https://doi.org/10.3311/PPci.23912
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Periodica Polytechnica Civil Engineering, 68(4), pp. 1031–1039, 2024

A Modified Reactive Powder Concrete Made with Fly Ash and River Sand: An Assessment on Engineering Properties and Microstructure

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Received: 21 November 2023, Accepted: 26 March 2024, Published online: 29 May 2024

Abstract

Containing a high quantity of both fine powders and steel fiber makes reactive powder concrete (RPC) a unique kind of ultra-high strength concrete. However, the cost of manufacture, shrinkage, and hydration heat are increased when silica fume and cement are used in significant amounts. To mitigate these negative consequences and the environmental impact, this study assessed the use of fly ash (FA) with high volume combined with natural-fine river sand (NFRS) in the manufacturing of RPC. FA was utilized to partially substitute cement at 0, 20, 40, and 60 wt% in RPC mixtures that had a set water/binder ratio of 0.2. Thermal conductivity, porosity, water absorption, and compressive strength tests were performed. Furthermore, RPC's microstructure was examined using a scanning electron microscope (SEM). This study also included a cost and global warming potential analysis of RPC production. Test results indicated that a modified RPC with a 60 MPa compressive strength value could be created by using NFRS and a large amount of FA. In comparison to the reference mixture, a higher compressive strength, reduced water absorption, and lesser porosity were observed in RPC when the FA replacement amount was less than 40%. Many FA particles did not engage in the hydration reaction when the FA replacement level was more than 40%, which had a detrimental impact on the RPC's characteristics. In general, using FA to produce RPC has certain benefits for the economy and the environment. It is recommended that 40% of FA be used in actual practice.

Keywords

fly ash, reactive powder concrete, river sand, global warming potential, production cost, microstructure

1 Introduction

There are numerous advantages to using concrete in construction projects for the advancement of civilization. Recent times have seen the consideration of sustainable development for concrete with remarkable strength and endurance. Reactive powder concrete (RPC) with a cement basis is widely recognized for its remarkable longevity, remarkable toughness, and extraordinarily high strength [1, 2]. The microstructure enhancement approaches for cementitious materials greatly improved the engineering attributes of RPC as compared to typical cement-based materials [1]. Inner hydration products like gels were created in RPC using a diffusion process, which is similar to high-performance concrete and produced a dense cement matrix [2]. Using packing density theories, the preparation of ultra-high strength concrete like RPC was shown to be possible by Cwirzen et al. [3], wherein the binder matrix's packing density was improved by adding the proper amount of quartz micro-fillers. Thus, for the regular curing concrete, the highest compressive strength (CS) value measured at 28 days was around 150 MPa [3]. According to Bentz and Jensen [4], the highly dense microstructure of RPC was produced by a combination of using a low water/binder ratio and a high cement content in the presence of silica fume (SF) and superplasticizer, which led to the excellent performances. Additionally, to produce RPC, ultra-fine aggregate is used rather than natural aggregate [3]. Also, steel fiber and superplasticizer are utilized to respectively enhance the mechanical strength and workability of RPC [3, 5, 6]. Additionally, RPC has strong resistance to freezing-thawing [3], fire [7], blast explosion [8], and chemical attack [9].

Cite this article as: Huynh, T.-P., Ngo, S.-H., Nguyen, V.-D. "A Modified Reactive Powder Concrete Made with Fly Ash and River Sand: An Assessment on Engineering Properties and Microstructure", Periodica Polytechnica Civil Engineering, 68(4), pp. 1031–1039, 2024. https://doi.org/10.3311/PPci.23912

However, excessive use of either cement or SF causes increased production costs, increased hydration heat, and RPC shrinkage. Cement substitutes include phosphorous slag [9], fly ash (FA) [5], ground granulated blast-furnace slag (GGBFS) [10], and metakaolin [11] are being explored as a means of mitigating these negative impacts. Numerous advantages of using FA for concrete have been shown by published studies, including a decrease in environmental pollutants and an improvement in the material's durability and engineering qualities [12, 13].

The majority of published studies also stated that FA and/or GGBFS, acting as substitute sources of silica, were useful in generating RPC. Yazıcı et al. [14] highlighted the efficiency of producing RPC utilizing FA and/or GGBFS. According to their report, RPC manufactured by FA and having a CS of >200 MPa replaced 60% of the cement [14]. Furthermore, as reported by Peng et al. [9], RPC showed exceptional qualities, such as good resistance to sulfate attack as well as CS and flexural strength of >150 MPa and >21 MPa, respectively, when 30% of the cementitious materials were substituted by phosphorous slag powder. Similarly, RPC with a CS over 200 MPa might potentially be generated by replacing up to 60% of the cement with GGBFS [10]. When a portion of the cement was replaced with both FA and GGBFS, the same strength value was likewise attained [1]. Furthermore, integrating FA in RPC resulted in a more compact microstructure, which greatly contributes to the enhancement of both strength and durability [15, 16]. It is evident that the majority of the earlier research, which was previously described, increased the RPC performance by adding steel fiber and using relatively high concentrations of cement, SF, and superplasticizer. Additionally, the RPC specimens were either autoclaved or cured in atmospheric steam, which increased the cost of manufacture. The typical condition of water curing, without the use of steel fiber, resulted in samples with a CS of only approximately 32.5–76.2 MPa [6].

