Effects of Mixing Techniques on Properties of Reactive Powder Concrete Containing Fly Ash

Jinhao Wei[1], Nida Chaimoon[2], Nantawat Khomwan[3] and Krit Chaimoon[1]*

[1] Structural Engineering Research Unit, Faculty of Engineering, Mahasarakham University, Maha Sarakham, 44150, Thailand

[2] Circular Resources and Environmental Protection Technology Research Unit, Faculty of Engineering, Mahasarakham University, Maha Sarakham, 44150, Thailand

[3] Department of Civil Engineering, Faculty of Engineering, Kasetsart University Kamphaeng Saen Campus, Nakhon Pathom, 73140, Thailand

*Corresponding Email: k.chaimoon@msu.ac.th

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Abstract. *Reactive powder concrete (RPC) is an ultra-high-performance concrete with exceptional mechanical properties and durability compared to conventional concrete. Due to its unique properties, RPC is a promising material for advancing sustainable, resilient, and eco-friendly infrastructure solutions on a global scale. Using RPC, infrastructures can achieve enhanced characteristics such as reduced cross-sections, extended spans, intricate design, and decreased maintenance requirements. Despite its immense potential, RPC remains in the early stage of development, with its properties highly influenced by various factors including ingredient selection, proportions, mixing techniques, and curing method. Typically composed of cement, silica fume, fine sand, superplasticizer, water, and small steel fiber, RPC features a very low water-to-cement (w/c) ratio and densely packed particles. Fly ash, a byproduct of coal combustion, offers a way to enhance RPC properties, while simultaneously reducing costs and environmental impact by substituting for a portion of cement. However, the challenges associated with mixing RPC, especially with low w/c ratios, remain significant, and studies on the effects of mixing techniques for RPC containing fly ash are limited. This study investigates the effects of mixing techniques on the properties of RPC containing fly ash. Specifically, it examines the impact of single-batching and double-batching methods, as well as the influence of different steel fiber types (single-size and mixed-size) and mixing temperatures (25℃ and 40℃). Both fresh and hardened properties of RPC were considered. Results indicate that the double-batching method significantly improves the properties of RPC compared to single-batching. While mixed-size fibers enhance the 28-day compressive strength, single-size fibers yield a higher flow value. Higher mixing temperatures negative impacted workability. The findings suggest that optimizing the batching method, fiber type, and mixing temperature can improve both the mechanical properties and workability of RPC.*

Keywords:

Reactive powder concrete, Mixing method, Workability, Strength

1. Introduction

Reactive powder concrete (RPC) was a significant development in the creation of ultra-high performance concrete (UHPC) during the 1990s. It was first developed in the early 1990s at the Bouygues Laboratory in France. RPC is characterized by its densely packed particles, very low water-to-cement (w/c) ratio, high cement content, and the inclusion of small steel fiber. Depending on its composition and curing processing methods, the compressive strength of RPC can range from 200 MPa to 800 MPa [1]. Noting that normal strength concrete (NSC) and high strength concrete (HSC) has compressive strength about 30 MPa and 80 MPa, respectively [2]. RPC demonstrates enhanced workability, superior mechanical properties, and greater durability compared to both NSC and HSC [3-4]. Due to its excellent properties, RPC is widely used in engineering fields such as bridges, tunnels, and high-rise buildings. Some studies have also confirmed that the bond strength and adhesion between RPC and steel is also greater than other conventional concrete both NSC and HSC [5-6]. These studies are also very helpful for its application in reinforced concrete structures.

