Performance Evaluation of Reactive Powder Concrete using Local Materials

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Abstract

Reactive Powder Concrete (RPC), a class of Ultra-High-Performance Concrete (UHPC), offers exceptional mechanical properties and durability, enabling reduced structural cross-sections, extended spans, intricate designs, and lower maintenance needs. Despite its potential, RPC remains in the early stages of development, with its performance highly dependent on material selection, mix proportions, mixing techniques, and curing methods. In Thailand, RPC is still relatively unexplored, necessitating further research using locally available materials. Additionally, the high production cost remains a significant barrier to its widespread application.

This study experimentally investigates the mechanical properties of RPC using local materials and designed to reduce material cost. Compressive strength was evaluated at 3, 5, 9, and 28 days, while flexural and splitting tensile strengths were assessed at 28 days. Additionally, predictive models from the literature were examined for their accuracy in estimating RPC's mechanical properties. Finally, correlations between compressive strength, splitting tensile strength, and flexural strength were analyzed.

Keywords: Reactive Powder Concrete, Ultra-High-Performance Concrete, low-cost concrete, mechanical properties, fiber-reinforced concrete

1. Introduction

Reactive powder concrete (RPC) was first developed in France in the early 1990s. it is distinguished by its densely packed particles, very low water-to-cement (w/c) ratio, high cement and silica fume content, and the inclusion of small steel fiber [1, 2]. As a subset of Ultra-High-Performance Concrete (UHPC), RPC represents a new generation of concrete characterized by high workability, compressive strength about 120 MPa, a high modulus of elasticity, low permeability, and outstanding durability [2]. These superior mechanical and durability properties make RPC suitable for reducing structural dimensions, extending spans, enabling complex designs, and lowering maintenance needs [3].

Despite its potential, RPC remains in the developmental stages, with its performance highly dependent on material selection, mix proportions, mixing techniques, and curing methods [4, 5]. In Thailand, RPC research and application are still limited, highlighting the needs for further investigation using locally available materials. One of the primary barriers to its broader adoption is its high production cost, mainly due to significant use of cement (typically 800 – 1200 kg/m^3) [6], silica fume (around 20% of cement content) [1], and steel fibers. As a result, recent research efforts have focused on partially replacing cement with alternative materials to reduce cost and environmental impact [2].

This study aims to experimentally investigate the mechanical properties of RPC produced with locally sourced materials and designed to reduce material cost by incorporating lower amounts of cement, silica fume, and steel fibers. Compressive strength was evaluated at 3, 5, 9, and 28 days, while flexural and splitting tensile strengths were assessed at 28 days. Additionally, predictive models from the literature were examined for their accuracy in estimating RPC's mechanical properties. Finally, the relationships between compressive strength, splitting tensile strength, and flexural strength were analyzed.

2. Materials and Methods

2.1 Materials

Most of the materials used in this study are commonly found in the concrete industry in Thailand. The binders adopted included cement, silica fume, and fly ash. The cement (C) used was a hydraulic type produced by Siam Cement Group, Thailand conforming to the TIS 2594-2556 industrial standards [7]. Silica fume (SF) was an undensified product supplied by Eikem company, Thailand. Fly ash (FA), compliant with ASTM C618, was provided by Taurus Pozzolan Company, Thailand.

Sand (S) was graded river sand from the Chi River, Thailand, with particle sizes ranging from 0.15 to 0.60 mm and used in a saturated surface dry (SSD) condition with 0.4% moisture content. The superplasticizer (SP) used was of the polycarboxylate type, and tap water (W) was used for mixing.

Straight steel fibers were incorporated in two types. The first type, referred to as single-size fiber (F1), has a diameter of 0.22 mm and a length of 13 mm, corresponding to an aspect ratio of 59. The second type, referred to as mixed-size fiber (F2), consisted of fibers with diameters ranging from 0.18 mm to 0.35 mm and lengths from 12 mm to 14 mm yielding an aspect ratio range of 34-78, with an average of 56. It is worth noting that the mixed-size fiber (F2) is cheaper than the single-size fiber (F1).

Table 1 Chemical compositions of silica fume and fly ash.