The majority of RPC experiments that have been done thus far, according to the literature study, have employed ultra-fine aggregate with extremely small particle sizes, and the samples were cured under unique circumstances with high pressure and temperature. This study looked at using NFRS and a large amount of FA together to produce RPC to lower production costs and make better use of FA, an industrial by-product that is readily available from nearby coal-thermal power plants. It is mentioned that large amounts of the NFRS and FA are readily available locally. They are employed directly, without any prior processing, to achieve financial goals. In order to lower production costs, all of the specimens in this investigation were created without the use of steel fiber and cured under conventional conditions. Thermal conductivity (TC), porosity, water absorption (WA), CS, and (SEM) tests were used to assess the changes in microstructure and engineering characteristics of RPC with the incorporation of FA. Additionally, research was done on the advantages of RPC with NFRS and a large amount of FA in terms of production costs and environmental effects.

2 Materials and experimental methods

The following is a possible description of the experimental works:

- Step 1-Selecting the raw ingredients.
- Step 2-Testing the properties of the materials.
- Step 3-Mix proportioning.
- Step 4- Prepare the sample, curing, and trial batch.
- Step 5-Assessing the properties of RPCs with various tests.
- Step 6-Analyzing the experimental results and making conclusions.

2.1 Materials

Cementitious materials were employed, including FA in accordance with ASTM C618-23e1 [17], SF in accordance with ASTM C1240-20 [18], and Portland cement (OPC) of Type I in accordance with ASTM C150/C150M-22 [19]. Table 1 provides the attributes of the cementitious materials. Figs. 1–3 display their particle size distributions, X-ray diffraction (XRD) patterns, and SEM pictures, in that order. It can be seen that FA had the biggest particle

Table 1 Properties of FA, SF, and OPC

Raw materials		OPC	SF	FA
Density (g/cm^3)		3.15	2.21	2.29
Strength activity index at 28 days (%)		100	107.5	86.5
Average particle size (µm)		19.1	16.5	21.5
Specific surface area (m^2/g)		0.78	0.82	0.66
Composition (wt%)	SiO_2	20.04	97.65	64.01
	CaO	62.43	0.35	2.75
	Fe_2O_3	3.12	0.05	5.64
	Al_2O_3	4.24	0.70	22.14
	MgO	4.17	0.42	0.92
	K_2O	0.43	0.29	1.36
	Na_2O	0.33	–	0.85
	SO_3	2.97	0.27	0.61
	Loss on ignition	1.75	1.39	2.74

