# Engineering Properties and Microstructure of Reactive Powder Concrete using High-Volume Fly Ash and Natural-Fine River Sand

**Si-Huy Ngo, Trong-Phuoc Huynh, Phuong-Trinh Bui**

***Abstract*****:** ***Reactive powder concrete (RPC) is an ultra-high strength concrete with a high amount of fine powders including cement, silica fume, fine quartz sand, and quartz powder. However, the use of a high amount of cement and silica fume increases hydration heat, shrinkage, and production cost of RPC. This paper evaluated the use of natural-fine river sand incorporating high-volume fly ash (FA) for the production of RPC. Four RPC mixtures with a fixed water-to-cementitious materials ratio of 0.2 were designed, and FA was used to replace cement in the proportions of 0, 20, 40, and 60% by mass. The RPC samples were subjected to the tests of compressive strength, water absorption, porosity, thermal conductivity, and scanning electron micrograph (SEM) observation. Test results showed that the use of natural-fine river sand could produce RPC with a compressive strength of approximately 60 MPa. Additionally, RPC samples with 20 and 40% FA replacements had higher compressive strength and thermal conductivity, and lower water absorption and porosity when compared with RPC samples with 0 and 60% FA replacements. SEM images confirmed that some microcracks and un-reacted FA particles were observed in RPC samples with 0 and 60% FA replacements, respectively. The results of this study showed a high application potential of this material in the construction activities.***

***Keywords*****:** ***Reactive powder concrete, High-volume fly ash, Natural-fine river sand, Microstructure.***

## I. INTRODUCTION

The use of concrete in construction leads to many positive effects on the development of society. In recent years, concrete with extremely high strength and excellent durability has been taken into account for sustainable development. Reactive powder concrete (RPC) is known as a based-cement material with the ultra-high-strength, superior toughness, and high durability [1], [2]. When compared with traditional cement-based materials, the engineering properties of RPC were enhanced more due to microstructure improvement techniques for cementitious materials (CMs) [1]. Similar to high-performance concrete, inner hydration products as gels were formed in RPC through a diffusion process, thereby resulting in a dense cement matrix [3]. Cwirzen et al. showed the feasibility of the production of ultra-high-strength concretes as reactive powder-based concrete through the packing density theories. In which, an appropriate portion of quartz micro-fillers was added to improve the packing density of the binder matrix. Hence, a maximum 28-day compressive strength (CS) value of about 150 MPa was achieved for the normal curing concrete [4]. Bentz and Jensen also indicated that a combination of the use of a high amount of cement, a low water-to-CMs ratio, superplasticizer (SP), and silica fume (SF) provided an extremely dense microstructure of RPC, resulting in the excellent performances [5]. In addition, ultra-fine aggregate instead of natural aggregate is applied for producing RPC. The SP and steel fiber are also employed to increase the workability and flexural strength of RPC, respectively. The CS and flexural strength of RPC could reach 810 and 141 MPa, respectively [3]. Moreover, RPC is good in fire resistance [6], blast explosion resistance [7], and freezing-thawing resistance [4].

However, the use of a high amount of cement and SF leads to not only a high production cost but also a high hydration heat and shrinkage of RPC. To overcome these adverse effects, alternative materials for cement such as fly ash (FA) [8], phosphorous slag [9], ground-granulated blast-furnace slag (GGBFS) [8] are considered. Published studies have demonstrated that the use of FA for concrete leads to several benefits, such as reducing environmental pollution and enhancing both the engineering properties and durability of concrete [10] – [12]. Most of the published works also reported that FA and/ or GGBFS were effective in producing RPC because these materials acted as the alternative silica sources. Yazici et al. pointed out the effectiveness of using FA and/ or GGBFS in the production of RPC. They reported that 60% of cement replaced by FA made RPC with a CS of higher than 200 MPa [8].

