mix-2-2 determined in the Series 2 dry packing density test (ternary binder system) is significantly larger than the minimum void ratio of 30.0% determined in Series 1 dry packing density test (binary binder system). This is probably because of the use of RFA in Series 2 tests. As the modern-day recycled aggregates are produced by multi-stage crushing procedure, it produces particles with angular shape and rough texture. It is more difficult to achieve optimum packing using RFA than it is using the more rounded and smooth natural silica sand.

Table - 8. Mix proportion for dry packing density test (unit: kg/0.001374$m^3$), Series 2

| Mixture | OPC | Fly ash | WGP | RFA | Theoretical wt. |
|---|---|---|---|---|---|
| 2-0 | 1.558 | 0.137 | 0 | 2.052 | 3.748 |
| 2-1 | 1.480 | 0.131 | 0.069 | 2.052 | 3.732 |
| 2-2 | 1.402 | 0.124 | 0.137 | 2.052 | 3.715 |
| 2-3 | 1.324 | 0.117 | 0.206 | 2.052 | 3.699 |

Note: 0.001374 $m^3$ is container volume.

Table - 9. Results of dry packing density test: Series 2

| Mixture | Compaction method | Measured wt. (kg) | Theoretical wt. (kg) | Solid ratio | Void ratio |
|---|---|---|---|---|---|
| 2-0 | Loose | 1.875 | 3.748 | 0.500 | 0.500 |
| | Rodded | 2.070 | 3.748 | 0.552 | 0.448 |
| | Vibrated | 2.311 | 3.748 | 0.617 | 0.383 |
| 2-1 | Loose | 1.843 | 3.732 | 0.494 | 0.506 |
| | Rodded | 2.064 | 3.732 | 0.553 | 0.447 |
| | Vibrated | 2.297 | 3.732 | 0.615 | 0.385 |
| 2-2 | Loose | 1.831 | 3.715 | 0.493 | 0.507 |
| | Rodded | 2.056 | 3.715 | 0.553 | 0.447 |
| | Vibrated | 2.298 | 3.715 | 0.618 | 0.382 |
| 2-3 | Loose | 1.824 | 3.699 | 0.493 | 0.507 |
| | Rodded | 2.040 | 3.699 | 0.552 | 0.448 |
| | Vibrated | 2.283 | 3.699 | 0.617 | 0.383 |

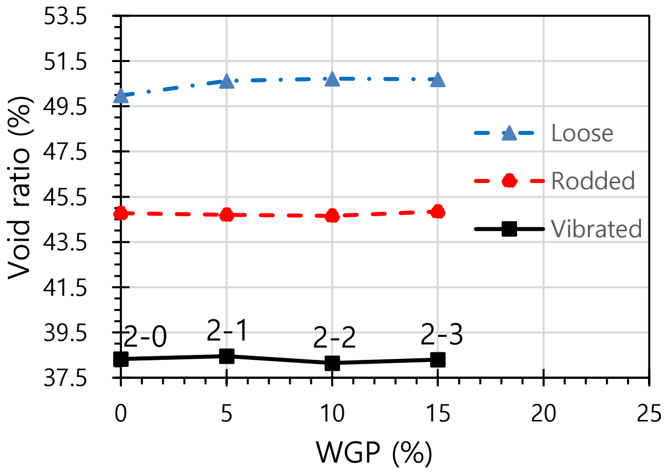



Fig. 7: Dry packing density test results: Series 2

### 3.2.2 Wet packing density, Series 2

In the wet packing density test of Series 2 mixtures, the ratio of OPC, fly ash, and WGP was 8:1:1 by vol. as a result of the dry packing density test. In the wet packing test, SF replaces the binder (OPC+ Fly ash +WGP) by 0%, 5%, 10%, and 15% by volume, as shown in Table 10, which shows the 1m3 of mixtures and the water-to-solid ratio (W/S). Table 11 shows the mix design of the wet packing density test for Series 2. Table 12 and Fig. 7 show the results of the wet packing density test. The results show that Mix 2-2* has the lowest void ratio of 23.1%. It must be noted that the minimum void ratio of 23.1% of Mix-2-2* is again larger than the minimum void ratio of 21.8% of Mix-1-1*. The reason why the void ratio is higher in Series 2 than it is in Series 1 must be traced to the use of RFA: i.e. The inter-particle interlocking is higher for the RFA, which is produced by crushing waste concrete, than for the more rounded natural silica sand.