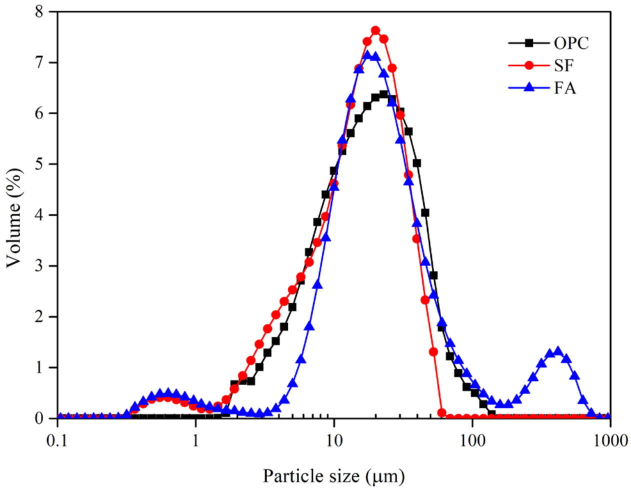


Fig. 1 Particle size distributions of FA, SF, and OPC

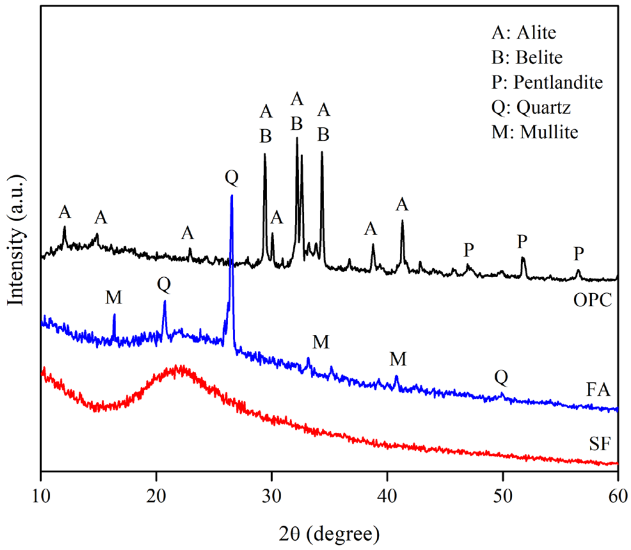
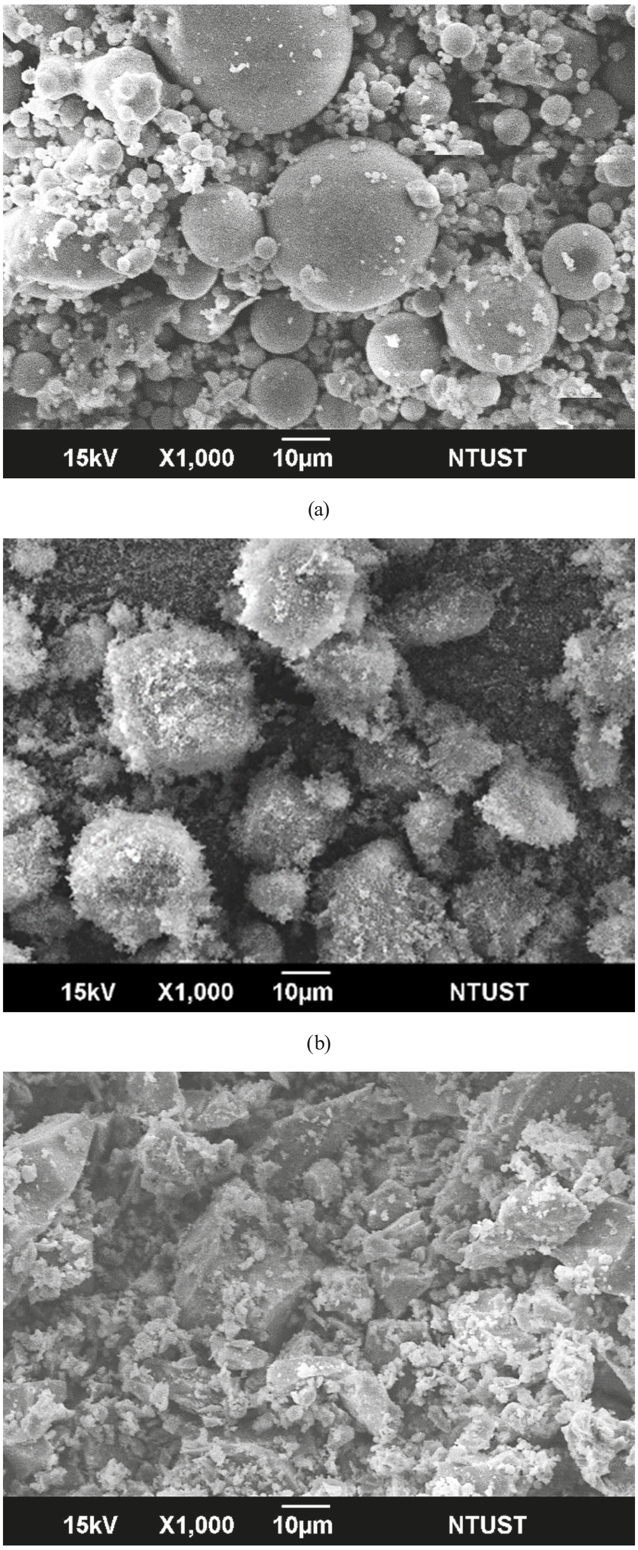


Fig. 2 XRD patterns of FA, SF, and OPC

size and a spherical shape, whereas SF had the smallest particle size and an irregular shape (Table 1, Fig. 4). Every binder material had a particle size of <22 μm. It is thought that adding spherical FA particle could make the fresh RPC mixture more workable. Further, it is common knowledge that the amount of materials involved in a chemical reaction increases with decreasing particle size. Whereas the primary components of FA were SiO_2 and Al_2O_3 and OPC was primarily composed of SiO_2, CaO, Al_2O_3, and Fe_2O_3 (Table 1). These outcomes were comparable to those of the XRD pattern (Fig. 2). While mullite and quartz were present in the FA, in the OPC, alite, belite, pentlandite, mullite, and quartz in form of stable crystals were detected.