Manuscript published on January 30, 2020.
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In addition, Peng et al. also reported that RPC, with 30% CMs replaced by phosphorous slag powder, exhibited excellent properties, including the CS of higher than 150 MPa, a flexural strength of higher than 21 MPa, and high sulfate resistance [9]. Similarly, the replacement of up to 60% cement by GGBFS could produce RPC with a CS of above 200 MPa [8]. The same value of strength was also obtained when using both FA and GGBFS to replace a part of cement. Moreover, the microstructure analysis conducted by Chen et al. and Demiss et al.

further proved that RPC incorporating FA exhibited a dense microstructure, which supports the mechanical strength and durability of the RPC [13], [14].

Most existing studies of RPC used ultra-fine aggregate with very fine particle sizes. To reduce the production cost and utilize more FA, which is an industrial waste material from locally coal-thermal power plants, this study investigated the combined use of natural-fine river sand and a high volume of FA for the production of RPC. It is noted that both the natural-fine river sand and FA are locally available materials with massive quantities. They are used directly without any pretreatment to obtain the economic purpose. Furthermore, the tests of CS, water absorption (WA), porosity, thermal conductivity (TC), and scanning electron micrograph (SEM) observation were performed to evaluate the effect of FA on engineering properties and microstructure of RPC. The experimental works could be described as follows:

Step 1: Raw materials selection.
Step 2: Materials' characteristics testing.
Step 3: PRC mixture proportion design.
Step 4: Trial-batch, sample preparation, and curing.
Step 5: RPC's properties evaluation (test programs).
Step 6: Experimental results analysis and conclusion.

## II. MATERIALS AND EXPERIMENTAL DETAILS

### A. Materials

Cementitious materials consisting of type-I Portland cement (OPC) conforming to ASTM C150, SF conforming to ASTM C1240, and FA conforming to ASTM C618 were used. The characteristics of the CMs are given in Table 1.

**Table 1: Characteristics of CMs.**

| Items | | OPC | SF | FA |
|---|---|---|---|---|
| *Specific gravity* | | 3.15 | 2.21 | 2.29 |
| *Mean particle size (μm)* | | 19.1 | 16.5 | 21.5 |
| *Specific surface area ($m^2$/g)* | | 0.78 | 0.82 | 0.66 |
| *28-day strength activity index (%)* | | 100 | 107.5 | 86.5 |
| *Chemical composition (wt.%)* | *$SiO_2$* | 20.04 | 97.65 | 64.01 |
| | *$Al_2O_3$* | 4.24 | 0.70 | 22.14 |
| | *$Fe_2O_3$* | 3.12 | 0.05 | 5.64 |
| | *CaO* | 62.43 | 0.35 | 2.75 |
| | *MgO* | 4.17 | 0.42 | 0.92 |
| | *$SO_3$* | 2.97 | 0.27 | 0.61 |
| | *$K_2O$* | 0.43 | 0.29 | 1.36 |
| | *$Na_2O$* | 0.33 | - | 0.85 |
| | *L.O.I$^a$* | 1.75 | 1.39 | 2.74 |

a. L.O.I – Loss on ignition

Their particle size distributions, SEM images, and X-ray diffraction (XRD) patterns are presented in Figs. 1–3, respectively. It is noticed that FA had a spherical shape with the largest particle size, whereas OPC and SF had irregular shapes, and the particle size of SF was the smallest among them. (Table 1, Fig. 1, and Fig. 2). The particle size of all binder materials was less than 22 μm. It is believed that the inclusion of FA with spherical shape may improve the workability of fresh RPC mixture. Additionally, it is well-known that the smaller the particle size of the material, the greater the level of the materials involved in the chemical reaction. The chemical compositions of OPC mainly consisted of $SiO_2$, CaO, $Al_2O_3$, and $Fe_2O_3$, while the main ingredients of FA included $SiO_2$ and $Al_2O_3$ (Table 1). These results were similar to the results of XRD pattern analysis, as shown in Fig. 3. The stable crystals of alite, belite, quartz, mullite, and pentlandite were found in the OPC powder sample, whereas quartz and mullite were found in the FA powder sample. It is worth noting that, although the main chemical composition of SF was $SiO_2$ as shown in Table 1, no silica ($SiO_2$) peaks were identified by the XRD pattern analysis, as shown in Fig. 3. This suggests that the silica in SF mainly existed as an amorphous phase, which is a sensitive phase, indicating that SF will participate in the chemical reaction of the system at a high rate.