Composition	SF	FA
SiO_2 (%)	94.80	53.03
Al_2O_3 (%)	0.15	16.97
Fe_2O_3 (%)	0.03	6.22
CaO (%)	0.88	15.69
MgO (%)	0.70	0.78
SO_3 (%)	0.96	4.09
Na_2O (%)	0.20	0.35
K_2O (%)	1.98	1.27
TiO_2 (%)	0	0.98
LOI (%)	0.01	0.01

The chemical compositions of SF and FA are presented in

Table 1. The SF contained more than 90% SiO_2, while the FA was classified as Class F, with the combined content of SiO_2, Al_2O_3, and Fe_2O_3 exceeding 70% and SO_3 content below 5%. Fig. 1 displays the main raw materials used in this study. The colors of the cement, silica fume, and fly ash were gray, light gray and light brown, respectively.

Fig. 1 Raw materials.

2.2 Mix Proportioning

To reduce material costs, the mix design utilized a low cement content (66% by mass), a high proportion of fly ash (32% by mass), and a minimal amount of silica fume (2% by mass). Typical RPC parameters include a water-to-binder ratio (w/b) of 0.15-0.25 [8], a binder-to-sand ratio (b/s) of 0.7-1.5 [9], and a fiber volume content of 2-5% [10]. In this study, the RPC mixture was designed with a w/b ratio of 0.18, a b/s ratio of 1.207, and fiber content not more than 2%.

A target flow of 200-250 mm was selected to ensure adequate workability. The mechanical properties of the developed RPC were evaluated and compared to a typical RPC reference. Additionally, the effects of fiber content and fiber type (F1 and F2) were investigated. The mix proportions and corresponding flow values are summarized in Table 2.

Table 2 Compositions (kg/m^3) and flow values (mm) of all mixes.

Mix	Ref-3%F1	M1-2%F1	M2-0.5%F2	M3-1%F2	M4-1.5%F2	M5-2%F2
C	935	728.44				
SF	187	20.35				
FA	-	349.65				
W	215	197.72				
S	1028.5	906.50				
SP	30	100	100	100	90	85
F1	233.8	157	-	-	-	-
F2	-	-	39.5	78.5	117.75	157
Flow	211	224	230	224	206	224

Fig. 2 illustrates the flow test conducted in accordance with ASTM C1437 [11], performed without the use of a flow table. The RPC mixture exhibited sufficient flowability under gravity alone.

Fig. 2 Flow test.

2.3 Specimen preparations

All specimens were prepared at room temperature in the laboratory. During the mixing process, all dry binders were first blended in a mixer. Subsequently, 80% of the premixed liquid part (W+SP) was added to the mixer. Sand was then incorporated into the mixture, followed by the remaining 20% of the liquid part. In the final stage, steel fibers were gradually introduced, and the mixture was blended until a fully uniform and consistent mix was achieved.

After mixing, the flow values were measured. The fresh mixes were then cast into steel molds and covered with plastic sheets to prevent moisture loss. After 24 hours, the specimens were demolded and transferred to water for curing until the designated testing age.

Table 3 Details of mechanical tests carried out on specimens of each mixture.

Property	Specimen	No. of specimen	Specimen Age	Standard
Compressive strength	50 mm x 50 mm x 50 mm cube	4	3, 7, 9, 28 days	ASTM C109
Splitting tensile strength	100 mm x 200 mm cylinder	4	28 days	ASTM C496
Flexural strength	75 mm × 75 mm × 280 mm prism	4	28 days	ASTM C78

2.4 Testing of mechanical properties

All mixtures were evaluated for three key mechanical properties: compressive strength, splitting tensile strength, and flexural strength. Compressive strength was determined at 3, 5, 9, and 28 days in accordance with ASTM C109 [12], using cube specimens measuring 50 mm x 50 mm x 50 mm. Splitting tensile strength was assessed at 28 days following ASTM C496 [13], using cylindrical specimens with a diameter of 100 mm and a height of 200 mm. Flexural strength at 28 days was determined according to ASTM C78, using prism specimens with dimensions of 75 mm × 75 mm × 280 mm.

Details of the specimen preparation and testing procedures are summarized in Table 3, while an overview of the testing setup is presented in Fig. 3.