(a)

(b)

(c)

Fig. 3 SEM images of (a) FA, (b) SF, and (c) OPC

It should be noted that, despite SiO_2 being the primary chemical component of SF, as indicated by Table 1, no SiO_2 peaks were found in Fig. 2 implying that since the majority of the silica in SF was found in the sensitive amorphous phase, this suggests that SF will quickly take part in the hydration processes.

Fine aggregate consisted of NFRS particles, which had a density of 2650 kg/m^3 and a size range of 150–600 μm.

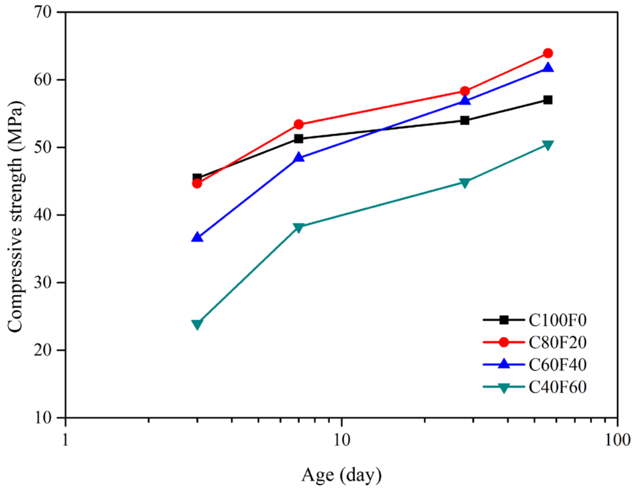


Fig. 4 The development in CS of the RPC

The intended RPC workability was ensured by using type-G superplasticizer. The dosage of superplasticizer that was utilized was 2% (by mass of cementitious materials) and the specific gravity was 1.34.

2.2 Mix proportioning

Table 2 displays the four RPC mixtures that were created, all of which had a fixed water/binder ratio of 0.2. OPC was substituted with 0, 20, 40, and 60% using the FA. It is noted that for all mixes, a 20% by weight of cementitious materials content of SF was utilized. The letters C and F in the name of each RPC mixture stand for OPC and FA, respectively; the percentages of OPC and FA replacement are indicated by the numbers that follow.

2.3 Sample preparation and test methods

Steel molds were utilized to create cubic RPC specimens of 50 × 50 × 50 mm. Following the de-molding process, all specimens underwent a conventional water cure, with a temperature of 20 ± 2 °C and a relative humidity of ≥95%). According to the respective protocols as outlined by ASTM C109/C109M-23 [20], ASTM C1403-22a [21], Huynh et al. [22], and Ngo et al. [23], the engineering parameters of RPC (i.e., CS, WA, porosity, and TC) were assessed. A JEOL scanning electron microscope was used to observe the microstructure of the toughened RPC. Other parameters were assessed on day 28 while CS was examined on sample ages of 3, 7, 28, and 56. The results for each test were the mean value obtained from three specimens.

As previously stated, the primary goal of employing NFRS and a large amount of FA is to produce positive effects on the environment and the economy. Based on local market prices and prior research, the production cost and the global warming potential (GWP) index per cubic meter of RPC were computed to evaluate these benefits [24–26]. Table 3 displays the unit price and GWP for each item in RPC mixes per kilogram. It can be seen that the GWP value, which was determined using the quantity of CO_2 emissions per kilogram of raw material utilized, represents the amount of greenhouse gas emissions.

3 Results and discussion

3.1 Compressive strength

The changes in CS for each RPC sample over time are displayed in Fig. 4. The respective 56-day CS values of the specimens with 0–60% FA substitutions (20% of interval) were approximately 57, 64, 61, and 51 MPa. Based on the results of the previous study [6], it can be concluded that the usage of NFRS can result in a specimen with a CS of about 60 MPa. The maximum CS was also shown by the specimen with 0% FA replacement (C100F0) at 3 days, whereas the highest CS was shown by the specimen with 20% FA replacement (C80F20) after 3 days. These findings are further supported by Fig. 4. Consequently, an appropriate FA content (i.e., 20% by weight) was used to make RPC with the greatest CS.

The comparative analysis of the C60F40 specimen revealed a lower CS at 3 and 7 days and greater CS at 28 and 56 days when compared to RPC with 0% FA. The main cause of the increased strength at later periods and decreased CS at early ages of C80F20 and C60F40

Table 2 Materials used for making RPC

Materials (kg/m^3)	Mixture ID.			
	C100F0	C80F20	C60F40	C40F60
OPC	897	703	516	337
FA	0.0	176	344	506
SF	224	220	215	211
NFRS	987	967	947	928
Water	224	220	215	211
Superplasticizer	22	22	22	21

Table 3 The cost and GWP per unit mass (1 kg) of raw material

Material	Unit cost (USD/kg)	GWP (kg CO_2/kg)	Reference sources
OPC	0.0679	0.8980	Kurda [24]
SF	0.4906	0.0011	Kurda [24]
FA	0.0102	0.0088	Chen et al. [25]
NFRS	0.0071	0.0099	Braga et al. [26]
Superplasticizer	0.4882	0.0020	Kurda [24]
Water	0.0002	0.00013	Braga et al. [26]

is the pozzolanic reaction of FA in the matrix. After several weeks of curing, this reaction starts to increase rapidly, happening incredibly slowly in the early stages of concrete [27]. A prior study by Sun et al. [28] likewise reported that FA improved CS after 28 days.