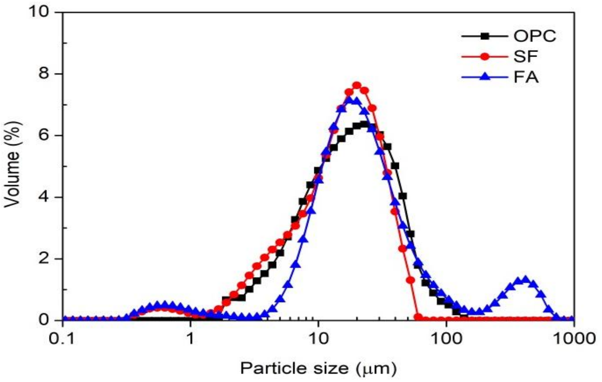
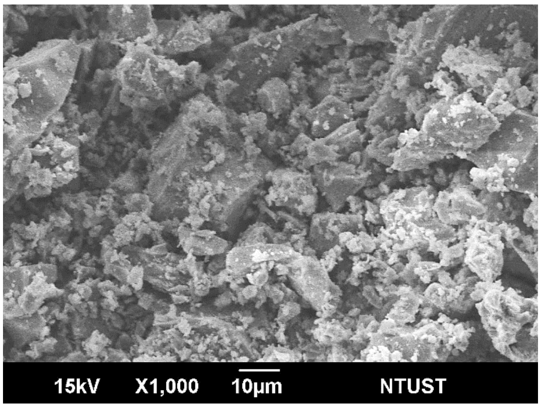
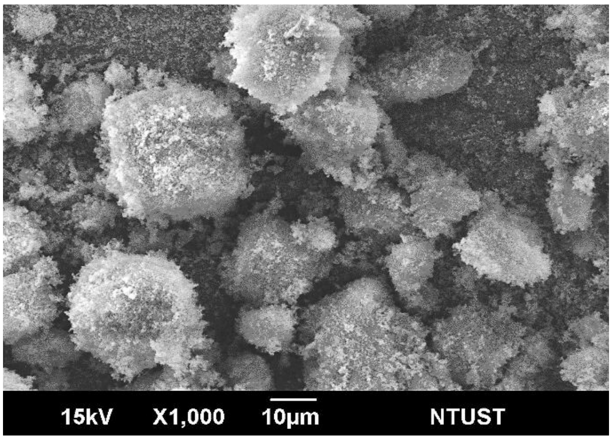


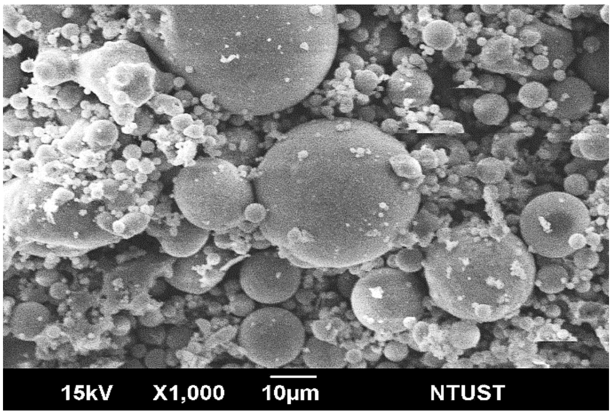
**Fig. 1. The particle size distribution of CMs.**



(a) OPC



(b) SF



(c) FA

Fig. 2. SEM morphologies of CMs.