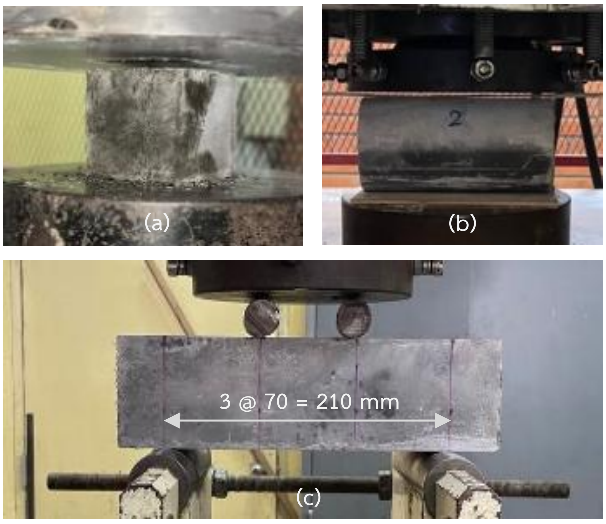

Fig. 3 Testing of mechanical properties: a) compressive strength, b) splitting tensile strength, and c) flexural strength.

3. Results and Discussion

3.1 Comparison of mechanical properties between developed and reference RPC mixes

The newly developed mix, Mix M1-2%F1 – designed to reduce material costs - was compared to Mix Ref-3%F1, a typical RPC mix. In terms of compressive strength, Fig. 4 illustrates that Mix M1-2%F1 exhibited reductions of 66%, 55%, 48%, and 45% at 3 days, 5 days, 9 days, and 28 days, respectively, compared to Mix Ref-3%F1. At 28 days, the compressive strength of Mix Ref-3%F1 reached 123.8 MPa, while Mix M1-2%F1 achieved 68.4 MPa. The significant reduction in compressive strength can be attributed primarily to the lower contents of cement and silica fume [1, 2]. However, the decreasing trend in strength reduction with increasing age may result from the pozzolanic activity of the high fly ash content and the prolonged hydration period [2]. Both mixes followed a similar pattern in strength development over time. Additionally, the high dosage of superplasticizer might have contributed to strength reduction, possibly due to delayed setting or dispersion effects.

Regarding tensile performance, Mix M1-2%F1 showed splitting tensile and flexural strengths of 8.9 MPa and 10.9 MPa, respectively – representing reductions of approximately 59% and 50% compared to Mix Ref-3%F1, which achieved 21.8 MPa and 21.9 MPa, respectively, as shown in Fig. 5.

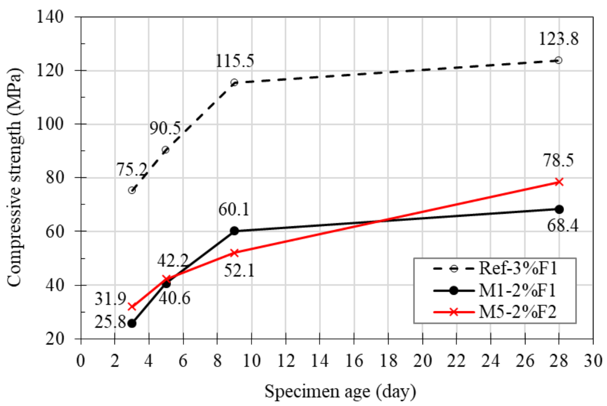

Fig. 4 Effects of new mix proportion and steel fiber type on compressive strength.

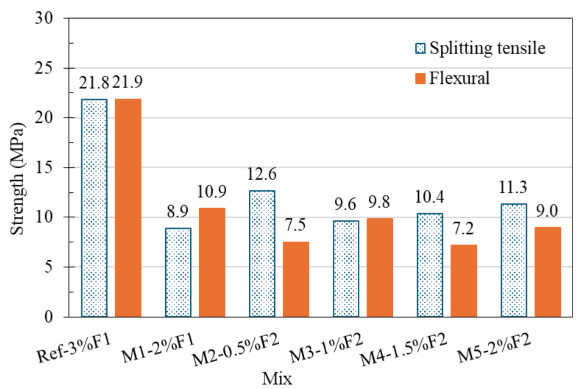

Fig. 5 Splitting tensile and flexural strengths of each mix.