Using a large amount of FA as a cement substitution in the RPC matrix produced a highly compacted microstructure, which improved CS, as Yiğiter et al. [5] noted. FA may function in this situation as a filler (filling the spaces in the system) as well as a pozzolanic substance (participating in the pozzolanic phase). Regardless of curing time, the CS of 60% FA specimen was nevertheless lower than that of FA-free RPC. This is because of the astronomically large proportion of cement that FA has replaced.

Yiğiter et al. [5] proved that the inclusion of 3% steel fiber significantly increased the CS of RPC, with strength values of around 130–150 MPa. On the other hand, special curing conditions such as pre-pressure and high temperature greatly attributed to the strength gain of RPC [3, 5, 9]. When RPC specimens were produced without steel fiber and cured in water under a standard condition, they had a CS of around 32.5–76.2 MPa [6], similar to the CS values in this study. The use of NFRS with a high amount of FA, without steel fiber, and under standard conditions are major causes for the lower CS of RPC in this study as compared to previous studies. However, all RPC specimens in this study have a CS of around 60 MPa with a low production cost and a significant environmental benefit, which will be presented in Section 3.5.

3.2 Water absorption and porosity

In general, the permeability and chemical resistance of concrete are correlated with both WA and porosity. Porosity is a measure of the interior structure that indicates the longevity of concrete by using characteristics like WA. Generally, the improvements in mechanical characteristics and durability of concretes were caused by reductions in porosity volume [29]. Thus, porosity and WA were the two parameters used in the present study to examine the impact of FA incorporation on the RPC's durability.

Fig. 5 displays the 28-day test results of porosity and WA of the specimens, showing that WA and porosity values fell between 4.69 and 7.61% and 9.48 and 13.71%, respectively. As a result, the lowest porosity and WA values were recorded in the specimens containing 20% FA, while the specimens containing 60% FA exhibited the highest values. When an appropriate FA content was used, almost all FA participated in the pozzolanic reaction to produce the secondary hydration product (C-S-H gels) under the ideal alkalinity environment produced by the hydration of cement. Consequently, the RPC microstructure thickened, which decreased its WA capability. But when its percentage was too high, some FA functioned as a fine aggregate that is, a filler rather than a pozzolanic substance [30]. This is explained by the fact that RPC has the maximum WA and porosity when a 60% FA replacement is used, and the minimum values were obtained when 20% FA is used to replace cement. This finding was also in good agreement with the CS results (see Fig. 4) as previously discussed in Section 3.1.

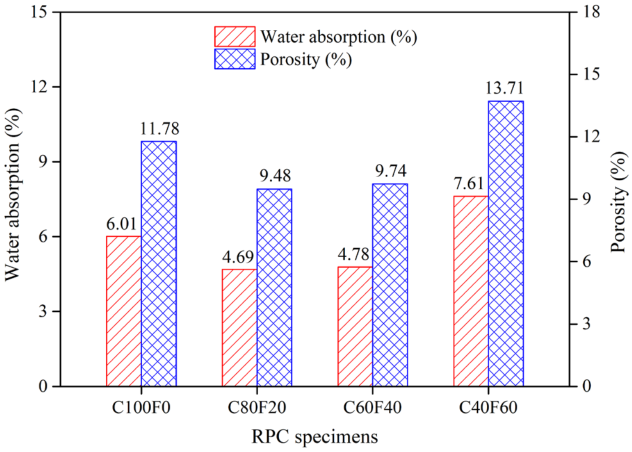


Fig. 5 WA and porosity of the 28-day RPC specimens

Fig. 5 illustrates that the porosity of no-FA specimens (C100F0) was higher than that of specimens containing 20% and 40% FA. As a result, RPC specimens with FA (i.e., 20% and 40%) exhibited a lower WA rate than the control one (0% FA). In this case, at a specific FA content, a portion of the FA functioned as a filler to fill in the small spaces in the system, lowering the pore volume. Li et al. [31] found that a reduction in pore size significantly increased the concrete strength while maintaining the same pore volume. This suggests that the pore size may be greatly influenced by the availability of ultra-fine FA particles, which would improve the properties of RPC. Furthermore, Tam et al. [32] noted that better packing density of the system associated with the positive packing effect of SF might be responsible for the smaller pore diameter and lower connectivity of the voids. Unfortunately, the addition of more than 40% FA had a detrimental effect on the durability, as evidenced by the 60% FA specimens having higher porosity and WA. According to Tangpagasit et al. [33], the packing effect of FA reduced the amount of bonding agent and increased the internal structure's vacant space. However, the unreacted

FA did not participate in the chemical reaction and left many pores in the RPC specimens; as a result, the excessive amount of inert FA increased the porosity and had a detrimental effect on the final products' durability.