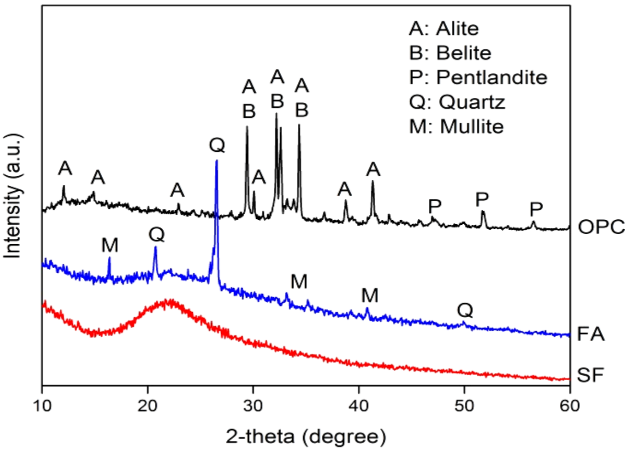


Fig. 3. XRD patterns of CMs.

The natural-fine river sand with a density of 2650 kg/m$^3$, and maximum and minimum diameters of 600 and 150 μm, respectively, was used as fine aggregate. In addition, type-G SP was used to ensure the desired workability of RPC. The specific gravity and dosage of SP used were 1.34 and 2% (by mass of CMs), respectively.

### B. Mixture proportions

Four RPC mixtures with a constant water-to-CMs ratio of 0.2 were designed, as shown in Table 2. The FA was used to replace cement by 0, 20, 40, and 60%. It is noticed that the content of SF of 20% by weight of CMs was used for all mixtures. In each RPC mixture's name, C and F denote cement and FA, respectively; the numbers after them represent the percentage amount of cement and the percentage of FA replacement.

Table 2: Mixture proportions of RPC.

| Ingredients (kg/m$^3$) | RPC mixtures | | | |
|---|---|---|---|---|
| | *C100F00* | *C80F20* | *C60F40* | *C40F60* |
| OPC | 897.4 | 702.9 | 516.3 | 337.3 |
| SF | 224.3 | 219.6 | 215.1 | 210.8 |
| FA | 0.0 | 175.7 | 344.2 | 506.0 |
| Fine aggregate | 987.1 | 966.5 | 946.6 | 927.6 |
| SP | 22.4 | 22.0 | 21.5 | 21.1 |
| Water | 224.3 | 219.6 | 215.1 | 210.8 |

### C. Samples preparation and test methods

The cubic RPC samples with dimensions of 5×5×5 cm were prepared by using the steel molds. The engineering properties of RPC including the CS, WA, porosity, and TC were evaluated following the procedures as described by ASTM C109, ASTM C1403, Huynh et al. [15], and Ngo et al. [16], respectively. The microstructure of RPC was also examined by SEM observation using a JEOL scanning electron microscope. The CS of RPC samples was tested at 3, 7, 28, and 56 days, while other properties were measured at 28 days. The values reported for all the tests herein were the average test results of three samples.

## III. RESULTS AND DISCUSSION

### A. Compressive strength

Fig. 4 shows the CS developments of all RPC samples over time. 4. The 56-day compressive strengths of RPC samples with 0, 20, 40, and 60% FA replacements were 57.0, 63.9, 60.7, and 50.5 MPa, respectively. It can be said that the use of natural-fine river sand can produce RPC with a CS of approximately 60 MPa.

Fig. 4 also shows that the RPC with 0% FA replacement (C100F00) exhibited the highest CS at three days; however, RPC with 20% FA replacement (C80F20) showed the highest CS after three days. It can be said that a suitable amount of FA (i.e., 20% by mass) was adequate to create RPC with the highest strength value. The CS of RPC with 40% FA replacement (C60F40) was lower at 3 and 7 days, and higher at 28 and 56 days when compared with that of RPC with 0% FA replacement. The lower CS at early ages and higher strength at later periods of C80F20 and C60F40 was mainly attributable to the pozzolanic reaction of FA in the blended mixture, which is extremely slow at the early ages of concrete and only starts to occur remarkably after several weeks of curing [17]. The improvement of CS after 28 days by FA was also found in a previous study of Madhavi et al. [18]. Yiğiter et al. pointed out that the presence of a high volume of FA as a pozzolanic material in the matrix of RPC created a very dense microstructure, leading to the improvement of CS [19]. In this case, FA may act as both a pozzolanic material that involves in the pozzolanic reaction and a filler that fills the voids within the system.