Table - 10. Mix proportion for wet packing density test (by vol.) and W/S: Series 2

| Mixture | C | Fly ash | WGP | SF | RFA | W | Total vol. | Solid vol. | W/S |
|---|---|---|---|---|---|---|---|---|---|
| 2-0* | 0.253 | 0.032 | 0.032 | 0.000 | 0.474 | 0.210 | 1 | 0.790 | 0.266 |
| 2-1* | 0.241 | 0.030 | 0.030 | 0.016 | 0.475 | 0.208 | 1 | 0.792 | 0.262 |
| 2-2* | 0.229 | 0.029 | 0.029 | 0.032 | 0.477 | 0.206 | 1 | 0.794 | 0.259 |
| 2-3* | 0.217 | 0.027 | 0.027 | 0.048 | 0.478 | 0.203 | 1 | 0.797 | 0.255 |

Note: Solid vol. = C+SF+Fly ash+WGP+RFA.

Table - 11. Mix design for wet packing density test (unit: kg/m$^3$): Series 2

| Mixture | w/b | C | Fly ash | WGP | SF | RFA | W | SP |
|---|---|---|---|---|---|---|---|---|
| 2-0* | 0.22 | 796 | 79 | 79 | 0 | 1180 | 210 | 17.0 |
| 2-1* | | 759 | 75 | 75 | 35 | 1184 | 208 | 25.5 |
| 2-2* | | 721 | 72 | 72 | 71 | 1187 | 206 | 34.0 |
| 2-3* | | 683 | 68 | 68 | 106 | 1190 | 203 | 38.3 |

Note: 0.5% DF of binder by wt. for all mixtures.

Table - 12. Results of wet packing density test: Series 2

| Method of compaction | Mixture | Measured wt. (kg) | Theoretical wt. (kg) | Measured vol. without air (mL) | Container vol. (mL) | Entrapped air vol. (mL) | Entrapped air vol. (%) | Entrapped air vol. ($m^3$) | Water vol. ($m^3$) | Solid ratio | Void ratio |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Loose | 2-0* | 3083 | 2345 | 1315 | 1373.75 | 59 | 4.27 | 0.0427 | 0.210 | 0.747 | 0.253 |
| | 2-1* | 3068 | 2336 | 1314 | 1373.75 | 60 | 4.37 | 0.0437 | 0.208 | 0.748 | 0.252 |
| | 2-2* | 3055 | 2327 | 1313 | 1373.75 | 61 | 4.42 | 0.0442 | 0.206 | 0.750 | 0.250 |
| | 2-3* | 3033 | 2318 | 1309 | 1373.75 | 65 | 4.73 | 0.0473 | 0.203 | 0.749 | 0.251 |
| Rodded | 2-0* | 3108 | 2345 | 1326 | 1373.75 | 48 | 3.50 | 0.0350 | 0.210 | 0.755 | 0.245 |
| | 2-1* | 3103 | 2336 | 1329 | 1373.75 | 45 | 3.28 | 0.0328 | 0.208 | 0.759 | 0.241 |
| | 2-2* | 3087 | 2327 | 1327 | 1373.75 | 47 | 3.43 | 0.0343 | 0.206 | 0.760 | 0.240 |
| | 2-3* | 3062 | 2318 | 1321 | 1373.75 | 53 | 3.84 | 0.0384 | 0.203 | 0.758 | 0.242 |
| Vibrated | 2-0* | 3145 | 2345 | 1341 | 1373.75 | 32 | 2.36 | 0.0236 | 0.210 | 0.766 | 0.234 |
| | 2-1* | 3130 | 2336 | 1340 | 1373.75 | 34 | 2.45 | 0.0245 | 0.208 | 0.768 | 0.232 |
| | 2-2* | 3115 | 2327 | 1339 | 1373.75 | 35 | 2.55 | 0.0255 | 0.206 | 0.769 | 0.231 |
| | 2-3* | 3087 | 2318 | 1332 | 1373.75 | 42 | 3.06 | 0.0306 | 0.203 | 0.766 | 0.234 |