Although RPC has been researched and developed globally for over 25 years, it remains relatively new compared to conventional concrete. Typically, RPC is composed of cement, silica fume, fine sand, superplasticizer, water, and steel fiber. Its performance is dependent on many factors, including the selection of ingredients, mix proportions, mixing methods, and curing methods. Mayhoub et al. [7] highlights the critical role of ingredient selection, proportions, and curing methods in determining the properties of RPC. The ingredient selection lies in its direct impact on the mechanical strength, durability, and overall performance under various curing methods. Recently, Li et al. [8] have presented an overview of the latest developments in research on this topic, with a particular focus on the mechanical properties of RPC. The authors have outlined the significant advancements that have been made in the field of RPC, including improvements in concrete formulation design, curing conditions, and fiber reinforcement. For instance, they have highlighted the crucial role of temperature, pressure, humidity, and curing duration in determining the strength of the RPC in question. Despite the differences in the materials and curing parameters employed in the various studies, it can be observed that autoclaving consistently yields the highest strength, followed by hot water curing, hot air curing and steam curing. The potential for future research in this field, including the optimization of mixed-fiber RPC and the development of new RPC materials, was also discussed. This would enable further exploration of the effects of different fibers on the properties of RPC and the identification of new processing and curing methods to enhance the mechanical properties and durability of RPC.

Mixing RPC with low w/c ratios results in different microstructure development and mixing torque requirements compared to conventional concrete. Noting that RPC has w/c ratio ranging from 0.11 to 0.26 [9] in contrast to NSC, which has a ratio between 0.3 to 0.4, and HSC, which typically exceeds 0.4. A major challenge in the structural application of RPC is its large-volume production [10]. As the production volume of RPC increases, it becomes challenging to mix the ingredients with standard mixers because the required mixing torque surpasses their capacity [11]. Using high-intensity mixers with greater torque capacity, the cost of the high-energy mixers are about 20 times more expensive than standard mixers [12]. To address this issue, Du et al. [10] investigated the mixing kinetics of UHPC, using a binder composed of Type I Portland cement, silica fume, and ground granulated blast furnace slag. They evaluated the effects of mixing temperature (10°C, 20°C, 30°C), mixing volume (1.5L, 3.0L, 4.5L, 6.0L), time interval for adding of the second half portion of ingredients (30s, 60s, 90s, 120s, 150s, 180s), and mixing method (single-batching, double-batching, and triple-batching) on the mixing torque. Traditional RPC mixing uses a single-batching method, where all ingredients are combined in a single step. Their results showed that the multi-batching method significantly reduced the peak mixing torque of UHPC without significantly reducing its key properties. Hiremath et al. [13] evaluated the effect of different mixing methods (three and four stages), different mixing speeds (25, 50, 100, 125, 150 rpm) and different total sustained mixing times (10, 15, 20, 25, 30 min) on the flow and strength properties of typical RPC (using binder composed of Type I Portland cement and silica fume). Their results showed that the improved four-stage mixing technique was beneficial in improving the fresh and hardened properties of RPC. Higher mixing speeds and longer mixing times reduced the flow and strength properties of RPC.

Fly ash (FA), a byproduct of pulverized coal combustion, presents an opportunity to enhance numerous concrete properties, while simultaneously reducing costs and environmental impact by substituting for a portion of cement. Huynh et al. [14] evaluated the effects of using FA in RPC. The test results showed that RPC with up to 40% FA improve 28-day compressive strength, water absorption, and porosity, while more than 40% FA had detrimental effects. However, the properties of RPC are significantly influenced by its ingredients [15] and mixing technique [11-13] and reports on the effects of mixing techniques on the properties of RPC containing fly ash, using different steel fiber sizes at different mixing temperature, remain limited. This study aims to investigate the effects of single-batching and double-batching methods on properties of fresh and hardened RPC using more environmentally friendly hydraulic cement, silica fume, and fly ash as binders. Two types of steel fiber, including single-size and mixed-size fibers, are considered. In addition, mixing temperatures of 25°C (normal) and 40°C (high) are evaluated.