However, the CS of RPC with 60% FA replacement (C40F60) was lower when compared with that of RPC with 0% FA replacement regardless of curing age. This is because of the extremely high amount of cement replaced by FA.

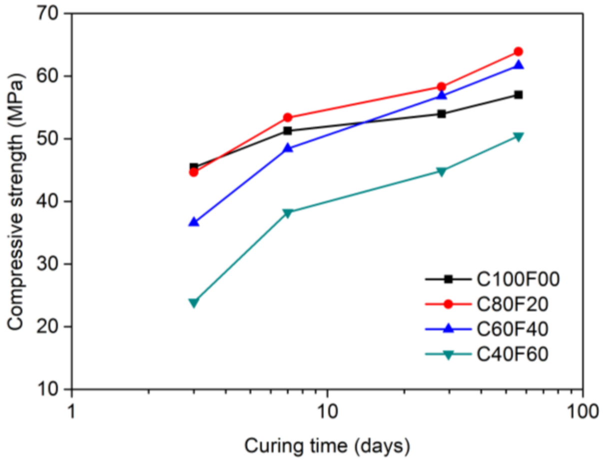


**Fig. 4. CS development of the RPC samples.**

### B. Water absorption and Porosity

Generally, WA and porosity are related to permeability and chemical resistance properties of concrete. Porosity is a parameter that reflects on the internal structure, and it represents the durability of concrete through the properties such as WA. Geslin et al. presented that the reductions in the volume of porosity led to an increase in mechanical properties and the improvement of the durability of concretes [20]. In this study, the influence of FA content on the durability of RPC samples was investigated based on two factors consisting of porosity and WA.

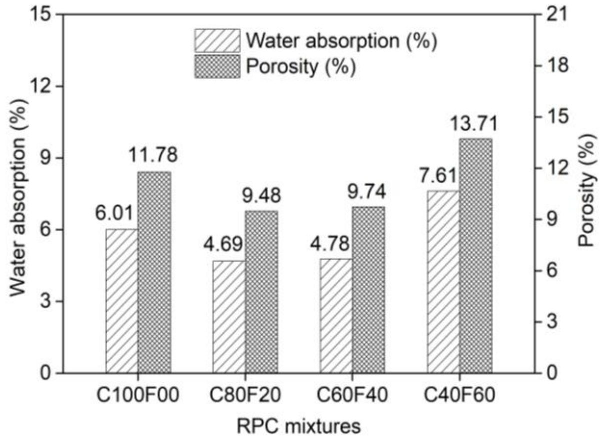


**Fig. 5. WA and porosity of the RPC samples at 28 days.**

The 28-day WA and porosity of RPC samples are shown in Fig. 5. The 28-day WA and porosity values of RPC samples were in the range of 4.69–7.61% and 9.48–13.71%, respectively. It can be seen that the RPC sample with 20% FA replacement exhibited the lowest WA and porosity, whereas the RPC sample with 60% FA replacement showed the highest values. Under the alkaline environment created from the cement hydration, almost FA took part in the pozzolanic reaction to create the second hydration products (C-S-H gels) when its content was suitable. As a result, the microstructure of RPC became denser, resulting in reducing the WA ability. However, a part of FA acted as fine aggregate (i.e., a filler) instead of a pozzolanic material when its content was too much. That is explained for the lowest WA and porosity of RPC with 20% FA replacement and the highest WA and porosity of RPC with a 60% FA replacement. This was also compatible with the highest CS at 28 days of RPC with 20% FA replacement and the lowest CS of RPC with 60% FA replacement at the same age, as seen in Fig. 4.