However, as can be seen in Figs. 4 and 5, the test results from this investigation demonstrated inverse CS-WA and CS-porosity relations, suggesting that lower porosity is tightly associated with lower WA and higher CS. Besides, a prior study reported that either active or inactive FA particles are involved in the reaction processes, causing changes in RPC properties. Also, the presence of unreacted FA particles increased voids and thus decreased the RPC strength [31]. The results of this study suggested using less than 40% as a cement replacement for enhancing the WA and porosity of RPC.

3.3 Thermal conductivity

Fig. 6 displays the results of TC measurement on the 28-day specimens under oven-dry (OD) and saturated-surface-dry (SSD) conditions. At 28 days, the TC values ranged respectively from 0.097 W/m · K to 0.167 W/m · K and from 0.777 W/m · K to 0.901 W/m · K for specimens under OD and SSD conditions. Similar trend with CS, the TC values of specimens containing 20% and 40% FA were generally higher than that of other specimens. The TC was connected to the sample's moisture content and density, as Kim et al. [34] reported. It is hence associated with WA levels and porosity. In spite of OD and SSD conditions, the relatively lower TC of the no-FA and 60% FA specimens in comparison with the 20% and 40% FA specimens was due to their higher porosity and WA (see Fig. 6). The unreacted FA particles are the cause of this phenomenon because they did not contribute to the formation of C-S-H gels that filled the pores in the RPC system.

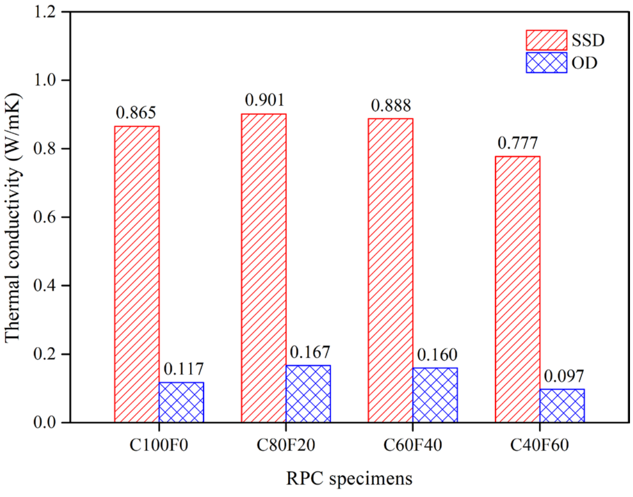


Fig. 6 TC values of the specimens at 28 days

In both OD and SSD settings, the TC values of C40F60 were less than those of C100F0, as shown in Fig. 6. As previously noted, it might be because of too much FA in C40F60, which would alter the hydration process and produce more pores, resulting in lower TC value. Furthermore, independent of FA replacement, greater TC values were recorded in the specimens under SSD than in the OD condition. It is explained by the fact that the SSD specimens had more water in them than the OD specimens did. A negative association was found between porosity and TC, and a negative relationship was found between WA and TC, as shown in Figs. 5 and 6 Consequently, the greater TC value was caused by the decreased WA and reduced porosity in RPC specimens.