2. Experiments

2.1 Materials and Mix Proportion

Most of the materials used in this study are common in the concrete industry. Cement (C) is hydraulic cement manufactured by Siam Cement Group, Thailand that meets TIS 2594-2556 industrial standards. Silica fume (SF) is undensified silica fume provided by Eikem company, Thailand. Fly ash (FA) according to American Standard ASTM C 618-15 was provided by Taurus Pozzolan Company, Thailand. Sand (S) is graded river sand with sizes of 0.15 to 0.60 mm in saturated surface dry condition. The original sand was from Chi river, Thailand. Superplasticizer (SP) is polycarboxylate type. Water (W) is tap water. Steel fiber (STF) is a straight fiber used in two types. The first type, referred to as single size, has a diameter of 0.22 mm and a length of 13 mm (aspect ratio = 59). The second type, referred to as mixed size, features diameters ranging from 0.18 mm to 0.35 mm and lengths from 12 mm to 14 mm (aspect ratio ranging from 34-78, with an average of 56). Fig. 1 shows SEM images of C, SF, and FA. It can be seen that C particles have an irregular shape, while both SF and FA particles have a rounded shape. SF particles have the smallest size. Fig. 2 depicts the examples of mixed-size and single-size steel fibers.

Table 1 Mix proportion of RPC

Material	Amount (kg/m^3)	Remark
Cement (C)	795	85% of (C+FA)
Fly Ash (FA)	140	15% of (C+FA)
Sand (S)	1028.5	S/(C+FA) = 1.1
Silica Fume (SF)	187	SF/(C+FA) = 0.20
Superplasticizer (SP)	50	SP/(C+FA) = 0.02
Water (W)	215	W/(C+FA) = 0.23
Steel Fiber (STF)	233.8	STF/(C+FA) = 0.25

In order to study the effects of mixing techniques on properties of RPC containing FA. A mix proportion was selected and utilized in this work as shown in Table 1. FA was adopted to partially replace cement at 15% by weight in the selected mix proportion that had a fixed water/(C+FA) ratio of 0.23. Noting that the amount of SP is the value to achieve a target flow value of about 200 mm for the control mixing.