As seen in Fig. 5, RPC with 0% FA replacement (C100F00) had higher porosity when compared with that with 20 and 40% FA replacements (C80F20 and C60F40). This results in the higher WA of C100F00 than those of C80F20 and C60F40 samples. At a certain replacement level of FA, a part of such FA acted as an ultra-fine aggregate to fill the voids or the gaps between the coarser ones and thus, reducing the pore volume and WA. According to the study of Li et al., with the same pore volume of the concrete samples, a decrease of the pore size effectively enhanced the concrete strength [21]. This indicates that the presence of ultra-fine FA particles may significantly contribute to the pore size, which positively affected the characteristics of RPC. Moreover, Tam et al. pointed out that the reduced pore size and less connectivity of the voids could be attributable to the high packing density of RPC and the positive packing effect of SF [22]. However, the FA addition of more than 40% negatively influenced the durability, resulting from the increases in porosity and WA of the RPC sample, namely the RPC with 60% FA replacement (C40F60). Tangpagasit et al. indicated that the result of the packing-effect of FA minimized the quantity of bonding agent and then multiplied the void space of structural inside [23]. On the other hand, the un-reacted FA almost does not involve in the chemical reaction and leaves a lot of pores within RPC samples, then the exceeding existence of inert FA increased the porosity and negatively affected the durability of the final products.

On the other hand, the experimental results obtained in this study, as shown in Figs. 4 and 5, exhibited negative relationships between CS and WA/ porosity. It implied that the reduction of porosity led to the enhancement of CS and the decrease in WA. The research of Li et al. indicates the CS was not proportional to the porosity [21]. It may be attributable to the presence of both active and non-active FA particles that participated in the chemical reaction and modified the characteristics of RPC samples. It was reported that the packing-effect of un-reacted FA particles increased voids and lowered the CS of RPC25. However, a suitable FA amount of less than 40% improved both WA and porosity of RPC samples.

### C. Thermal conductivity

The thermal conductivities of RPC samples at 28-day age under oven-dry (OD) and saturated-surface-dry (SSD) conditions are shown in Fig. 6. The values of TC of RPC samples at 28 days under OD and SSD conditions were in the range of 0.097–0.167 W/m.K and 0.777–0.901 W/m.K, respectively.

Similar to CS, the RPC samples with 20 and 40% FA replacements showed a higher TC at 28 days than the others regardless of OD and SSD conditions. As indicated by Kim et al., the TC was associated with the density and moisture of the sample [24].

Therefore, it is related to porosity and WA values. The RPC samples with 0 and 60% FA replacements had the higher porosity and WA than those with 20 and 40% FA replacements (see Fig. 5), resulting in the lower TC regardless of OD and SSD conditions. The un-reacted FA particles which did not take part in forming secondary C–S–H gels filling the porosity in the concrete structure.