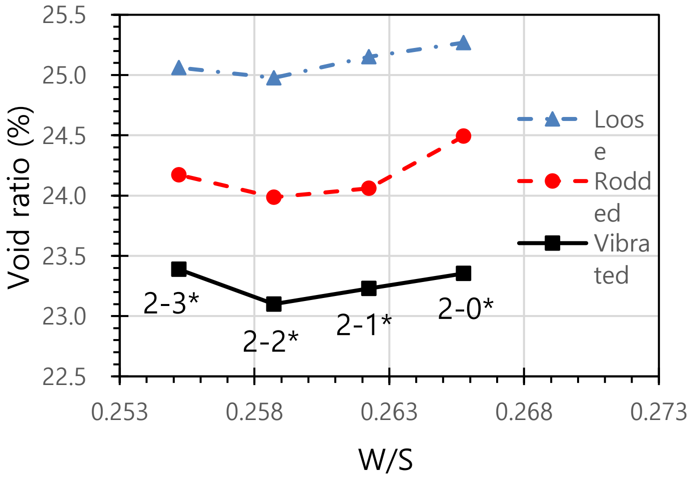



Fig. 8: Wet packing density test results: Series 2

## 4. Test results: strength development and mechanical properties

### 4.1 Series 1 versus Series 2

Table 13 and Figure 8 summarize the strength development, density, absorption, and void ratio for Mix 1-1* and Mix 2-2*, the optimum mixtures chosen as a result of Series 1 and Series 2 packing density tests, respectively. For the Mix 1-1*, made of natural silica sand, both 3d heat-cured and 28d wet-cured compressive strengths are 101 MPa: i.e. For the Mix 2-2*, made of 100% recycled sand, the 28d compressive strength is 71.1 MPa which is only 70.3% of that of Mix 1-1*. Density, absorption, and void ratio are 2,290 kg/m3, 7.96%, and 16.9% for Mix 2-2* and 2,340 kg/m3, 4.23%, and 9.51%, respectively for Mix 1-1*. The absorption increases and the void ratio decreases by 46.9% and 43.7%, for Mix 2-2%, respectively, from Mix 1-1* while w/b = 0.22 for both mixes.

### 4.2 Series 2 – additional mixes

Test results summarized in Table 13 and Fig. 8 clearly indicate that it is needed to lower w/b for the Series 2 mixes to achieve the compressive strength comparable to that of Series 1 mixes. Therefore, it was determined to continue study using Series 2 – additional mixes. It should be noted that, in the Series 2 – additional mixes, the packing density test was not performed. Instead, the mix proportions of

Mix 2-2* was maintained except for the amount of water. w/b changed from 0.22 to 0.20, 0.18, and 0.17. Table 14 shows the mix design of Series 2 – additional mixes, while other details of the mixing and testing were the same as Series 1 and Series 2. Table 15 summarizes the test results. The 28d compressive strength of mixtures with w/b ratio of 0.22, 0.20, 0.18, and 0.17 is 71.1 MPa, 79.6 MPa, 96.8 MPa, and 85.3 MPa, respectively, as shown in Table 15 and Fig. 9. It is noted that the mixture with w/b = 0.17 does not develop strength higher than the mixture with w/b =0.18 despite the lower w/b, which reveals that the water that lubricates the particles is not sufficient for this specific w/b. The flow value of fresh mortar after jolting decreases with decreasing w/b: i.e. 25.0 cm, 25.0 cm, 23.4 cm, and 21.9 cm with w/b ratio of 0.22, 0.20, 0.18, and 0.17, respectively, as summarized in Table 15. In Fig. 10(a), the density decreases with decreasing w/b ratio, which seems to indicate that the packing density is not optimum for mixes with w/b = 0.20, 0.18, and 0.17. It is noted that authors performed packing density tests only for Mix 2-2* with w/b = 0.22. Therefore, although the compressive strength increases with decreasing amount of water for the mixes with w/b = 0.20 and 0.18, an optimum mix may be determined, respectively, by performing the wet packing density test for each RPC.