3.2 Effects of fiber type

The comparison between Mix M1-2%F1 and Mix M5-2%F2 highlights the influence of fiber type on mechanical properties. As shown in Fig. 4, Mix M5-2%F2 achieved higher compressive strengths than Mix M1-2%F1 by 24%, 4%, and 15% at 3, 5, and 28 days, respectively, with the exception of the 9-day result. The 28-day compressive strength of Mix M5-2%F2 was 78.5 MPa. Although both fiber types have similar average aspect ratios – 59 for F1 and 56 for F2 – the variation in fiber dimensions in F2 may contribute to a denser internal structure, potentially improving compressive strength. Previous study has also reported similar trends [4], lower or varied aspect ratios can enhance compressive strength.

In terms of tensile performance, Mix M5-2%F2 exhibited a 27% increase in splitting tensile strength compared to Mix M1-2%F1, reaching 11.3 MPa. However, its flexural strength was 18% lower, at 9.0 MPa, as shown in Fig. 5. This contrasting behavior may be attributed to the different fiber geometries and distributions, which can affect crack-bridging efficiency under bending stress. The complex interaction between fiber dimensions and mechanical performance needs further investigation.

3.3 Effect of fiber content

In general, compressive strength is expected to increase with higher fiber content. However, based on the results from Mixes M2, M3, M4, and M5 – containing mixed-size fibers (F2) at 0.5%, 1%, 1.5%, and 2%, respectively – early-age compressive strength (up to 9 days) appeared to be relatively unaffected by fiber content. At 28 days, the highest compressive strength of 83.3 MPa was recorded for the mix with 0.5% fiber content. In comparison, the mix with 2% fiber content showed a 6% reduction in strength, as illustrated in Fig. 6.

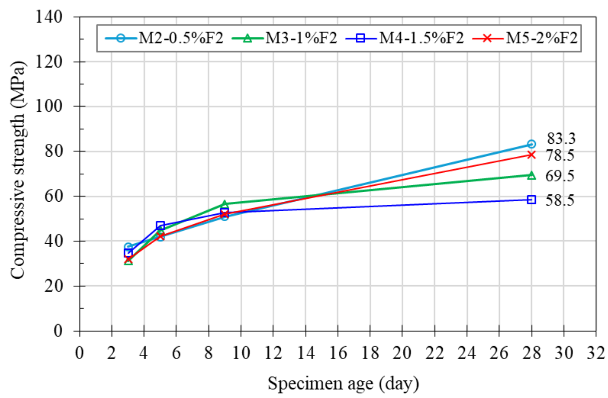

Fig. 6 Effects of fiber content on compressive strength.

For splitting tensile strength, the optimal result was also observed at 0.5% fiber content, reaching 12.6 MPa. The mix with 2% fiber content showed a 10% decrease in strength relative to this peak value. In contrast, flexural strength reached its maximum at 1% fiber content, reaching 9.8 MPa. The mix with 2% fiber content followed, with a 9% reduction, as depicted in Fig. 5.

These findings suggest that while moderate fiber content can enhance mechanical performance, excessive fiber dosage may lead to fiber clumping, potentially offsetting strength gains.

3.4 Relationship between splitting tensile strength and compressive strength

Based on the test results, the 28-day splitting tensile strength (f_{spt}) generally increased with the 28-day compressive strength (f'_c), as shown in Fig. 7. A relationship between these properties was established and is proposed in Eq. (1). This proposed relationship was compared with predictive models from ACI 318-19 [14] and Arioglu et al. [15], expressed in Eqs. (2) and (3), respectively.

$$f_{spt} = 0.82\sqrt{f'_c} \quad \text{(MPa)} \tag{1}$$

$$f_{spt} = 0.56\sqrt{f'_c} \quad \text{(MPa)} \tag{2}$$

$$f_{spt} = 0.387\left(f'_c\right)^{-0.37} f'_c \quad \text{(MPa)} \tag{3}$$

The comparison reveals that the ACI 318-19 model provides the most conservative estimates, followed by the equation proposed by Arioglu et al. [15]. In contrast, the equation developed in this study yielded the least conservative predictions, offering values more closely aligned with the experimental data, as illustrated in Fig. 7.