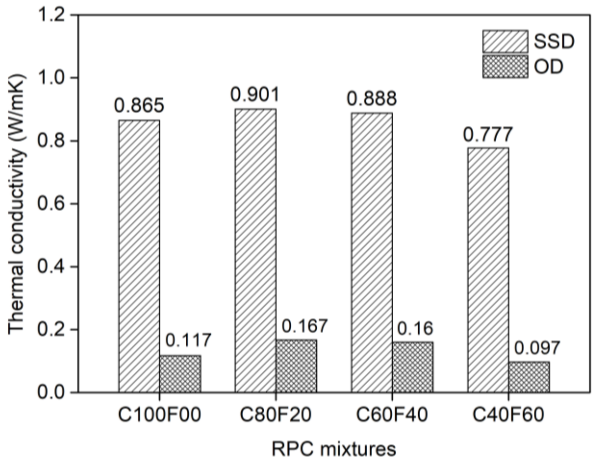


**Fig. 6. Thermal conductivity under OD and SSD conditions of the RPC samples at 28 days.**

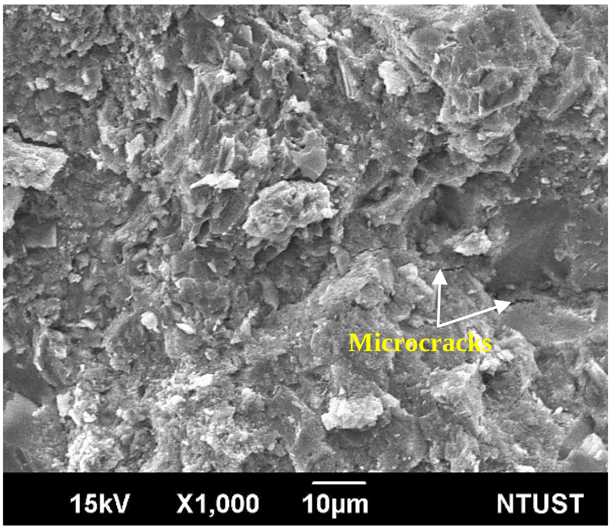
Fig. 6 shows that the TC value of C40F60 was lower than that of C100F00 regardless of OD and SSD conditions. It could be due to an excessive amount of FA in C40F60, as aforementioned, affecting the chemical reaction and creating a lot of pores, thus decreasing the TC value of RPC samples. Moreover, the SSD samples had a higher TC than OD samples regardless of FA replacement. It is attributed to the higher water content in the SSD samples when compared with that in OD samples.

It can be observed from Figs. 5 and 6 that there was a negative correlation between WA and OD-thermal conductivity, as well as a negative correlation between porosity and OD-thermal conductivity. As a result, the lower WA and less porosity resulted in the higher TC value of the RPC samples. Cwirzen et al. previously reported that the presence of a high volume of entrapped air and voids was the leading cause of the low TC value of the RPC [25].

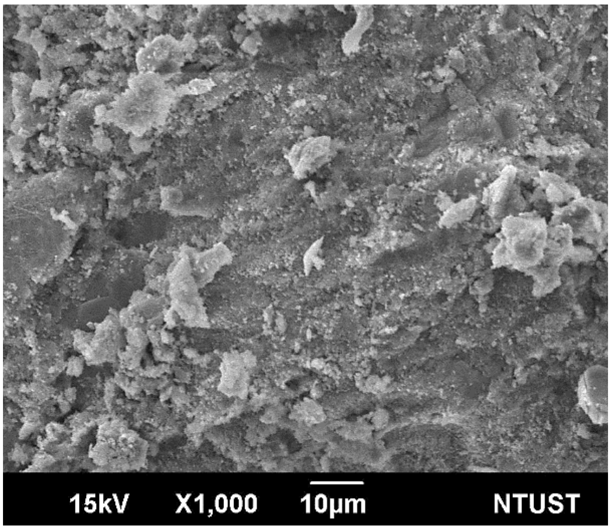
## D. Microstructure

Fig. 7 presents the SEM morphologies of RPC samples with 0, 20, 40, and 60% of FA replacements. The RPC samples with 20 and 40% FA replacements (Figs. 7b and 7c) exhibited the dense structure. It can be explained that at a suitable FA replacement level, the active FA particles involved in the chemical reaction, generating binding gels, while the non-active ones may act as the inner fillers, filling the pores inside the RPC, creating the dense microstructure, and thus leading to improve the characteristics of RPC samples.