Table - 13. Summary of compressive strength, flexural strength and void ratio for Mix 1-1* and Mix 2-2*

| Mix type | | Compressive strength (MPa) | | | | Flexural strength (MPa) | Density, absorption and void | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Heat cure | Wet cure | | | | Density (kg/m$^3$) | Absorp-tion (%) | Void (%) |
| | | 3d | 7d | 28d | 56d | 28d | | | |
| Mix 1-1* | Mean | 101 | 79.0 | 101 | 104 | 13.4 | 2,340 | 4.23 | 9.51 |
| | Stdev. | 0.18 | 2.43 | 6.39 | 11.8 | 0.13 | | | |
| | COV (%) | 0.17 | 3.07 | 6.32 | 11.3 | 2.49 | | | |
| Mix 2-2* | Mean | -- | 53.1 | 71.1 | 74.7 | 7.9 | 2,290 | 7.96 | 16.90 |
| | Stdev. | -- | 1.39 | 1.55 | 5.49 | 2.78 | | | |
| | COV (%) | -- | 2.62 | 2.19 | 7.36 | 35.29 | | | |

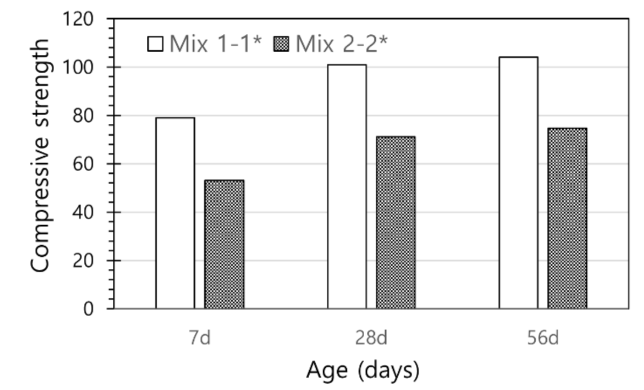



Fig. 9: Compressive strength test results: Mix1-1* vs. Mix 2-2*

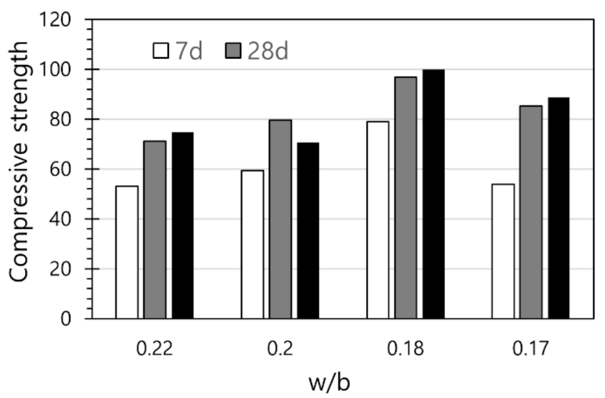



Fig. 10: Compressive strength development: Series 2 – additional mixes

Table - 14. Mix design of Mix 2-2* – additional mixes (unit: kg/m$^3$)

| Mix 2-2* | OPC | fly ash | WGP | SF | RFA | W |
|---|---|---|---|---|---|---|
| w/b=0.22 | 721 | 72 | 72 | 72 | 1187 | 206 |
| w/b=0.20 | 734 | 73 | 73 | 72 | 1210 | 190 |
| w/b=0.18 | 749 | 74 | 74 | 73 | 1233 | 175 |
| w/b=0.17 | 756 | 75 | 75 | 74 | 1245 | 167 |

Note: Same amount of SP and DF was used for all mixtures (See Table 11, Mix-2-2*).