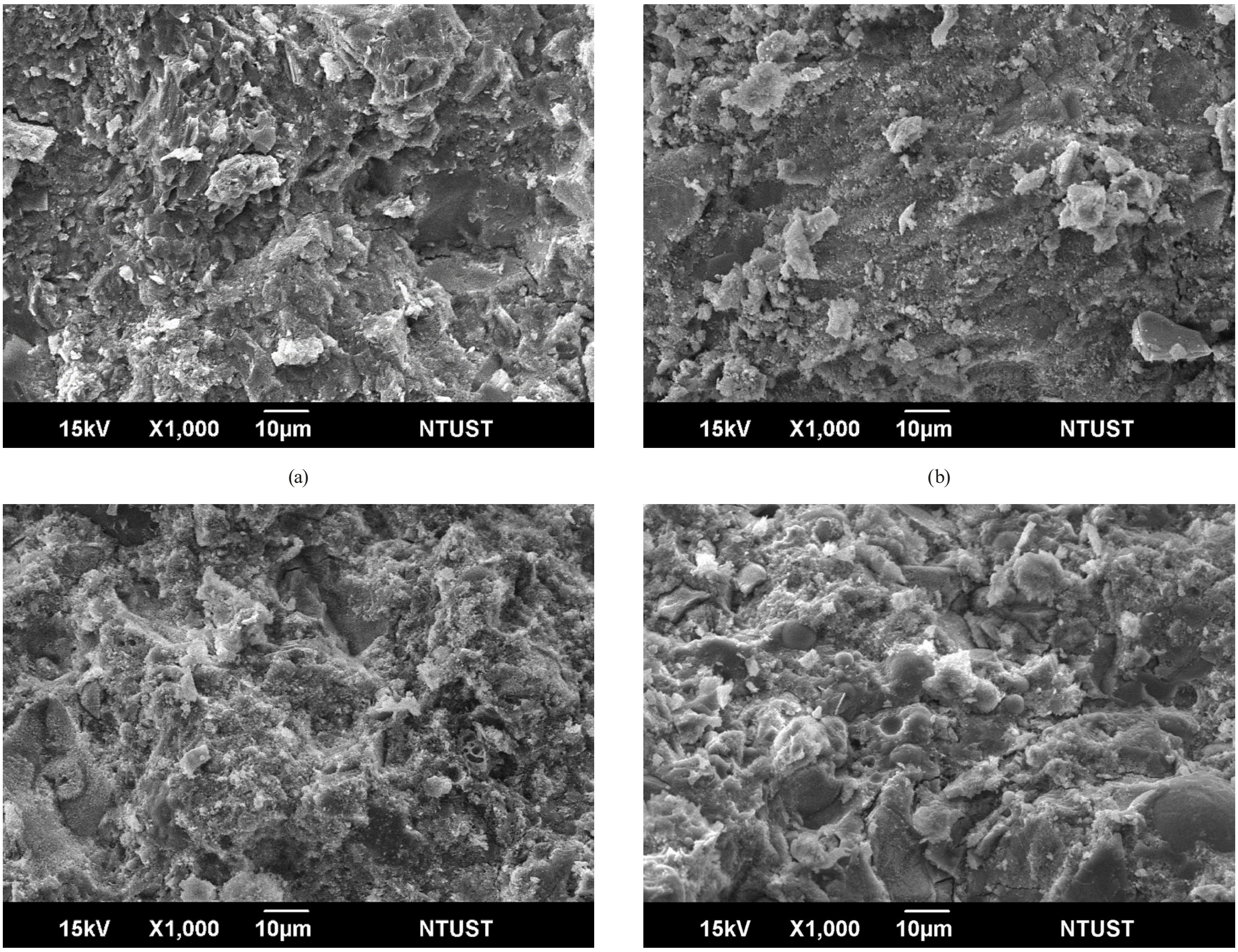
3.4 Microstructure

The SEM images of specimens with 0, 20, 40, and 60% FA substitutions are shown in Fig. 7. Dense microstructure was seen in the specimens containing 20% FA (Fig. 7 (b)) and 40% FA (Fig. 7 (c)). It can be explained that, at an appropriate level of FA substitution. In this case, as previously mentioned, both binding and filling effects of the active and inactive FA particles formed a compact microstructure and improved the properties of RPC specimens. A few microcracks and unreacted FA particles were visible in the specimens with no FA (Fig. 7 (a)), 40% FA (Fig. 7 (c)), and 60% FA (Fig. 7 (d)). Due to the high hydration heat produced by the high cement quantity in C100F0, various microcracks were created inside the concrete structure. Also included were some unreacted FA particles in the C40F60 specimen. As a result, the mixes lost their homogeneity, and the RPC specimens' durability and strength declined. This result is consistent with the deleterious impact of unreacted FA from a prior study [30].

3.5 Economical and environmental benefits

The total cost and GWP of one cubic meter for all RPC specimens were calculated and shown in Table 4. The reference mixture (C100F0) has the highest production cost and GWP value. When the FA replacement level increased, the production cost and the GWP were reduced. With 20% of FA replacement, the production cost was reduced by 14.05%, while the environmental impact (GWP) was reduced by 21.24% in comparison with the reference mixture. Similarly, when the FA replacement level increased to 40% and 60%, the production cost was reduced by 27.59% and 40.52%; meanwhile, the GWP value was reduced by 41.62% and 61.17%, respectively.