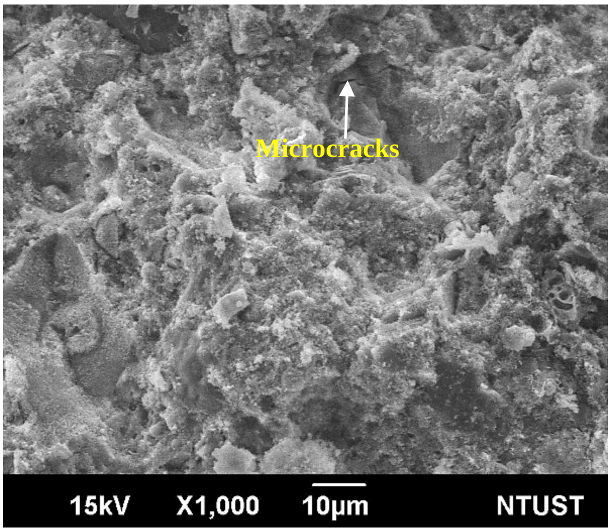
It is clear that the RPC samples with 0, 40, and 60% FA replacements showed some micro-cracks (Figs. 7a, 7c, and 7d) and un-reacted FA particles (Fig. 7d).



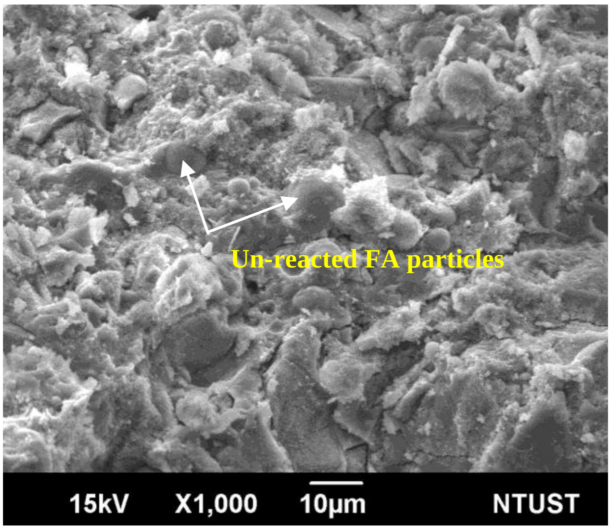
(a) C100F00



(b) C80F20



(c) C60F40



(d) C40F60

**Fig. 7. SEM morphologies of the RPC samples at 28 days.**

The high cement content in C100F00 resulted in high hydration heat, generating some microcracks inside the concrete structure. Moreover, the use of high volume FA in C40F60 led to the presence of some un-reacted FA particles. As a result, the mixtures became non-homogeneous, and the strength and the durability of RPC samples decreased.

## IV. CONCLUSION

The present study evaluated the engineering properties and microstructure of RPC using the natural-fine river sand and the high volume of FA. Based on the experimental outcomes, the following conclusions may be drawn:

1) The 56-day compressive strengths of RPC samples with 0, 20, 40, and 60% FA replacements were 57.0, 63.9, 60.7, and 50.5 MPa, respectively. The use of natural-fine river sand as a fine aggregate can produce RPC with a CS of approximately 60 MPa.
2) The 28-day WA and porosity values of RPC samples were in the range of 4.69–7.61% and 9.48–13.71%, respectively. Whereas, the values of TC of RPC samples at 28 days under OD and SSD conditions were in the range of 0.097–0.167 W/m.K and 0.777–0.901 W/m.K, respectively. The RPC with 20 or 40% FA replacement had the higher CS and TC and the lower WA and porosity as compared to the RPC with 0 or 60% FA replacement.
3) The cracks due to hydration heat and un-hydrated FA particles were observed in RPC samples with 0 and 60% FA replacements, respectively, thereby leading to the lower CS, and higher WA and porosity of these samples in comparison with the RPC containing 20% and 40% FA.
4) The results of this study demonstrated a high feasible to produce high-quality RPC with the inclusion of a high volume FA and natural-river sand. Further investigation on the long-term durability performance of RPC with the incorporation of either FA or other pozzolanic materials is required in order to provide a better understanding of RPC, as well as to evaluate the potential application of such RPC in the construction industry.

## ACKNOWLEDGMENT

Special thanks go for Mr. Ngoc-Duy Do at Can Tho University (Vietnam) and Ms. Thanh-Tam Thi Le at Hong Duc University (Vietnam) for enthusiastic assistance provided during the experimental works.

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