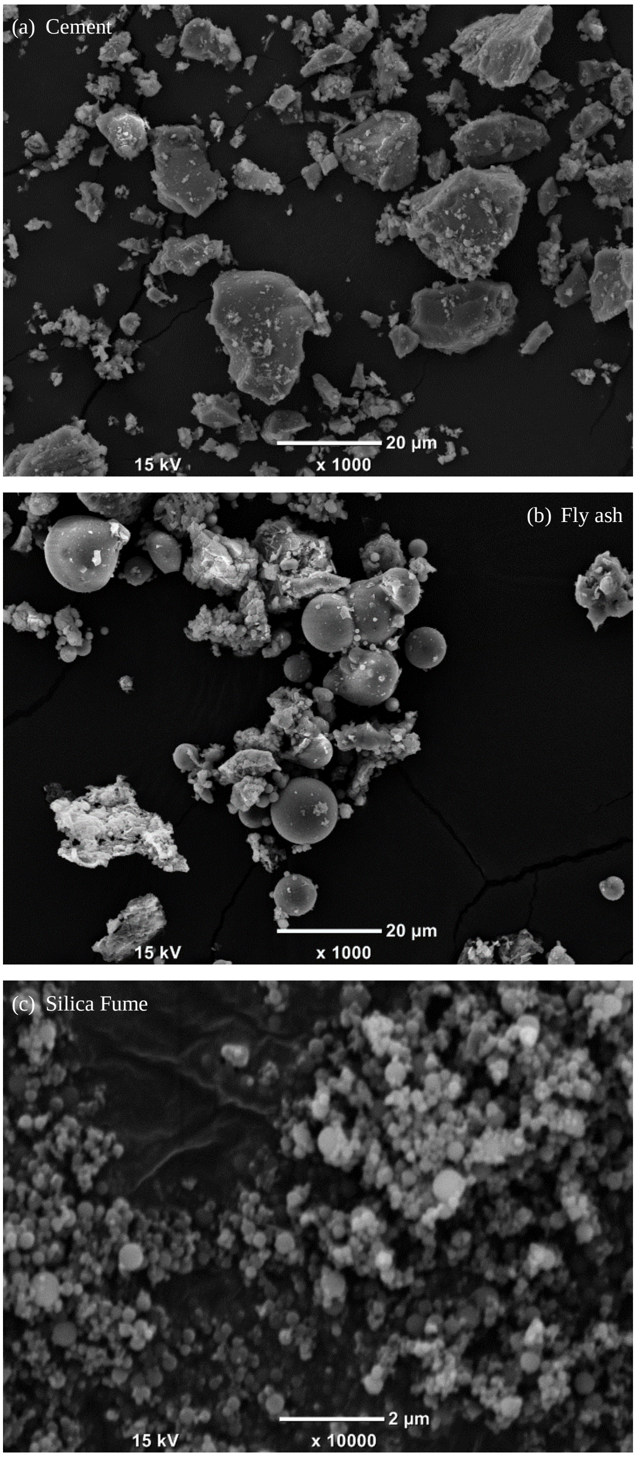

Fig. 1 SEM images of (a) cement, (b) fly ash, and (c) silica fume.

Fig. 2 Examples of steel fibers: (a) single-size and (b) mixed-size.

2.2 Mixing Methods

In this study, two mixing methods were chosen to investigate the effects of different techniques at mixing temperatures of 25°C and 40°C, using two types of steel fiber (single-size and mixed-size). The first method is the single-batching approach, commonly used for RPC mixing. The second method is the double-batching approach, introduced by [10], which employs a multi-step process aimed at reducing mixing torque. To maintain simplicity, more complex methods, such as triple-batching and other multi-step processes, were not considered. A mixer with a capacity of 5 liters, generally used for conventional concrete, was employed for the mixing process.

The single-batching method involved the following main steps: (1) mix all binders (C, SF, and FA), (2) add 80% of the premixed liquid (W and SP), (3) add all aggregate (S) along with the remaining 20% of the premixed liquid (W and SP) and continue mixing, and (4) add all fibers (STF) for the final mixing stage. The double-batching method used the main steps as follows: (1) mix all binders (C, SF, and FA) with all aggregate (S), (2) take half of the mixed binder and aggregate and add half of the premixed liquid (W and SP), (3) add the remaining half of the mixed binder and aggregate, along with the remaining half of the premixed liquid, and (4) add all fibers (STF) during the final mixing stage. In each step, the ingredients were continuously mixed until they were fully homogenized. The total mixing time was standardized to 14 minutes for both the single-batching and double-batching methods. Fig. 3 illustrates material preparing for the double-batching method.

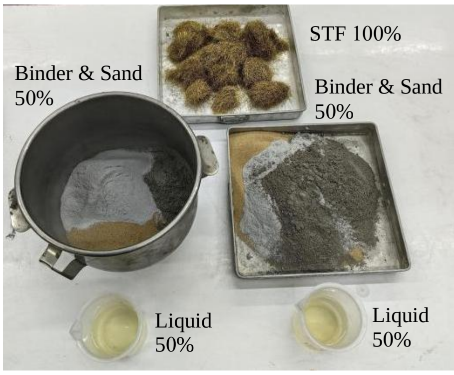

Fig. 3 Material preparing for the double-batching method.

2.3 Specimens and Tests

Test specimens for 7-day and 28-day compressive strength were prepared at temperature of 25°C, divided into three groups: Mix C served as the control mix, using the single-batching method with mixed-size steel fibers; Mix 1, using the double-batching method with mixed-size steel fibers; and Mix 2, using the double-batching method with single-size steel fibers.

Fig. 4 Specimen casting.

Fig. 5 Curing of specimens in water.