To evaluate the economic and strength effectiveness, the production cost and the GWP per MPa of CS



(a) (b)

(c) (d)

Fig. 7 SEM images of hardened RPC: (a) C100F0, (b) C80F20, (c) C60F40, (d) C40F60

Table 4 The total cost and GWP of producing 1 m³ of each RPC mixture

Mixture	Total cost (USD/m³)	Cost change (%)	GWP (kg CO_2/m³)	GWP change (%)
C100F0	188.96	–	815.96	–
C80F20	174.91	−14.05	642.63	−21.24
C70F30	161.37	−27.59	476.35	−41.62
C60F40	148.43	−40.52	316.83	−61.17

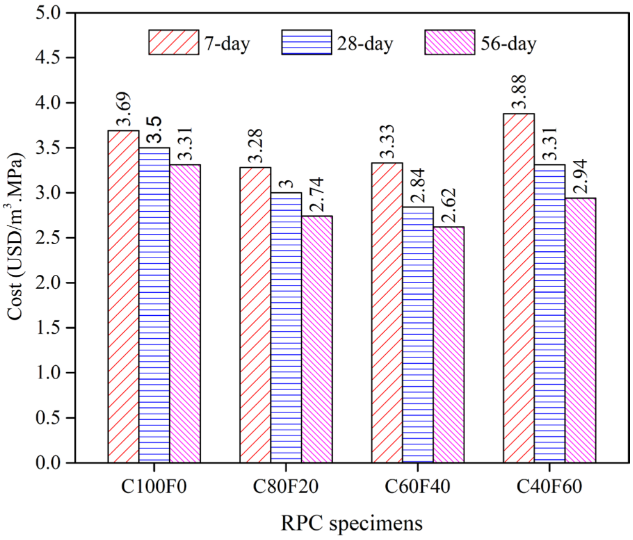


Fig. 8 The cost per CS of concrete mixes

were estimated and plotted in Figs. 8 and 9, respectively. According to Fig. 8, the production cost per MPa at 28 and 56 days of C60F40 was the lowest, followed by the C80F20 and C40F60, while the production cost per MPa of C100F0 was the highest among the mixtures. It means that the FA replacement level of 40% was the most economically efficient, while the free-FA replacement level was the worst. For the environmental impact, the GWP per MPa decreased with increasing FA content (Fig. 9). The amount of CO_2 emission reduced significantly with increasing FA replacement levels. In other words, the RPC mixture with FA replacement of 60% demonstrated the most effectiveness in terms of environmentally friendly. However, if both economic and environmental benefits were fully considered, the FA replacement level of 40%

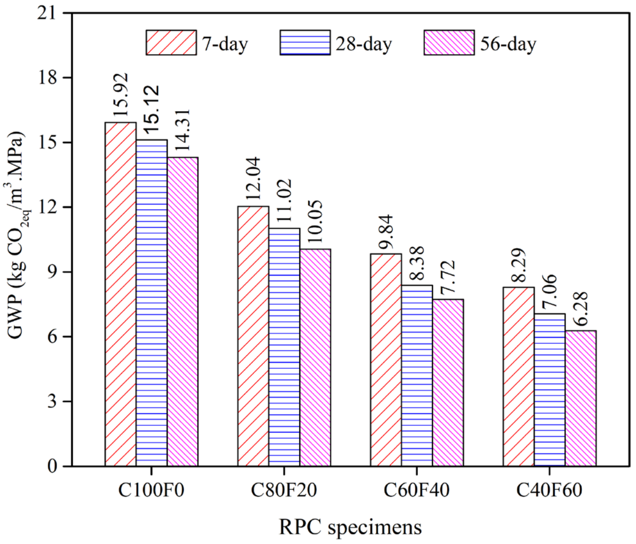


Fig. 9 The CO_2 emission per CS of concrete mixes

was proposed for use in real practice. It means that the use of a suitable amount of FA to replace cement will result in both economic effectiveness and environmental benefit.

4 Conclusions

RPC was produced using NFRS and a large amount of FA to lower manufacturing costs and treat a portion of the solid by-products from coal thermal power plants. The changes in RPC properties with various FA contents were investigated. Additionally examined were the benefits to the environment and the cost of manufacture of RPC with FA. The following conclusions can be made in light of the experimental results:

- RPC with a 28-day CS of roughly 60 MPa can be produced with the use of local raw materials like NFRS and a large amount of FA.
- The use of a suitable amount of FA (20% or 40%) resulted in improving the quality of RPC with a higher CS, and lower WA and porosity. When FA content was over an optimal limit, many unreacted FA particles were detected in SEM observation, negatively affecting the properties of RPC.
- The RPC specimens cured under the SSD condition registered a significantly greater TC value than the specimens cured under the OD condition.
- The results of this study demonstrated that the use of FA yielded both economic and environmental benefits. The FA replacement level of 40% is recommended for use in real practice.

Acknowledgment

We especially appreciate the enthusiastic help during the experimental activities offered by Ms. Le Thi Thanh Tam (Hong Duc University) and Mr. Do Ngoc Duy (Can Tho University).

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