Table - 15. Summary of compressive strength, flexural strength and void ratio for Series 2 – additional mixes

| Mixture | | Compressive strength (MPa) | | | | Flexural strength (MPa) | Density, water absorption and void ratio | | | Flow |
|---|---|---|---|---|---|---|---|---|---|---|
| w/b | Series 2 | Heat cure | Water cure | | | | Density (kg/m$^3$) | Absorp-tion (%) | Void (%) | (cm) |
| | | 3d | 7d | 28d | 56d | 28d | | | | |
| 0.22 | Mean | - | 53.1 | 71.1 | 74.7 | 7.9 | 2290 | 7.96 | 16.90 | 25.0 |
| | Stdev | - | 1.39 | 1.55 | 5.49 | 2.78 | | | | |
| | COV (%) | - | 2.62 | 2.19 | 7.36 | 35.29 | | | | |
| 0.20 | Mean | 82.78 | 59.4 | 79.6 | 70.7 | 11.3 | 2260 | 7.02 | 14.84 | 25.0 |
| | Stdev | 5.96 | 1.79 | 4.09 | 2.02 | 2.37 | | | | |
| | COV (%) | 7.20 | 3.02 | 5.14 | 2.86 | 20.94 | | | | |
| 0.18 | Mean | 80.83 | 78.9 | 96.8 | 99.9 | 11.3 | 2260 | 5.35 | 11.49 | 23.4 |
| | Stdev | 8.36 | 0.36 | 2.29 | 1.88 | 0.18 | | | | |
| | COV (%) | 10.34 | 0.451 | 2.36 | 1.89 | 1.64 | | | | |
| 0.17 | Mean | 67.96 | 53.9 | 85.3 | 88.7 | 12.1 | 2250 | 5.83 | 12.41 | 21.9 |
| | Stdev | 10.09 | 1.95 | 1.52 | 2.89 | 2.18 | | | | |
| | COV (%) | 14.85 | 3.62 | 1.79 | 3.26 | 18.07 | | | | |

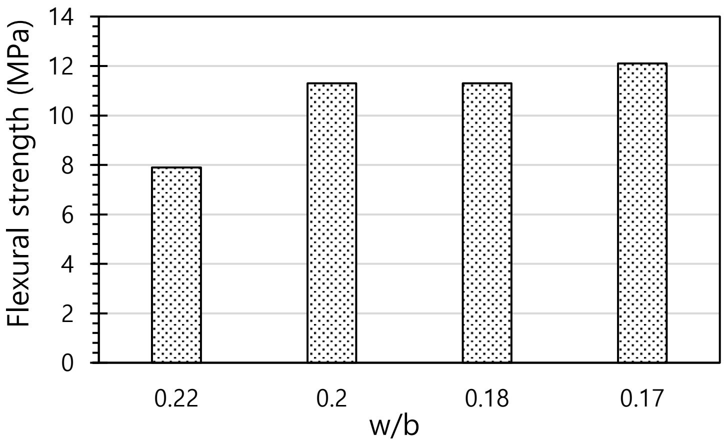
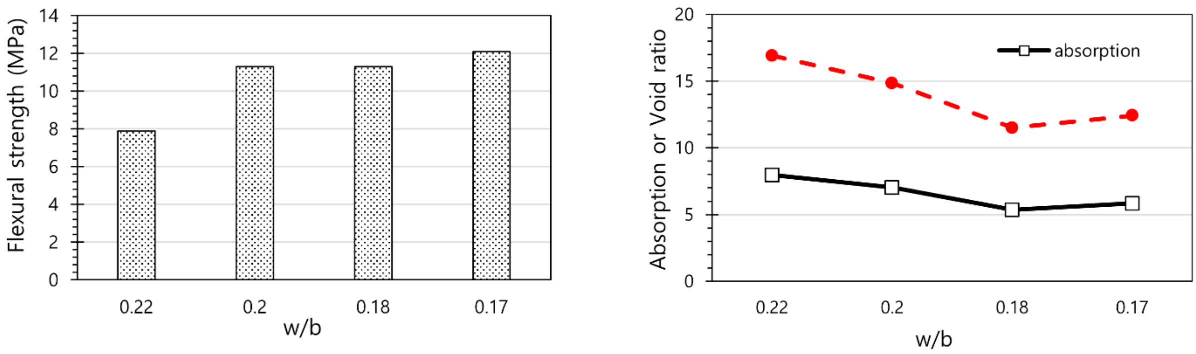