At the end of mixing, the workability of RPC in terms of flow value was evaluated according to ASTM C 1437 [16]. Afterwards, the specimens were cast into steel cube molds with dimensions of 50 x 50 x 50 mm. All samples were wrapped in plastic sheeting to prevent moisture loss, as shown in Fig. 4. After one day, the samples were removed from the molds and then cured in water until the day of the compression test, as shown in Fig. 5. The compressive strengths at 7 and 28 days were determined according to ASTM C 109/C 109M [17]. Fig. 6 shows an example of a sample before and after a compression test.

Fig. 6 Specimen examples before and after compression test.

3. Results and Discussion

3.1 Effects of Mixing Method

The results of the flow and compression tests of the RPC at temperature of 25°C are detailed in Table 2. The compressive strength values represent the average of four specimens. The results of the control mix (C) and Mix 1 illustrate the effects of the single-batching and double-batching methods. The double-batching method resulted in a 21.7% higher flow value (241 mm) compared to the single-batching method (198 mm). This increase is likely because the peak mixing torque of the double-batching method can be approximately halved compared to the single-batching method, as noted in [10]. In other words, the double-batching method requires less energy to achieve a homogeneous mix. This result aligns with the trend observed by [10], where a 3.5% increase was presented. However, as shown in Fig. 7, the double-batching method significantly affected only the 28-day compressive strength, yielding a 7.6% higher strength than the single-batching method. The 7-day compressive strengths were similar between the two methods. This result contrasts with the finding of [10], where no significant effect on compressive strength at any age was observed. The larger increases in both flow value and 28-day compressive strength observed in this study may be attributed to the influence of the rounded particles in the FA and SF as depicted in Figs. 1(b) and 1(c), respectively.

Table 2 Test results of RPC mixing at temperature of 25°C

Mix	Mixing Method	Steel Fiber Type	Flow Value (mm)	Comp. Strength (MPa)	
				7d	28d
C	Single-Batch	Mixed Size	198	89.4 (8.7%)	123.2 (12.2%)
1	Double-Batch	Mixed Size	241	88.3 (2.7%)	132.6 (8.6%)
2	Double-Batch	Single Size	257	88.5 (7.7%)	118.4 (10.4%)

Remark: 1) C is the control mix; 2) Values in the parentheses are coefficient of variation (COV).

However, in the practical application of RPC, each of these two approaches has some challenges and limitations that need to be further discussed and addressed. For example, although the processing of the single-batching method is simpler, due to the large amount of mixing at one time, local mixing inhomogeneity may occur during the mixing process, leading to problems such as fluctuating performance and poorer flowability of the RPC. Although the double-batching method helps to improve flowability, it is more complex to construct than the single-batching method, and the technical requirements for the construction personnel are even higher. If the mixing time, speed and material placement are not exactly the same in each batch, it can still result in uneven material properties, affecting the final quality and consistency. It also increases the complexity and cost of site management.

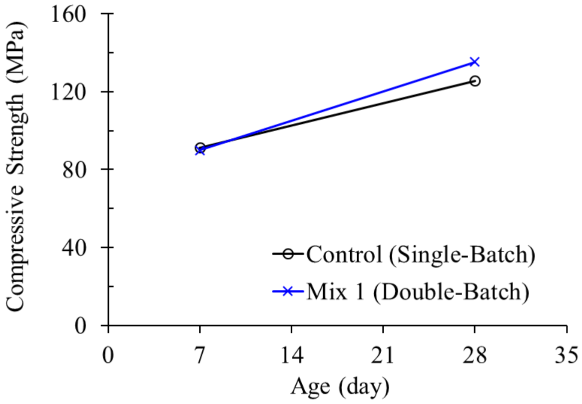

Fig. 7 Effect of mixing method on RPC strength.