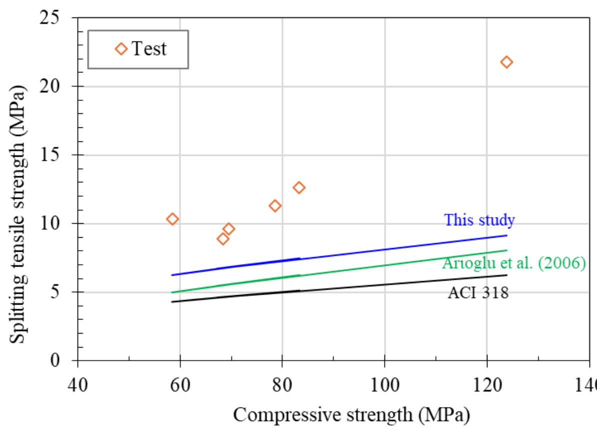

Fig. 7 Splitting tensile strength – compressive strength relationship.

3.5 Relationship between flexural strength and compressive strength

Based on the test results, the 28-day flexural strength (f_r) generally increased with the 28-day compressive strength (f'_c), although a high degree of scatter was observed, as shown in Fig. 8. Despite this variability, a relationship between the two properties was formulated and is proposed in Eq. (4). This proposed model was compared with predictive equations from ACI 318-19 [14] and Leemann and Hoffmann [16], presented in Eqs. (5) and (6), respectively.

$$f_r = 0.82\sqrt{f'_c} \quad \text{(MPa)} \tag{4}$$

$$f_r = 0.62\sqrt{f'_c} \quad \text{(MPa)} \tag{5}$$

$$f_r = 0.11 f'_c \quad \text{(MPa)} \tag{6}$$

The comparison indicates that the ACI 318-19 model provides the most conservative estimates, followed by the equation developed in this study, while the model proposed by Leemann and Hoffmann [16] offered the least conservative predictions. These trends are illustrated in Fig. 8.

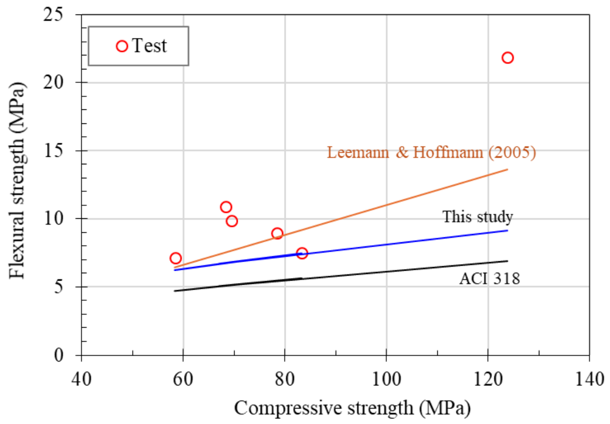

Fig. 8 Flexural strength – compressive strength relationship.

4. Conclusions

This study experimentally investigated the mechanical properties of Reactive Powder Concrete (RPC) produced with locally sourced materials and designed to reduce material costs. The results revealed that significant reductions in cement, silica fume, and fiber content can produce a more economical RPC mix, although with some compromises in strength when compared to a conventional RPC. The key conclusions are summarized as follows:

1) The designed mix (M1-2%F1) achieved a 28-day compressive strength of 68.4 MPa, which is lower than the reference mix (123.8 MPa) but still suitable for many structural applications.
2) The use of mixed-size steel fiber (F2), a more economical alternative to single-size steel fiber (F1), resulted in improved compressive and splitting tensile strengths but reduced flexural strength.
3) The optimal content of F2 fibers for balancing cost-effectiveness and performance was found to be between 0.5% and 1%.

4) Empirical relationships were developed to correlate compressive strength with both splitting tensile and flexural strengths, providing useful predictive tools for practical applications.

It is also noted that the designed RPC mixtures required a relative high dosage of superplasticizer to achieve the target flowability, which may have contributed to strength reduction. Therefore, further research is recommended to explore improved mixing techniques or alternative admixtures that could reduce the demand for superplasticizer while maintaining workability and strength.

Acknowledgement

This research project was financially supported by Faculty of Engineering, Mahasarakham University. This support is gratefully acknowledged.

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