Fig. 11: Flexural strength at 28d: Series 2 – additional mixes




(a) Density (b) Absorption and Void ratio

Fig. 12: Absorption and Void ratio: Series 2 – additional mixes

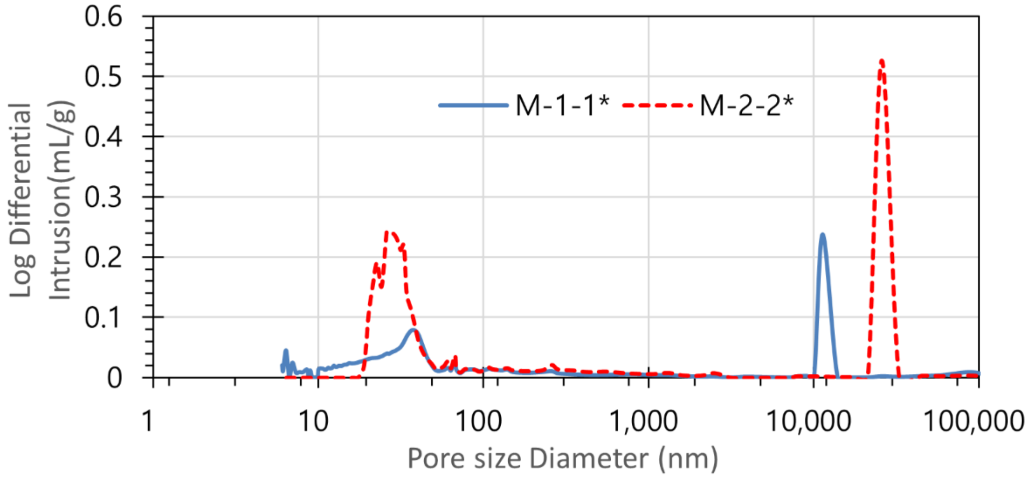



Fig. 13: Pore size distribution

### 4.3 Void structure investigation by mercury intrusion porosimetry

The results of investigation of void structures by mercury intrusion porosimetry (MIP) are shown in Fig. 12 for Mix 1-1* and Mix 2-2*. Figure 12 shows two peaks for Mix 1-1* and Mix 2-2*, respectively. For Mix 1-1*, the larger voids are in diameters between 10-14 μm while the smaller voids are between 10-50 nm. On the other hand, for Mix 2-2*, the larger voids are in the range of 20-33 μm and the smaller voids are in the range of 15-50 nm. Both micro voids and nano voids of Mix 2-2* are shifted to right compared to those of Mix 1-1*. At the same time, both peaks are higher for the Mix 2-2* than Mix 1-1*. As a result, the total amount of voids is larger for Mix 2-2* made with the recycled sand than Mix 1-1* made with the natural silica sand. Current MIP results clearly show that it is more difficult for the mix with recycled sand to form efficient particle packing than the mix with silica sand probably due to rough texture and angular morphology of the recycled sand with higher inter-particle friction.

## 5. Conclusions

In this study, 100-MPa grade green RPC was developed that used OPC and substitutive cementitious materials such as silica fume, waste glass powder, type-F fly ash as well as recycled sand. The optimal mixture design was determined by an experimental packing density methodology which consists of two-stage investigation: dry packing density test and wet packing density test. From Series 1 which used natural silica sand, 100-MPa grade RPC was developed at w/b = 0.22. From Series 2 which used recycled sand, the comparable strength grade RPC was developed at w/b = 0.18. Findings of this study are summarized as follows:

- The dry packing density test results showed that the minimum void ratio was 38.2% for Mix-2-2 with ternary binder system and recycled sand, which was larger than the minimum void ratio of 30.0% for Mix-1-1 with binary binder system and natural silica sand. It was more difficult to achieve the optimum dry packing using the recycled sand with angular shape and rough texture than the natural silica sand.
- In the wet packing density test, the minimum void ratio of 23.1% of Mix-2-2* with recycled sand was larger than the minimum void ratio of 21.8% of Mix-1-1* with natural silica sand at the same w/b = 0.22. The difference in the void ratios must be traced to the use of recycled sand with higher degree of inter-particle friction.
- 28d compressive strength of Mix-1-1* was 101 MPa while it was 71.1 MPa for Mix-2-2*, which is only 70.3% of Mix-1-1* at the same w/b = 0.22. In addition, the absorption increased and the void ratio decreased by 46.9% and 43.7%, for Mix 2-2* with recycled sand, respectively, from Mix 1-1* with natural silica sand.
- In Series 2-additional tests, the mix proportions of Mix 2-2* was maintained except for the amount of water: i.e. w/b changed from 0.22 to 0.20, 0.18, and 0.17. The target compressive strength of 100 MPa was reached after 56d at w/b = 0.18.
- The MIP test results showed that the diameter of larger voids was between 10-14 μm while the smaller voids were between 10-50 nm for Mix 1-1*. For Mix 2-2*, the larger voids were 20-33 μm and the smaller voids were 15-50 nm. Both micro voids and nano voids of Mix 2-2* shifted to right compared to those of Mix 1-1*. As a result, the total amount of voids was larger for

Mix 2-2* made with the recycled sand than Mix 1-1* made with the natural silica sand.

- It is more difficult for the mix with recycled sand to form efficient particle packing than the mix with natural silica sand probably due to rough texture and angular morphology of the recycled sand with significant inter-particle friction.


## Acknowledgment

Authors appreciate generous support for this research by the National Research Foundation of Korea (NRF) funded by the Ministry of Science and ICT.(No.2021K1A3A1A20001722111258207142010 1) and Construction Engineering Research Institute of Hankyong National University.


## Reference


[1] Richard, P., Cheyrezy, M., (1995). Composition of Reactive Powder Concretes, *Cement and Concrete Research*, 25, 7, 1501-1511.

[2] Zhang, Y.S., Sun, W., Liu, S.F., Jiao, C.J., Lai, J.Z., (2008). Preparation of C200 green reactive powder concrete and its static-dynamic behaviors, *Cement & Concrete Composites*, 30, 9, 831-838.

[3] A.D.Agharde, S.A.Bhalchandra, (2015). Mechanical properties of reactive powder concrete by using fly ash, *International Journal of Advanced Technology in Engineering and Science* 03, 01, 603-608.

[4] Mao, X.Q., Qu, W.J., Zhu, P., (2019). Mixture Optimization of Green Reactive Powder Concrete with Recycled Powder, *Journal of Materials in Civil Engineering*, 31, 5,

[5] Salahuddin, H., Qureshi, L.A., Nawaz, A., Raza, S.S., (2020). Effect of recycled fine aggregates on performance of Reactive Powder Concrete, *Construction and Building Materials*, 243,

[6] Dawood, E.T., Abdullah, M.H., (2021). Behavior of green reactive powder mortar reinforced with steel fibers, *Journal of the Mechanical Behavior of Materials*, 30, 1, 130-143.

[7] Stovall, T., De Larrard, F., Buil, M., (1986). Linear Packing Density Model of Grain Mixtures, *Powder Technology*, 48, 1, 1-12.

[8] KS F 2573, (2014). Recycled aggregates for concrete, *Korea Standard Association*.

[9] Li, L.G., Kwan, A.K.H., (2014). Packing density of concrete mix under dry and wet conditions, *Powder Technology*, 253, 514-521.

[10] KSL 5201, (2016). Portland Cement, *Korean Standards Association*.

[11] Soliman, N.A., Tagnit-Hamou, A., (2017). Partial substitution of silica fume with fine glass powder in UHPC: Filling the micro gap, *Construction and Building Materials*, 139, 374-383.

[12] KS F 2504, (2014). Test method for density and absorption rate of fine aggregates, *Korea Standard Association*.

[13] Gombosuren CHINZORIGT, D.C., Odontuya ENKHBOLD, Batzaya BAASANKHUU, Myung Kwan LIM, Hee Seob LIM,, (2018). Strength, shrinkage and creep of concrete including CO2 treated recycled coarse aggregate, *Journal of Asian Concrete Federation*, 4, 2, 89-102.

[14] ASTM C642, (2013). Standard Test Method for Density, Absorption and Voids in Hardened Concrete, *American Society for Testing and Materials*.