3.2 Effects of Type of Steel Fiber

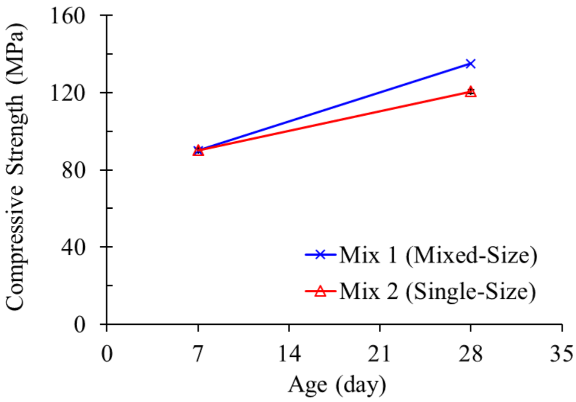

Fig. 8 Effects of type of steel fiber on RPC strength.

The previous section highlights the benefits of the double-batching method on the workability and 28-day strength of RPC with mixed-size steel fibers. In this section, the effects of steel fiber type on the double-batching method are presented and discussed by comparing the results of Mix 1, which used single size fibers with a constant aspect ratio of 59, and Mix 2, which used mixed-size fibers with an average aspect ratio of 56. The single-size fiber provided a 6.6% higher flow value compared to the mixed-size fiber, likely due to its constant aspect ratio and uniformity. However, as shown in Fig. 8, the single-size fiber negatively impacted the 28-day compressive strength, resulting in a 10.7% lower strength than the mixed-size fiber. The 7-day compressive strengths were similar between the two mixes as found and discussed in the previous section. The aspect ratio may be responsible for this effect, as a lower aspect ratio tends to result in higher compressive strength.

3.3 Effects of Mixing Temperature on Flow Value of RPC

In addition, the influence of mixing temperature, a critical factor affecting the mixing kinetics and workability of RPC, was examined in relation to the double-batching method, specifically its impact on flow value. The control mix with a lower SP of 45 kg/m^3 was used to for this investigation, with mixing at temperatures set at 25°C and 40°C to simulate RPC production under varying seasonal conditions. The test results are listed in Table 3. The test results show that increasing the mixing temperature from 25°C to 40°C caused the flow value to decrease by approximately 5.9%. At higher temperatures, water in the mixture generally evaporates more easily than at lower temperatures, contributing to this reduction. Du et al. [10] also reported that as mixing temperature increased, peak mixing torque was monotonically increased, implying reduced workability. These results confirm the trend that higher mixing temperatures result in lower flow values.

Table 3 Test results of RPC with different mixing temperature

Mix	SP (kg/m^3)	Mixing Temp.	Flow Value (mm)
C	45	25°C	187
		40°C	176

Remark: 1) C is the control mix.

4. Conclusions

This study highlights the significant effects of mixing techniques (single-batching and double-batching methods) and mixing temperatures (25°C and 40°C) on the properties of reactive powder concrete (RPC) containing fly ash with different steel fiber types (single-size and mixed-size). The findings demonstrate that the double-batching method enhances workability, as seen by a 21.7% increase in flow value, and also improves the 28-day compressive strength by 7.6% compared to the single-batching method.

The type of steel fiber used also impacts RPC performance; single-size fibers improve flow value but decrease 28-day compressive strength by 10.7% compared to mixed-size fibers. Additionally, higher mixing temperatures, specifically from 25°C to 40°C, reduce the flow value by approximately 5.9%, likely due to increased water evaporation. These findings suggest that optimizing mixing techniques, fiber types, and temperatures can significantly improve RPC's workability and mechanical properties.

Despite the increased complexity of the double batching method, it offers better mechanical properties and enhanced workability, which are especially crucial for large-scale production, where consistency and strength are key priorities. Future research should explore other factors that may influence the RPC properties, such as varying ingredient proportions, different raw materials, mixing speed, mixing duration, sequence of material addition, and mixing volume. This would help validate existing findings and provide deeper insights for optimizing the RPC production process, particularly for large-scale engineering projects. Furthermore, future studies should also assess the long-term performance of RPC and conduct comprehensive cost analyses to ensure both performance and economic feasibility in practical applications.

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